NITROGEN DYNAMICS AND NITROUS OXIDE EMISSIONS IN IMPROVED SUGARCANE FARMING SYSTEMS

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Abstract

THE AUSTRALIAN SUGAR industry is under increasing environmental pressure to improve nitrogen (N) use efficiency. This will require a greater understanding of processes affecting N availability and crop N demand in sugarcane farming systems. A field experiment was established at Mackay to improve understanding of: nitrogen availability in the soil when legume break crops are grown in the farming system; the effect of tillage on N availability; and nitrous oxide emissions from these farming systems to determine appropriate management strategies for reducing greenhouse gas emissions. The experiment was arranged as a split plot with tillage (zonal or no tillage) prior to planting sugarcane as the main plot and fallow management (bare (BF) or soybean fallow (SF)) as the sub-plot. The soybean crop achieved above ground dry biomass of 6.1 t/ha 100 days after planting. Sugarcane received 138 kg N/ha in BF plots and 18 kg N/ha following soybean. High levels of soil mineral N were present at the commencement of the experiment. In BF, mineral N moved down the soil profile prior to sugarcane planting. In SF, some mineral N was captured for soybean crop growth. N_2O emissions were significantly greater in BF than SF (1.9 vs. 1.0 kg N_2O-N/ha) during the fallow period, most likely due to greater mineral N availability. During the sugarcane cropping period, significantly higher cumulative N_2O emissions were observed in BF (2.3 kg N_2O-N/ha) than SF (1.5 kg N_2O-N/ha), most likely due to differences in mineral N availability following fertilisation. Emissions were low compared to other sugarcane studies. Tillage had no effect on mineral N availability or N_2O emissions. This was most likely due to the low level of soil disturbance in the zonal tillage treatment. Cane and sugar yield were similar across farming systems treatments. These results reinforce recommendations for management of legume residues on the soil surface and reduced N fertiliser rates on sugarcane following good legume crops.

Introduction

The Australian sugar industry is under increasing environmental pressure to improve nitrogen use efficiency (NUE), mostly due to declining water quality in the Great Barrier Reef lagoon (Kroon *et al*., 2012).

Agricultural soils are also a major source of anthropogenic nitrous oxide (N_2O) emissions. Nitrous oxide is a potent greenhouse gas with a global warming potential of 310 times higher than carbon dioxide. Improving NUE will require a greater understanding of processes affecting N availability and crop N demand in sugarcane farming systems.

While not specifically associated with NUE, the benefits of farming systems that include legume rotation breaks, reduced tillage and controlled traffic have been demonstrated both agronomically (Garside *et al*., 2004) and economically (Schroeder *et al*., 2009). These practices have been adopted to varying degrees in different growing regions.

The inclusion of a legume fallow crop in the farming system changes N fertiliser recommendations (Schroeder *et al*., 2005). Plant crop yields can be maintained without fertiliser N following 'good' legume crops (Garside *et al*., 1997; Bell *et al*., 2003). However, N fertiliser responses have been found in sugarcane plant crops following legumes under certain conditions (Garside *et al*., 2006; Salter *et al*., 2010).

Management of the legume biomass affects the amount and timing of N availability. Incorporation of green legume residue resulted in rapid mineralisation and potential N losses through leaching when compared with residue that was managed on the soil surface (Garside and Berthelson, 2004). In Mackay, tillage of legume residue resulted in increased nitrous oxide (N_2O) emissions compared to a bare fallow system in an unusually wet year (Wang *et al*., 2012).

High N_2O emissions (3–25 kg N/ha/yr) have been recorded from Australian sugarcane soils (Wang *et al*., 2008; Denmead *et al*., 2010). Reducing N losses by denitrification should result in improved NUE and environmental outcomes. However, most studies have either quantified emissions from sugarcane soils under current management practices (Denmead *et al*., 2006, 2007, 2008) or assessed nitrification inhibitors and coated fertiliser products (Wang *et al*., 2008, 2012, 2014). These investigations identified that further work is required to understand the impact of changing farming system practices.

