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NITROUS OXIDE EMISSIONS FROM A SUGARCANE SOIL UNDER DIFFERENT FALLOW AND NITROGEN FERTILISER MANAGEMENT REGIMES

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Abstract

NITROUS OXIDE (N_2O) EMISSIONS from a sugarcane soil at Mackay were monitored during a fallow period and the subsequent sugarcane cropping year using both automatic and manual gas sampling chambers to determine the effects of legume fallow, N fertiliser application and a nitrification inhibitor (DMPP). Substantial N_2O emissions were observed from the bare fallow soil (5.3–6.0 kg N_2O-N/ha in seven months), although no nitrogen fertiliser was applied. Growing soybean during the fallow period did not significantly affect N_2O emissions but substantially increased the emissions in the months after incorporation of the soybean biomass (2.5 t/ha without harvest of grain). The cumulative N_2O emissions from the unfertilised soil amounted to 6.3 kg N_2O-N/ha/year and 16.4 kg N_2O-N/ha/year during the twelve-month sugarcane cropping following bare fallow and soybean fallow, respectively. Application of N fertiliser (urea) at 150 kg N/ha to the sugarcane grown on the bare-fallowed soil increased N_2O emissions by 6–9 kg N_2O-N/ha/year. Addition of the nitrification inhibitor in urea reduced N_2O emissions by 4.2 kg N_2O-N/ha/year from the fertilised soil. Application of fertiliser at 75 kg N/ha to the sugarcane following soybean fallow increased N_2O emissions by 4.5–5.4 kg N_2O-N/ha/year as compared to the no fertiliser treatment. The high N_2O emissions, particularly following soybean residue incorporation and N fertiliser application, demonstrated the need for developing best management strategies to reduce N losses and N_2O emissions while increasing N use efficiency by sugarcane crops. Further studies are required to ascertain the efficacy of nitrification inhibitors in other soil and climate conditions and to investigate optimum soybean residue management practices.

Introduction

Reliance on the use of nitrogen (N) fertiliser in crop production increases the farming cost and the risk of N pollution to the environment. Growing a leguminous break crop such as 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 for some fertiliser N can also save greenhouse gas emissions that would otherwise result from fertiliser manufacture and transportation and from urea hydrolysis in soil.

Nitrous oxide (N_2O) is a potent greenhouse gas with a global warming potential 298 times higher than that of carbon dioxide. Agricultural soils are the major source of anthropogenic N_2O emissions, largely owing to the increasing N fertiliser use (Dalal *et al*., 2003).

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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). While the wet and warm climate and the large amounts of cane trash left over on the soil surface after harvest (particularly where green cane trash blanketing is performed) are inductive to N_2O production through microbial processes such as denitrification, the large amounts of N fertiliser applied to sugarcane crops (>120 kg N/ha/yr) also contribute to the high N_2O emissions. In spite of the above mentioned agronomic, economic and environmental benefits of soybean rotation during the fallow period of sugarcane cropping, its impacts on N_2O emissions remain unclear.

The objectives of this study were to (i) examine the effects of soybean cropping on N_2O emissions during the fallow period and the subsequent plant cane cropping year, (ii) investigate the effectiveness of nitrification inhibitor DMPP on reducing N_2O emissions from N fertiliser, and (iii) quantify annual N_2O emissions on a sugarcane farm where green cane trash blanketing and bare fallow were practiced, to provide data for the national greenhouse gas inventory.

Materials and methods

The experimental site

The field trial was located on a sugarcane farm near Mackay, Queensland (21°11' S, 149°06' E). Annual mean temperature in this area is 23.3 °C and the mean annual rainfall is 1672 mm. The soil is a Chromosol with a sandy loam layer in the 0–35 cm underlain by sandy clay between 35 and 100 cm depth. The top 30 cm soil contains 1.1% organic carbon, 0.065% organic N, 15.7% clay and 17.7% silt with pH 5.2 (1:5 soil: water ratio) and a bulk density of 1.54 g/cm^3. Green cane trash blanketing had been practised for several years. At the commencement of the trial in January 2010, about 8 t/ha of cane trash was present on the soil surface. The initial mean mineral N content in the top 30 cm soil was 5 mg N/kg soil.

