# SOYBEAN ROTATION AND CROP RESIDUE MANAGEMENT TO REDUCE NITROUS OXIDE EMISSIONS FROM SUGARCANE SOILS

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## Abstract

NITROUS OXIDE ($N_2O$) IS a potent greenhouse gas and the predominant ozone-depleting substance in the atmosphere. Agricultural nitrogenous fertiliser use is the major source of human-induced $N_2O$ emissions. A field experiment was conducted at Bundaberg from October 2012 to September 2014 to examine the impacts of legume crop (soybean) rotation as an alternative nitrogen (N) source on $N_2O$ emissions during the fallow period and to investigate low-emission soybean residue management practices. An automatic monitoring system and manual gas sampling chambers were used to measure greenhouse gas emissions from soil. Soybean cropping during the fallow period reduced $N_2O$ emissions compared to the bare fallow. Based on the N content in the soybean crop residues, the fertiliser N application rate was reduced by about 120 kg N/ha for the subsequent sugarcane crop. Consequently, emissions of $N_2O$ during the sugarcane cropping season were significantly lower from the soybean cropped soil than those from the conventionally fertilised (145 kg N/ha) soil following bare fallow. However, tillage that incorporated the soybean crop residues into soil promoted $N_2O$ emissions in the first two months. Spraying a nitrification inhibitor (DMPP) onto the soybean crop residues before tillage effectively prevented the $N_2O$ emission spikes. Compared to conventional tillage, practising no-till with or without growing a nitrogen catch crop during the time after soybean harvest and before cane planting also reduced $N_2O$ emissions substantially. These results demonstrated that soybean rotation during the fallow period followed with N conservation management practices could offer a promising $N_2O$ mitigation strategy in sugarcane farming. Further investigation is required to provide guidance on N and water management following soybean fallow to maintain sugar productivity.

## Introduction

Nitrous oxide ($N_2O$) is a potent greenhouse gas with a global warming potential approximately 300 times higher than carbon dioxide. Agricultural soil is the major source of human-induced $N_2O$ production mainly because of nitrogen (N) fertiliser application.

Growing soybean during the fallow period between sugarcane cropping cycles provides a low-cost alternative of supplying N to the following crop while improving soil health (Garside and Berthelsen, 2004).

Substitution of the biologically fixed $N_2$ for some fertiliser N can also save greenhouse gas emissions during fertiliser manufacture and transportation as well as subsequent urea hydrolysis in soil. However, our recent study found that $N_2O$ emissions from sugarcane soil increased significantly following soybean residue incorporation as compared to normal N fertiliser application (Wang *et al.*, 2012). This was probably because the co-existence of readily mineralisable organic carbon and N (including unharvested grain at 1.2 t/ha) and wet soil favoured microbial denitrification and thus $N_2O$ production.

Improved soybean residue management practices need to be investigated to maximise the economic and environmental benefits of soybean rotation in sugarcane cropping systems. There is usually a gap period of several months between the soybean crop maturity and sugarcane planting. If plentiful rainfall is received after incorporation of the soybean crop residues under conventional tillage, substantial amounts of the crop residue N could be released through microbial mineralisation.

The mineralised N would build up in soil, which is susceptible to losses by denitrification and leaching if high rainfall events occur before it can be taken up by the sugarcane crop. No-till, which leaves crop residues on the soil surface in the months between soybean harvesting and cane planting, could slow down mineralisation of soybean residues and thus reduce potential loss of the mineralised N from denitrification and/or leaching before uptake by the subsequent sugarcane crop (Garside and Berthelsen, 2004).

Nitrification inhibitors have been used with nitrogenous fertilisers to retard the microbial transformation of ammonium N ($NH_4^+$) into nitrate ($NO_3^-$) and thus reduce the risk of $NO_3^-$ losses from denitrification including $N_2O$ emissions (Dalal *et al.*, 2003; Chen *et al.*, 2008). Among the nitrification inhibitors commercially available, DMPP (3,4-dimethylpyrazole phosphate) was considered to have a number of advantages including high efficiency, low application rate and low toxicity (Zerulla *et al.*, 2001). It remains to be investigated as to whether DMPP could reduce $N_2O$ emissions following the incorporation of soybean crop residues.

