Green-house gas emissions from the sugar industry in Guatemala: First glimpse of Nitrous Oxide (N\textsubscript{2}O) losses from sugarcane fields

Anne Baily\textsuperscript{a}, Alejandra Hernández\textsuperscript{b}, Gonzalo López\textsuperscript{b}, Ovidio Pérez\textsuperscript{c}

\textsuperscript{a} Associated researcher, Climate Change Research Institute (ICC), Ireland/Guatemala.
\textsuperscript{b} Climate Change Research Institute (ICC), Guatemala.
\textsuperscript{c} Guatemalan Sugarcane Research and Training Center (CENGICAÑA), Guatemala.

Guatemala, June 2014.

Introduction

Nitrogen (N) is a major elemental component of the Earth; it is present in the atmosphere, geosphere, biosphere and hydrosphere and is essential for sustaining life (Galloway et al., 2002). As a resource, N use is a fundamental part of soil management for agricultural production and has enabled a high level of intensification (Galloway et al., 2008). Nitrogen losses from intensive agricultural systems have, however, environmental consequences, particularly as gaseous emissions to the atmosphere (NO, N\textsubscript{2}O and N\textsubscript{2}) and as nitrate (NO\textsubscript{3}) leached to ground water (Snyder et al., 2007).

Worldwide, scientists are involved in research related to the use and management of nitrogen (N) as awareness of the environmental problems associated with excess reactive nitrogen cascading through the biosphere is growing. In the absence of reliable data, many countries still use the International Panel on Climate Change (IPCC) default emission factor (EF) of 1% of N applied, as either mineral or organic fertilizer, to calculate N\textsubscript{2}O losses to the atmosphere (IPCC 2006).

In the last National Inventory for Emissions and the Removal of Greenhouse Gases (GHG), agriculture was claimed to be responsible for nearly half of Guatemala’s total carbon dioxide equivalent (CO\textsubscript{2}e) emissions; nitrous oxide (N\textsubscript{2}O), with a global warming potential at least 296
times that of CO$_2$, unit for unit, is estimated to be responsible for about 81% of these (MARN, 2012).

So far, studies in sugarcane production systems support the understanding that the strongest influence on N$_2$O emissions is the rate of application of N fertilizer (either mineral or organic) but that, as in the temperate world, type and timing of fertiliser application, soils, meteorological conditions and irrigation and harvesting processes are also concerned (e.g. Matson et al., 1996).

Sugarcane is one of the main crops in Guatemala therefore it is important to understand how N$_2$O emissions are related to its agricultural management. With no previous work to form a basis from which to design a project it was necessary to decide what would be of most relevance to the sugarcane industry in general and possibly lead to the reduction of N$_2$O losses to the environment. Information about soil types, fertilizer regimes, the sugarcane plant and its life cycle and meteorological conditions was gathered over 2013; also about harvesting, irrigation and fertilization methods. All these factors are known to influence the nitrification and denitrification processes leading to N$_2$O losses.

Mineral N (urea) is the most common fertilizer used in sugarcane plantations in Guatemala and it is usually applied about 30 days after harvest; in addition vinasse, the recycled organic waste product from ethanol production, rich in C and N (Macedo et al., 2008), is increasingly used; the main harvesting method is pre-burning and hand-cutting; the most typical sugarcane growing soil is a mollisol; and, finally, ratoon crops are more plentiful than plant cane as there is re-growth of ratoon crops over several years. Thus sites were chosen to reflect these factors.

With limited logistical and financial resources, it was decided that a simple comparison of N$_2$O emissions from different fertilizer regimes would be the best use of such resources. Therefore, this study provides a glimpse of N$_2$O losses from the initial stage of the crop cycle (regrowth after harvest). Much work has already been done on the applicability of N application rates for maximum economic sugarcane production in different soil types, specific cane type and between
plant and ratoon crops (Perez et al., 2010); it is hoped that this trial may bring new insights to the economic and environmentally sustainable growth of sugarcane.

As in all such field trials, if there are too many variables results will not be definitive. The primary research purpose was, therefore, to measure N$_2$O emissions from different rates of application and between organic and mineral fertilizer and, from research results, to make a provisional estimate of emission factors.