The objectives of the work reported here were to:

(i) improve understanding of N availability in the soil when legume break crops are grown in the farming system

(ii) improve understanding of the effect of tillage on N availability and

(iii) quantify N_2O emissions from these farming systems to determine appropriate management strategies for reducing greenhouse gas emissions.

These outcomes will contribute to improvements in NUE in the Australian sugar industry.

Materials and methods

A farming systems experiment was established at the Sugar Research Australia experiment station near Mackay (21^o 09'47.27'' S, 149^o 06'46.71'' E). The soil was a sandy clay loam (Chromosol). The experiment commenced in December 2011 and concluded in September 2013 when the first crop of sugarcane was harvested.

The farming systems included soybean fallow (SF) or bare fallow (BF) treatments followed by zonal (ZT) or no tillage (NT) prior to planting sugarcane. The experiment was arranged as a split plot design with tillage prior to planting sugarcane as the main plot (100 m by 6 planting beds) and fallow management as the sub-plot (50 m by 6 planting beds). There were four replicates.

Site details and management

Prior to the experiment, sugarcane was last harvested at the site on 2 September 2010. The site was managed as a bare fallow and received herbicide applications as required. The block was then prepared for the experiment: tillage (off-set discs) on 16 and 25 August 2011; deep ripping on 25 August 2011; planting beds were formed on a 1.8 m row spacing on 25 October 2011 with a bed renovator; tops of beds were rotary hoed on 7 December 2011 in preparation for planting the soybean crop. A background soil sample (0–20 cm) was collected from the site in September 2011. Soil characteristics were: pH (1:5 water) 4.9; organic carbon 1.0 % (Walkley and Black, 1934); phosphorus (BSES) 40 mg/kg; cation exchange capacity 3.59 meq/100g; colour – grey. Agricultural lime was applied at 2.5 t/ha on 21 September 2011 to ameliorate low soil pH. Soybean (cv. Leichhardt) was planted on 20 December 2011.

Two soybean rows were established on each planting bed. The soybean crop was terminated on 18 April 2012 with the application of Glyphosate (RoundUp PowerMax 3L/ha). Soybean grain was not harvested. Zonal tillage was conducted on 30 July 2012 with one pass of a wavy (scalloped)-disc cultivator. Only the tops of the planting beds were tilled and soil in the interrows was undisturbed. Soil in the NT treatments was not disturbed. Sugarcane (cv. Q208[⁽ᴰ⁾]) was planted on 7 August 2012 with a double disc-opener planter.

Soybean crop assessment

Biomass samples were collected from the soybean crop on 22 February 2012 and 29 March 2012. The latter was when biomass was expected to be at a maximum. On each occasion the soybean material was collected from two quadrats (1.8 m^2) per plot. Plants were cut at the base, weighed and a sub-subsample taken to determine moisture content. These samples were ground in a micro-hammer mill followed by tissue N analysis (Dumas).

Nitrous oxide emissions

N_2O fluxes were measured using manual gas sampling chambers. Wang *et al*. (2011, 2012) described manual chamber dimensions, methodology and analysis of gas samples. Two chamber bases were installed in each plot. One chamber was directly on the planting bed and the other positioned on the edge of the planting bed and furrow. Gas samples were collected approximately twice per week. The emission rate for the whole plot was estimated by weight-averaging the measurements from the beds and furrows.

Fertiliser rates and N treatments

During sugarcane planting all plots received 18.1 N, 18.4 P, 0 K and 12.8 S (kg/ha). On 25 October 2012, plots following the bare fallow treatment received an additional 120 kg N/ha as urea. All plots also received 100 kg K /ha.

Soil mineral N

Soil samples were collected from plots over the experimental period (Table 1). On each occasion two cores were collected from each sampling position and depth increments pooled prior to analysis. When sampling after fertilisation, cores on the planting bed were collected from the fertiliser band. In February 2012 and March 2013 the soil profile was saturated due to heavy and on-going rainfall so sampling was only possible from the 0–10 and 10–30 cm depth increments.

Table 1—Summary of soil sampling strategy used to monitor soil mineral nitrogen in bare fallow (BF) and soybean fallow (SF) plots.

