INTERACTIONS BETWEEN ROTATION BREAKS, TILLAGE AND N MANAGEMENT ON SUGARCANE GROWN AT BUNDABERG AND INGHAM

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Abstract

THE IMPACT of cropping histories (sugarcane, maize and soybean), tillage practices (conventional tillage and direct drill) and fertiliser N in the plant and 1st ratoon (1R) crops of sugarcane were examined in field trials at Bundaberg and Ingham. Average yields at Ingham (Q200⁽ᵇ⁾) and Bundaberg (Q151⁽ᵇ⁾) were quite similar in both the plant crop (83 t/ha and 80 t/ha, respectively) and the 1R (89 t/ha v 94 t/ha, respectively), with only minor treatment effects on CCS at each site. Cane yield responses to tillage, break history and N fertiliser varied significantly between sites. There was a 27% yield increase in the plant crop from the soybean fallow at Ingham, with soybeans producing a yield advantage over continuous cane, but there were no clear break effects at Bundaberg – possibly due to a complex of pathogenic nematodes that responded differently to soybeans and maize breaks. There was no carryover benefit of the soybean break into the 1R crop at Ingham, while at Bundaberg the maize break produced a 15% yield advantage over soybeans and continuous cane. The Ingham site recorded positive responses to N fertiliser addition in both the plant (20% yield increase) and 1R (34% yield increase) crops, but there was negligible carryover benefit from plant crop N in the 1R crop, or of a reduced N response after a soybean rotation. By contrast, the Bundaberg site showed no N response in any history in the plant crop, and only a small (5%) yield increase with N applied in the 1R crop. There was again no evidence of a reduced N response in the 1R crop after a soybean fallow. There were no significant effects of tillage on cane yields at either site, although there were some minor interactions between tillage, breaks and N management in the 1R crop at both sites. Crop N contents at Bundaberg were more than 3 times those recorded at Ingham in both the plant and 1R crops, with N concentrations in millable stalk at Ingham suggesting N deficiencies in all treatments. There was negligible additional N recovered in crop biomass from N fertiliser application or soybean residues at the Ingham site. There was additional N recovered in crop biomass in response to N fertiliser and soybean breaks at Bundaberg, but effects were small and fertiliser use efficiencies poor. Loss pathways could not be quantified, but denitrification or losses in runoff were the likely causes at Ingham while leaching predominated at Bundaberg. Results highlight the complexity involved in developing sustainable farming systems for contrasting soil types and climatic conditions. A better understanding of key sugarcane pathogens and their host range, as well as improved capacity to predict in-crop N mineralisation, will be key factors in future improvements to sugarcane farming systems.

Introduction

Research by the Sugar Yield Decline Joint Venture has shown that introducing a legume rotation crop into the sugarcane farming system reduces the need for fertiliser nitrogen, provides some control of sugarcane pathogens and improves crop yields (Garside and Bell, 2001; Garside *et al.*, 1999; Pankhurst *et al*., 2005; Stirling *et al*., 2002).

These yield benefits have sometimes persisted for the whole crop cycle (Garside and Bell, 2007), although environmental conditions and crop damage during harvesting can curtail benefits to a plant crop only (Garside, 2004).

Similarly, there have been well demonstrated cost savings from reducing tillage between crop cycles (Braunack *et al*., 1999), while yields can be maintained, or in combination with a fallow legume crop, enhanced significantly (Bell *et al*., 2003; Garside *et al*., 2006).

These benefits are maximised when crop row spacings match wheel spacings of the harvesters and haulouts (i.e. controlled traffic) and compaction damage is minimised.

More recent studies of new farming systems combining the elements of reduced tillage, controlled traffic and fallow cropping have highlighted the interactions of these system changes on different soil properties that impact crop performance.

For example, soil N dynamics are significantly altered as the amount of tillage is reduced (Bell *et al*., 2006b; Garside *et al*., 2006), with significant implications for N management. An enhanced rate of early N mineralisation from legume residues due to tillage can lead to poor N recovery by the developing cane root system, especially when combined with environmental conditions conducive to leaching losses.

Conversely, reduced N mineralisation in direct drill (DD) systems with legumes can lead to increased N mineralisation late in the growing season, and in some cases lead to lower CCS.

In a similar fashion, pathogen incidence and biological pathogen suppression can be influenced by different combinations of crop rotation and residue management (Bell *et al*., 2006a; Pankhurst *et al*., 2005; Stirling *et al*., 2005).

The relative suppressiveness to pathogenic nematodes is reduced in soils with high concentrations of inorganic N, and that suppressiveness is enhanced by addition of high C:N residues like cane trash but reduced under conventional tillage. However, the balance between minimising soil inorganic N to enhance pathogen suppression and supplying adequate N to meet the demands of the cane crop are not yet well understood.

This paper reports results of field trials at Ingham and Bundaberg in which combinations of rotation crops (ploughout-replant [PORP] versus a short fallow of soybeans or maize), tillage prior to cane re-establishment and N fertiliser applications were assessed in plant and first ratoon (1R) cane crops.

This paper focuses on crop yields and soil and crop N dynamics in the study, while a companion paper in this conference (Stirling *et al*., 2010) reports the impacts of treatments on the nematode community.

Methods

Crop agronomy

The experiments were conducted in commercial cane fields at Ingham (Raiteri property) and Bundaberg (Halpin property), on land that had been under long term cane monoculture, with the existing cane crops growing on 1.8 m beds. The block at Ingham was growing Q120$^{\Phi}$ while the block at Bundaberg had equal parts of Q170$^{\Phi}$ and Q138$^{\Phi}$.

Both blocks were relatively light textured, although there were texture gradients across both blocks and increasing clay contents at depth at Bundaberg. The soil types at both Bundaberg and Ingham varied across the block, ranging from a sandy loam to a duplex soil at Bundaberg (clay contents effectively doubled below 3 cm) and from a clay loam to a silty clay at Ingham. Surface soil properties from both sites are shown in Table 1.

Table 1—Site characterisation data for the sites at Ingham and Bundaberg.

		Bundaberg		Ingham	
		0–10 cm	10–30 cm	0–10 cm	10–30 cm
pH	(1:5, water)	6.0	5.8	5.3	ND
Clay content	(%)	7.3	7.7	ND	ND
Bulk density	(Mg/m^3)	1.28	1.51	1.29	1.49
Total organic C	(%)	1.04	0.65	1.61	1.00
Total N	(%)	0.06	0.03	0.12	0.08
C:N		17	26	13	13

The experiments were established in a split-split-split-split plot design with main plots being rotation history (plough out – replant cane, or cane sown after a 9-12 month fallow under soybeans or maize), sub plots being full tillage or no tillage (DD) prior to re-establishment of a cane crop, sub-sub plots being N fertiliser application in the plant crop and sub-sub-sub plots being N fertiliser application in the 1R crop. The N fertiliser rates varied slightly according to district practice, being 0 or 140 kg N/ha in both the plant and 1R crops at Bundaberg and 20 or 150 kg N/ha in the plant crop and 0 or 150 kg N/ha in the 1R crop at Ingham.

