Emission factors for estimating fertiliser-induced nitrous oxide emissions from clay soils in Australia’s irrigated cotton industry

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Abstract. As a significant user of nitrogen (N) fertilisers, the Australian cotton industry is a major source of soil-derived nitrous oxide (N\textsubscript{2}O) emissions. A country-specific (Tier 2) fertiliser-induced emission factor (EF) can be used in national greenhouse gas inventories or in the development of N\textsubscript{2}O emissions offset methodologies provided the EFs are evidence based. A meta-analysis was performed using eight individual N\textsubscript{2}O emission studies from Australian cotton studies to estimate EFs. Annual N\textsubscript{2}O emissions from cotton grown on Vertosols ranged from 0.59 kg N ha\textsuperscript{-1} in a 0N control to 1.94 kg N ha\textsuperscript{-1} in a treatment receiving 270 kg N ha\textsuperscript{-1}. Seasonal N\textsubscript{2}O estimates ranged from 0.51 kg N ha\textsuperscript{-1} in a 0N control to 10.64 kg N ha\textsuperscript{-1} in response to the addition of 320 kg N ha\textsuperscript{-1}. A two-component (linear + exponential) statistical model, namely \( \text{EF} (\%) = 0.29 + 0.007(e^{0.037N} - 1)/N, \) capped at 300 kg N ha\textsuperscript{-1} describes the N\textsubscript{2}O emissions from lower N rates better than an exponential model and aligns with an EF of 0.55% using a traditional linear regression model.

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Introduction

Nitrous oxide (N\textsubscript{2}O) is a greenhouse gas with a global warming potential 298-fold higher than that of carbon dioxide (Intergovernmental Panel on Climate Change (IPCC) 2013). Agriculture produces approximately 60% of global N\textsubscript{2}O emissions, predominantly from emissions after application of nitrogen (N) fertilisers to soils (Reay \textit{et al.} 2012). The rate of N fertiliser applied is the best single predictor of N\textsubscript{2}O emissions from agricultural soils (Shcherbak \textit{et al.} 2014). The current global mean value for fertiliser-induced N\textsubscript{2}O emissions as determined by the IPCC in its Tier 1 (default) calculations (IPCC 2006) for national inventories is 1% of the applied N after correction for background (0N) emissions. For example, for every 100 kg of N input as fertiliser, 1.0 kg of N in the form of N\textsubscript{2}O is estimated to be emitted directly from soil. A 1% emission factor (EF) assumes a linear relationship between N input and N\textsubscript{2}O emissions that is indifferent to biological thresholds that may occur; for example, when the availability of soil inorganic N exceeds crop N demands. Country-specific (Tier 2) EFs can be used in national greenhouse gas inventories or in the development of emissions offset methodologies (e.g. Millar \textit{et al.} 2010) provided the EFs are evidence based.

As a significant user of N fertilisers, the Australian cotton industry is a major source of N\textsubscript{2}O emissions from soils. Changes in cotton farming systems from 2004 to 2011 have occurred, with N application rates increasing under irrigation and decreasing under dryland systems (Braunack 2013). The average annual N application to irrigated cotton is currently 243 kg N ha\textsuperscript{-1}, with as much as 370 kg N ha\textsuperscript{-1} being applied (Roth Rural 2013) over several applications. Dryland application rates are one-third of those under irrigation.

Irrigated cotton is grown in eastern Australia on alkaline grey and black clay soils known as Vertosols (Isbell 2002). These soils are typically described as inefficient with regard to N usage due largely to significant losses of gaseous N\textsubscript{2}O and N\textsubscript{2} via denitrification. Chen \textit{et al.} (1994) reported that 72–84% of N applied before sowing cotton was lost.

Rochester (2011) found that 79% of the 82 commercial cotton crops surveyed applied 50 kg N ha\textsuperscript{-1} in excess of the optimum N fertiliser required. The most recent current practices survey (Roth Rural 2013) also reports that only 13% of irrigated growers are in the optimum range of N use efficiency recommended by researchers. The main reason for excess application of N fertiliser is to ensure maximum crop yield is achieved if the right climate conditions and water storages are available. More N is applied to compensate for what are significant gaseous losses of N, particularly in irrigated cotton.