Furthermore, N catch crops that grow quickly have been used in areas with high rainfall between two crops to help reduce nitrogen losses from soil by absorbing N and subsequently releasing N from decomposition of the crop residues for the following main crop (Vos and van der Putten, 2001). This technique appears attractive for managing the legume crop residue N in the months prior to sugarcane planting.

We hypothesised that $N_2O$ emissions following soybean rotation may be reduced if the mineralisation, nitrification and/or denitrification processes could be suppressed by performing no-till, applying an effective nitrification inhibitor, or growing a N catch crop.

The major objectives of this study were to assess the impacts of soybean rotation during the fallow period and subsequent soybean crop residue management practices on $N_2O$ emissions and sugar productivity in the subtropics where leguminous crop rotation is recommended as one of the sustainable management practices in sugarcane farming systems.

This paper focuses on $N_2O$ emissions under different management strategies; crop and sugar yields and plant N uptakes are reported in a companion paper by Halpin *et al*. (2015)

## Materials and Methods

### Experimental site

The experiment was established on a sugarcane farm at Bundaberg (24°57'53"S, 152°20'0"E) on 31 October 2012 at the early stage of a fallow period between two sugarcane cropping cycles (about five years per cycle).

The long-term (1959–2012) annual mean temperature in this subtropical region is 21.5°C (Bundaberg Aero Station, the Bureau of Meteorology, Australia), with the lowest monthly mean temperature in July (16.1°C) and the highest in January (25.8°C). Mean annual rainfall is 1027 mm, with ca. 56% of rainfall received from December to March.

In the present study, rainfall and air temperature were recorded by an on-site weather station (Campbell Scientific, Australia).

The soil is a redoxic Hydrosol (Isbell, 2002) with loamy sand in the 0–30 cm layer, underlain by sandy loam at about 30–60 cm depth and sandy clay loam at about 60–100 cm depth (Table 1). Sugarcane was grown with the practice of green cane trash blanketing from 2007 to 2012, following a peanut crop rotation in 2006/07. The last sugarcane crop (cv Q205⁽ᵇ⁾) was harvested in September 2012 with a fresh cane yield of approximately 70 t/ha. Based on the relationship: trash dry matter = 0.046 × fresh cane yield + 5.84 ($r^2$ = 0.20; $n$ = 325) and the average N content of 0.64% in trash (Halpin, unpublished data), the amount of cane trash on the ground immediately after harvest was approximately 9 t/ha, containing about 58 kg N/ha.

**Table 1**—Physiochemical properties in soil profile of the experimental site.

| Depth (cm) | Clay (%) | Silt (%) | Sand (%) | TOC (mg/g) | TN (mg/g) | $pH_{water}$ | EC (dS/m) |
|---|---|---|---|---|---|---|---|
| 0–10 | 8 | 7 | 85 | 10.0 | 0.68 | 5.9 | 0.054 |
| 10–20 | 8 | 7 | 85 | 9.6 | 0.64 | 6.0 | 0.050 |
| 20–30 | 9 | 7 | 84 | 8.0 | 0.54 | 6.0 | 0.040 |
| 30–60 | 15 | 6 | 79 | 4.0 | 0.34 | 6.0 | 0.037 |
| 60–100 | 25 | 6 | 69 | 1.6 | 0.23 | 5.7 | 0.033 |

### Treatments and management practices

The experiment consisted of the following treatments:

(1) BF-TL-S+0N

(2) BF-TL-S+25N+120N

(3) SF-TL-S+25N

(4) SF-NT-S+25N

(5) SF-NI+TL-S+25N

(6) SF-NT-NCC-S+25N

where BF stands for bare fallow; SF for soybean fallow; TL for tillage; NT for no-till; NI+TL for spraying of the nitrification inhibitor DMPP onto soybean crop residues (1.67 kg active ingredient/ha) followed by tillage; NCC for growing a N catch crop, triticale (×*Triticosecale*), after soybean harvest; S for sugarcane cropping; +0N, +25N and +120N for application of N fertiliser as urea at 0, 25 and 120 kg N/ha, respectively.