The crop histories of the main plots at Bundaberg were 10 × (1.8 m) cane rows each 56 m in length, with the tillage subplots each 5 × (1.8 m) cane rows of 56 m length and the subsequent plant and 1R N rates split lengthways to produce 28 m plots in the plant crop and 14 m plots in the 1R.

At Ingham, main plots were 120 m long and 4 × (1.8 m) cane rows wide, with each split representing half the length of that from the previous split (i.e. tillage subplots were 60 m long, plant crop N rate sub-subplots were 30 m long and the 1R N rates were 15 m long).

Rotation treatments were commenced after the 2005 (Bundaberg) and 2006 (Ingham) cane harvests, with plots designated to be sown to maize or soybean having the re-establishing ratoon crop killed with herbicide before cultivation using discs, deep rippers and rotary hoes to ameliorate compaction and prepare seed beds.

The continuing cane plots received normal ratoon fertiliser mix and grew through to harvest the following year at both sites, although the crop at Ingham was removed in late May prior to commencement of the commercial crushing period.

At Bundaberg, maize (cv. Hycorn 901) and soybean (cv. Leichardt) were established in late November 2005, with grain harvests conducted in mid-April (maize) and early May (soybean) 2006.

In both cases, crops were immediately re-sown the week following harvest, after stubble was mulched onto the bed surface using a flail mower, and grown until the continuous cane plots were harvested in mid July 2006.

At Ingham, soybeans (cv. Leichardt) and maize (cv. C79) were sown in early January 2007 but were not harvested for grain. Rather, crops were treated as green manures and mulched back to the bed surface at the same time as the continuous cane plots were harvested in mid May 2007.

At both sites, DD plots were then undisturbed until cane was planted using double disc openers in late September 2006 (Bundaberg) or mid August 2007 (Ingham), establishing one cane row per bed. The conventionally tilled treatments were disced and rotary hoed to incorporate crop residues and trash and then allowed to consolidate until cane planting.

At Bundaberg, basal K fertiliser (75 kg K/ha as KCl) was band-applied into the beds of all plots using Daybreak® disc openers prior to planting, while P fertiliser (22 kg P/ha applied as Triphos) was applied at planting. Planting material (cv. Q151) was treated with Sportak® and Lorsban® at recommended rates to control Pineapple disease and wireworm, respectively.

At Ingham, all plots received basal applications of 20 kg N and 20 kg P applied as DAP at cane planting, with Q200$^{\text{⑁}}$ planting material treated with Shirtan® and Lorsban® at recommended rates.

Crop establishment was poor in the DD continuous cane treatments at Bundaberg, necessitating re-planting of this treatment in late November 2006 after spraying out the original planting. The establishing shoots in other treatments were mowed to just above ground level twice (late November and mid December) while the re-planted DD cane treatment re-established.

The plots receiving plant crop N fertiliser (140 kg N/ha at Bundaberg and an additional 130 kg N/ha at Ingham) were side dressed as urea at *ca.* 3 months after cane planting (Ingham) or in mid January at Bundaberg (2 months after replanting of the DD cane treatment).

The crop at Bundaberg received supplementary irrigation using an overhead travelling irrigator, while the crop at Ingham was rainfed. The plant crops were harvested in October 2007 (Bundaberg) and September 2008 (Ingham), while the 1R crops were harvested *ca*. 12 months later at both sites.

Soil and plant sampling

Shoot counts were recorded at regular intervals during crop establishment, with destructive sampling of crop biomass undertaken at *ca*. 3 month intervals at Ingham (i.e. 3, 6 and 9 months after planting), and at 2.5 months and 6 months after replanting of the DD cane treatments at Bundaberg.

Biomass samples were collected from 10–15 m^2 areas in each plot, fresh and dry weights were determined and a subsample of plant material was ground for analysis of nutrient concentrations. Crop N uptake (kg N/ha) at the various stages of crop growth was determined as dry biomass × tissue N concentration.

Immediately after each biomass harvest, soil profile samples were collected to 150 cm (Bundaberg) or 90 cm (Ingham) to determine mineral N (the sum of NH_4-N and NO_3-N) after extraction with 2M KCl.

In addition, samples of the surface trash and the 0–10 cm soil layer immediately below the surface trash were collected at the termination of the continuous cane and break crop treatments, at cane planting and 6 weeks after cane planting (both DD and tilled subplots), and then at the same time as biomass and mineral N sampling (DD plots at the nil/low N fertiliser rate only).

These soil and trash samples were analysed for total N and C using a Leco analyser, while mineral N was also determined in each of soil, trash and the embedded soil material in the surface trash (‘fines’) using the 2M KCl extraction technique.

At final harvest of the plant crop, yields and components were determined from 18m^2 sample area (5 m quadrats from the centre 2 rows in each plot) by hand harvesting and recording total stalk number and fresh weight. A subsample representing 10–15% of the total plot biomass was split into millable stalk and trash (dead leaf and tops), with tops separated from millable cane at the 5th visible dewlap from the top of the stalk.

The proportions of millable cane and trash were used to calculate trash and cane yields from the whole biomass sample, while sub samples of the cane and trash were mulched and dried to determine moisture content. These dried sub samples were subsequently ground and analysed to determine crop N uptake. Juice samples for CCS determination were extracted from a further subsample of the millable stalks using a small mill.

Trash samples were collected from the DD, low/nil N subplots immediately prior to the commercial cane harvest that removed the bulk material from each plot and returned the new cane trash blanket. Profile mineral N samples were collected immediately after the plant crop harvest.

During the 1R crop a second round of biomass, soil and plant sampling was undertaken, but at a reduced frequency compared to the plant crop. Biomass samples were collected from all plots in a midseason (6 months after plant crop harvest) sampling, but profile mineral N samples were only collected from the continuous cane and soybean histories, and only for the sub-sub-sub plots without N fertiliser in the 1R crop.

At final harvest of the 1R crop, yields and components were determined as in the preceding plant crop, dry biomass and crop N content were determined and profile mineral N was determined for the continuous cane and soybean histories with no N applied in the 1R crop (Ingham), although at Bundaberg additional profile samples were collected from sub-sub-sub plots receiving 140 kg N/ha in the plant crop and 140 kg N/ha in the 1R crop.

