IMPACT OF FALLOW LENGTH, ORGANIC AMENDMENTS, BREAK CROPS AND TILLAGE ON SOIL BIOTA AND SUGARCANE GROWTH

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Abstract

FIELD experiments were established at Bundaberg (South Queensland) and Abergowrie (North Queensland) to quantify the impact of different durations of bare fallow and inputs of organic materials of differing quality (grass, legume or grass/legume mixtures) and origin (grown *in situ* or imported) on soil biota and growth and yield of sugarcane crops. Fallow lengths ranged from 1 month to 30 (Bundaberg) or 35 months (Abergowrie). Imported organic materials were added as finely chopped hays to add 10 t C/ha, while C inputs from crops grown *in situ* varied depending on crop frequency and seasonal conditions. The impacts of tillage prior to cane planting were also investigated for the *in situ* organic matter treatments at both sites, while soil fumigation was used to benchmark potential biological constraints in the bare fallow treatments. Significant differences between treatments were recorded in soil C, general soil biology and the incidence of known cane pathogens. All parameters declined with increasing length of bare fallow, although cane specific pathogens like *Pratylenchus zeae* declined more rapidly than general biological activity. Imported organic amendments caused only small changes in soil biology and chemistry, but *in situ* grass pastures were able to achieve soil C and biological activity similar to those found in soil in the cane rows. Long-term legume cropping generally resulted in less soil C and biological activity, especially when plots were tilled conventionally. There were significant differences in the resident soil microbial communities under cane, grass pastures and legume cropping. Despite the large changes in soil biota in the long bare fallows and *in situ* grass or legume treatments, growth responses of a subsequent plant cane crop were negligible at Abergowrie and relatively small at Bundaberg (10–30%). No treatment was able to match improvements achieved in fumigated ploughout/replant. The best crop responses were achieved from the *in situ* organic matter treatments, especially the grass pastures, with part of this response possibly due to slower re-establishment of pathogens like lesion nematode. Tillage after both grass pasture and legume cropping increased the rate of recovery of lesion nematode populations. Results have implications for management of residues and cane trash in the sugarcane cropping system. Future cropping systems need to maximise the soil health benefits of sugarcane cropping (perennial growth, regular returns of organic matter) by adopting complementary management strategies (short legume fallows, reduced tillage, optimal use of cane trash) that build on these strengths.

Introduction

The sugar industry in north-eastern Australia has experienced a productivity plateau which has been evident for most of the past 30 years (Garside *et al.*, 1997). A number of factors have contributed to this industry-wide statistic, but the health of soils supporting the sugarcane farming systems is seen as a major contributing factor (Bell *et al.*, 2005; Garside *et al.*, 1997).

The presence of soil-borne pests and diseases in the sugar industry is an obvious symptom of poor soil health. There are many clearly identified pests and diseases causing yield losses in sugarcane fields (e.g. many species of white grubs [*Coleoptera: Melolonthinae*], collectively known as canegrubs (Allsopp and Chandler, 1989); root rots caused by *Pachymetra chaunorhiza* (Magarey, 1994); lesion nematode [*Pratylenchus zeae*] (Blair *et al.*, 1999a, b)). However, there is also evidence of a complex of minor pathogens reducing sugarcane root health (e.g. unidentified deleterious fungi (Pankhurst *et al.*, 2005c); dematiaceous fungi (Magarey *et al.*, 2005); other plant parasitic nematodes (Stirling *et al.*, 2001)) and impairing root system function (Bell *et al.*, 2004).

The beneficial impact of rotation breaks on the productivity of subsequent sugarcane crops has been well documented (e.g. Garside *et al.*, 1999, 2000; Bell *et al.*, 2001a). These yield benefits have been attributed in part to improved soil health via a reduction in cane-specific pathogens and/or a better balanced soil microbial community (Pankhurst *et al.*, 1999, 2003; Stirling *et al.*, 2001).

While yield improvements in different types of long breaks are often of a similar magnitude relative to a cane monoculture (i.e. $\geq$ +20% – Garside *et al.*, 1999, 2000, 2002), each break has changed different components of the soil microbial community (Pankhurst *et al.*, 2003) and been differentially effective at eliminating cane-specific pathogens (Pankhurst *et al.*, 2005b).

These studies were not designed to investigate the impact of break length on the magnitude of the break response, although longer (>30 months) rotation breaks did produce larger growth responses in the following cane crop than short (9–12 months) rotation breaks at Mackay (Garside *et al.* 1999).

Biological suppression of crop-specific pathogens has developed under wheat monocultures in southern Australia (e.g. Roget *et al.*, 1999), although only with stubble retention and the elimination of tillage. While there has been no evidence of suppression of cane-specific pathogens with trash retention and green cane harvesting, Stirling *et al.* (2003, 2005) have demonstrated that amending sugarcane soils with large quantities of selected organic materials, including cane trash, could suppress lesion nematodes. Unfortunately, these organic amendments were less successful at suppressing other organisms in the yield decline complex (Pankhurst *et al.*, 2005a).

The role of organic matter inputs from the alternate crop and pasture breaks in cane yield increases after rotation breaks has not yet been explained. Similarly, the relative importance of break crop root systems (and associated rhizosphere organisms), as opposed to different crop residues, and the extent and frequency of tillage during the rotation breaks have not been clarified. This paper reports the findings from experiments established in north and south Queensland to address these gaps in understanding of the break response.

Materials and methods

Experiments were run in parallel in long-term cane fields near Abergowrie in North Queensland and near Bundaberg in South Queensland. In each case, blocks were chosen for uniformity and then divided into three replicates, with each of the 18 treatments (Table 1) randomly allocated to plots that consisted of 6 individual cane rows (1.8 m inter rows) wide and 20 m (Abergowrie) or 30 m (Bundaberg) long. Laneways 3–3.6 m wide were established between plots longitudinally to allow access, with 5 m gaps between plots. The first long fallow plots had cane removed after the 2000 harvest, with cane replanted into all plots during September 2003.

At Abergowrie, plots with added organic matter were split longitudinally at the time of organic matter incorporation into subplots 3 rows wide by 20 m long. At Bundaberg, the bare fallow treatments with no added organic matter were split into 6 rows by 15 m subplots to allow soil fumigation to be undertaken. Soil was not fumigated at Abergowri.e.

Table 1—List of treatments employed at the Bundaberg and Abergowrie experimental sites.