Days after soybean planting	Date	Fallow	Depth	Position	Tillage
15	4/01/2012	BF SF	0–10, 10–30, 30–50, 50–80	Bed	Zero
71	29/02/2012	BF SF	0–10, 10–30	Bed, Interrow	Zero,
177	14/06/2012	BF SF	0–10, 10–30, 30–50, 50–80	Bed, Interrow	Zero
280	25/09/2012	BF SF	0–10, 10–30, 30–50, 50–80	Bed, Interrow	Zero, Zonal
387	10/01/2013	BF SF	0–10, 10–30, 30–50, 50–80	Bed, Interrow	Zero, Zonal
440	4/03/2013	BF SF	0–10, 10–30	Bed, Interrow	Zero, Zonal
673	23/10/2013	BF SF	0–10, 10–30, 30–50, 50–80	Bed, Interrow	Zero, Zonal

Sugarcane biomass and harvest

At 117 days after sugarcane planting (DASCP), stalks in a 7.5 m^2 sub-plot were counted, cut at the base, and weighed to ascertain fresh biomass. A sub-sample was taken from each plot to determine crop moisture content. A similar procedure was followed at 233 DASCP. However, additional data were obtained from a 15-stalk sub-sample that was collected from the harvested sub-plot. These 15 stalks were partitioned into two components: (i) millable stalk and (ii) green leaf and cabbage. Samples were ground in a micro-hammer mill and tissue N analysis (Dumas) performed. At final harvest (407 DASCP) this procedure was repeated except the sub-plot area sampled was increased to 15 m^2. In addition to this, 6 stalks were taken from each plot to determine sugar content using near infrared spectroscopy (Berding *et al*., 2003).

Statistical analyses

Data were analysed with analysis of variance procedures (GenStat 16.1). Cumulative N_2O emission data were $\log_e$ transformed prior to analysis in order to achieve homogeneity of variance. Soil mineral N data from each sampling date were analysed separately.

Results and discussion

Climatic conditions

Weather data were taken from the Bureau of Meteorology sites at Dumbleton Rocks Alert (4.5 km NW of the site), Pleystowe Sugar Mill (7 km W of the site) and Mackay Aero (7 km E of the site). Daily rainfall from each station was averaged (Figure 1) as an approximation of conditions at the trial site. Rainfall totals for the 2012 and 2013 calendar years were 2171 and 1771 mm, respectively. Rainfall from 20 December 2011 to 18 April 2012, the duration of the soybean crop, was 1663 mm. Rainfall from 7 August 2012 to 18 September 2013, the duration of the sugarcane crop, was 1929 mm. An additional 150 mm was applied as irrigation (Figure 1).