Data analysis and calculations

Estimates of apparent net N mineralisation or losses were derived for each crop at each site by comparing the sum of (profile mineral N at harvest, N in residual surface trash and N in standing biomass) minus (initial profile mineral N, initial N in surface trash and N fertiliser addition). This analysis did not include changes in soil total organic N, as significant differences between treatments were not recorded in either study.

Treatment effects were analysed using analysis of variance techniques in the Genstat statistical software, with the plant crop at each site analysed as a split-split plot (main plots of crop history, subplots of tillage and sub-subplots of N fertiliser) and the 1R crop as a split-split-split plot (the sub-sub-subplot was N application in the 1R).

Results

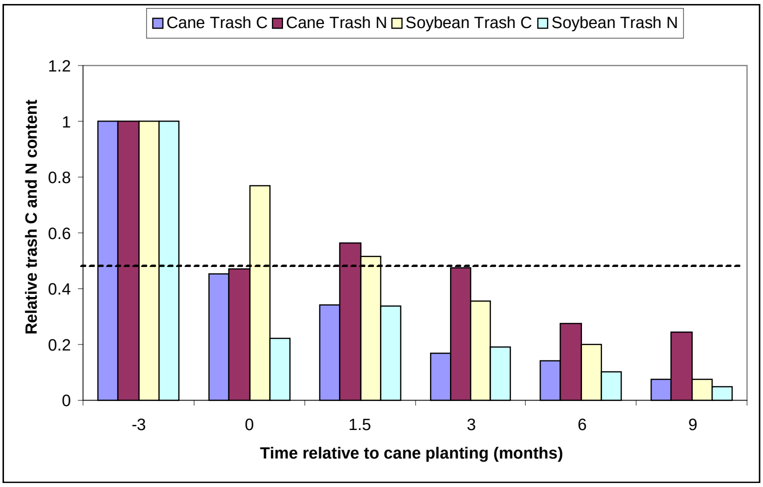
Residue and N inputs from the different histories

The surface trash blanket generated from the soybean or continuous cane histories contained differing amounts of both C and N and was characterised by very different C:N ratios.

The surface trash in the continuous cane histories contained similar amounts of C at both sites (7330 $\pm$ 820 kg C/ha and 7420 $\pm$ 280 kg C/ha at Bundaberg and Ingham, respectively), but there was more N in trash at Bundaberg (123 $\pm$ 24 kg N/ha, with a C:N ratio of 60) than at Ingham (90 $\pm$ 5 kg N/ha, with a C:N ratio of 82). In contrast, there was more C and less N in the surface trash after the soybean crops at Bundaberg (4445 ± 400 kg C/ha and 129 ± 13 kg N/ha) than at Ingham (3170 ± 675 kg C/ha and 210 ± 57 kg N/ha), such the C:N ratios were much lower at Ingham (15) than at Bundaberg (34). The difference in N contents and C:N ratios between locations is probably a result of the differing methods of handling soybean grain (removed at Bundaberg but retained in the green manure crop at Ingham).

The decomposition of the surface trash was followed by monitoring C and N contents in the trash and embedded soil particles throughout most of the plant crop, with results shown relative to the initial amounts discussed above (Figure 1a, b).

(a)



(b)

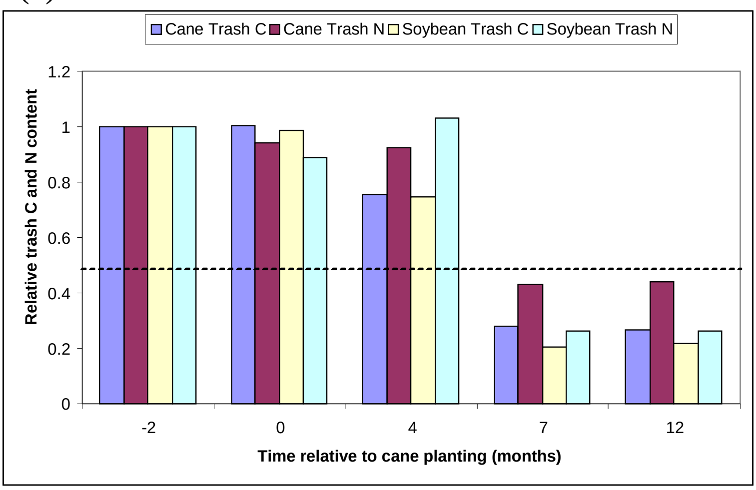


Fig. 1—Relative total C and N in surface trash and associated soil particles in untilled (DD) plots of the continuous cane and soybean crop histories at (a) Ingham and (b) Bundaberg. Data represent samples from prior to cane planting to 9 months (Ingham) or 12 months (Bundaberg) after planting and are relative to C and N contents of the initial sample date, with the dashed line indicating 50% of the initial trash C and N contents.

Using the C content of surface residue as an indicator of the rate of decomposition, it is apparent that decomposition occurred faster at Ingham than at Bundaberg. The cane trash had lost 50% of the initial C content in the 3 months leading up to cane planting and the soybeans reached a similar position *ca*. 1.5 months later. This contrasts with Bundaberg, where both soybean and cane residue C was 70–75% of the initial quantities 6 months later (i.e. 4 months after cane planting).

There was evidence of apparent conservation of N in the surface residues during the early phase of decomposition at Bundaberg (both cane and soybean residues) but not at Ingham, especially for soybean residues. The apparent rapid N mineralisation from the latter was consistent with the very low C:N ratio (15) in that material, while the apparent early N retention in residues from both cane and soybeans at Bundaberg was similarly consistent while the relatively high C:N ratios of both residues (60 for cane and 34 for soybean) that were not conducive to net N mineralisation.

The very high starting C:N ratios in the cane residues at Ingham (82) also suggested a greater likelihood of N immobilisation than net N mineralisation during the early stages of residue decomposition, but this was not observed until 1.5 months after planting or 4.5 months after residues were returned to the soil surface (Figure 1a). The reasons for this inconsistency could not be determined, but may be related to the relatively young age of the crop at the time of harvest and residue return.

There were only small amounts of N remaining in surface residue 9 months after planting at Ingham (10 and 22 kg N/ha in soybean and cane histories, respectively), but greater quantities were still evident at Bundaberg just before plant crop harvest (34 and 54 kg N/ha in soybean and cane histories, respectively).