**Materials and Methods**

**Sites**

In order to find two plantations with similar soils which had been hand-harvested at the same time and which were awaiting the annual application of N fertilizer, it was necessary to use widely separated sites – driving time between them approx. 45 minutes. The sampling sites were both mollisols, both soils had been harvested by hand about 30 days previously and both were ratoon crops (Fig. 1). On 17$^{th}$ January 2014 both sites were fertilized and chamber bases placed. There were 12 replications at each of sites 1 and 2. Because there was a limit of 300 samples, this left only a small number for a control treatment, also at Site 2.

![Fig. 1: Choosing the two sites: La Union (left) and Pantaleon (right).](image)

At La Union (Site 1) the sugarcane variety was CG 98-78 and the ratoon crop was in its second year. This site was fertilized with urea at the rate of 120 kg N h$^{-1}$. Fertiliser was spread in the
furrows at either side of the sugarcane plants and chamber bases were placed in the furrows (Fig. 2).

Fig. 2: Site 1 showing placement of chamber bases at either side of sugarcane

At Pantaleon (Site 2) the variety was CP72-2086 and the ratoon crop was in its fourth year. Fertiliser was applied as urea dissolved in vinasse at the rate of 158 kg N h⁻¹ (including N in vinasse applied at 2.85 cu m h⁻¹). This was applied along the middle of the row directly onto the sugarcane. We therefore placed the chamber bases between the plants (Fig. 3). The small control treatment (3 reps) was also at Pantaleon (Site 2b).

Fig. 3: Site 2 showing chamber bases placed between plants rather than to the side
At both sites, on January 17\textsuperscript{th}, fertilizer was directly applied to only about one fifth of a hectare providing, in effect, a high rate of fertilizer to the actual cane rows. First samples were collected on January 18\textsuperscript{th}. Later that day a serious error occurred at the Pantaleon site when fertilizer was applied again to both the control area and the site itself. This time urea dissolved in vinasse was applied at the rate of 110 kg N h\textsuperscript{-1} (including N in vinasse). Now there were no controls and three different fertilizer rates.

Samples were collected for the first 5 days after fertilizer application, then less frequently until day 20 over 12 measurement days. Meteorological data from a local station suggested that average temperature over 24 hours, at that time of year, was approximately 25\textdegree{} C. Sampling at Site 1 was therefore arranged to begin at approx. 7.30 am when temperatures were deemed to be average. Since the sites were not adjacent, sampling did not begin at site 2 until approx. 9.30 when temperatures were approximately 30\textdegree{}C. Temperature differences were, however, allowed for in calculations. A further problem was different management of the two sites: while irrigation occurred twice at La Union it did not happen at all at Pantaleon.

Samples were sent off via DHL to The Irish Agricultural Institute (Teagasc) at Johnstown Castle in Wexford, on February 6\textsuperscript{th} for analysis in their laboratory. Headspace gas analysis of N\textsubscript{2}O was done by gas chromatography (Varian CP 3800 GC, Varian, USA) using an electron capture detector at 300\textdegree{} C. Evolved N\textsubscript{2}O was expressed as parts per million (ppm) allowing for ambient concentrations and was up-scaled to a flux in g ha\textsuperscript{-1}d\textsuperscript{-1}.

\textbf{Results, discussion and analysis}

\textbf{Site 1 (La Union)}

At Site 1, fertilized with an application of 120 kg N ha\textsuperscript{-1} as urea, N\textsubscript{2}O fluxes were very low for several days after application of fertilizer (Fig. 4). Fluxes remained below 5 g ha\textsuperscript{-1}d\textsuperscript{-1} over the first five measurement days. Such a delay would be expected after application of urea since the N must be hydrolysed before it is available for the nitrification and denitrification processes to occur (Signor et al., 2010). Also, in such low soil moisture conditions (aerobic or semi-
First glimpse of Nitrous Oxide (N$_2$O) emissions from Guatemalan sugarcane fields

Baily et al.

ICC

anaerobic), N$_2$O is produced by nitrifying bacteria rather than denitrifier bacteria and this ‘nitrifier’ denitrification results in very much lower emissions than ‘classical’ denitrification (e.g. Machefert et al., 2002). As shown in Fig. 4 fluxes rose slowly from day 1 to day 5. On day 7 we arrived to find the site under water as a result of irrigation.