Detailed descriptions of the agronomic management of this experiment were given by Halpin *et al.* (2015). Briefly, the site was ploughed out and crop beds (~126 cm wide with ~57 cm wide depressed inter-row space) were formed during 19–22 November 2012. Twenty four plots were marked out in a randomised block design with four replicates for each treatment.

Each plot measured 20 m long with a 1 m gap between two adjacent plots and 9.2 m wide (5 beds) with one crop bed as a buffer between two neighbouring plots. Soybean (cv A6785) was sown on 13 December 2012 in two rows 80 cm apart on each bed.

After harvest of the soybean grain on 2 May 2013, different soybean residue management treatments (tillage, nitrification inhibitor spray and triticale sowing) were implemented on 3–4 June 2013. Sugarcane (cv Q238⁽ᵇ⁾) was planted in the middle of the bed on 2 September 2013, using a conventional whole-stick planter. All treatments were fertilised at 25 kg N/ha (except the 0N control), 28 kg P/ha, 23 kg K/ha and 13 kg S/ha as base by placing a blended fertiliser in bands (~10 cm under the surface) on both sides of the cane setts (~5 cm away).

The soybean crop residues in the NT treatments were partly buried by these operations. On 28 November 2013, the remaining N fertiliser (120 kg N/ha) was applied for Treatment 2, and 73 kg K/ha and 12 kg S/ha were applied for all treatments before the crop row was filled in with soil to the bed height. The crop was manually harvested on 16 September 2014 by cutting an area encompassing 3 rows × 5 m in each plot.

**Measurement of greenhouse gas fluxes**

Emissions of $N_2O$ were measured using a combination of manual and automatic gas sampling chambers. The manual chamber (Wang *et al.*, 2011) consisted of a square stainless-steel base (50 cm W × 50 cm L × 15 cm H) and a cover box with white plastic panels (50 cm L × 50 cm W × 55 cm H). Two chamber bases were installed in each plot with one covering the middle area on the bed and another covering one side of the bed shoulder and half of the inter-row area. The chamber bases were relocated occasionally to minimise the effect of chambers on soil moisture and crop growth and to obtain better spatial representation.

To measure greenhouse gas fluxes between soil and the atmosphere, the chambers were closed for 1–1.5 h between 09:00 and 11:00 am. Subsequently, gas samples were taken with a syringe at the beginning and end of the enclosure period and injected into evacuated glass vials for storage.

The cover boxes were removed from the bases immediately after the gas sampling to minimise potential microclimatic modification of the sampling area. Gas samples were taken about two to three times per week during the high emission periods (e.g., after rainfall) and less frequently at low emission times (e.g. dry periods).

The gas samples were analysed in the laboratory with a gas chromatograph (Varian CP-3800, Varian Inc., Middelburgh, the Netherlands). Alpha grade standard $N_2O$ gases (0, 0.5, 5, 12, and 20 µM/M; BOC Ltd, Sydney, Australia) were used for calibration of the gas chromatograph (Wang *et al.*, 2011).

The automatic gas sampling system consisted of twelve chambers and allowed measurement of greenhouse gas fluxes at a sub-daily frequency (eight samplings/day). Each chamber (Wang *et al.*, 2011) included a stainless-steel base that was identical to the manual chamber base, an extension (30 cm deep) and a cover box (15 cm deep) with stainless-steel frames and two lids on the top panel that can be opened and closed automatically at pre-set intervals.

Placement and management of the chamber bases were similar to those described above for the manual chambers. Air samples were automatically extracted from the headspace of the chamber into a gas chromatograph (SRI 8610C, SRI Instruments, CA, USA) that analysed simultaneously the concentrations of $N_2O$ and methane ($CH_4$).

The automatic chambers were deployed on 31 October 2012 in the early stage of the fallow period. Immediately after soybean planting, six auto-chambers were installed in the soybean fallow plots and the other six were used in the bare fallow plots. In the meantime, manual gas sampling chambers were installed in both the bare fallow and the soybean fallow plots with four replicates each. After implementation of different soybean residue management practices, more manual chambers were installed for the new treatments. Following the second N fertiliser application for Treatment 2, the automatic chambers were used for Treatments 1 and 2 only.