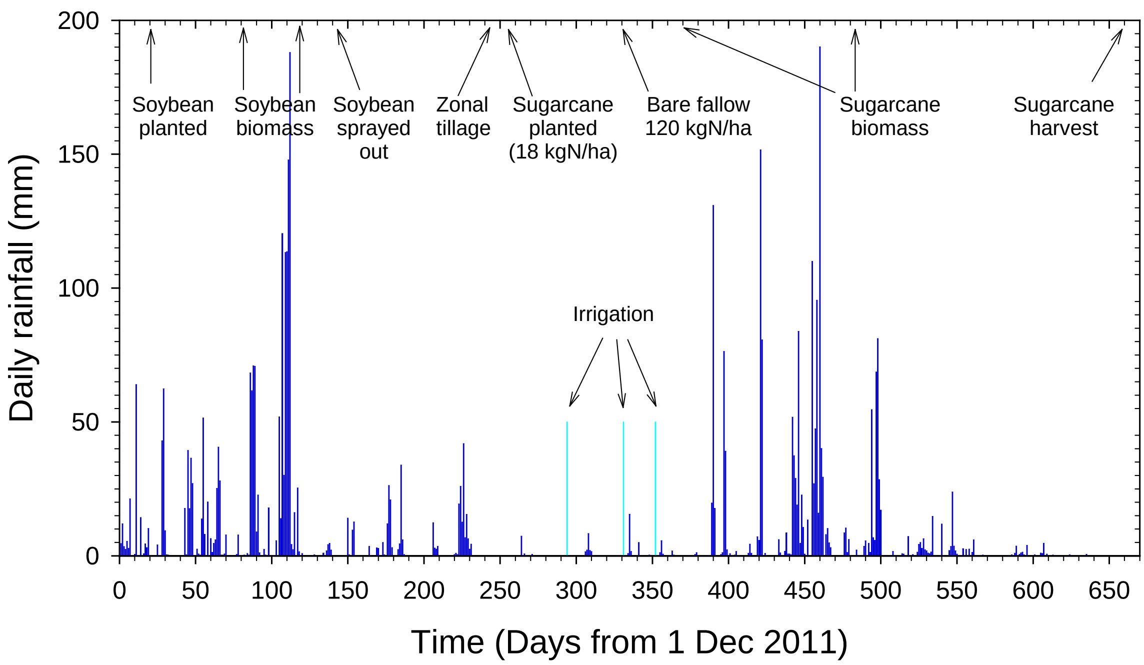

Fig. 1—Daily rainfall from 1 December 2011 to 18 September 2013 and timing of significant events at the trial site. The data is an average of three BOM weather stations that are in close proximity (~ 7 km) to the trial site.

Soybean crop

Soybean crop biomass and its components changed significantly between sample times (Table 2). At 100 days after soybean planting (DASP), the dry biomass of 6.1 t/ha recorded here is considered a good crop for the Mackay region (Schroeder *et al*., 2005).

It was lower than the 7–10 t/ha reported by Garside and Bell (2001). Nitrogen content (N%) of the biomass was low for a soybean crop, with 3.0–3.5% N being more typical (Garside and Bell 2001, Schroeder *et al*., 2005).

This meant that N returned to the soil from the soybean biomass was relatively low. Others have reported well grown soybean crops contributing in excess of 300 kg N/ha (Garside *et al*., 1996; Garside and Bell, 2001).

Table 2—Soybean biomass, dry matter and nitrogen contents 64 and 100 days after soybean planting at Mackay.

Sample date	Days after soybean planting	Fresh biomass (t/ha)	%DM	Dry biomass (t/ha)	N%	Above ground biomass N (kg/ha)	Total biomass N (kg/ha)*
22/02/2012	64	13.6a	24.5a	3.3a	2.5a	82.8a	107.6a
29/03/2012	100	22.4b	27.7b	6.1b	2.1b	130.0b	169.0b

*Includes additional 30% N assumed in root biomass (Schroeder *et al*., 2005)

Soil mineral N

There was no difference in soil mineral N between BF and SF at 15 DASP. At that stage the soybean crop had only recently emerged. However, soil mineral N in the top 30 cm was relatively high (~ 20 mg/kg soil) (Table 3).

The high initial soil mineral N concentration values were potentially due to the extended fallow prior to initiating the experiment, tillage prior to establishing the soybean crop and mineralisation of N over that period. The availability of N to the soybean crop during early development could have caused poor nodulation.

At later stages of crop development this could have contributed to the low % N in the soybean tissue (Table 2). Significant differences among soil depths were found in all samplings and are only discussed when a significant interaction was present.

At 71 DASP, BF had significantly higher mineral N than SF in the 10–30 cm depth increment. This was most likely due to the soybean crop utilising the available mineral N. At 177 DASP, soil mineral N was significantly higher in BF than SF for the bottom two depth increments only.

This indicates movement of N down the profile in the BF system prior to planting the sugarcane crop, and possible losses in the BF system due to leaching. The observations are also consistent with the use of available mineral N for soybean crop growth. At 280 DASP, SF contained significantly higher soil mineral N than BF in the 0–10 cm depth increment. This difference could be attributed to mineralisation of the soybean crop residue at the soil surface. Both BF and SF had higher mineral N in the 0–10 cm increment at 280 DASP in comparison to 177 DASP (Figure 2).