![Graph showing N$_2$O fluxes at Site 1 on all sampling days (days 1,2,4,5,7,9,11,13,16,19 and 20)](image)

*Fig.4: N$_2$O fluxes at Site 1 on all sampling days (days 1,2,4,5,7,9,11,13,16,19 and 20)*

![Photo of irrigation day at La Union (chambers 1 & 2)](image)

*Fig.5: Irrigation day at La Union (chambers 1 & 2).*

On this day, therefore, this site was sampled second, by which time all but 2 of the chambers were out of the water (Fig. 5). Fluxes were considerably higher on this day and continued to
increase until day 9 as a result of high denitrification rates following irrigation. Thereafter fluxes decreased on each sampling day, as expected with no further irrigation or rainfall. We know that after N fertilizer application rate water filled pore space (WFPS) is the single most significant influence on ‘classical’ denitrification rates (Davidson and Seitzinger, 2006). After N fertilizer application, high WFPS (above about 70-75%) leads to high N₂O losses as it did here.

Irrigation occurred again on day 19 when fluxes continued to fall from the previous measurement day; this may well have been the result of denitrification going to completion (in saturated soil) resulting in losses of N₂ rather than N₂O. However, on the following day (the final sampling day) fluxes increased to the same height as on day 9. Highest fluxes are thus directly related to denitrification after irrigation.

At this stage, as a result of no rainfall and only two irrigation events, with consequent low emissions, it is likely that a lot of mineral N remained in the top 10 cm of the soil. Therefore this pattern of low daily fluxes, combined with occasional higher losses after irrigation, would have been repeated for several weeks; after each irrigation event fluxes would be lower as available N was reduced.

Although approximately 370 g ha⁻¹ N₂O-N emitted over 3 weeks is high it is unlikely that such emissions would continue. It is likely that fluxes decreased quickly after day 20 as they did after day 9.

**Site 2a (Pantaleon)**

At Site 2a fertilizer was applied on January 17th in the form of urea dissolved in vinasse at the rate of 158 kg N ha⁻¹ (urea + vinasse). As at Site 1, fertilizer was applied to the cane lines only, providing exceedingly high levels of N to about one fifth of a hectare.

Fluxes were much higher for the first 4 days than at Site 1 rising to their highest point on day 4 (Fig. 6). This is in accord with several reports as to the immediacy of rising N₂O fluxes after
application of vinasse. Reports also say high fluxes are short-lived as can be seen here as, by day 5, they were decreasing in spite of the exceedingly high application(s) of urea at this site.

![Graph showing N₂O fluxes at Site 2a on all sampling days](image)

*Fig. 6: Graph showing N₂O fluxes at Site 2a on all sampling days*

It seems strange that emissions are very much lower than at La Union even though urea was applied at a much higher rate. These comparatively low N₂O fluxes seem particularly strange in that a further 110 kg N ha⁻¹ (urea + vinasse) was applied on Saturday 18th. However, with no rainfall or irrigation over the duration of the trial it is likely that little denitrification occurred. The small fluxes were probably produced by nitrifier denitrification in this very dry soil. As explained above, WFPS is the single most significant influence on denitrification rates after application of N fertilizer. A further reason for such low N losses here could actually be a result of the extremely high N fertilizer additions at this site. Signor et al. (2013) suggest that urea applied in sugarcane at rates above 120 kg N ha⁻¹ may reduce emissions of N₂O as high rates may have a negative effect on microbial biomass and respiration (Treseder, 2008; Ramiez et al., 2010). At this site 268 kg N was applied.

On day 7 fluxes were lower than on days 5 and 9 and this may be because, unlike all other trial days, we measured Site 2 early in the morning (Site 1 was under water after irrigation and was
measured later). It is therefore possible that the lower air temperature reduced fluxes on this date.

**Site 2b (Pantaleon)**

As was previously mentioned, this site was set up as a small control (3 chambers) in order to calculate background N₂O emissions which are occurring everywhere and may be influenced by previous cultivation and fertilizer history. However, the site was fertilized by mistake on the afternoon of the second day. It received 110 kg N h⁻¹ (including vinasse) (Fig.7).

![Graph showing N₂O fluxes at Site 2b on all sampling days](image)

*Fig.7: Graph showing N₂O fluxes at Site 2b on all sampling days*

On the first day no fertilizer had been applied where the 3 control chambers were placed. Thereafter N₂O fluxes rose daily as might be expected from an addition of 110 kg N h⁻¹ (urea dissolved in vinasse), until day 11. These N₂O losses were much lower than in 2a as a result of the application of a much lower rate of N fertilizer. After day 11 N₂O losses reduced daily and almost certainly would have continued to do so over the next week or so. As in Site 2a, there was no rainfall or irrigation throughout the trial.