**Determination of soil mineral N contents**

Soil profile samples were taken from 0–10 cm, 10–30 cm, 30–60 cm and 60–100 cm depths shortly before soybean sowing, after soybean harvest and after sugarcane harvest. After N fertiliser application, soil samples were collected at 0–10 cm and 10–30 cm from three positions in each plot: (i) the fertiliser band (ii) bed sides and (iii) the bed shoulder and depressed inter-row area.

The samples for each position were randomly taken from three points and bulked by depth. The soil samples were air-dried immediately after collection. The contents of soil mineral N ($NH_4^+$and $NO_3^-$) were determined using 2 M KCl extraction and colorimetric techniques (Rayment and Lyons, 2010). Gravimetric soil water content was determined by oven-drying at 105°C for 24 h. Soil mineral N contents were expressed on a dry mass basis.

**Data processing and statistical analysis**

Hourly emission rates during the chamber closure period were calculated from the increase of gas concentration in the headspace.

Daily emission rates for the automatic chamber measurements were obtained by averaging all hourly emission rates for that day. Daily emission rates for the manual chamber measurements were estimated by extrapolating the hourly emission rates measured between 09:00 and 11:00 am; automatic chamber measurements in a previous study showed that $N_2O$ emission rates during this time were generally close to the daily averages (Wang *et al.*, 2011).

The daily emission rates between the days of manual chamber measurements were estimated by linear interpolation. In rare cases where a major rainfall or irrigation event occurred following a prolonged (>1 week) dry period after a gas sampling, the emission rates measured before the rainfall were used for the dry period. All statistical analyses were performed using GenStat V.14 (VSN International Ltd, UK). Prior to analysis of variance (ANOVA), data were tested for normality and log-transformed where appropriate. Differences and interactions among treatments were assessed using the ANOVA procedure.

## Results and discussion

### Dynamics of soil mineral nitrogen

Soil mineral N contents (0–30 cm) were low with no substantial differences between the bare fallow and soybean fallow treatments during the fallow period before tillage (Figure 1). The soybean grain yield was high at 4.0±0.1 t/ha and the total above-ground biomass (including grain) yield was 9.6±0.2 t/ha.