This reflected the addition of 18.1 kg N/ha fertiliser at sugarcane planting in both systems. At 387 DASP, very high soil mineral N concentrations were found in BF due to fertiliser N application (120 kg N/ha applied 310 DASP). Mineral N in SF was low.

At 440 DASP, soil mineral N concentrations were low. This large change over a 53-day period coincided with 841 mm rainfall and is likely to be associated with N losses, N uptake by the crop and immobilisation. These values remained low after the sugarcane crop was harvested (673 DASP). Tillage had no effect on soil mineral N levels (data not shown). This may have been due to the zonal tillage treatment resulting in a relatively low amount of soil disturbance.

Table 3—Changes in soil profile (0 – 80 cm) mineral nitrogen (mg/kg) over time (days after soybean planting) during a fallow (bare or soybean) and following sugarcane crop at Mackay. Nitrogen (18 kgN/ha) was applied to all plots 231 DASP and 120 kgN/ha to bare fallow (BF) plots 310 DASP. Data are an average of samples collected from the planting bed and furrow.

Time (DASP)	Depth (cm)	BF	SF
15	0–10	26.3	31.1
	10–30	14.0	17.0
	30–50	5.5	6.1
	50–80	6.2	4.4
LSD(0.05): Depth.Fallow ns			
71	0–10	6.0	3.9
	10–30	12.4	4.1
LSD(0.05): Depth.Fallow 7.2			
177	0–10	7.0	7.3
	10–30	8.5	7.3
	30–50	9.6	5.8
	50–80	8.4	3.5
LSD(0.05): Depth.Fallow 2.3			
280	0–10	12.5	18.3
	10–30	9.6	10.1
	30–50	8.9	5.6
	50–80	5.6	2.8
LSD(0.05): Depth.Fallow 3.2			
387*	0–10	61.7	7.3
	10–30	49.4	6.4
	30–50	24.3	7.0
	50–80	8.4	3.8
LSD(0.05): Depth.Fallow 22.0			
440	0–10	3.3	3.3
	10–30	2.9	2.7
LSD(0.05): Depth.Fallow ns			
673	0–10	4.2	4.5
	10–30	4.5	4.0
	30–50	3.9	3.3
	50–80	2.6	2.0
LSD(0.05): Depth.Fallow ns			

*Samples were collected from the fertiliser band and therefore overestimate total mineral N
ns – no statistically significant difference

Nitrous oxide emissions

Nitrous oxide emissions were strongly associated with rainfall events (Figure 3) with two major periods coinciding with the 2011–2012 and 2012–2013 wet seasons (Dec – Apr). Cumulative N_2O emissions were significantly greater in BF than SF (1.9 vs. 1.0 kg N_2O-N/ha) during the fallow period (Figure 4). This was most likely associated with differences in the availability of nitrate between the two systems.

Lower mineral N in SF at 71 DASP and lower N_2O emissions again suggests that the soybean crop removed some of the mineral N that was present at 15 DASP. Despite the differences between fallow treatments, emissions at this site during the fallow period were lower than those reported by Wang *et al*. (2012), most likely due to drier climatic conditions at this site and differences in soil properties.