**Emission factors**

It is not possible to give robust annual N₂O emission factors (EF) for the above sites after 3 weeks of sampling. True annual EFs would need to cover the whole crop cycle. In this trial air
samples were collected from fertilized areas only, which, in sugarcane crops here, are calculated as one-fifth of a hectare at each site. Emissions from unfertilized areas are known as ‘background’ emissions and are not the direct result of N fertilizer applications. Thus, approximate emission factors (Table 1) are calculated from measured cumulative N\(_2\)O losses from fertilized areas over 20 days: Site one 0.31\%, Site 2a 0.06\% and Site 2b 0.05\% of fertilizer N applied (total emissions divided by fertilizer applied multiplied by 100). These losses equate with 0.37 kg ha\(^{-1}\), 0.17 kg ha\(^{-1}\) and 0.05 kg ha\(^{-1}\).

<table>
<thead>
<tr>
<th>Day</th>
<th>(\text{N}_2\text{O} \text{ g d}^{-1}) Site 1</th>
<th>Cumulative (\text{N}_2\text{O} \text{ g d}^{-1}) Site 1</th>
<th>(\text{N}_2\text{O} \text{ g d}^{-1}) Site 2a</th>
<th>Cumulative (\text{N}_2\text{O} \text{ g d}^{-1}) Site 2a</th>
<th>(\text{N}_2\text{O} \text{ g d}^{-1}) Site 2b</th>
<th>Cumulative (\text{N}_2\text{O} \text{ g d}^{-1}) Site 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26</td>
<td>0.26</td>
<td>1.63</td>
<td>1.63</td>
<td>0.50</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
<td>0.93</td>
<td>8.05</td>
<td>9.68</td>
<td>0.68</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>1.19</td>
<td>2.12</td>
<td>13.83</td>
<td>23.51</td>
<td>0.80</td>
<td>1.49</td>
</tr>
<tr>
<td>4</td>
<td>2.33</td>
<td>4.45</td>
<td>17.33</td>
<td>40.84</td>
<td>1.82</td>
<td>3.31</td>
</tr>
<tr>
<td>5</td>
<td>3.68</td>
<td>8.13</td>
<td>14.31</td>
<td>55.15</td>
<td>3.53</td>
<td>6.84</td>
</tr>
<tr>
<td>7</td>
<td>20.16</td>
<td>31.97</td>
<td>6.69</td>
<td>76.15</td>
<td>2.98</td>
<td>13.35</td>
</tr>
<tr>
<td>9</td>
<td>39.83</td>
<td>91.96</td>
<td>10.55</td>
<td>93.39</td>
<td>3.48</td>
<td>19.81</td>
</tr>
<tr>
<td>11</td>
<td>33.24</td>
<td>165.03</td>
<td>10.14</td>
<td>114.08</td>
<td>5.38</td>
<td>28.67</td>
</tr>
<tr>
<td>13</td>
<td>24.31</td>
<td>222.58</td>
<td>8.36</td>
<td>132.58</td>
<td>2.84</td>
<td>36.89</td>
</tr>
<tr>
<td>16</td>
<td>19.04</td>
<td>287.61</td>
<td>4.89</td>
<td>152.46</td>
<td>2.17</td>
<td>44.40</td>
</tr>
<tr>
<td>19</td>
<td>10.49</td>
<td>331.90</td>
<td>4.11</td>
<td>165.96</td>
<td>1.71</td>
<td>50.22</td>
</tr>
<tr>
<td>20</td>
<td>40.26</td>
<td>372.16</td>
<td>4.08</td>
<td>170.04</td>
<td>2.00</td>
<td>52.22</td>
</tr>
</tbody>
</table>

Table 1: Cumulative N\(_2\)O emissions over 20 days

Estimated in this way over 20 days, these EFs are all low in relation to the IPCC annual estimated loss of 1\% of N applied. However, results from Sites 2a and 2b are unrealistically low as no irrigation or rainfall occurred over the 20 day measurement period. It is likely that all sugarcane crops under regular irrigation and fertilized at a similar rate to Site 1 and higher, as in Site 2a, will produce high levels of N\(_2\)O ha\(^{-1}\) over the post-fertilizer period.

There are few published estimated annual EFs from sugarcane but Lisboa et al. (2011) have collated such results as there are. Collation of these results gave an average N\(_2\)O EF of 3.87 ± 1.16\%. It is likely that total annual EFs for Sites 1, and 2a would fall within this range. It is
interesting to note that such an EF for N fertilizer-induced GHG emissions accounted for about 40% of the total GHG emissions of bioethanol production from sugarcane, slightly less for unburnt and slightly more for burnt harvesting systems.