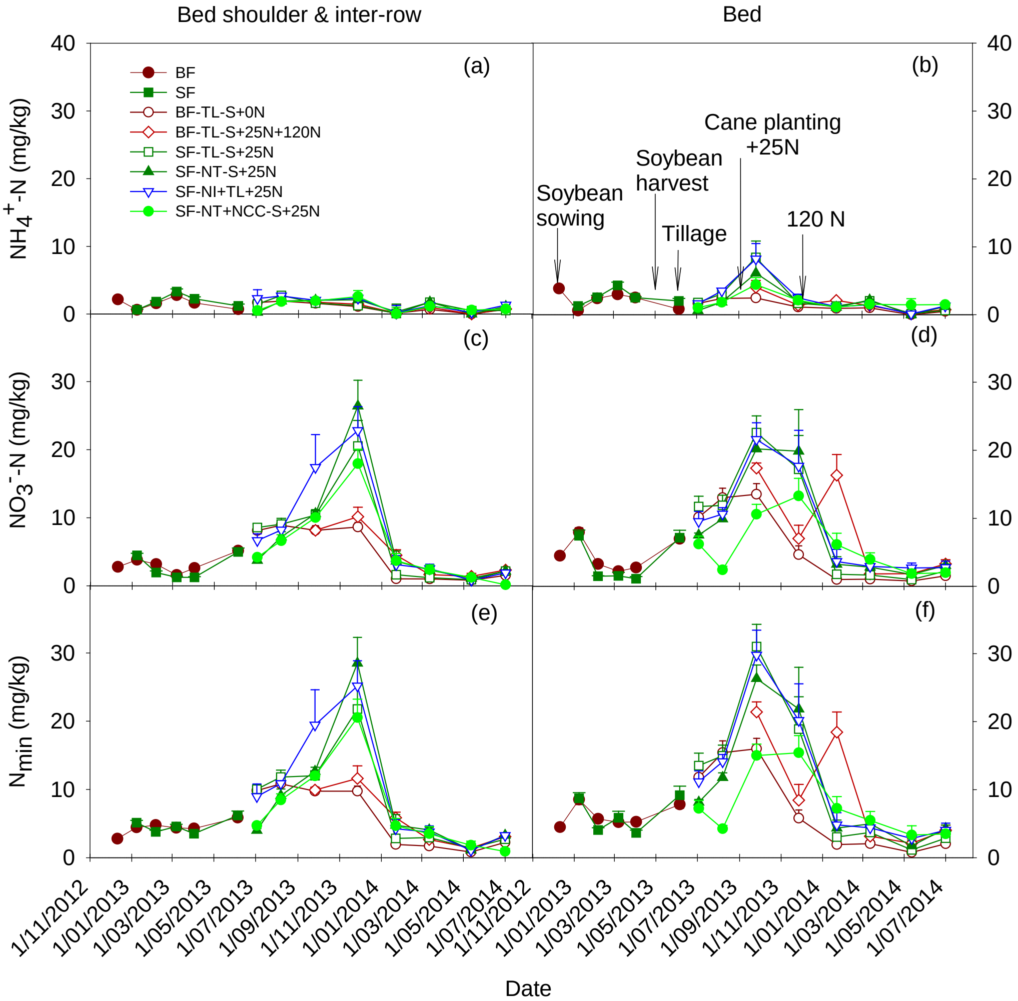


Fig. 1—Dynamics of soil mineral N contents (mean+SE in 0–30 cm) in the bed shoulder & inter-row area and the bed area at the Bundaberg site. BF: bare fallow: SF: soybean fallow; TL: tillage; NT: no-till; NI: nitrification inhibitor DMPP spray; NCC: N catch crop; S: sugarcane crop. 25N and 120N: fertilised with urea at 25 and 120 kg N/ha, respectively.

Total amount of N contained in the soybean crop residues (including roots) after grain harvest was estimated to be about 172 kg N/ha (Halpin *et al.*, 2015). Tillage resulted in increases in soil mineral N contents in the first month compared to the no-till treatments. Among the treatments receiving tillage, the soybean fallow treatments had significantly higher soil mineral N than the bare fallow treatments during the first three months after sugarcane planting, most likely due to N mineralisation from the soybean crop residues. The soil mineral N contents in the legume fallow treatments declined dramatically from December 2013 to early January 2014, at least in part attributable to losses through leaching and/or denitrification prompted by a high rainfall event and irrigation (Fig. 1f). Compared to other soybean fallow treatments, the N catch crop substantially reduced soil mineral N contents during the two-month triticale growing season and the four months following spraying out of the crop. Slightly higher soil mineral N contents were observed in this treatment than other SF treatments from January to April 2014, indicating N release from the residues of the N catch crop during this time.

**Dynamics of $N_2O$ emissions in relation to key driving factors**

Emissions of $N_2O$ were generally low during the fallow period (Figure 2). The irrigation (60 mm) on 10 January 2013 and the high rainfall events in late January 2013 prompted moderate increases in $N_2O$ emissions. Despite the wet conditions from late January to February, $N_2O$ emissions seldom exceeded 50 g N/ha/d, consistent with the low soil mineral N contents (Figure 1).