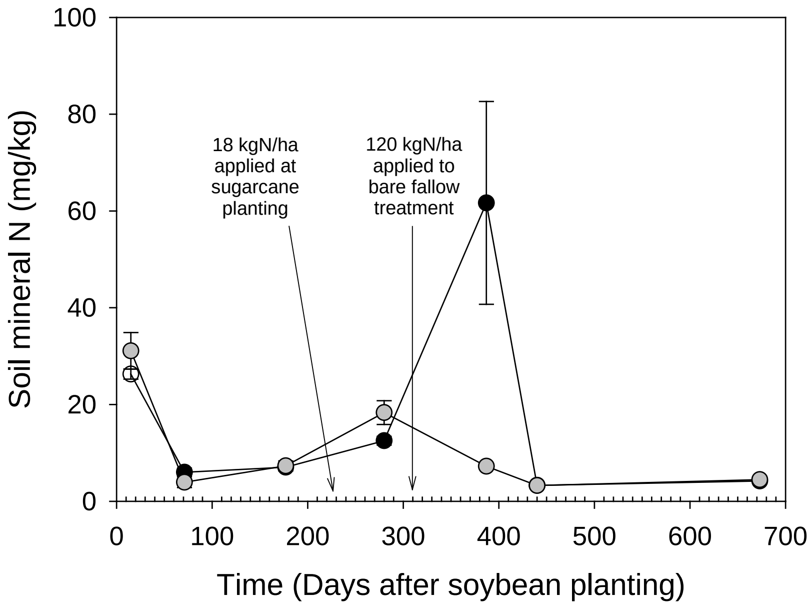

Fig. 2—Soil mineral nitrogen in the top 10 cm of soil over a fallow period and following sugarcane crop at Mackay. ● Bare fallow ● Soybean fallow. Data are an average of samples collected from the planting bed and furrow. Error bars + SEM.

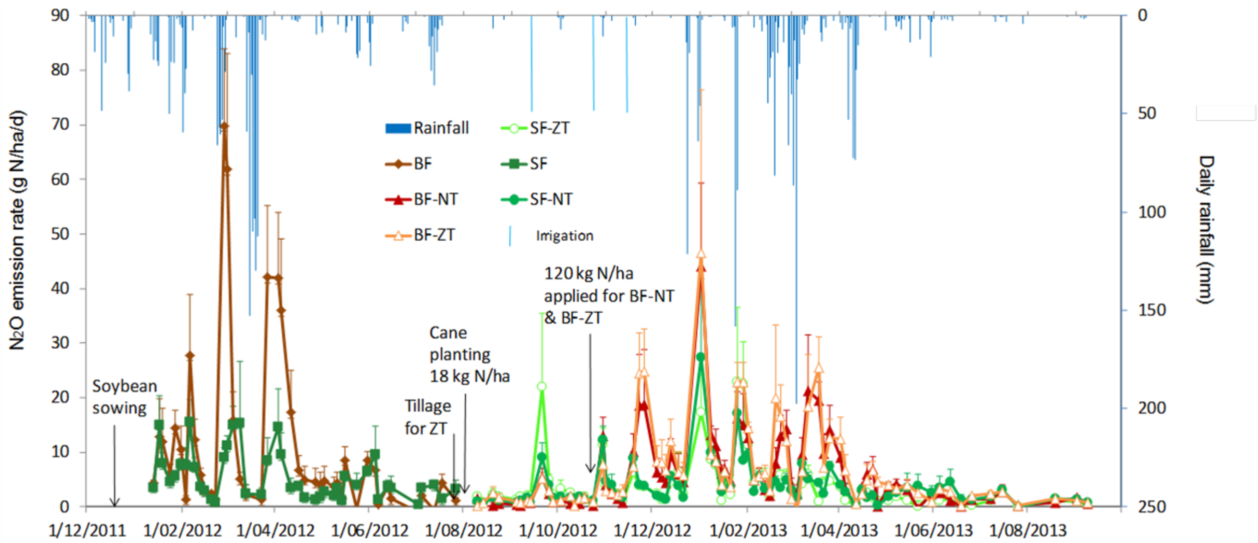

Fig. 3—Nitrous oxide emissions from a bare fallow or soybean fallow and following sugarcane crop at Mackay. BF – Bare fallow; SF – Soybean fallow; NT– no tillage; ZT – zonal tillage with a wavy disc cultivator. Blue bars show daily rainfall taken from the Bureau of Meteorology site at Dumbleton Rocks (4.5 km from the site). Error bars + SEM.

During the sugarcane cropping period significantly higher cumulative N_2O emissions were observed in the BF farming system (2.3 kg N_2O-N/ha) than the SF farming system (1.5 kg N_2O-N/ha). The addition of 120 kg fertiliser N in BF accounts for this difference. No difference between tillage treatments was found, again possibly due to the relatively low amount of soil disturbance in the zonal tillage treatment. The period of increased N_2O emissions from Sept 2012 to Nov 2012 from the soybean fallow system (Figures 3 and 4) corresponds with higher soil mineral N availability reported at 280 DASP from the 0–10 cm depth increment (Table 2 and Figure 2). This is further evidence for the mineralisation of N from the soybean residue at this time, and coincides with the likely N demand from the developing sugarcane crop.