Treatments and management schedules

The experiment commenced in the fallow period (December 2009) following harvest of sugarcane at the end of a five-year cropping cycle. Five treatments were applied to examine the effects of soybean rotation during the fallow period and various N fertiliser application rates in the subsequent plant cane crop on greenhouse gas fluxes:

(1)   BF-S+0N: Bare fallow followed by sugarcane with no N fertiliser application;
(2)   BF-S+150N: Bare fallow followed by sugarcane with 150 kg N/ha applied as urea;
(3)   BF-S+150N+NI: Same as (2) except that nitrification inhibitor DMPP was added to the urea;
(4)   SF-S+0N: Soybean fallow followed by sugarcane with no N fertiliser application; and
(5)   SF-S+75N: Soybean fallow followed by sugarcane applied with 75 kg N/ha as urea.

Planting beds (105 cm wide beds with 52 cm wide furrows) were formed in December 2009. Due to continued dry weather conditions, soybean (Leichardt) was sown on 15 January 2010, with dual rows on each bed and a row spacing of 45 cm. Numerous high rainfall events and flooding of soil in the following months (Figure 1) resulted in low grain yields of the soybean crop and damaged the cropping beds.

As a consequence, the soybean grains were not harvested. Beds were reformed in June 2010, which also resulted in the incorporation of the soybean residue. Sugarcane (KQ228) was planted in late July 2010 with a single row in the middle of each bed (row spacing = 157 cm). N fertiliser was applied as urea for treatments 2 and 3 in late October. The treatments were arranged in a randomised block design with four replicates. Each plot was 14.1 m wide (9 rows) and 20 m long. The sugarcane was harvested on 20 July 2011.

Measurement of N_2O fluxes

The N_2O fluxes were measured using both manual and automatic gas sampling chambers. The manual chamber consisted of a square stainless steel base with open top and bottom (length × width × height = 50 cm × 50 cm × 15 cm) and a removable cover box (length × width × height = 50 cm × 50 cm × 55 cm) made with aluminium frames and plastic panels tinted with a layer of white film.

The cover box was fitted with a sampling outlet in the middle of the top panel, a mini fan inside the top panel for mixing air and a closed-cell foam seal under the bottom frame. Two chambers were installed in each plot, one in the bed and the other in the furrow. The chamber bases were inserted into the soil to a depth of ~10 cm and relocated every a few weeks to minimise the effect of chambers on soil moisture and to obtain better spatial representation. To measure gas fluxes between soil and the atmosphere, the chambers were closed for 1~1.5 hrs between 9 and 11 am because the soil temperature during this time was close to the daily mean soil temperature.

Gas samples were taken with a syringe at the beginning and end of the enclosure period and injected into evacuated glass vials (Extainer, Labco Ltd, UK) for storage. The cover boxes were removed from the bases immediately after the gas sampling to minimise potential micro-climatic modification of the sampling area.

Gas samples were taken about 2–3 times per week during the high emission periods (e.g. following fertilisation and substantial rainfall) and less frequently at low emission times. The gas samples were analysed with a gas chromatograph as described by Wang *et al*. (2011).

The automatic chamber consisted of a stainless steel base that was identical to the manual chamber base, an extension (30 cm high) and a top (30 cm high) with stainless steel frames and two lids on the top panel that can be opened and closed automatically at pre-set intervals (Wang *et al*., 2011).

Placement and management of the chamber bases were similar to those described above for the manual chambers. Air samples were automatically extracted from the chambers into a gas chromatograph (SRI 8610C, SRI Instruments, CA, USA) that analysed simultaneously the concentrations of N_2O and CH_4 on-site. Because of the limited number of chambers (nine altogether as supplied), the automatic chambers were installed for only treatments 2 and 4 in two blocks, with one chamber on the bed and the other in the furrow in each plot.