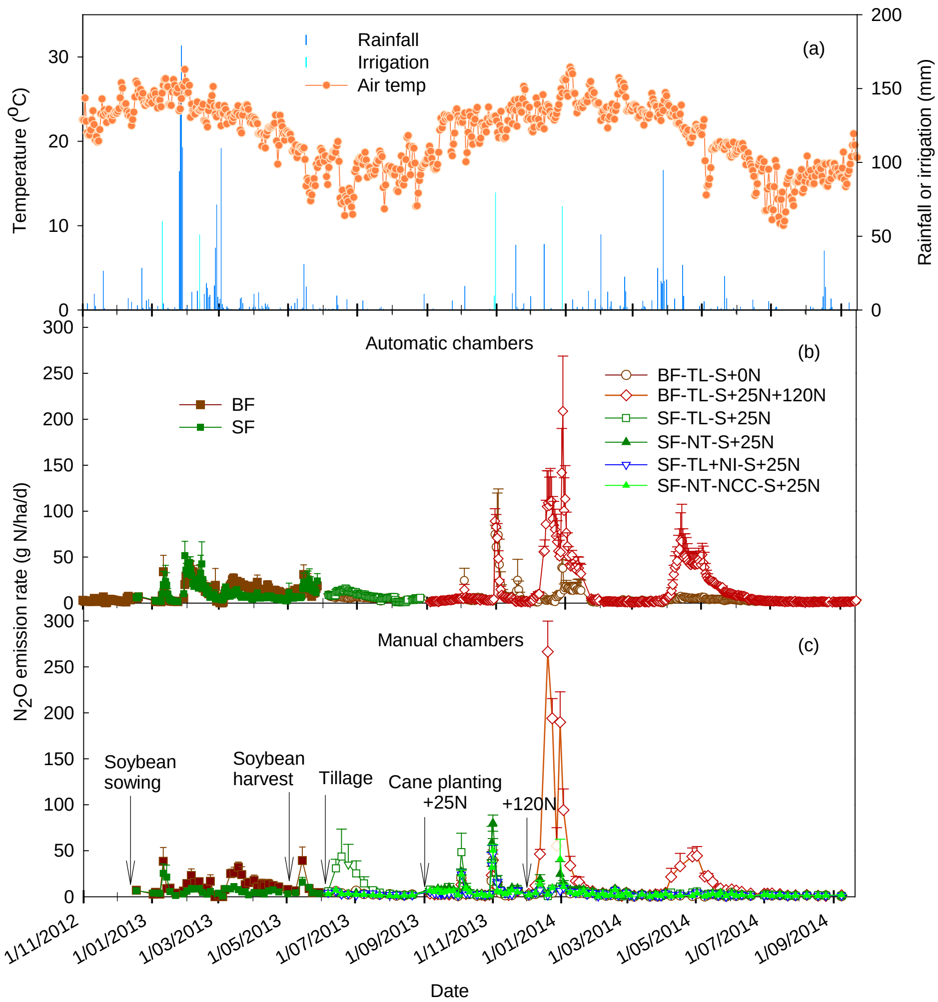


Fig. 2—Dynamics of $N_2O$ emissions (mean+SE) under different fallow and soybean residue management practices in relation to climatic conditions at Bundaberg. BF: bare fallow; SF: soybean fallow; TL: tillage; NT: no-till; NI: nitrification inhibitor spray; NCC: N catch crop; S: sugarcane crop; 0N, 25N and 120N: fertilised with urea at 0, 25 and 120 kg N/ha, respectively.

In addition, growing soybean appeared to have reduced $N_2O$ emissions during the cropping season compared to the bare fallow. This could be attributed partly to the lower soil $NO_3^-$ contents resulting from crop uptake of N from soil (Figure 1d), and partly to reduction in soil water contents due to evapotranspiration of the growing plants.

The tillage in early June 2013 promoted $N_2O$ emissions in the following month for the SF-TL treatment (Figure 2c) probably because incorporation of the soybean residues into soil accelerated mineralisation of the organic N and thus supplied more substrate N for $N_2O$ production during nitrification and denitrification. No-till and growing the N catch crop prevented the spikes in $N_2O$ emissions during the same period perhaps due to lower soil $NO_3^-$ contents.

Spraying the soybean residues with DMPP before tillage also inhibited $N_2O$ emissions. However, the net $NO_3^-$ accumulations under this treatment were not significantly lower than those under the conventional tillage treatment (Figure 1d). Further studies are required to quantify the gross nitrification and denitrification rates under different soybean residue management practices.

Basal fertiliser N application (25 kg N/ha) at cane planting did not increase $N_2O$ emissions in the following three months perhaps due to lack of rainfall and the dry soil conditions. Irrigation of 89 mm in late October 2013 substantially enhanced $N_2O$ emissions (Figure 2).

The highest fluxes (>100 g N/ha/d) occurred under the BF-TL-S+25N+120N treatment (referred as BF+145N hereafter) following N fertiliser application at 120 kg N/ha in late November and significant rainfall (45 mm) and irrigation (70 mm) in December 2013 (Figure 2). Another $N_2O$ emission spike was observed for this treatment from April to May 2014 following a series of high rainfall events.

The SF treatments that did not receive the large amount of fertiliser N had substantially lower $N_2O$ emission in response to the rainfall and irrigation events compared to the BF+145N treatment. It appeared that soil moisture and mineral N contents are the key drivers to $N_2O$ emissions in this cropping system.