Treatment description	Nominal fallow length[A]	Site	Organic matter added	Source of organic matter	Tillage prior to cane
			Part A		
Ploughout/Replant	1 month	Both	Nil	NA	Yes
Bare6	6	Both	Nil	NA	Yes
Legume6	6	Both	10t C/ha	Imported hay	Yes
Grass6	6	Both	10t C/ha	Imported hay	Yes
Mix6	6	Both	10t C/ha	Imported hay	Yes
Bare12	12	Bundaberg	Nil	NA	Yes
Legume12	12	Bundaberg	10t C/ha	Imported hay	Yes
Grass12	12	Bundaberg	10t C/ha	Imported hay	Yes
Mix12	12	Bundaberg	10t C/ha	Imported hay	Yes
Bare18	18	Both	Nil	NA	Yes
Legume18	18	Abergowrie	10t C/ha	Imported hay	Yes
Grass18	18	Abergowrie	10t C/ha	Imported hay	Yes
Mix18	18	Abergowrie	10t C/ha	Imported hay	Yes
Bare30	30	Both	Nil	NA	Yes
Legume30	30	Both	10t C/ha	Imported hay	Yes
Grass30	30	Both	10t C/ha	Imported hay	Yes
Mix30	30	Both	10t C/ha	Imported hay	Yes
			Part B		
ContinualgrassCT[B]	30	Both	Hay, litter, roots	Grown *in situ*	Yes
ContinualgrassDD[B]	30	Both	Hay, litter, roots	Grown *in situ*	No
ContinualsoyCT[B]	30	Both	Hay, litter, roots	Grown *in situ*	Yes
ContinualsoyDD[B]	30	Both	Hay, litter, roots	Grown *in situ*	No

[A] Fallow lengths at Abergowrie were ca. 5 months longer than intended (11, 23 and 35) due to a delay in planting time caused by dry conditions.

[B] DD refers to direct planting cane following the break with no soil disturbance other than using a disc opener planter; CT refers to full conventional soil tillage prior to cane planting.

Site description

The Bundaberg site was in the same block as the farming systems study at South Kalkie reported by Bell *et al*. (2003). Briefly, the experiment was established on a yellow podsolic soil with a fine, loamy sand A horizon. The variety Q124 was growing in 1.8 m dual rows on the site, with initial treatments imposed after a green cane harvest of the plant crop late in the 2000 crushing season. A commercial cane block on a river alluvial (sandy loam) soil at Elphinstone was chosen as the Abergowrie site, with Q115 growing in 1.5 m single rows on this block. Initial treatments were imposed after the 2R harvest in August 2000.

Supplementary irrigation was applied to the Bundaberg site using either flood irrigation (during the fallow/break sequences) or by overhead application using a low pressure boom (during the cane cycle). The Abergowrie site was grown under rainfed conditions in both the pre-treatment and test crop phases.

Treatment details

The existing ratoon cane at each site was maintained as a normal commercial crop with green cane harvesting, with cane removed from each plot as the desired fallow length was achieved. At this time, the cane was harvested commercially, regardless of crop age, with trash and tops returned to the field. Plots were tilled to remove the old stool, reformed into beds to suit 1.8 m cane planting and kept bare using a combination of tillage and knockdown herbicides (bare fallows) or sown to grass (Rhodes grass [*Chloris gayana*] or signal grass [*Brachiara decumbens*]) or soybean (*Glycine max.*) in the i*n situ* organic matter treatments.

Imported organic matters were applied to the relevant plots 6 months prior to cane planting and incorporated using conventional tillage. Prior to application, the 'grass' (cane trash at Bundaberg and Rhodes grass at Abergowrie) and legume (soybean at Bundaberg and lucerne [*Medicago sativa*] at Abergowrie) materials, obtained as dry hays, were hammer milled to reduce fragment size, improve uniformity of distribution, and make incorporation easier. Materials were spread over the soil surface and incorporated with a rotary hoe at Bundaberg at rates equivalent to 10 t C/ha. At Abergowrie, the organic matters were placed in a slot some 30 cm wide and 30 cm deep in the position of the future cane rows. This band of organic matter was buried by filling in the slot in one subplot ('slotted material'), and by incorporating the organic matter through the profile in the 30 cm band ('mixed material') by use of a rotary hoe. The rates of C addition at Abergowrie were only 30% of those at Bundaberg on a total area basis, but were at similar concentrations to Bundaberg in the band (i.e. 10 t C/ha based on the surface area of the band).

The *in situ* soybean (cv Leichhardt and cv CLS1112 at Bundaberg and cv Leichhardt at Abergowrie) or grass (Katamboora Rhodes grass at Bundaberg and signal grass at Abergowrie) treatments were managed according to species. The grass plots were established as a sward on the preformed cane beds, and then slashed periodically and allowed to regenerate throughout the next 25–28 months. Soybean crops, on the other hand, were sown in rows 45–50 cm apart (3 rows per 1.8 m cane 'bed') and biomass was mulched when crops were near maturity, or left as a standing residue. Plots were then re-sown as soon as weather permitted using direct drilling to achieve minimal soil disturbance, in an attempt to achieve a near-permanent legume sward within the confines of the future 1.0 m wide cane bed. Dry seasons and a lack of irrigation meant soybean cropping at Abergowrie was intermittent, especially during the latter part of the break period. Only 3 soybean crops were grown, covering the periods Jan–May 2001, June–Oct 2001 and Dec 2001–March 2002, with the last crop left standing until cane planting some 17 months later.

Prior to cane planting, the current grass or soybean standing biomass in the *in situ* treatments was slashed and residues returned to the soil surface. In the DD plots (in which cane was to be direct planted), regrowth was controlled with herbicides, while the CT plots were prepared using conventional tillage. All bare fallow plots were worked conventionally prior to cane planting.

Before replanting, fallow plots without added organic matter at Bundaberg were split into 6 row, 15 m subplots, with one of the subplots fumigated with methyl bromide at a rate of 1000 kg/ha. The methyl bromide was injected at a depth of 20 cm using commercial fumigation equipment and the soil was sealed immediately with polyethylene sheeting.