Other measurements

Soil samples were taken from four points per plot (two in beds and two in furrows) to 0–10 and 10–30 cm depths shortly before sowing and after harvesting the crops and intermittently during the crop growing seasons. The samples were bulked for each layer in the same plot, stored at 4 °C in a fridge, and extracted with 2 M KCl solution within a few days. Mineral N contents in the solution were determined using colorimetric techniques (Rayment and Higginson, 1992).

Soybean crop samples were taken at pod-filling and maturity from four 1-m sections in each plot to estimate the above-ground biomass and/or grain yields. Moisture probes (ThetaProbe, Delta-T Devices Ltd, UK) were installed at the 7–13 cm depth in both the bed and furrow areas in a bare fallow plot and a soybean fallow plot. Soil temperature in the 5–7 cm layer was also measured using temperature probes (Measurement Engineering Australia, SA).

Data analysis

N_2O flux rates during the measurement period were calculated from the rate of concentration change in the head space. The emission rate for the whole plot was estimated by

weight-averaging the measurements from the beds and furrows. An analysis of the continuous measurements obtained with the automatic chambers suggested that the N_2O emission rates between 9.00–11.00 am were close to the daily mean emission rates and thus the manual chamber measurements were used to estimate the daily emission rates without correction for the diurnal variations. The daily emissions between the days of manual chamber measurement were estimated by linear interpolation. Cumulative greenhouse gas emissions were estimated by summing the direct (automatic) and interpolated (manual) measurements over a monitoring period.

All statistical analyses were performed using GenStat V14 (VSN International Ltd, UK). Prior to analysis of variance, data were tested for normal distribution and log-transformed where appropriate. Differences and interactions among treatments were assessed using the analysis of variance procedure of GenStat.

Results and discussion

Climatic conditions and soil mineral N contents

Extraordinarily wet weather conditions were experienced following commencement of this study (Figure 1a), with the annual rainfall reaching 2952 mm in 2011 and the cumulative rainfall amounting to 3403 mm during the twelve months of sugarcane cropping.

The site was waterlogged intermittently in the first three months of the soybean growing season and saturated for prolonged periods in the six months following N fertiliser application during the sugarcane growing season.

Due to the wet conditions, the soybean grain yield was low at 1.2 t/ha and the above-ground biomass yield was 2.5 t/ha. Without harvesting the grain, the above-ground biomass contained about 87 kg N/ha. Assuming that the above-ground biomass contributes 77% of the total crop N (Rochester *et al.*, 1998; Schroeder *et al.*, 2005), the soybean crop residues including root could add about 110 kg N/ha into soil. This was similar to the amount of N supplied from a good soybean crop (6–8 t above-ground biomass/ha) with grain harvested (Schroeder *et al.*, 2005).

Following incorporation of the soybean biomass, soil mineral N content remained markedly higher in the soybean cropped soil than in the bare fallow soil for about eight months (Figure 1a). This difference disappeared after approximately ten months.

Dynamics of N_2O emissions

High N_2O emissions (>100 g N_2O-N/ha/d) were recorded on a few occasions during the fallow period although no N fertiliser was applied (Figure 1b and c). There was no consistent difference in the N_2O emission rates between the different fallow regimes during the soybean growing season. Incorporation of the soybean crop residues into soil substantially increased N_2O emissions in the first 4–5 months (Figure 1b and c; $P < 0.05$), which coincided with increases in soil mineral N content in this treatment.

Nitrogen fertiliser application during the sugarcane-growing season significantly increased N_2O emissions (Figure 1c) for both the BF-S+150N and the SF-S+75N treatments. N_2O emissions from N fertiliser were effectively suppressed by the addition of nitrification inhibitor (DMPP) in the urea (Figure 1c), particularly in the first 2–3 weeks after fertiliser application.