Soil mineral N

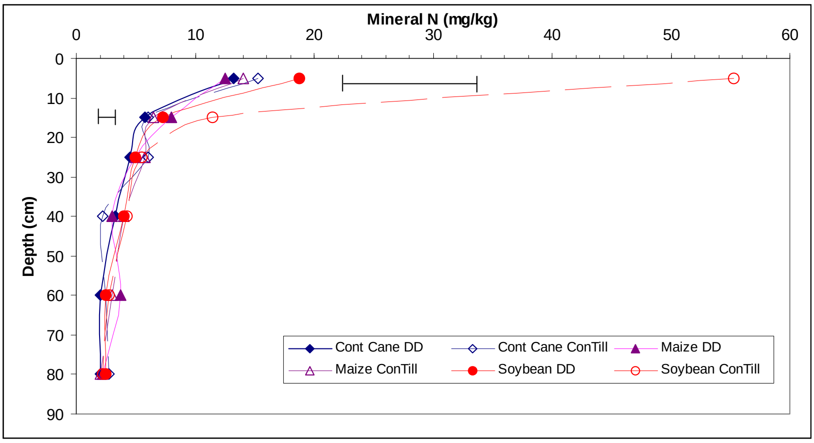
Soil mineral N concentrations in the profile taken at the time of cane planting at Ingham and Bundaberg are shown in Figure 2. At the Ingham site (Figure 2a) there were significant effects of crop history (soybean > maize or continuous cane) only in the 0–10 cm and 10–20 cm layers, and a significant effect of tillage only in the 0-10 cm sample (tillage > direct drill).

However there was a significant tillage × crop history interaction recorded in the 0–1 cm layer, with tilled soybeans resulting in a significantly higher mineral N than under direct drill (19 v 55 mg/kg), but no similar tillage effects recorded in either the continuous cane of maize histories.

The total mineral N in the soil profile to 9 cm (Figure 3) also showed significant history × tillage interactions, with no differences between DD and tilled cane (55 and 64 kg/ha, respectively), maize (64 and 67 kg N/ha, respectively) and DD soybeans (71 kg N/ha), but much higher mineral N in the tilled soybean history (134 kg/ha).

Results from Bundaberg (Figure 2b) produced similar crop history effects (soybean > maize or continuous cane) and while smaller than those in the surface layers at Ingham, these effects were recorded much deeper in the soil profile (to 120 cm).

(a)



(b)

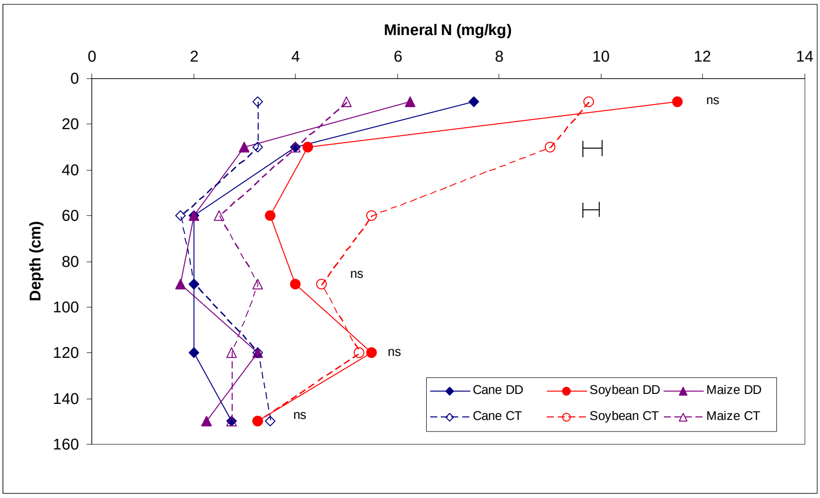


Fig. 2—Mineral N (the sum of NH_4-N and NO_3-N) at different depths in the soil profile at the time of cane planting in (a) Ingham and (b) Bundaberg. Significant differences at P=0.05 are shown with horizontal bars; non significance indicated as *ns*.

Effects of tillage were also recorded deeper in the soil profile (in 10–30 cm, 30-60 cm and 60–90 cm, as well as in 0–10 cm), and while the tilled soils generally contained higher mineral N levels than the direct drill equivalents, this condition was reversed in the 0–10 cm layer.

There were also significant tillage × crop history interactions in the Bundaberg site in which mineral N levels were increased by tillage after soybean but not after maize or continuous cane, but unlike at Ingham these effects were recorded in the 10–30 cm and 30–60 cm layers rather than in the 0–10 cm layer.

There were again significant history × tillage interactions in total mineral N to 90 cm, but unlike at Ingham there were also differences between histories in DD (Figure 3). Totals were lowest in the continuous cane history (31 and 41 kg N/ha in tilled and DD, respectively) and highest in the soybean history (87 and 63 kg N/ha in tilled and DD, respectively), with the maize treatments either similar to continuous cane (35 kg N/ha under DD) or only marginally greater (45 kg N/ha after tillage). The effects of tillage were only significant in the soybean history.

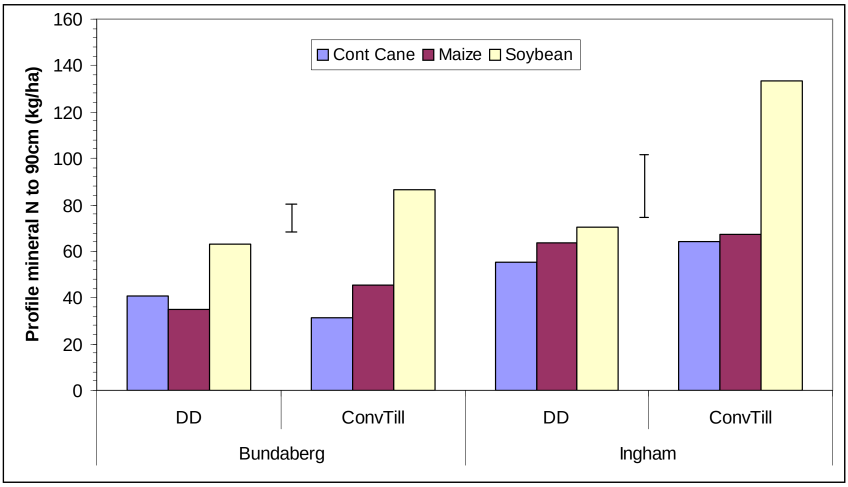


Fig. 3—Profile mineral N (kg/ha) summed to 90 cm depth in the soil profile at cane planting at Ingham and Bundaberg. Vertical bars indicate the tillage × crop history lsd (P=0.05) at each site.

Interestingly, while the dominant mineral N species recorded at Bundaberg was nitrate-N, with ammonium-N consistently in the range of 1–2 mg/kg or less, the situation at Ingham was quite different, especially in the top 20 cm of the profile. In these surface layers, ammonium-N levels were similar to those for nitrate-N, or in the case of mineralising soybean residues, much greater than nitrate-N (viz. 13 mg/kg nitrate-N v 55 mg/kg ammonium-N, and 4 mg/kg nitrate-N v 7 mg/kg ammonium-N in the 0–10 cm and 10–20 cm layers of the tilled soybean history, respectively).