Cane cultural practices

Cane (var. Argus at Abergowrie and var. Q188$^{\phi}$ at Bundaberg) was planted in August and September 2003, respectively, with the Abergowrie site terminated after the plant crop and the Bundaberg site after the 1st ratoon crop. A single row, double disc opener planter was used to establish 1.8 m single rows at Abergowrie while, at Bundaberg, a two row, double disc opener was used to plant dual rows (50 cm interspaces) on 1.8 m centres. Setts were treated with a fungicide dressing at both locations (Shirtan^R), while the insecticide chlorpyrifos was applied using different methods at each site—a below furrow application of Suscon^R granules at Abergowrie and an in-furrow spray of Lorsban^R at Bundaberg.

Basal fertiliser was applied at Bundaberg (40 kg N/ha, 44 kg P/ha and 200 kg K/ha), with the K applied in 3 bands across the bed top pre-planting (and prior to the final cultivation in the conventionally tilled plots), while N and P were applied in a band at planting. Due to the inherently higher fertility levels at Abergowrie, no basal fertiliser was applied, but both sites had N applied at ca. 3 months to ensure total fertiliser N inputs of 200 kg N/ha.

Soil, plant and soil biota sampling

Shoot counts were taken at regular intervals during the first 6–8 weeks after planting to determine crop establishment, at the time of destructive samples and at maturity. Biomass samples were taken at 3 months after planting (early biomass) at Bundaberg, 6–7 months after planting at both sites (mid-season biomass) and at maturity. Samples were taken from 5 m lengths of the centre row at Abergowrie (9 m^2), and from 5 m lengths of the centre 3 rows (early biomass) or 2 rows (mid season biomass and maturity) at Bundaberg.

At maturity, all experiments were harvested by hand, with the number of stalks harvested and total fresh weight recorded and a sub-sample of 20–30 randomly selected stalks stripped to determine the proportions of millable stalk and trash (cabbage, green and dead leaf). Millable stalk was separated from the leaf and cabbage between the 5th and 6th leaves from the top of the plant.

Samples of millable stalk and trash from each plot were collected for determination of moisture content, while total fresh and dry weights and total stalk numbers were used to determine individual stalk weights. A subsample of 6 millable stalks was selected from the larger subsample to determine ccs following juice extraction using the small mill, and sugar yields (t/ha) were calculated.

Samples to determine the impact of fallow length on soil profile C and N stores (to 90 cm) were collected just before the addition of imported organic matters (i.e. after up to 24 months bare fallow). Profiles were partitioned into 10 cm increments in the top 30 cm and then in 20 cm increments to 90 cm, with at least 6 cores (10 cm diam.) taken in each plot and bulked. Soils were dried at 40°C and analysed for C and N contents using a Leco combustion furnace (Rayment and Higginson, 1992).

Samples were also collected from the top 30 cm of the profile at cane planting to compare C and N status of soils with imported or *in situ* organic matter inputs and to assess the impact of treatments on labile C, determined as the amount of C oxidised by 33 mM $KMnO_4$ (Bell *et al.*, 1998). These soil samples were also used to determine the impact of treatments on soil biology, with additional samples taken at harvest of the plant crop.

Microbial biomass C and microbial activity, culturable fungi and bacteria and numbers of spores of *Pachymetra chaunorhiza* were determined using methods described in Pankhurst *et al.* (1995, 1999) and Magarey *et al.* (1997). Plant-parasitic nematodes (PPN) and free living nematodes (FLN) were also extracted and counted (Stirling *et al.* (2001).

Statistical analyses

Standard analysis of variance techniques were used to determine the impact of treatments on soil parameters, crop biomass production and final yields. A nested design was employed to test factorial treatment combinations within the larger treatment group. Soil biological data (especially nematode numbers) were generally transformed using log (x + 1) before analysis. Least squares linear regression techniques were used to describe the relationship between length of fallow and a range of biological, chemical and plant parameters.

Results and discussion

Organic matter addition

The availability of irrigation at Bundaberg allowed *in situ* organic matter treatments to input similar amounts of total C as in the imported organic matter treatments. The 5 consecutive soybean crops sown in the *in situ* soybean plots returned *ca*. 21 t tops dm/ha from April 2001 until April 2003, with the final 4 months maintained as a clean fallow.

Similarly, the Rhodes grass sward was mowed 5 times, returning *ca*. 20 t tops dm/ha. Root biomass was also measured in these treatments in May 2003, 6 months prior to cane planting, with significant differences in below ground root biomass recorded between soybean and grass.

The continuous cane treatments contained 6.3 ± 1.2 t/ha root dm in the top 80 cm of the soil profile while the 24 month bare fallow still contained 3.1 ± 0.7 t/ha root dm—approximately half the root biomass of the continuous cane treatment. Root biomass recorded under continuous soybean cropping (3.6 ± 0.3 t/ha root dm) was similar to the bare fallow, while the Rhodes grass pasture (12.6 ± 0.5 t/ha) contained twice the root biomass of the continuous cane.

Using an approximate C concentration in biomass of 40%, the total C inputs were 10 (soybean) to 13 (grass) t C/ha, similar to the C inputs from the imported organic materials (Table 1).

The grass pasture at Abergowrie returned 24 t/ha tops dm in 6 cuttings from January 2001 until February 2003, but dry seasonal conditions only allowed 3 soybean plantings that produced 11 t/ha tops dry matter—approximately half the dry matter return from the grass pasture at the same site and with an extended bare fallow of 18 months prior to cane planting. Root biomass was not recorded.

Soil carbon and nitrogen status

The extreme treatments (24 month bare fallow, continuous cane, grass pasture and continuous soybean cropping) resulted in significant differences in soil C and N stores at Bundaberg but not Abergowrie, and the differences in Bundaberg were not necessarily in line with expectations (Figure 1 a, b, c, d).

As a general rule total soil C declined in long bare fallows at both sites but, while total N tended to increase with the continuous soybean cropping at Abergowrie, it actually declined significantly at Bundaberg.

The reasons for the Bundaberg N effect are unclear, but may be associated with the high N, high soluble C residues produced by soybean combined with a poorly drained soil and flood irrigation/periodic wet conditions. These conditions would have favoured denitrification losses that could explain the apparent conservation of C but loss of N under continuous soybean.

Samples from the row and inter-row positions in the soybean and continuous cane treatments were combined to calculate the average C and N contents for the whole soil profile (as would be relevant after conventional tillage and random row repositioning), and this changed the relative impact of these treatments.

Profile C in the inter-rows in both cane and soybean treatments was not significantly different to that in 24 month bare fallows, indicating a distinct lack of root activity in the compacted inter-row areas. The main C inputs in inter-rows would have been crop residues from trash blankets or mulched material on the soil surface.