The original Tier 2 EF for cotton production in Australia is 0.5% (Galbally \textit{et al.} 2005), based on a limited dataset collected by Grace \textit{et al.} (2004). The inclusion of new datasets would enable a more accurate estimation of emissions in both the National Greenhouse Accounts and in relevant offset methodologies that may be developed under the Emissions Reduction Fund (Department of Environment 2015), a voluntary scheme that provides incentives to adopt new
practices and technologies to reduce emissions. For projects with an excess of N, a variable EF (in response to N applied) would potentially provide greater incentive to reduce excess N fertiliser applications, driving greater abatement of greenhouse gases.

Results from a growing number of non-Australian field experiments with multiple N fertiliser rates indicate that emissions of N\textsubscript{2}O respond non-linearly to increasing N inputs across a range of fertiliser formulations, climates and soil types (e.g. McSwiney and Robertson 2005; Ma et al. 2010; Hoben et al. 2011; Kim et al. 2013; Signor et al. 2013), suggesting that EFs are not constant but increase with N additions. Scherbak et al. (2014) demonstrated that an increasing EF with N fertiliser additions is a global phenomenon largely independent of climate, soil type, crop and management factors.

The present study describes the development of both linear and non-linear N\textsubscript{2}O emissions response models to N fertiliser additions and EFs based on an analysis of peer-reviewed data from eight field experiments from Australia’s cotton industry.

Materials and methods

Data collection and analysis

Seasonal estimates of N\textsubscript{2}O emissions from cotton soils of Australia in response to N fertiliser applications were determined. Daily estimates of N\textsubscript{2}O emissions from high temporal frequency automated measuring systems (e.g. Scheer et al. 2013) or regular manual gas sampling (e.g. Scheer et al. 2016) were integrated over defined measurement periods. Because the EF is essentially a fertiliser-induced estimate of N\textsubscript{2}O emissions (as a proportion of total N applied), the mean seasonal background N\textsubscript{2}O emissions (with no N fertiliser applied) were also determined for each of the three sites located in major cotton-growing regions of eastern Australia (Narrabri, Kingsthorpe and Dalby) used in our analysis. Narrabri is located in the Namoi Valley in the state of New South Wales, 500 km north-west of Sydney, with an annual precipitation of 646 mm and a mean annual temperature of 19°C. Kingsthorpe and Dalby are both located on the Darling Downs in the state of Queensland, and 150 km and 200 km west of Brisbane respectively. Kingsthorpe has a mean annual precipitation of 684 mm and mean annual temperature of 18°C. Dalby has a mean annual precipitation of 676 mm and mean annual temperature of 19°C.

Where no field specific data for background emissions were available, a site average was estimated based on existing data collected at the same site from similar experiments with similar histories. In the absence of any site data, because most of the N\textsubscript{2}O from fertiliser is emitted within a month after application, after which emissions decline to a background level (Bouwman 2005 before harvest. The CC treatment received 140 kg N ha\textsuperscript{–1} before harvest. The soil was a grey Vertosol with a soil organic carbon (OC) content (0–30 cm) of 1.1% and pH\textsubscript{w} of 8.2. Of the 10 treatments, nine were from the original factorial design (i.e. rotation × N rate: continuous cotton including a winter fallow (CC), wheat–summer fallow–vetch–cotton (WVC) and wheat–summer fallow–cotton (WC) × 0, 100 and 200 kg N ha\textsuperscript{–1} applied as a single application). The 10th treatment was WVC receiving an industry high rate of 300 kg N ha\textsuperscript{–1}. Manual gas sampling began after N application on 18 September 2002 and finished at harvest on 6 December 2002. This is the original dataset used by Galbally et al. (2005) in developing the original EF for cotton in the National Greenhouse Accounts of 0.5%. We reanalysed this dataset using the same interpolation method between temporal sampling points to be consistent with other studies listed herein.