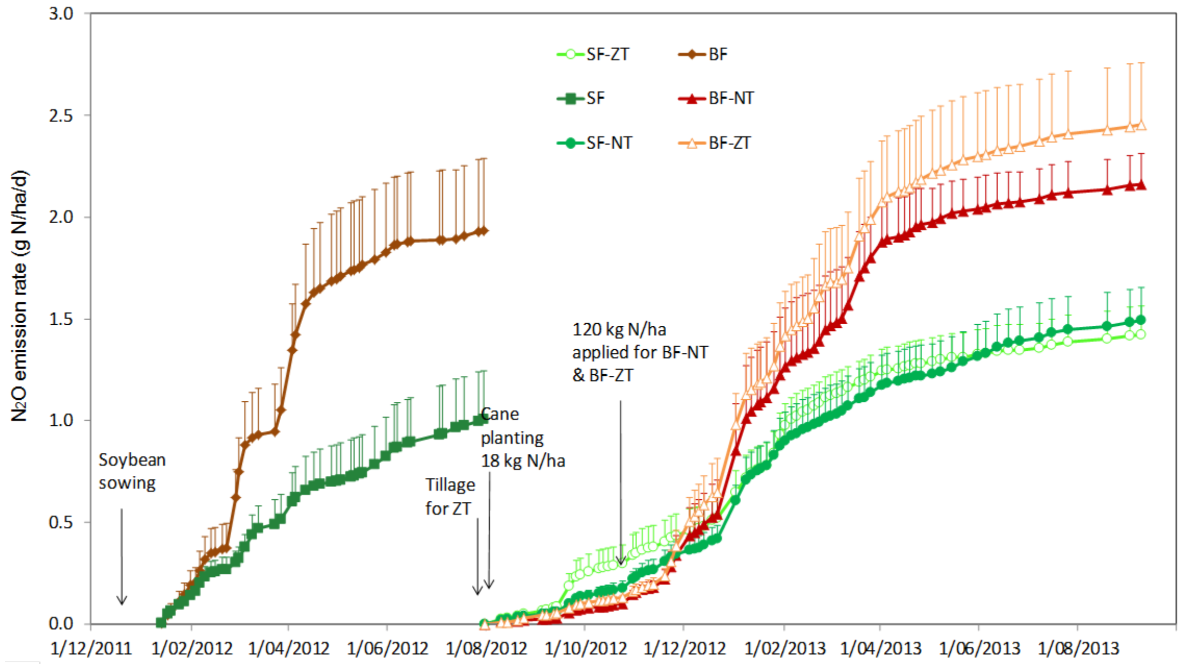

Fig. 4—Cumulative nitrous oxide emissions from bare fallow or soybean fallow and following sugarcane crop at Mackay. BF – Bare fallow; SF – Soybean fallow; NT– no tillage; ZT – zonal tillage with a wavy disc cultivator. Error bars + SEM.

Increased N_2O emissions have been reported from a sugarcane crop following a soybean fallow (Wang *et al*., 2012). This result appeared to be associated with tillage of the soybean residue, to a greater extent than in this experiment, and significant rainfall events in August and September 2010 associated with a *La-Nina* weather pattern.

Lower N_2O emissions following a legume fallow crop reported in this study may be more representative. However, tillage of soybean residue followed by heavy rainfall will most likely result in increased gaseous and other N losses due to enhanced mineralisation. The practice of managing soybean residue on the soil surface, with minimum or no tillage, to slow mineralisation is recommended (Garside and Berthelson, 2004).

Annual cumulative N_2O emissions during the sugarcane cropping period were considerably lower than those observed in sugarcane cropping systems at Murwillumbah (Denmead *et al*., 2010; Wang *et al*., 2008), Mackay (Wang *et al*., 2012) and Ingham (Wang *et al*., 2014). This is most likely due to seasonal, mostly rainfall, conditions and differences in soil characteristics at each site. Very high emissions at Murwillumbah have been associated with high organic carbon content (Thorburn *et al*., 2013) in combination with periodic wet conditions.