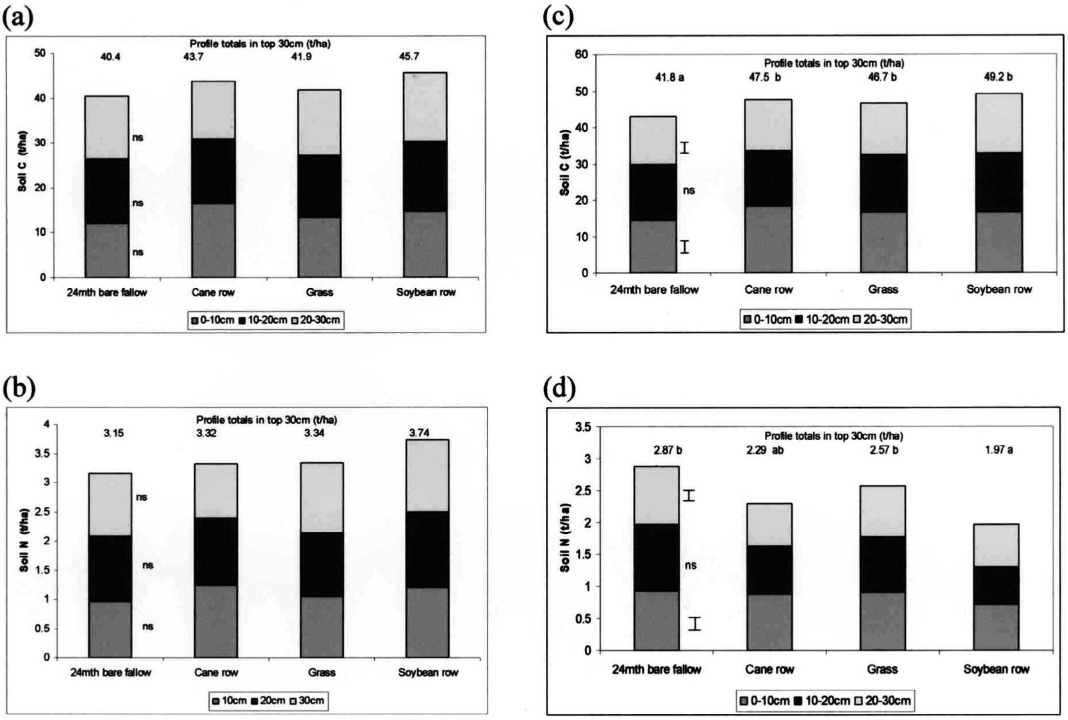

Fig. 1—Effect of selected treatments on soil C and N stores at Abergowrie (a, b) and Bundaberg (c, d). Vertical bars indicate lsd values for each depth increment where significant (P<0.05), while profile totals are shown with differing letters indicating statistically significant differences).

Imported organic materials had a similar impact on total and labile C as the treatments grown *in situ*, although neither *in situ* nor imported organic materials were able to achieve the same C concentrations (and in most cases N concentrations) as the continuous cane treatment (Table 2).

All the *in situ* alternate species except the tilled grass pasture resulted in lower C:N ratios than the continuous cane treatment, but the imported organic materials had no significant effect.

While the impact of treatments on total soil C and N was small, the impact on mineral N in the top 30 cm was significant. Data from Abergowrie (Figure 2) collected 7 months after organic matter incorporation (6 weeks after cane planting) showed that mineral N concentrations were similar in the ploughout/replant, 30 month bare fallow and grass-amended treatments, the latter regardless of whether the grass was imported or grown *in situ*.

Imported grass/legume mixtures resulted in significantly higher mineral N concentrations, with pure legume additions significantly greater again.

The effect of the *in situ* legume was smaller than expected, but this was due to low legume frequency and resulting biomass production during the fallow period caused by drought, combined with the extended period since the last soybean crop was grown (approx 17 months). Most of the soybean N would have mineralised during the intervening period, even with the lack of tillage.

Table 2—Impact of organic matter amendments (grass, legume or grass/legume mixtures) on total and labile C and total N in the top 15 cm of the soil profile at cane planting at the Bundaberg site. Values of lsd (P<0.05) are indicated where differences are statistically significant.

Fallow length	Organic matter	Source	Labile C	Total C	Total N	C:N ratio
			(g/kg)			
1 month (PO/RP)	Cane trash	*In situ*	1.60	15.80	0.77	20.50
30 month	Nil	–	0.98	11.63	0.54	21.46
30 month	Grass	Imported	1.26	12.70	0.66	19.27
30 month	Soybean	Imported	1.44	14.20	0.74	19.13
30 month	Grass/Soybean	Imported	1.31	12.84	0.70	18.57
30 month	Grass (tilled)	In situ	1.28	13.50	0.71	19.06
30 month	Soybean (tilled)	In situ	1.22	12.17	0.68	17.89
30 month	Grass (Not tilled)	In situ	1.25	12.30	0.68	17.99
30 month	Soybean Not tilled	In situ	1.27	12.80	0.72	17.81
LSD (0.05)			0.19	1.68	0.08	1.84

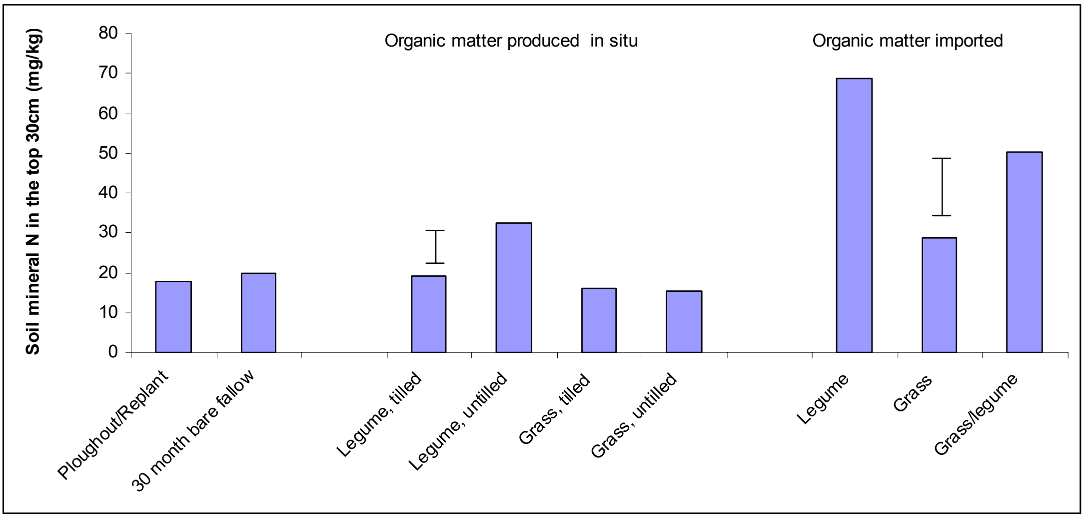

Fig. 2—Effect of imported organic matter or organic matter grown *in situ* on soil mineral N concentrations in the top 30 cm of the soil profile at Abergowrie prior to N fertiliser application. Vertical bars indicate lsd values between in situ or imported organic materials and the 30 month bare fallow and ploughout/replant treatments.