**Cumulative $N_2O$ emissions**

During the seven-month fallow period before tillage, 2.2–2.4 kg $N_2O$-N/ha and 1.2–1.8 kg $N_2O$-N/ha (varying with the measurement methods) were released in the bare fallow and soybean fallow treatments, respectively (Figure 3). The BF+145N treatment resulted in the highest cumulative $N_2O$ emissions during the fallow and sugarcane cropping seasons. The cumulative $N_2O$ emissions during the sugarcane cropping season for this treatment amounted to 5.6 kg $N_2O$-N/ha and 6.45 kg $N_2O$-N/ha based on automatic and manual chamber measurements, respectively.

The $N_2O$ emission factor of fertiliser N was 2.6% (auto chambers) and 3.7% (manual chambers). These emission factors were substantially higher than those measured in cereal cropping systems in Queensland (Wang *et al.*, 2011; Scheer *et al.*, 2012).

Soybean cropping and consequently the replacement of fertiliser N reduced the cumulative $N_2O$ emissions under conventional tillage by 50% during the fallow and the sugarcane cropping seasons (4.0 kg $N_2O$-N/ha for the SF+25N treatment *vs*. 8.9 kg $N_2O$-N/ha for the BF+145N treatment). However, incorporation of the soybean residues into soil by tillage increased the cumulative $N_2O$ emissions by 0.9 kg N/ha in comparison to the no-till treatment during the following two months (Figure 3b).

The cumulative $N_2O$ emissions in the no-till treatment increased faster after cane planting than those in the tillage treatment, but were still 22% lower at harvest.

Spraying DMPP on the soybean crop residues before tillage and growing a N catch crop under no-till further decreased the cumulative $N_2O$ emissions by 36% and 44%, respectively, compared to the conventional tillage treatment following soybean fallow (Figure 3b).

Growing soybean during the fallow period followed with N-efficient management practices appeared to be a promising strategy for mitigating $N_2O$ emissions in sugarcane cropping systems.

The lower $N_2O$ emissions under the SF treatments were mainly because these treatments avoided the very high $N_2O$ emissions observed in the BF+145N treatment in December 2013 which were prompted by a high rainfall event and irrigation shortly after application of 120 kg N/ha (Figure 2).

While high $N_2O$ emissions were observed following incorporation of the soybean residues into soil by tillage, the magnitudes were much lower than those observed at Mackay (Wang *et al.*, 2012). This was probably because the dry weather conditions in the 150 days following tillage in this study (Figure 2a) restricted denitrification and thus $N_2O$ production.

The sugar yields following soybean fallow tended to be lower ($P$ = 0.10) than the BF+145N treatment (Halpin *et al.*, 2015). In spite of the large amount of N in the soybean residues (172 kg N/ha) that could partly be mineralised during the sugarcane cropping season, the relatively lower sugar yield for the SF treatments indicated that the sugarcane growth was restricted by soil N availability in these treatments.

This was evident from the low soil mineral N levels in the SF treatments during the summer season (Figure 1f) when the crop growth was rapid and thus demanded plentiful N supply. The inadequate soil mineral N supply in the SF treatments during this critical time might be partly due to insufficient N mineralisation of the legume crop residues, but more likely due to N losses through leaching and/or denitrification triggered by the high rainfall and irrigation events in December 2013.