High N_2O emissions generally occurred following substantial rainfall events (Figure 1). However, N_2O emissions were low when the soil was waterlogged for prolonged periods such as from February to March in 2010 and 2011. Such low emissions might be attributable to (i) low NO_3^- contents in soil due to losses from leaching and/or denitrification, and (ii) the anaerobic conditions favoured conversion of the denitrification products into N_2 instead of N_2O.
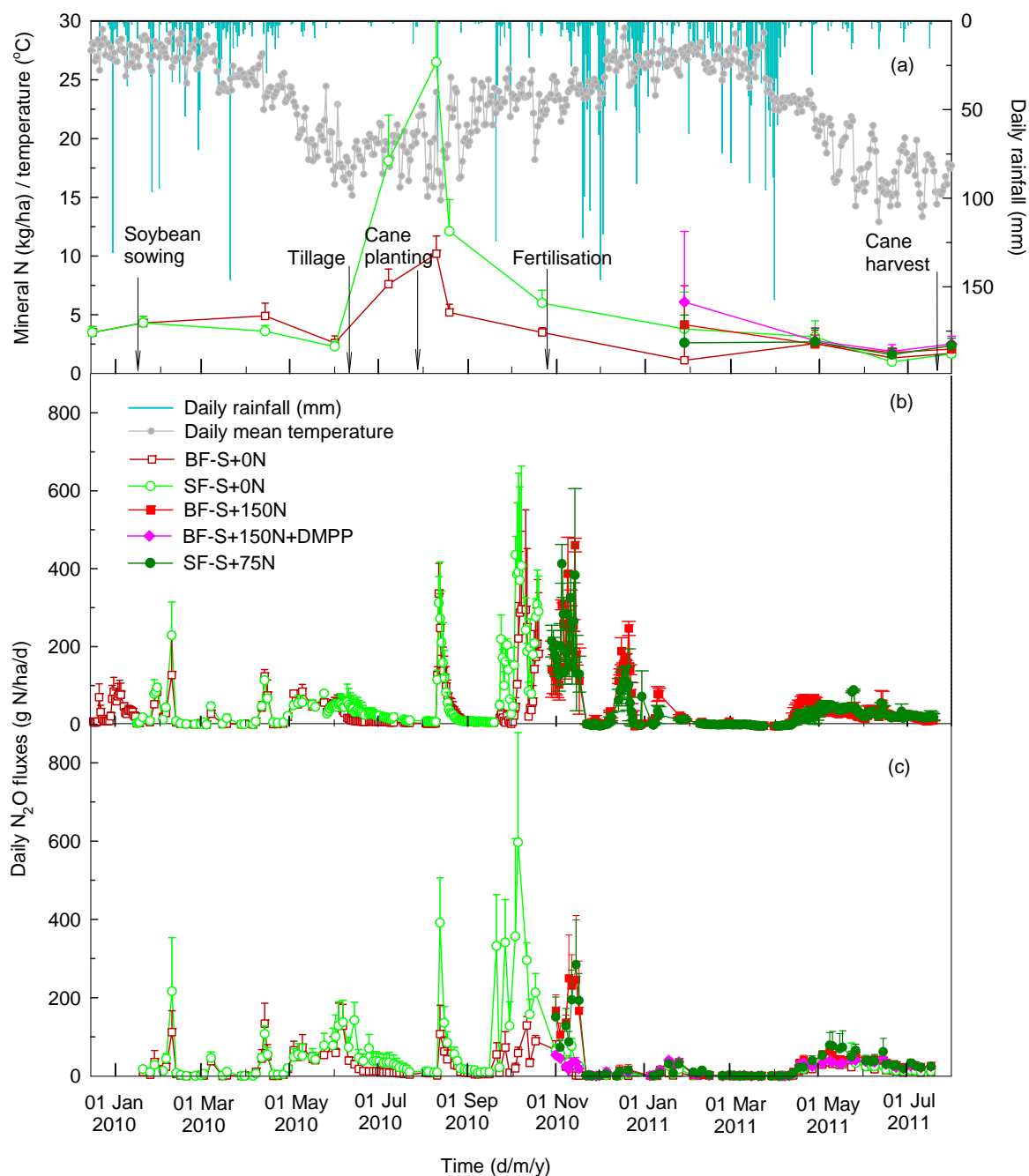
Fig. 1—Soil mineral N content (0–30 cm) and daily rainfall and temperature (a) in relation to daily N$_2$O fluxes (mean±SE) as measured with automatic (b) and manual chambers (c) in different treatments during the fallow and sugarcane cropping seasons. BF-S: bare fallow followed by sugarcane; SF-S: soybean fallow followed by sugarcane; 0N, 75N and 150N: fertiliser N applied at 0, 75 and 150 kg N/ha, respectively; DMPP: nitrification inhibitor added.