Soil biota

The impact of length of bare fallow at Bundaberg on general microbial activity (measured by hydrolysation of fluorescein diacetate [FDA], Figure 3a) and persistence of lesion nematode (*Pratylenchus zeae,* Fig. 3b) shows how both the general microbial community and cane-specific pathogens are affected by lack of plant roots and residue inputs, although the change in obligate grass species pathogens like lesion nematodes is much greater than that of the general community.

For example, after 12 months bare fallow, FDA activity had fallen by 28% while numbers of lesion nematodes had declined by 87%.

Pathogens like *Pachymetra chaunorhiza*, which have spores that enable better survival in the absence of host root system, behaved quite differently to lesion nematodes.

The initial rate of decline in spore numbers appeared quite rapid (*ca.* 50% after 6 months at Abergowrie), but then there was no further significant decline with increasing fallow lengths up to 36 months at the time of sampling (data not shown).

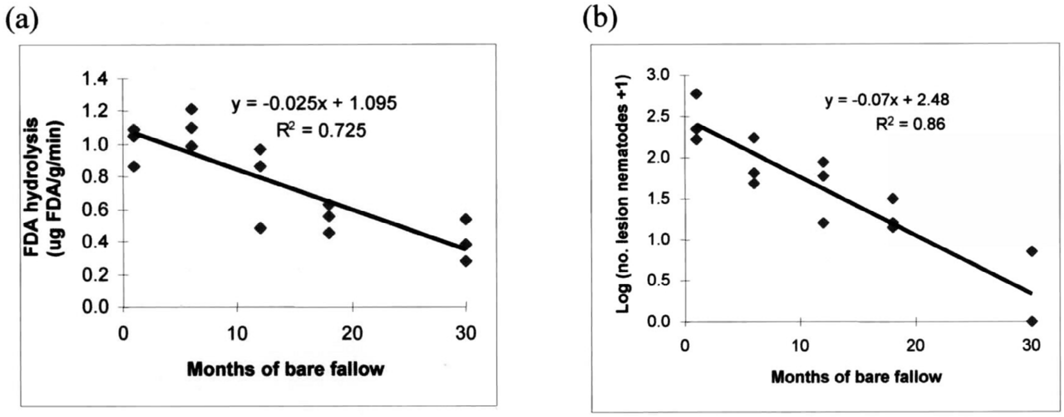

Fig. 3—Effects of length of bare fallow at Bundaberg on (a) general microbial activity, measured as the rate of hydrolysis of FDA, and (b) the number of lesion nematodes in 200 mL soil.

Addition of imported organic matters 6 months before cane planting had minimal impact on the incidence of individual cane pathogens, but there were some variable effects on the general soil biological activity. For example, at Bundaberg (Table 3) there was a strong impact of added organic materials on the incidence of FLN after a long bare fallow, with similar increases recorded in all fallow lengths (data not shown). However, effects were not significant at Abergowrie, mainly due to a lack of decline in FLN numbers with long bare fallows at this site. The reasons for this are not known.

Table 3—Effects of imported and *in situ* organic matter on various soil biological components at cane planting in Bundaberg. Long term bare fallow and ploughout/replant treatments are presented for contrast, and LSD values (P<0.05) are shown.

Treatment	Microbial biomass C (mg/kg)	Microbial activity (µg FDA/g/min)	Free living nematodes Log (FLN) /200mL soil	Lesion nematodes Log (lesion + 1) /200mL soil
Ploughout/Replant	51.3	1.00	3.417	2.456
ContinualgrassCT	46.0	0.98	3.295	1.912
ContinualgrassDD	30.2	1.04	3.372	2.102
ContinualsoyCT	27.2	0.62	3.285	0.159
ContinualsoyDD	20.9	1.02	3.547	0.259
Bare30	33.9	0.40	2.702	0.282
Grass30	38.5	0.51	3.544	0.259
Legume30	32.0	0.54	3.653	0.201
LSD (0.05)	25.5	0.27	0.302	0.593

Comparing organic matter amendments with both long bare fallows and ploughout/replant cane treatments (Table 3) showed that most measures of biological activity were greater with organic matter inputs, regardless of source. There were only small and variable effects of tillage at this stage (i.e. 6 months after imported organic amendments were incorporated and 1.5–2 months after ploughout of the pastures and replant cane). As with total and labile C (Table 2), general microbial activity was as high or higher in ploughout/replant cane soil as in any other organic amendment. However, the differences in numbers of lesion nematodes between treatments (Table 3) show that the composition of the biological community can be quite different, with obvious implications for cane growth.

While measures of soil biological activity at the end of the plant crop showed only small residual treatment effects, there were some clear differences in the rate of recovery of lesion nematodes during the growing season. At Bundaberg (Table 4), the long bare fallows, fumigated treatments and *in situ* legume cropping all showed very low lesion nematode numbers at cane planting. However, by midway through the growing season, lesion nematode numbers in the long bare fallow treatments without added organic matter had increased rapidly, reaching similar numbers as in the ploughout/replant treatment. Numbers of FLN hardly changed during the period, or indeed during the whole growing season in those treatments, so the nematode community after the bare fallows became increasing dominated by lesion nematodes during the plant crop.

The rate of increase in lesion nematodes during the plant crop in the *in situ* pasture treatments (Table 4), with the exception of tilled soybeans, was much slower than in the bare fallow or fumigated treatments.

Similarly, while the addition of imported organic matter 6 months before planting may appear to have had only a minor impact (Table 4), analyses of the factorial combinations of fallow lengths, types of imported organic matter and sampling times shown in Table 4 indicated that numbers of lesion nematodes were significantly reduced by the imported grass and grass legume mixture in the 30 month fallow, and by the imported legume in the 12 month fallow (data not shown).