Sugarcane biomass development

Fallow and tillage treatments did not produce any statistically significant differences in sugarcane crop traits throughout crop development (Table 5). There were trends ($p < 0.1$) for greater crop % dry matter in the zonal tillage treatment, greater crop N in BF, and greater crop % dry matter in SF at 407 DASCP.

Table 5—Sugarcane crop traits at 118, 233 and 407 days after sugarcane planting (DASCP).

Trait	DASCP	Bare fallow			Soybean fallow		
		ZT	NT	Mean	ZT	NT	Mean
Millable stalk %	118	No millable stalk					
	233	77.3	77.4	77.3	76.3	76.4	76.3
	407	90.1	89.6	89.9	90.9	89.1	90.0
Crop % dry matter	118	25.3	23.5	24.4	23.6	21.1	22.4
	233	20.3	20.2	20.3	20.8	20.8	20.8
	407	33.6	33.2	33.4	34.6	34.2	34.4
Crop N (kg/ha)*	118	14.6	19.7	17.2	15.3	11.8	13.6
	233	88.4	111.3	99.9	83.7	80.7	82.2
	407	68.4	89.1	78.7	44.9	58.3	51.6

*Nitrogen in above ground biomass

The lack of significant differences may be associated with N management in both BF and SF reflecting current industry recommendations (Schroeder *et al*., 2005) rather than treatments where N was over or under applied. Differences between tillage treatments were also small.

Sugarcane yield

No difference in sugarcane (TCH) and sugar (TSH) yield at harvest were found across fallow and tillage treatments (Table 6). The poorer performance with zonal tillage in BF was not statistically significant. CCS was significantly higher following SF than BF. This result, plus a trend for higher crop % dry matter at final harvest in SF, indicates a decline in growth rate in the later stages of development was more advanced following SF than BF. High % millable stalk (~90 %) and high % crop dry matter (~ 34%) across treatments reflect a crop that was not actively growing due to very dry conditions prior to harvest. Possibly these data are related to lower crop N content in SF, however the difference in N content was not sufficient to affect crop yield.

Table 6—Sugarcane yield (TCH, CCS and TSH) following bare or soybean fallow and zonal (ZT) and no-tillage (NT) treatments prior to planting sugarcane. Values in brackets represent the SEM.

Yield trait	Bare fallow			Soybean fallow		
	ZT	NT	Mean	ZT	NT	Mean
TCH	81.9 (8.8)	98.1 (7.5)	90.0a	92 (6.0)	94.8 (5.1)	93.4a
CCS	17.7 (0.1)	17.5 (0.1)	17.6a	18 (0.1)	18.0 (0.2)	18.0b
TSH	14.5 (1.6)	17.2 (1.3)	15.8a	16.5 (1.1)	17.1 (1.1)	16.8a

Conclusions

High levels of soil mineral N were present at the commencement of this study. In BF, mineral N moved down the soil profile prior to sugarcane planting. In SF, some mineral N was captured for soybean crop growth. This was evident from the decline in mineral N near the soil surface.

The lower mineral N availability during the fallow period in SF was also demonstrated by lower N_2O emissions. N_2O emissions were low in comparison to other sugarcane studies. However, the application of fertiliser N in the bare fallow system caused higher emissions than in SF. Tillage did not affect N_2O emissions, most likely due to the low level of soil disturbance with zonal tillage in this study. Sugarcane crop growth was largely unaffected by the different fallow and tillage treatments.

The results suggest that following a soybean crop no tillage is required in order to establish sugarcane. Similar results have been observed previously (Garside and Berthelson, 2004). Higher CCS in SF may have been associated with lower crop N content and a generally more mature crop. However no difference in sugar yield was observed.

This suggests that sufficient N was available from the soybean crop and supports current industry N recommendations for plant crops following legume fallows (Schroeder *et al*., 2005).

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