Narrabri (2002–03)

Nitrous oxide emissions were measured in an existing long-term cotton rotation experiment at the Australian Cotton Research Institute (ACRI) comprising three rotation treatments with multiple levels of N fertiliser management (Grace et al. 2004). The soil was a grey Vertosol with a soil organic carbon (OC) content (0–30 cm) of 1.1% and pH\textsubscript{w} of 8.2. Of the 10 treatments, nine were from the original factorial design (i.e. rotation × N rate: continuous cotton including a winter fallow (CC), wheat–summer fallow–vetch–cotton (WVC) and wheat–summer fallow–cotton (WC) × 0, 100 and 200 kg N ha\textsuperscript{–1} applied as a single application). The 10th treatment was WVC receiving an industry high rate of 300 kg N ha\textsuperscript{–1}. Manual gas sampling began after N application on 18 September 2002 and finished at harvest on 6 December 2002. This is the original dataset used by Galbally et al. (2005) in developing the original EF for cotton in the National Greenhouse Accounts of 0.5%. We reanalysed this dataset using the same interpolation method between temporal sampling points to be consistent with other studies listed herein.

Narrabri (2004–05)

Automated gas sampling was undertaken on an existing long-term experiment at ACRI (Grace et al. 2006). The soil was a grey Vertosol with an OC content (0–30 cm) of 1.07% and pH\textsubscript{w} of 8.2. The CC treatment received 140 kg N ha\textsuperscript{–1} on 10 September 2003 as anhydrous NH\textsubscript{3} and the crop was sown on 23 September 2004. Gas sampling on three replicate treatments commenced in early October 2004 and finished in mid-February 2005 before harvest.
Narrabri (2011–12)

The aim of this experiment at the ACRI was to examine the effect of N fertiliser rate on N₂O emissions through a complete summer–winter rotation within an irrigated cotton–faba bean–fallow cropping system (Macdonald et al. 2015). Nitrogen fertiliser treatments were applied on 20 September 2011, before sowing cotton (11 October 2011) on a grey Vertosol with a soil OC content (0–30 cm) of 1.1% and pH₅₀ of 8.3. Three replicate automated gas sampling chambers were installed in each of four subplots after they had received N fertiliser application at rates of 0, 120, 200 and 320 kg N ha⁻¹. Gas sampling ceased on 1 April 2012, before harvest of the cotton crop.

Kingsthorpe (2009–10)

Automated gas sampling for N₂O was conducted at the Agriculture and Science Queensland, Department of Employment, Economic Development & Innovation (DEEDI) Kingsthorpe research station on the Darling Downs near Toowoomba (Qld). The experiment was after a winter wheat crop on a black Vertosol with a OC content (0–10 cm) of 1.6% and pH₅₀ of 7.3 with three irrigation scheduling treatments and three replications (Scheer et al. 2013). The irrigation treatments were designated Low, Medium and High based on the relative depletion of plant-available water. All treatments received a total N application of 200 kg N ha⁻¹ applied as urea in three split applications of 100, 50 and 50 kg N ha⁻¹ on 17 November 2009, 28 December 2009 and 28 February 2010 respectively. Nitrous oxide fluxes were measured during the entire cotton growing season from 17 November 2009 to 20 May 2010.

Kingsthorpe (2010–11)

In October 2010, a second irrigated cotton experiment was initiated at the Kingsthorpe site to mimic the 2009–10 experiment and to investigate the effect of different rates of N fertiliser on N₂O emissions (Scheer et al. 2016). The three replicate plots of the Medium irrigation treatment (i.e. irrigation was only applied when 60% of plant-available water capacity (PAWC) was depleted) were divided into four subplots for an N fertiliser response trial with the following treatments: 0, 90, 180 and 270 kg N ha⁻¹. Nitrous oxide fluxes were measured over an entire year using manually sampled static chambers including the cotton cropping season from 5 November 2010 to 9 June 2011 and the following fallow phase from 9 June to 15 November 2011.

Dalby (2005–06)

This was the first of three automated greenhouse gas monitoring studies (Grace et al. 2006, 2010) undertaken on the Crothers farm at Nandi, west of Dalby (Qld) on a black Vertosol with an average soil OC content (0–10 cm) of 1.0% and a pH₅₀ of 8.5. The field had been under continuous cotton (with winter fallow) for 10 years. Urea was banded on 10 and 30 August 2005, at 92 and 70 kg N ha⁻¹ respectively. Cotton was sown on 2 November 2005 and 30 kg N ha⁻¹ NH₃ applied with irrigation water on 26 January 2006, with an additional 15 kg N ha⁻¹ water run urea applied on 24 February 2006. Three chambers were assigned to a single bed and three to an adjacent furrow after skipping two rows. Gas sampling was undertaken from 9 October 2005 to 23 March 2006, and the average daily N₂O emission of the bed and furrow treatments was used in the present analysis.