Stirling *et al.* (2003) had previously noted slower rates of multiplication of lesion nematode with soil amendments that produced low soil N and a high level of microbial activity. We explored the relationship between the general soil biota measured at cane planting (e.g. Table 3) and the rate of increase in lesion nematodes between planting and the midseason sampling (calculated from Table 4), excluding the fumigated subplots because of the almost total elimination of lesion nematodes by the biocide. There was a strong negative correlation between the increase in lesion nematode numbers (nematodes midseason – nematodes at planting) and general soil microbial activity at the time of cane planting, with the strongest relationship being with microbial activity measured by FDA hydrolysis ($r = -0.60$, $n=18$). A similar negative correlation between the size of the microbial community at planting and the increase in lesion nematodes during the first 6 months of the plant crop was recorded at Abergowrie, with the strongest correlation with culturable fungi ($r = -0.74$, $n=10$).

Growth response by the cane crop

Cane growth responses were considered in terms of dry biomass production during the season, as well as end-of-season millable stalk yields. While length of bare fallow was shown to have the largest effects on C stores, general soil biota and cane-specific pathogens (Tables 2–4, Figures 1–3), the impact on cane biomass production was only small at Bundaberg and not significant at all at Abergowrie (Figure 4a, b).

The only significant response to bare fallows at Bundaberg was in 12 and 18 month fallow lengths without added organic matter (11–14% increases in biomass production), but these effects were very small compared to the impact of soil fumigation in ploughout/replant (Figure 4a). Interestingly, these effects were not obvious at 3 months after planting, but became significant later in the growing season.

Table 4—The effect of fumigation, fallow length and added or *in situ* organic matter on numbers of lesion and total free living nematodes in the Bundaberg experiment during the plant crop.

Treatment	Log (number of lesion nematodes/200 mL soil +1)			Log (number of free-living nematodes/200 mL soil +1)		
	Planting	6 months	13 months	Planting	6 months	13 months
Bare30	0.282	3.145	3.043	2.702	2.691	2.635
Grass30	0.259	2.972	2.954	3.544	2.720	2.810
Legume30	0.201	3.140	3.177	3.653	2.939	3.059
Mix30	0.000	3.258	2.883	3.781	3.375	2.930
Bare18	1.281	3.045	2.588	2.808	2.681	2.870
Bare12	1.646	3.120	3.088	2.984	2.723	2.803
Grass12	1.498	3.027	3.011	3.557	2.786	2.943
Legume12	0.842	2.984	3.024	3.879	3.358	3.054
Mix12	1.467	2.875	2.889	3.704	2.747	3.017
Bare6	1.914	2.901	2.863	3.302	2.880	3.116
Grass6	2.234	2.903	3.012	3.510	3.170	3.210
Legume6	2.069	2.914	2.823	3.722	3.085	3.175
Mix6	2.051	2.742	2.866	3.493	2.833	3.030
Ploughout/Replant	2.456	3.032	2.891	3.417	3.149	3.004
ContinualgrassCT	1.912	2.831	2.680	3.295	2.816	3.054
ContinualgrassDD	2.102	2.732	2.498	3.372	2.844	3.286
ContinualsoyCT	0.159	2.637	2.982	3.285	2.841	2.916
ContinualsoyDD	0.259	2.543	2.578	3.547	2.903	2.940
Ploughout/Replant + fumig.	0.100	1.730	2.533	0.629	3.081	3.132
Bare6 + fumig.	0.000	1.445	2.124	0.888	2.631	2.963
Bare12 + fumig.	0.000	1.745	2.364	0.159	2.590	2.880
Bare18 + fumig.	0.000	0.441	2.279	0.233	2.758	2.873
Bare30 + fumig.	0.000	0.538	1.900	0.282	2.705	2.962
Treatment × Time LSD	0.566			0.420		
Within treatment LSD	0.544			0.412		

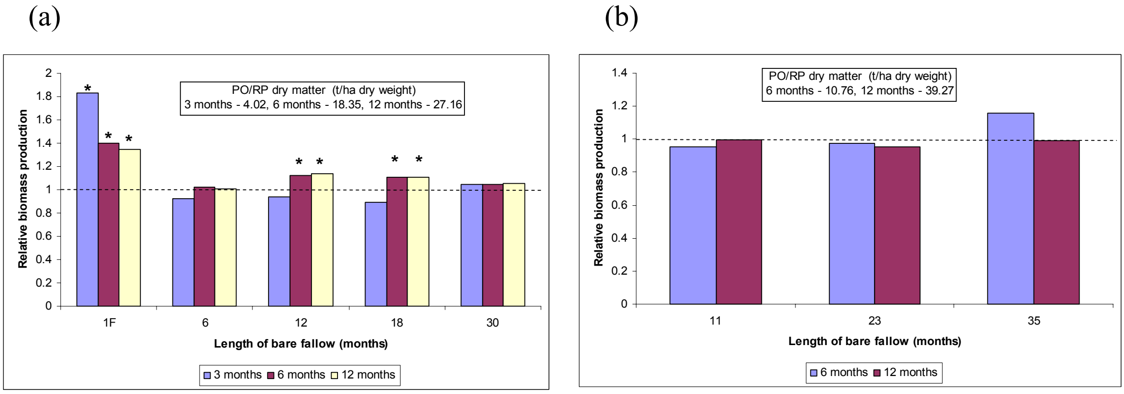

Fig. 4—Effects of length of bare fallow on cane biomass production, relative to that in ploughout/replant treatments, at (a) Bundaberg and (b) Abergowri.e. Data are also shown for the fumigated ploughout/replant treatment at Bundaberg (1F). Asterisks are used to indicate significant differences to ploughout/replant within each sample date, while actual dry matter at each sample date in the ploughout/replant treatment is shown.

The reasons for this limited crop response are unknown. While other studies (e.g. Garside *et al.*, 1999, 2000, 2002) report strong growth increases after long bare fallows (30–90%), there are also instances where responses have been relatively small (e.g. in the case of irrigated, high N application systems in the Burdekin, Garside *et al.*, 2000).

The small response to intermediate fallow lengths at Bundaberg was similar to that recorded for a 12 month bare fallow in an irrigated, high N system (Garside *et al.*, 1999), although yields at the current site were poor due to a combination of a poorly drained soil and limited irrigation in a dry year.