Soil mineral N dynamics were followed during the plant crop, with some consistency between locations in the effects of history in the absence of added N. The higher mineral N evident in the top 10–20 cm of the profile at Ingham at planting compared to Bundaberg (Figure 2a, b) were again evident 3 months after planting, although the magnitude of site differences had increased.

Mineral N levels at Ingham in early November ranged from 38 mg N/kg (DD maize) to 110 mg N/kg (tilled soybean) in the 0–10 cm layer, while at Bundaberg levels in the same layer in January ranged from only 4 mg N/kg (DD maize) to 8 mg N/kg (DD soybean). However, while mineral N rapidly decreased with depth at Ingham (10–22 mg N/kg at 20 cm, 4–11 mg N/kg at 30 cm and <5 mg N/kg below that) and treatment differences were not significant below 20 cm, significant relative enrichment of mineral N after tilled soybeans (6–8 mg N/kg) was recorded to depths of 90 cm at Bundaberg relative to other treatments (3–5 mg N/kg).

Throughout the rest of the plant crop mineral N was always highest in the 0-10 cm layer at Ingham, but at Bundaberg levels were more uniform down the profile or, in the case of the tilled soybean and maize treatments, highest in the deeper layers (60–150 cm). The Bundaberg data provided clear evidence of leaching of nitrate into deeper layers, but there was no evidence of leaching at Ingham. Mineral N in the top 10 cm layer at Ingham in the 6, 9 and 12 month samplings (3–12 mg N/kg) was much lower than that recorded 3 months after planting (i.e. 38–110 mg N/kg), and the lack of enrichment of deeper layers suggested significant mineral N loss, to plant accumulation, immobilisation in organic matter, leaching beyond the sampling depth or gaseous loss, in a period coinciding with the onset of the wet season.

Profile mineral N (kg/ha) data were collected to 150 cm at Bundaberg and to 90 cm at Ingham after harvest of the plant crop, with profile totals shown for both sites to 90 cm in Figure 4. In this 90 cm profile, the only statistically significant effects at Bundaberg were of tillage (tilled 82 kg/ha v DD 62 kg/ha) and plant crop N fertiliser (0N, 42 kg/ha and 140N, 102 kg/ha), although the result from Ingham suggested near-significance of the history × tillage × N fertiliser interaction (P=0.09). Treatments at Ingham had 47% (±1%) of remnant profile mineral N in the top 30 cm, compared to 35% (±2%) at Bundaberg, with the top 90 cm at Bundaberg containing only 54% (±2%) of the mineral N measured to 150 cm. There were no differences in the proportion of mineral N in deeper layers in treatments with and without N fertiliser.

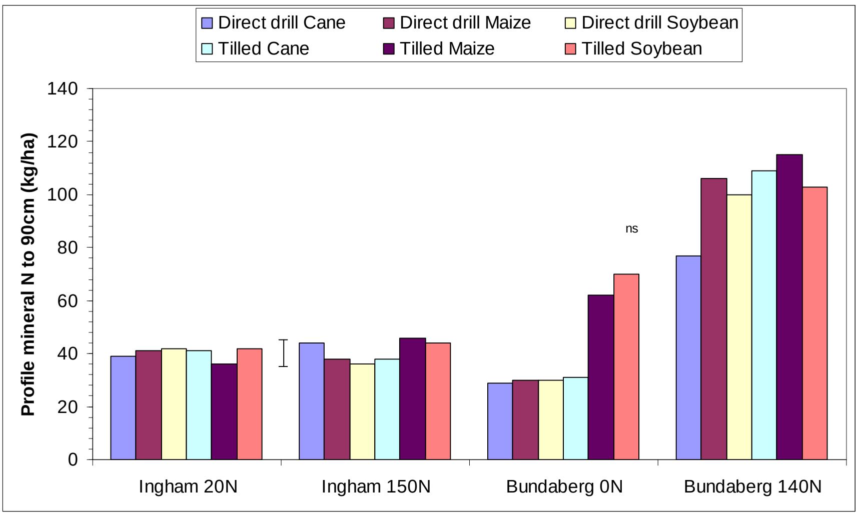


Fig. 4—Profile mineral N (kg/ha) summed to 90 cm depth in the soil profile after harvest of the plant cane crop at Ingham and Bundaberg. Vertical bars indicate the tillage × N × crop history lsd (P=0.05) at Ingham; at Bundaberg the interaction lsd was *ns*, although there were significant main effects of tillage and N fertiliser.

Soil mineral N during the 1R crop was also determined to 90 cm (Ingham) and 150 cm (Bundaberg) at only a mid-season (6 months) and final harvest sampling, and used to indicate residual effects of both rotation history (soybeans v continual cane) and plant crop N fertiliser use (Table 2). The additional residual mineral N in the profile after fertiliser use in the R1 crop at Bundaberg was also assessed. Consistent with the sampling at harvest of the plant crop, there were no significant effects of plant crop N inputs on profile mineral N during the 1R. However, there was also a similar lack of residual mineral N from the 140N applied in the plant crop at Bundaberg, despite clear evidence of residual mineral N in the profile after plant crop harvest (Figure 3). There was also no significant effect of N management at Bundaberg on mineral N at R1 harvest either, including application of an additional 140N during ratoon establishment.

Table 2—Profile mineral N (kg/ha) for samples collected in the R1 crops at Ingham (to 90 cm) and Bundaberg (to 150 cm). Samples were collected midseason (6 months after plant crop harvest) and immediately after harvest of R1, from profiles with differing rates of N in the plant crop (P), and in the case of Bundaberg, in the R1 crop (R).

	Ingham		Bundaberg		
6 months	20 N (P)/nil N (R)	150 N (P)/nil N (R)	Nil N (P)/nil N (R)	140 N (P)/nil N (R)	140 N (P)/140 N (R)
Continuous cane	85.5	84	56.4	57.2	ND
Soybean fallow	62.5	67	55.7	60.8	ND
lsd	*History effect only; lsd = 17*		*ns*		
After harvest					
Continuous cane	40.5	37.5	61.4	66.3	70.6
Soybean fallow	36	40.5	69.8	90.6	98.3
lsd	*ns*		*History effect only; lsd = 15*		

Crop history effects were also minimal, with a slightly higher mineral N midseason at Ingham in the continuous cane treatment, due primarily to slightly higher concentrations in the 50–70 cm and 70–90 cm layers only (data not shown) and no differences at R1 harvest. There was a significant history effect at R1 harvest at Bundaberg (soybean > continuous cane) but, while the history × N rate interaction was not statistically significant, this soybean effect seemed greater at higher rates of fertiliser N input (i.e. 140/140 > 140.Nil > Nil/Nil).