Cumulative N$_2$O emissions

Based on the auto chamber measurement, the cumulative N$_2$O emissions for the bare and soybean fallow treatments during the seven-month fallow period were 5.3 and 6.7 kg N$_2$O-N/ha, respectively (Table 1).

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The differences in the cumulative N_2O emissions between the contrasting fallow management regimes during this time were not statistically significant (at $P = 0.05$) although higher N_2O emissions occurred from the soybean-cropped soil in the last months of the fallow period (Figure 1b). The annual cumulative N_2O emissions during the sugarcane crop (27 July 2010 to 20 July 2011) were 15.3 kg N_2O-N/ha for the BF-S+150N treatment and 17.1 kg N_2O-N/ha for the SF-S+75N treatment. The higher annual emissions from the latter treatment ($P < 0.05$) were due to its greater cumulative emissions before fertiliser application; the cumulative N_2O emissions after fertiliser application were similar for both treatments. Therefore, increased N mineralisation and/or bio-available carbon supply following the incorporation of soybean residues promoted N_2O emissions both before and after fertiliser application in that the lower N fertiliser application rate would otherwise have resulted in lower N_2O emissions (Wang *et al*., 2008).

Similar cumulative N_2O emissions in different fallow management regimes (bare and soybean) were also observed (6.0 and 8.2 kg N/ha, respectively) using manual chambers (Table 1). The cumulative emission during the twelve-month sugarcane cropping seasons following bare fallow without N fertiliser application (control) was 6.3 kg N_2O-N/ha on average. This emission could be viewed as the 'background' emission rate from a production system without organic or inorganic N fertilisation. Application of urea at 150 kg N/ha increased the emission in the same period to 12.3 kg N_2O-N/ha. Addition of nitrification inhibitor in urea significantly reduced the cumulative emission by 4.2 kg N_2O-N/ha as compared to the use of normal urea ($P < 0.05$). The average cumulative N_2O emission during sugarcane cropping from the soybean fallow soil without N fertiliser application was 16.4 kg N_2O-N/ha, which was 10.1 kg N_2O-N/ha higher than from the bare fallow counterpart. Application of N fertiliser at 75 kg N/ha during sugarcane cropping in the soybean fallow soil increased the cumulative emissions by 4.5 kg N_2O-N/ha, as compared to the SF-S+0N treatment. The SF-S+75N treatment released 8.6 kg N_2O-N/ha more than the BF-S+150N treatment during the sugarcane crop ($P < 0.05$).

Table 1—Cumulative N_2O emissions (mean±SE, kg N_2O-N/ha) in different periods as influenced by management.