Declining inoculum density of cane-specific pathogens with increasing length of bare fallows should result in significant cane yield increases, and the trend for a reduction in fumigation response with increasing length of bare fallow at Bundaberg seems to support this hypothesis (Figure 5).

The improved performance in the intermediate (particularly) and longer bare fallows was consistent with the observed decline in obligate cane pathogens like lesion nematode (Figure 3b), and the lack of large fumigation response in these treatments suggests these detrimental organisms represent less of a constraint to crop performance.

However, poorer growth in fumigated long bare fallow plots suggests that other beneficial components of soil fertility have been lost during the extended fallows, and that the management inputs employed (fertiliser, irrigation etc.) did not overcome the new constraint.

The addition of organic materials to soils after differing lengths of bare fallow had no significant impact on cane crop growth at any stage at Abergowrie, while a positive growth response was recorded to the addition of cane trash, compared to no added organic matter, in the 6 and 12 month samples at Bundaberg.

Although the Bundaberg response was small (14–17%), it occurred in all fallow lengths (data not shown) and provides further evidence of the value of the cane trash blanket in the longer term sustainability of the sugarcane farming system.

The lack of large crop responses to imported organic materials was disappointing, but was consistent with the relatively minor changes in biochemical and biological properties that were induced by our treatments (Tables 2 and 4). The results demonstrate the difficulties involved in sustaining high levels of soil biological activity in tropical and subtropical environments and suggest that higher application rates or more frequent organic inputs may be required to obtain the desired shifts in soil biology and crop growth.

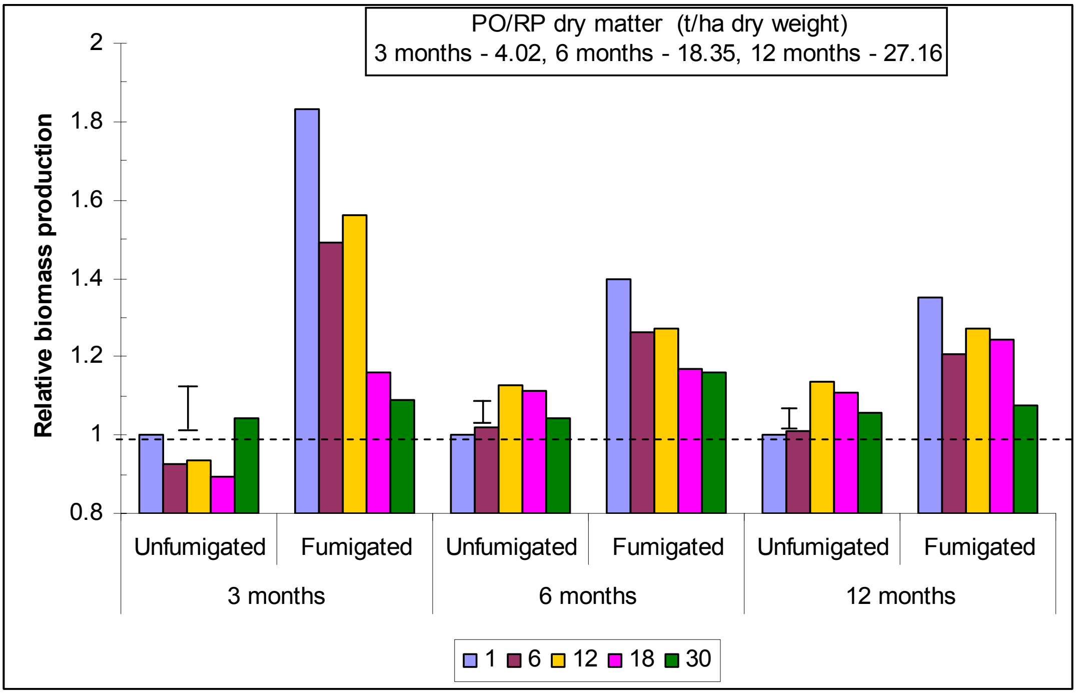

Fig. 5—Effects of soil fumigation and length of bare fallow on cane biomass production, relative to that in ploughout/replant treatments, in samples taken 3, 6 and 12 months after planting at Bundaberg. Vertical bars indicate the interaction LSD (P<0.05) in each sample date, while actual dry matters for the ploughout/replant treatment are shown.

Finally, the long-term breaks in grass pastures or continuous direct drilled legume crops were generally not able to duplicate the pasture break responses recorded in other studies (e.g. Garside *et al*. 1999, 2000, 2002), especially at Abergowrie (Figure 6).

There were significant responses at Bundaberg, with a larger increase in biomass production after Rhodes grass pasture (average 29% increase) than after soybean (average 17% increase).

Unfortunately, the role that slower multiplication of lesion nematodes during the growing season (Table 4) played in these better grass pasture responses at Bundaberg cannot be determined from the current study.

However, the responses at Abergowrie were not statistically significant, averaging *ca* 10% increases for the signal grass and nothing for soybean cropping. The soybean treatments probably performed poorly due to the low crop frequency and the long drought-induced bare fallow prior to cane planting, but the grass pasture result was disappointing.

Part of the smaller response may be related to the fact that this was a grass-only pasture, where other studies had used grass/legume mixed swards. A similarly poor response to a long-term pangola grass pasture was obtained in the 2nd phase of the rotation trial in Bundaberg (M.J. Bell, unpublished data), largely due to an inability to provide sufficient N early in the crop life cycle, but the higher N rates in the current studies should have prevented this from happening.

Both sites showed poorer early crop growth when cane was direct drilled after long-term grass or soybean breaks (data not shown), although this difference had disappeared by final harvest at Abergowrie.

The continued persistence of the effect at Bundaberg may have been related to much slower crop establishment in cooler soil under heavy residue cover in the direct drill treatments, especially after Rhodes grass (data not shown).

The effect was greatest during crop establishment (e.g. direct planted grass treatments were only 55% of the biomass of the conventionally tilled treatments at 3 months) and, although the direct planted treatments caught up later in the season, the gap never closed completely.

This negative effect of direct sowing into residues from cane or other break species at Bundaberg is in sharp contrast to results obtained at the same block and reported in Bell *et al.* (2003), where direct sowing cane after soybeans resulted in significant yield improvements compared to sowing after conventional tillage.

Garside and Berthelsen (2004) showed similar positive benefits of direct planting cane after soybeans at Tully.