Crop yields

Cane yields, CCS and sugar yields were determined for all treatments at both sites, but only cane yields are presented in this paper (Table 3). There were occasional small and variable main effects of treatments on CCS recorded in both studies (e.g. a 0.3 unit depression of CCS with DD in the Bundaberg plant crop but no tillage effects at Ingham; and a 0.3 unit depression of CCS with 150N in the 1R crop at Bundaberg compared to a 0.2 unit increase in CCS with 150N in R1 at Ingham), but there were never significant higher order interactions between treatments on CCS, so in large part variation in sugar yields reflected that of cane yields.

Table 3—Effects of break history, tillage and N fertiliser in the plant and 1R crop on cane yields (t/ha fresh weight) at Ingham and Bundaberg. Values in parentheses are lsd values (P<0.05) for the appropriate means comparisons.

Plant crop N	Ratoon crop N	Continuous cane		Maize		Soybean	
		Tilled	DD	Tilled	DD	Tilled	DD
Ingham plant crop							
20N		67	65	71	74	80	97
150N		84	82	94	88	95	104
lsd		*History (11); N rate (5)*					
Ingham R1							
20N	Nil N	71	76	69	91	71	70
20N	150N	97	101	102	99	105	94
150N	Nil N	75	83	74	72	75	85
150N	150N	99	98	113	109	105	104
lsd		*Plant N (9); Ratoon N (4); Tillage × Ratoon N (5); History × Tillage × Plant N (10); and History × Plant N × Ratoon N (11)*					
Bundaberg plant crop							
Nil N		77	58*	84	89	78	78
140N		76	77*	94	73	84	75
lsd		*History x N (15)*					
Bundaberg R1							
Nil N	Nil N	82	80	101	108	84	92
Nil N	140N	98	93	94	109	102	96
140N	Nil N	88	83	98	108	82	89
140N	140N	92	92	97	103	92	86
lsd		*History (9); Ratoon N (4); and History × Ratoon N (10)*					

*Direct drill continuous cane plots likely to be disadvantaged due to replanting

Plant crop treatment responses at Ingham were relatively simple, with significant main effects of history (cane 74 t/ha $\leq$ maize 82 t/ha < soybean 94 t/ha) and N fertiliser input (20N 76 t/ha < 150N 91 t/ha), and no interactions. The situation was less clear at Bundaberg, although the apparent treatment interactions were partly due to the replant of the DD continuous cane treatment.

This replanted treatment was the only one to show a significant positive response to N fertiliser in Table 3. However, if the DD continuous cane treatments were excluded from the analysis there continued to be a significant treatment (history × tillage × N rate) interaction which was driven by a positive N response in tilled maize soil but a negative N response in DD maize soil. There were no positive responses to a soybean break like those recorded at Ingham.

Ratoon crop yields showed a number of main effects and higher order interactions, especially at Ingham. At this site the history × tillage × plant N interaction is relatively uninformative, showing no significant yield responses to plant crop N or history under conventional tillage, but a significant difference between relatively high yielding maize (95 t/ha) and low yielding soybean (82 t/ha) histories at the 20N rate . The history × plant n × ratoon N interaction shows no differences in yields between histories or plant N fertiliser rates with no applied N in the ratoon cycle (73–80 t/ha), positive responses to ratoon N fertiliser in all cases (98–111 t/ha), but highest yields in the maize/150N plant/150N ratoon treatment.

However, the key points from this are (a) effectively no residual effects of N applied in the plant crop, (b) strong responses to ratoon N fertiliser, and (c) no notable residual effects of either breaks or tillage.

At Bundaberg, the significant history × ratoon N interaction is driven by high yields in the maize history regardless of ratoon N application (101–104 t/ha), lower yields in continuous cane or soybean histories with ratoon N (94 t/ha), and lowest yields in cane (83 t/ha) and soybean (87 t/ha) histories with no ratoon N.

Again, the key points are (i) the response to ratoon N in both cane and soybean histories, and (ii) the consistently positive response to maize at both ratoon N rates, compared to cane or soybean histories.

Crop N recovery

Biomass samples and final crop yields in the plant and 1R crops were used to quantify crop N contents at the two sites, with data from final harvests of the plant and 1R crops at Ingham and Bundaberg shown in Table 4.

Table 4—Effects of break history, tillage and N fertiliser in the plant and 1R crop on plant N contents (kg N/ha) at Ingham and Bundaberg. Values in parentheses are lsd values (P<0.05) for the appropriate means comparisons.

Plant crop N	Ratoon crop N	Continuous cane		Maize		Soybean	
		Tilled	DD	Tilled	DD	Tilled	DD
Ingham plant crop							
20N		43.4	42.3	44.1	45.1	57.3	47.2
150N		65.0	54.6	60.0	65.4	85.1	63.2
lsd		*History (9.0); N rate (4.6); Tillage (6.6); and HistoryxTillage (11.0)*					
Ingham R1							
20N	Nil N	41.9	43.0	43.0	40.8	35.3	50.0
20N	150N	62.0	57.0	55.6	63.8	49.9	64.0
150N	Nil N	47.9	39.8	36.4	36.6	53.9	37.0
150N	150N	57.6	59.8	64.8	56.6	57.9	51.6
lsd		*TillagexPlant NxRatoon N (5.2); and HistoryxTillagexPlant N (10.2)*					
Bundaberg plant crop							
Nil N		161.2	146.3[*]	183.6	191.9	183.2	208.8
140N		174.6	168.1[*]	216.4	176.5	234	197.3
lsd		*History (20.8); N rate (15.3); Tillage (10.4); and N ratexTillage (17.5)*					
Bundaberg R1							
Nil N	Nil N	109.1	116.4	174.8	171.0	126.1	131.3
Nil N	140N	149.4	148.4	160.1	193.3	152.9	163.0
140N	Nil N	129.6	132.4	153.5	135.9	158.7	138.0
140N	140N	169.7	151.4	171.5	188.5	185.5	152.9
lsd		*History (19.1); Ratoon N (9.2); History × Plant N (20.5); Tillage × Plant N (13.3); and HistoryxTillagexRatoon N (25.7)*					

[*]Direct Drill continuous cane plots likely to be disadvantaged due to replanting

There were clearly marked differences between sites in the ability of the cane crops to accumulate N, with both plant and 1R crops at Ingham containing approximately 1/3 of the biomass N to those at Bundaberg (e.g. averages of 56 kg N/ha in the plant crop and 50 kg N/ha in the 1R, compared to 186 kg N/ha and 153 kg N/ha in the respective crop classes at Bundaberg).