Dalby (2006–07)

This is the second of three summer experiments performed at the Crothers farm near Dalby (Grace et al. 2007). Because there was little residual N in the soil profile after the previous crop, the grower applied 200 kg N ha⁻¹ in August 2006 and planted in late October 2006, but much of this N may have been lost over the 3-month period before sowing. Two N fertiliser treatments were initiated in early November 2006, with three automated gas sampling chambers on each. Treatment A received 60 kg N ha⁻¹ and Treatment B received 120 kg N ha⁻¹ equivalent. The grower applied 23 and 46 kg N ha⁻¹ as urea in the irrigation water, 98 and 135 days after the start of the experiment; in total, Treatments A and B received 129 and 189 kg N ha⁻¹ respectively. Nitrous oxide emissions were monitored from 2 November 2006 until 30 March 2007.

Dalby 2007–08

This was the third experiment on the Crothers farm near Dalby (Grace et al. 2008). On 20 August 2007, 92 kg N ha⁻¹ was uniformly applied across the experimental field. On 28 December 2007, before irrigation, 40 kg N ha⁻¹ as urea was added to three automated chambers (low N treatment) and 80 kg N ha⁻¹ urea added to an adjacent chambers (high N treatment). An additional 23 kg N ha⁻¹ was applied to all chambers on 12 January 2008, with a total of 155 and 195 kg N ha⁻¹ applied to the respective treatments. Daily N₂O emissions were monitored with an automated system from 17 September 2007 until 17 April 2007.

Results and discussion

In all, 27 individual fertiliser treatments were used to develop a Tier 2 fertiliser-induced EF for N₂O emissions from Australia’s cotton industry. Annual N₂O emissions (including the post-season fallow) ranged from 0.59 kg N ha⁻¹ in a 0N control to 1.94 kg N ha⁻¹ in a treatment receiving 270 kg N ha⁻¹ at Kingsthorpe (Scheer et al. 2016). Seasonal N₂O estimates ranged from 0.51 kg N ha⁻¹ in a 0N control to 10.64 kg N ha⁻¹ in response to the addition of 320 kg N ha⁻¹ at Narrabri (Macdonald et al. 2015). The latter value is at the upper level of N₂O emissions from the limited amount of data available for irrigated cotton reported from other countries (Mahmood et al. 2008; Scheer et al. 2008; Liu et al. 2010; Watts et al. 2015) and of a similar magnitude to that reported by Grace et al. (2004) at the same site. Scheer et al. (2008) reported a comparable response to N in irrigated cotton in Uzbekistan (6.5 kg N₂O-N ha⁻¹) after application of 250 kg N ha⁻¹. The Australian cotton studies were all undertaken on alkaline heavy black clays that rapidly become anaerobic, producing ideal conditions for prolonged periods of denitrification (Rochester 2003) compared with the relatively free-draining sandy loams and loams studied in other countries.

The magnitude of seasonal N₂O emissions in response to high N fertiliser inputs in Australian cotton systems is only
surpassed by those from sugar cane (Wang et al. 2016), even though the latter normally receives significantly lower N inputs compared with cotton. The large amount of fresh residues retained in cane systems reduces evaporative losses and supplies carbon to fuel denitrification on low pH soils, which increases the proportion of N₂O emitted (Rochester 2003). This is in direct contrast with the conditions and soils under which cotton is grown in Australia.

EFs ranged from –0.26% to 3.15% across the 22 treatments receiving N inputs. Using replicate data for all treatments increased the variance in both linear and exponential models, with an EF of 0.55% for the linear model ($r^2 = 0.33$) and an EF for the statistically superior exponential model ($r^2 = 0.85$) of EF (%) = 0.65($e^{0.023N-1}$)/N (Fig. 1). In addition, every experiment with more than two N fertiliser input rates available (Table 1) shows a faster-than-linear N₂O emission growth with N fertiliser additions. This finding is consistent with a recent meta-analysis by Shcherbak et al. (2014), who demonstrated the non-linear response to N application to be a global phenomenon.