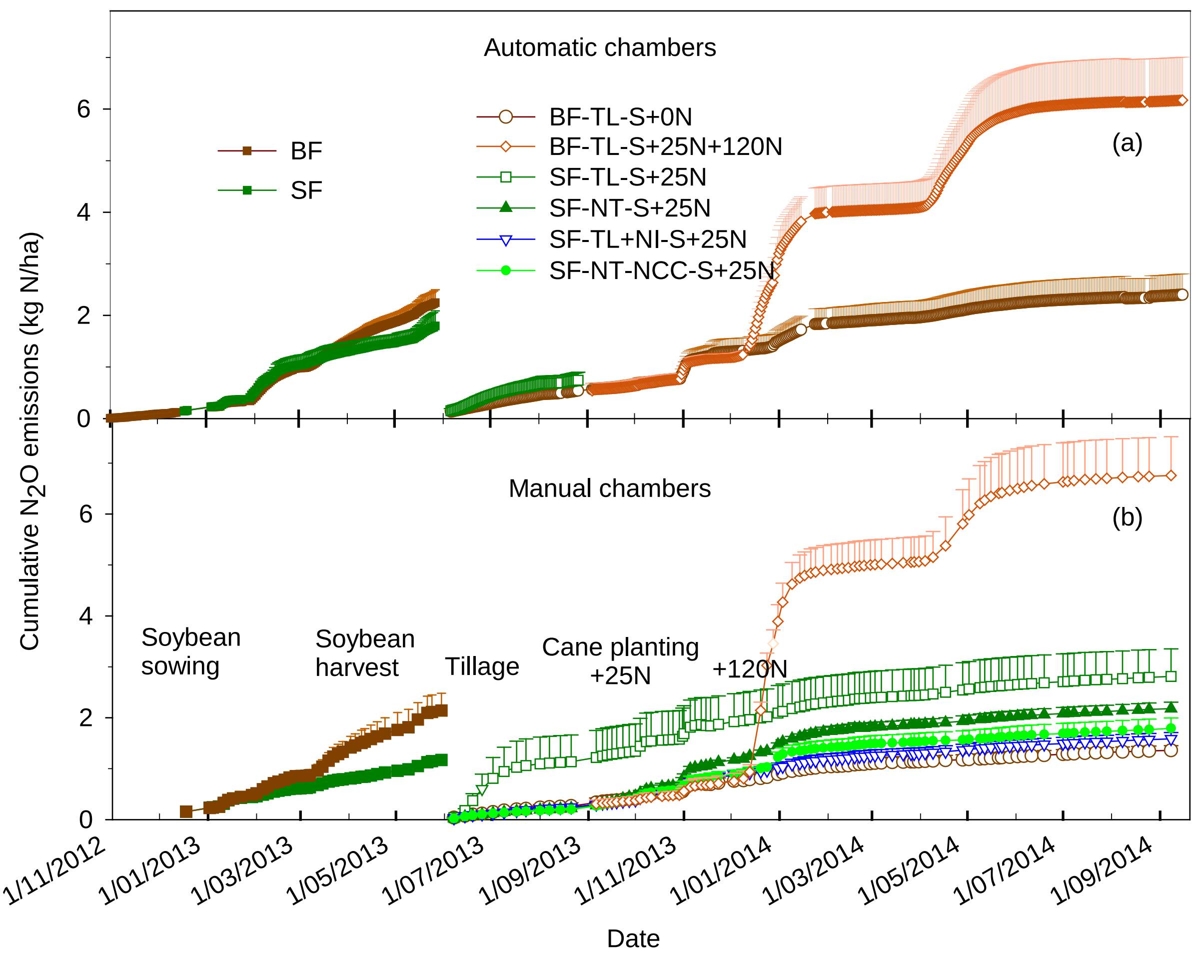


Fig. 3—Cumulative $N_2O$ emissions (mean+SE) under different fallow and soybean residue management practices at Bundaberg. The cumulative emissions in the first one and a half months for the manual chambers (b) were estimated from the automatic chamber measurements. BF: bare fallow; SF: soybean fallow; S: sugarcane; TL: tillage; NT: no-till; NI: nitrification inhibitor; NCC: N catch crop; 0N, 25N and 120N: fertilised with urea at 0, 25 and 120 kg N/ha, respectively.

## Conclusions

Soybean fallow could substantially reduce $N_2O$ emissions during the fallow period and the sugarcane cropping season compared to BF followed by application of a large amount of N fertiliser.

The $N_2O$ mitigation potential of SF could be further enhanced by adopting N-efficient soybean residue management practices such as no-till, growing a N catch crop between soybean harvest and sugarcane planting and spraying the soybean residues with the nitrification inhibitor DMPP before tillage.

Further studies are required to develop an integrated management approach that better synchronises legume N mineralisation to sugarcane N demand and minimises N losses. In addition to the improved soybean residue management practices mentioned above, this approach should also take into account irrigation intensity and timing, soil mineral N contents, and if necessary, supplementary use of fertiliser N at a suitable time and in an appropriate quantity.

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