These differences occurred despite quite similar cane yields (trial average yields of 80 t/ha and 94 t/ha at Bundaberg compared to 83 t/ha and 89 t/ha at Ingham, Table 3), and although trial average CCS was higher at Ingham in both crop classes (16.5 v 15.5 in the plant crop and 16.9 v 15.4 in 1R), sugar contents were still high at Bundaberg.

Despite the large differences in apparent crop N status at the two sites, there were only small (although often statistically significant) impacts of any of the management practices (tillage, crop history and N fertiliser application) on crop N contents.

For example, in the absence of additional fertiliser N the soybean rotation crop was able to provide only an additional 14 (Ingham)–22 (Bundaberg) kg N/ha to the above-ground biomass of plant crops and 0 (Ingham)–16 (Bundaberg) kg N/ha to biomass in the 1R crops.

In considering these impacts, the DD treatments in the plant crop were not considered due to the different planting date of the DD cane treatment at Bundaberg.

Similarly, application of additional N fertiliser in the plant crop (140 kg N/ha at Bundaberg and 130 kg N/ha at Ingham) only resulted in an additional 15 (Bundaberg)–19 (Ingham) kg N/ha accumulating in crop biomass.

Similarly in the 1R, the additional N recovered from a combined 280 kg N/ha at both sites over the crop cycle (i.e. Nil N/Nil N v 140 N/140 N in Bundaberg, or 20N/Nil N v 150 N/150 N in Ingham) was only 32 kg N/ha in Bundaberg and 16 kg N/ha at Ingham.

Apparent N budgets

Estimates of net N mineralisation or loss (undifferentiated between leaching and gaseous N loss and immobilisation in the stool and soil organic N pool) from the soil-plant system during the plant and R1 crops were calculated for the treatments receiving minimal/no N and the full N fertiliser rate in the plant crop (Table 5).

The starting N pool was assumed to comprise (trash N, fertiliser N additions and soil mineral N), while the N pool at crop harvest was assumed to contain (trash N, profile mineral N and N in above ground crop biomass).

After plant crop harvest, the new starting N pool for the R1 crop was taken as containing (profile mineral N, residual trash N and fresh trash N from the plant crop), while the harvest N pool was calculated from the same pools as in the plant crop cycle.

The starting N pools were similar for the cane and soybean histories at planting in Bundaberg (146 kg N/ha for cane and 153 kg N/ha after soybeans) and marginally lower at Ingham (117 and 137 kg N/ha for cane and soybean histories, respectively), with fertiliser N addition adding an extra 130 (Ingham) to 140 (Bundaberg) kg N/ha to those treatments.

Table 5—Estimated N budgets (kg N/ha) from the DD continuous cane and soybean histories at Ingham and Bundaberg for the plant and 1R crop cycles. Data are shown for treatments receiving minimal N fertiliser input (0N at Bundaberg or 20N at Ingham) and treatments receiving a standard plant crop N application (140N at Bundaberg and 150N at Ingham), but no N fertiliser during the 1R crop.

	Ingham						Bundaberg					
	Starting N pool		Harvest N pool		Net N balance		Starting N pool		Harvest N pool		Net N balance	
	20N	150N	20N	150N	20N	150N	0N	140N	0N	140N	0N	140N
Plant crop												
Continuous cane	117	247	91	106	–26	–141	146	286	217	380	71	94
Soybean fallow	137	267	94	110	–43	–157	153	293	271	379	118	86
1st ratoon												
Continuous cane	64	69	98	96	34	26	179	323	200	227	21	–94
Soybean fallow	60	63	97	90	36	27	200	303	227	263	27	–40

At plant cane harvest at Bundaberg, the new N pools had increased to 217 and 271 kg N/ha for cane and soybean histories without N fertiliser and to 380 and 379 kg N/ha with 140N applied. This suggested net N mineralisation (not accounting for possible leaching or gaseous N losses) of 71–118 kg N/ha (without N fertiliser) and 84–96 kg N/ha (with 140N fertiliser) had occurred from soil reserves during the plant crop season. This contrasted markedly with findings at Ingham, where the N pool at plant crop harvest had decreased to 91 (cane)–94 (soybean) kg N/ha with 20N and 106 (cane)–10 (soybean) kg N/ha with 150N. This suggested net N losses of 26-43 kg N/ha during the plant crop with fertiliser N inputs of 20N and 141–157 kg N/ha with 150N.

A similar budgeting exercise undertaken for these treatments during the 1R crop provided strongly contrasting results. During this cycle, there was a further 21-27 kg N/ha net N mineralisation from the cane and soybean histories without N fertiliser input at Bundaberg and a net mineralisation of 34 (cane)–36 (soybean) kg N/ha at Ingham in the 20N treatments. However in the 140N treatments at Bundaberg there had been a net N loss of 40 (soybean)-94 (cane) kg N/ha, while in the comparable 150N treatments at Ingham there was a net N mineralisation from soil N reserves of 26 (cane)–27 (soybeans) kg N/ha.

Discussion

This study has illustrated the complexity of interactions between farming systems changes (e.g. adoption of rotation/break cropping and reduced tillage systems), N management decisions and crop productivity in contrasting environments in both wet tropical and dry subtropical environments. Our results clearly show that while the underlying principles of the new farming system can provide real productivity and profitability benefits, there may also be mitigating circumstances that constrain those benefits from being realised.

The first example from this study is the expectation of increased sugarcane yields and profitability resulting from the inclusion of a legume fallow crop (Garside *et al*., 1999; Garside and Bell, 2001; Loeskow *et al*., 2006), with those benefits expected to be maintained throughout the subsequent crop cycle (Garside and Bell, 2007).

The plant crop yields at Ingham did show significant benefits from the soybean break treatment in plant cane yields (Table 3), but there were no significant benefits in the Bundaberg study and there were no residual yield benefits from the soybean break at either site.

The reasons for the poor response to a soybean fallow probably differ between sites. The Bundaberg site was characterised by a wide diversity of pathogenic nematode species detailed by Stirling *et al*. (2010), and while the soybean fallow achieved the desired aim of reducing populations of the widespread pathogenic species *Meloidogyne javanica* (root-knot nematode) and *Pratylenchus zeae* (lesion nematode), it maintained a similar population of the less widespread but very damaging *Xiphinema elongatum* (dagger nematode) as under continuous cane, and significantly increased populations of *Helicotylenchus dihystera* (spiral nematode) relative to either cane or maize histories.