The reason for the negative impact recorded here may be due to a combination of already cool soil temperatures in spring combined with heavy rainfall during crop establishment. Further studies on the intricacies of successful crop establishment with direct planting in these cooler southern cane areas are needed.

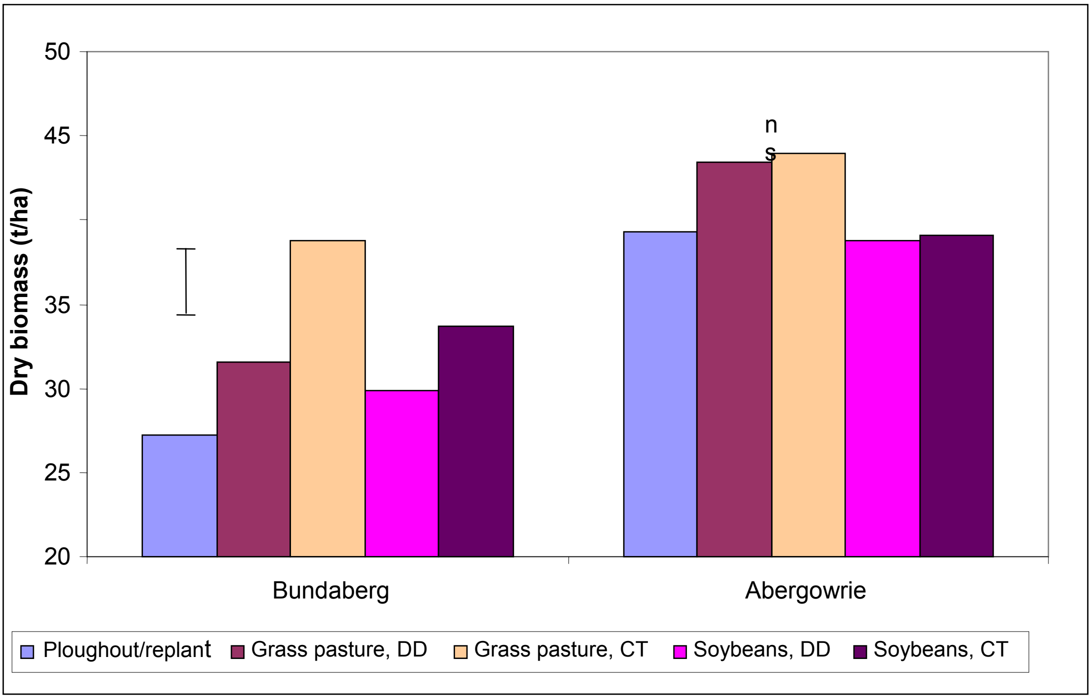

Fig. 6—Effect of long term grass pastures and tillage system upon return to sugarcane cropping at Bundaberg and Abergowri.e. The conventionally tilled ploughout/replant treatment at each site has been included for contrast, with vertical bars showing the appropriate LSD (0.05) for Bundaberg.

Discussion and conclusions

This study has shown that the soil chemical and biological fertility can be manipulated by combinations of simple management strategies—bare fallows, crop residues/organic materials and tillage. However, with the exception of long bare fallows, the relatively small biological and biochemical changes that were achieved by treatments, and the resulting lack of crop response, highlight how difficult it is to substantially change the health of agricultural soils in the tropics and subtropics. There are, however, some clear messages that can be derived from these studies.

Firstly, sugarcane (at least within the untrafficked row area) is very effective at sequestering carbon and supporting soil biota, and it is difficult to match this capacity by the culture of other crops or the importation of organic amendments.

What has been shown in other studies (e.g. Bell *et al*., 2001b) is that excessive tillage during a short fallow at the end of the cane crop cycle can undo some of the benefits in terms of labile C (and to a lesser extent total C) achieved during the crop cycle. Similarly, studies have also shown that tillage can minimise the increase in some beneficial components of soil biota like earthworms after a soybean fallow (Bell *et al*., 2003).

The apparent loss of some of the natural suppression of lesion nematode populations when the continual soybean, and to a lesser extent the grass pasture treatments, were tilled prior to cane planting (Table 4) are further evidence that there can be negative effects of tillage on beneficial components of soil biota. Further research on the impact of reducing tillage on soil biota and functions in the cane farming system is required.

Secondly, use of short-term legume crops like soybean and readily available organic materials like cane trash are useful for manipulating soil biology in sugarcane soils. However, they need to be considered as part of the sugarcane farming system, rather than isolated management inputs.

For example, while lesion nematode populations decline after a soybean fallow (e.g. Stirling *et al*, 2002; Pankhurst *et al*., 2005c), populations recover quite rapidly when those fields were conventionally tilled and returned to sugarcane (Stirling *et al*., 2001).

The data from our studies (Table 4) suggest that it may be easier to maintain these reduced nematode densities through the cane crop cycle without tillage, and so perhaps improve crop performance even more in the ratoons. These short-term break crops should therefore be considered as a way of fine tuning the existing soil biology of the cane soils, rather than a quick fix for poor soil health.

Similarly, Stirling *et al*. (2005) have shown that organic amendments can regulate lesion nematode populations in cane soils, although Pankhurst *et al*. (2005a) showed that they were not as effective against a broader suite of biological constraints in 'yield decline' soils. In our experiments, the impact of organic amendments was inconsistent and cane growth responses were not significant, but this may have been due to the decline in soil C stores that occurred in the preceding bare fallows or following the tillage prior to cane planting. Further work is needed to evaluate the benefits of using cane trash to supplement the already substantial C stores in the cane row area at the end of a crop cycle, with as little tillage as possible after incorporation.

Finally, the role of soil-borne pathogens in constraining crop productivity needs to be kept in perspective, as pathogen impact is modulated by other soil organisms and other non-biological constraints in the farming system.

The reduction in fumigation response at Bundaberg with increasing lengths of bare fallow (Figure 5) was, at first glance, a seeming endorsement of the effects of reducing biotic constraints by removing the sugarcane host plant from the system (e.g. Figure 3a). However, the relatively low yields in the fumigated 30 month bare fallow treatments, combined with the poor yields in all fumigated plots (only 70–80 t/ha millable stalk) despite adequate fertiliser inputs and supplementary irrigation suggests that other factors are limiting yield at this site.

This highlights the need to better understand the role of all soil-plant-management interactions that determine crop performance on any given site. This understanding would allow an assessment of the management inputs that were likely to produce the most beneficial returns to land managers.

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