Treatment[*]	Fallow period 15/12/2009–6/07/2010	Whole sugarcane cropping year 27/07/2010–20/07/2011	After fertilisation in sugarcane cropping 20/10/2010–20/07/2011
	Auto-chamber measurements[**]		
BF-S-0N	5.3±0.2 [a]		
BF-S+150N		15.3±2.4 [a]	11.0±1.5 [a]
BF-S+150N+NI			
SF-S+0N	6.7±0.6 [a]		
SF-S+75N		17.1±2.6 [b]	10.5±3.2 [a]
	Manual chamber measurements[**]		
BF-S-0N	6.0±1.2 [a]	6.3±0.8 [a]	3.5±0.6 [a]
BF-S+150N		12.3±1.2 [bc]	9.5±1.4 [c]
BF-S+150N+NI		8.1±0.3 [ab]	5.3±0.4 [b]
SF-S+0N	8.2±2.1 [a]	16.4±2.1 [cd]	5.1±0.7 [ab]
SF-S+75N		20.9±2.0 [d]	9.6±1.2 [c]

* BF-S: bare fallow followed by sugarcane; SF-S: soybean fallow followed by sugarcane; 0N, 75N and 150N: fertiliser N applied at 0, 75 and 150 kg N/ha, respectively; NI: nitrification inhibitor added in urea.
** The numbers followed by the same letter in a column for the same measurement method were not significantly different at $P = 0.05$.

The cumulative N_2O emissions after fertiliser application during sugarcane cropping were not significantly different between the auto and manual chamber measurements. Automatic chambers could make measurements on a sub-daily basis and gave more reliable estimation of the

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daily mean emissions. However, the automatic chambers could only be installed for two treatments in two blocks. The manual chamber method allowed measurement in all blocks with improved spatial representation. Given the above strengths and weaknesses of each method and the similarity in the cumulative N_2O emissions after fertilisation as measured with different methods, averages of the auto and manual chamber measurements were used for the BF-S+150N and SF-S+75N treatments to calculate the emission factors of fertiliser N (i.e. percentage of fertiliser N lost as N_2O-N). As such, the emission factors of fertiliser N were 4.5% and 1.2% for the BF-S+150N and the BF-S+150N+NI treatments, respectively, using the BF-S-0N as the control.

The emission factor for the SF-S+75N treatment was 6.6%, using the SF-S+0N as the control. Apart from the nitrification inhibitor treatment, these emission factors were significantly higher than the IPCC's international average value of 1.0% (IPCC, 2006). The high emission factors may be associated with the wet and warm conditions experienced during the course of the experiment as well as the retention of sugarcane and soybean crop residues.

While a significantly lower emission factor was measured when the nitrification inhibitor DMPP was used, more investigations in different climatic and soil conditions are required to verify its effectiveness on reducing N_2O emissions from Australian sugarcane lands.

Assuming that the life cycle greenhouse gas emission during N fertiliser production and transport was 4.02 kg CO_2-e /kg N (Wood and Cowie, 2004) and that all the carbon contained in urea was released as CO_2 after hydrolysis in the acidic soil (i.e. 1.6 kg CO_2/kg N), a saving of 75 kg N/ha in N fertiliser use was equivalent to a reduction of 421 kg CO_2-e/ha or 0.9 kg N_2O-N/ha.

The enhanced N_2O emissions following the soybean biomass incorporation far outweighed the reduction in CO_2 emissions associated with N fertiliser displacement by the biological N source. Therefore, improved soybean crop residue management practices such leaving the crop residues standing or on the soil surface (Garside and Berthelsen, 2004) need to be investigated to minimise N_2O emissions following a soybean fallow.

Conclusions

N_2O emissions from this sugacane soil were high during both fallow and sugarcane cropping periods, which was consistent with our previous observations. These results suggested that there could be great mitigation potential of greenhouse gas emissions for Australian sugarcane soils. Growing soybean during the fallow period did not significantly affect N_2O emissions during the crop growing season, but substantially enhanced N_2O emissions following incorporation of the soybean crop residues into soil.

On a CO_2 equivalent basis, this increase in N_2O emissions far outweighed the reduction in CO_2 emissions resulting from N fertiliser displacement by the biologically fixed N. Further study is required to investigate better soybean residue management practices to reduce N losses and N_2O emissions while increasing N use efficiency by sugarcane crops.

Addition of nitrification inhibitor DMPP reduced N_2O emissions effectively from the fertiliser N. More investigations are required to verify its effectiveness in other climatic and soil conditions.

Acknowledgements

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