The lack of effect of soybeans on these pathogenic nematode species at this site, combined with the rapid resurgence of populations of both *P. zeae* and *M. javanica* observed in the soybean treatments, suggest that this group of pathogens may have negated any potential soybean rotation benefits at this site. Indeed, it is likely that the enhanced soil mineral N status recorded in this history (Figure 2b, Figure 3) may have contributed to reduced biological suppression of these pathogens, and so facilitated the rapid recovery during the plant crop (Stirling *et al*., 2003).

The unexpected beneficial effects of the maize history on cane yields, despite maintaining populations of *P. zeae* and *M. javanica* similar to the continuous cane treatment, may have been due to the reduction in populations of *X. elongatum* recorded after maize (Stirling *et al*. 2010) and the greater inputs of low C:N crop residues that may have enhanced general suppressiveness during the plant crop.

In contrast, the Ingham site was behaving as expected during the plant crop, especially during the early stages of the season, with significant improvements in cane yields recorded in the soybean treatment. However, there were no significant interactions between N fertiliser application and crop history, with the soybean treatment responding positively to N fertiliser addition (Table 3). This result, combined with the very low crop N contents at this site and the relatively minor impact of both soybean crops or fertiliser on crop N contents in both the plant and 1R crops (Table 4) suggest yields may have been N limited. While there was strong evidence of enhanced soil mineral N in the soybean treatments early in the plant crop and no evidence of N leaching down the profile at planting (Figure 2a) or three months later, there was a rapid disappearance of mineral N between the 3 month and 6 month sampling dates (data not shown).

This apparent loss coincided with an intense part of the wet season (500 mm in a 21 day period in January 2008, combined with prolonged waterlogging) and suggests gaseous N losses could have been significant through denitrification.

A more prolonged intense wet season in the 1R crop in 2009, in which >1000mm fell in each of January and February 2009, is likely to have caused similar N losses from the fertiliser N applied to the 1R crop and contributed to the very poor fertiliser N recoveries in crop biomass (Table 4).

The second example is the expected N benefit from fallow legumes such that N fertiliser rates can be reduced or eliminated in the plant crop (Bell *et al*., 2003; Garside and Bell, 2003).

As discussed earlier, it is apparent that N losses during the wet season at Ingham significantly eroded the residual N benefits from soybean which were clearly evident at planting (Figure 1a) and at the three month sampling just prior to the wet season onset.

This is supported by the low crop N contents and the negative N budgets recorded in the plant crop at that site (Table 5). While seemingly not as large as the apparent losses from the fertiliser N treatments, losses seem to have been comprehensive enough to eliminate any residual N benefits from the soybean crop in the 1R crop (Table 4).

There was still a significant Tillage × History interaction in plant crop N accumulation in which the tilled soybean treatment (71 kg N/ha) contained significantly more N than that in tilled maize or cane (52–54 kg N/ha) and DD for all histories (48–55 kg N/ha, Table 4).

This reflected the higher early season mineral N (Figure 1a) and resulting crop N accumulation (data not shown) recorded in that treatment during early season growth, before the waterlogging events occurred.

Soil and crop N dynamics at Bundaberg contrasted strongly with Ingham, as a site with apparently much low starting soil organic matter reserves (Table 1) was able to mineralise enough N from decomposing residues and soil organic matter to supply 150–160 kg N/ha in the continuous cane history (Table 4).

Additional N supplied from decomposing soybean residues or N fertiliser had little impact on crop N accumulation (Table 4), and was primarily found as NO_3-N in deeper layers of the soil profile at harvest (e.g. Figure 4).

While this did not result in apparent N losses in the plant crop (Table 5), it was reflected by negative N budgets in the 1R crop, primarily due to continued leaching losses over the early part of the 2007/08 summer season when rainfall was plentiful and crop N demand relatively low.

There was still evidence of a residual N benefit from the soybean fallow compared to continuous cane, but this was generally small (i.e, < 20 kg N/ha, Table 4).

The third example is the lack of expected yield and N benefits from elimination of tillage which have been attributed to better synchronisation of legume N mineralisation with N demand by the cane crop (Bell *et al.*, 2003, 2006b; Garside *et al.*, 2006), as well as enhanced suppression of cane pathogens (Bell *et al.*, 2006a; Stirling *et al.*, 2010). Given the N losses which seemed to occur at Ingham, it is not unexpected that residual N benefits from legumes were not recorded.

If N limitations were significant in the 1R crop as suggested by crop N contents in Table 4, any potential yield benefit accruing from pathogen minimisation may not have been able to be expressed.

While leaf samples were not analysed at this site, the N concentrations in cane in all treatments in the 1R crop at Ingham were $\leq$ 0.1% N. Similar low cane N concentrations have been recorded in some other studies without significant responses to higher N fertiliser rates (e.g. Thorburn *et al.*, 2008), but the lack of N accumulating in crop biomass in fertilised treatments in our studies suggests significant environmental N losses may be the cause, rather than low crop N demand.

In contrast, crops at Bundaberg were able to access ample quantities of N from soil reserves and/or supplementary fertiliser reserves regardless of tillage system, so although there was evidence of accelerated N mineralisation and deep leaching in the conventionally tilled plots (especially in the soybean history – Figure 4), there was no evidence of N limitations in any treatment in the 1R crop.

Concentrations of N in cane in the 1R crop ranged from 0.18–0.2% in the nil N treatments to 0.27–0.31% in the 140N/140N treatments, with no significant differences between crop histories (data not shown). It is unclear whether this high N status was associated with reduced biological suppression/greater pathogenic nematode constraints at the site, although the positive effect of the maize history was consistent with that theory.

Finally, the contrasting N use efficiencies at Ingham and Bundaberg highlight the difficulties in N management in sugarcane farming systems in different soils and climates.

Assumptions made about the potential inputs from mineralising organic N reserves or legume residues (Schroeder *et al.*, 2005) will inherently be conservative to try to accommodate situations with significant environmental losses in the crop season (as occurred at Ingham in both the plant and 1R crop in this study) without incurring major yield losses.

Similarly, systems that base N fertiliser rates on the amount of N removed in the previous crop (Thorburn *et al.*, 2007, 2008) will not be able to account for major N losses above and beyond those due to crop removal and will result in a reduction in soil N reserves.

While this may be desirable from environmental perspectives, it will ultimately create difficulties in N management in a high C, low N system that will result in yield penalties for growers. There is clearly a need to invest further resources into improving N use efficiency in sugarcane farming systems, especially now that legume fallows and reduced tillage are becoming more prevalent. A particular focus needs to be on the N status of the sugarcane crop, rather than yield response *per se*, as the Ingham data showed that a lack of N fertiliser response may not be indicative of a crop with an adequate N status.

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