**GHG as Carbon Equivalent**

To get a complete picture of GHG emissions, usually calculated as carbon dioxide equivalent (CO$_2$e), we need data on CH$_4$ and CO$_2$ as well as N$_2$O (Lisboa et al., 2011). However, negative fluxes of CH$_4$ are reported from several studies and de Oliveira et al. (2013) found that cumulative fluxes from their evaluation period were negative in both control and vinasse fertilized areas – as they were in this study. It is likely that CH$_4$ adds little, if anything, to total CO$_2$e from sugarcane here – at least in the dry season.

Even if CO$_2$ is analysed, it cannot be used as a reliable balance output without information on net ecosystem exchange i.e. balancing annual C loss through respiration with C input, e.g. CO$_2$ assimilated through photosynthesis in the next sugarcane cycle (de Oliveira et al., 2013) while carbon (C) sequestering in the soil can only be confirmed over at least a 10 year cycle (Denmead et al., 2010). The best estimate for Guatemala is shown in Fig. 8.

The greatest lack was probably that of soil analysis before the trial began; after all, it is the interplay between N cycling in soils and soil conditions (e.g. soil moisture, temperature, pH, oxygen, organic C and N and bulk density) that governs the microbial processes causing the production and consumption of gaseous N (Weitz et al., 2001). It is the multitude of these interacting controls that cause the dynamic and variable character of N$_2$O losses from soil (Butterbach-Bahl et al., 2013) which, as a result, are characterised by ‘hot spots’ and ‘hot moments’ (Groffman et al., 2009) and which make their measurement such a challenge.
Also irrigation was, to say the least, irregular and we were unable to measure soil moisture content. Soil moisture content is needed for assessment of water filled pore space (WFPS) which is universally seen as an important driver of denitrification and, thus, $\text{N}_2\text{O}$ losses to the atmosphere as both $\text{N}_2\text{O}$ and $\text{N}_2$. Finally we ‘lost’ our control site which means we have no real idea as to approximate background emissions from sugarcane plantations under these conditions.

**Conclusions**

The primary research, to measure N2O emissions from different rates of application and between organic and mineral fertilizer was not achieved as a result of having to do the trial in widely separated areas; this lead to different timing of sampling (temperature), differing soils (i.e. soil moisture) and, crucially, different management decisions as to irrigation.
However, results from this trial confirm that N$_2$O losses are related first and foremost to mineral and organic N applications but that these are strongly mediated by soil moisture. As shown from all sites, dry soil conditions have kept emissions low; in Site 1, until the first irrigation, emissions were exceptionally low; in Sites 2a and 2b emissions were low over the entire 20 days apart from a brief period of heightened flux caused by the application of semi-liquid vinasse.

While EFs from La Union and Pantaleon are low: Site 1: EF 0.31%, Site 2a: EF 0.06% and Site 2b: 0.05% of fertilizer N applied, it is important to remember that they are only for 20 days and that soils were very dry over much of the measurement period in Site 1; Sites 2a and 2b remained dry over the whole of the three week trial. This trial was, therefore, only a ‘snap shot’ in time. Looking at this ‘snapshot’, the annual EF may well remain at or below the IPCC 1% for all treatments fertilized to these levels and under this management system (e.g. single N application after harvest and application only beside or in the centre of cane lines).

Further research programmes could be designed to investigate management options to reduce harmful and expensive N$_2$O losses from sugarcane and improve the economic efficiency and environmentally sustainable management of this important crop: e.g. irrigation timing and level; possible split fertilizer applications (e.g. two much lower applications); use of nitrification inhibitors and/or controlled-release or enhanced-efficiency fertilizers.

However, there is still the remaining unknown to be taken into account: what happens to N$_2$O emissions from similar fertilized crops in such sub-tropical climates during the hot wet season? For a reliable estimate of annual emissions measurements during the wet season would be essential.

**Acknowledgments**

We thank Dr. Karl Richards, Dr. Gary Lanigan and Cathal Somers from Johnstown Castle (Teagasc) for their generous support in equipment and, critically, analysis of gas samples.
Support from Ingenio La Union and Ingenio Pantaleon were essential to carry out this study not only providing the field sites but also information and staff to guard the sites.

References


First glimpse of Nitrous Oxide (N$_2$O) emissions from Guatemalan sugarcane fields