The best fit of the complete dataset using replicate data for each treatment is a two-component model with linear and exponential elements ($r^2 = 0.9$) that yields a variable EF in response to N inputs (Fig. 2), namely:

$$EF(\%) = 0.29 + 0.007(e^{0.037N-1})/N$$

Table 1. Mean (± s.e.m.) N₂O emissions and associated fertiliser-induced emission factors (EFs) in response to N applications to cotton in Australia

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Rotation</th>
<th>N rate (kg N ha⁻¹)</th>
<th>N₂O-N (kg N ha⁻¹)</th>
<th>EF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grace et al. (2004)</td>
<td>Narrabri, NSW</td>
<td>Cotton</td>
<td>0</td>
<td>1.07 ± 0.06</td>
<td>–</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>1.10 ± 0.07</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>1.53 ± 0.18</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cotton–wheat–vetch</td>
<td>0</td>
<td>1.54 ± 0.26</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>1.92 ± 0.21</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>2.34 ± 0.32</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>8.33 ± 3.06</td>
<td>2.27</td>
</tr>
<tr>
<td>Grace et al. (2006)</td>
<td>Narrabri, NSW</td>
<td>Cotton</td>
<td>140</td>
<td>0.64 ± 0.03</td>
<td>–0.26</td>
</tr>
<tr>
<td>Macdonald et al. (2015)</td>
<td>Narrabri, NSW</td>
<td>Cotton–faba</td>
<td>0</td>
<td>0.51 ± 0.37</td>
<td>–</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>0.95 ± 0.49</td>
<td>0.35</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>0.78 ± 0.04</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>320</td>
<td>10.62 ± 8.34</td>
<td>3.15</td>
</tr>
<tr>
<td>Scheer et al. (2013)</td>
<td>Kingsthorpe, Qld</td>
<td>Cotton–wheat</td>
<td>200</td>
<td>0.77 ± 0.11</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>0.96 ± 0.15</td>
<td>0.19</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>0.78 ± 0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Scheer et al. (2016)</td>
<td>Kingsthorpe, Qld</td>
<td>Cotton</td>
<td>0</td>
<td>0.59 ± 0.14</td>
<td>–</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>0.72 ± 0.15</td>
<td>0.09</td>
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<td></td>
<td>180</td>
<td>1.11 ± 0.10</td>
<td>0.29</td>
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<td></td>
<td></td>
<td>270</td>
<td>1.94 ± 0.33</td>
<td>0.50</td>
</tr>
<tr>
<td>Grace et al. (2006)</td>
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<td>Cotton</td>
<td>129</td>
<td>1.69 ± 0.26</td>
<td>1.05</td>
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<td>Cotton</td>
<td>189</td>
<td>1.16 ± 0.14</td>
<td>0.44</td>
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<tr>
<td>Grace et al. (2008)</td>
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<td>Cotton</td>
<td>155</td>
<td>1.83 ± 0.11</td>
<td>0.97</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>195</td>
<td>1.33 ± 0.18</td>
<td>0.51</td>
</tr>
</tbody>
</table>
replicated factors (EFs) versus N fertiliser application to cotton in Australia using models (including 95% confidence intervals) describing N2O emission factors (EFs) versus N fertiliser application to cotton in Australia using replicated field data from sites outlined in Table 1. One (x, y) data point (300, 4.79) is not shown.

Fig. 3. Modelled emission factors (EFs) in response to nitrogen fertiliser application as predicted by linear, exponential (EXP) and two-component (linear and exponential; LIN+EXP) statistical models using replicated treatment data for irrigated cotton in Australia.

so at 320 kg N ha\(^{-1}\). An extensive multiyear study by Rochester (2011) found the average seasonal N uptake by high-yielding irrigated cotton to be 247 kg N ha\(^{-1}\), which supports the hypothesis that the non-linear increase in N\(_2\)O emissions after 250 kg N ha\(^{-1}\) is sourced from mineral N in the soil profile that is excess to crop demand.

A comparison of EFs for the three models at various N rates using the replicated treatment data is presented in Fig. 3.

Conclusion

Globally, the majority of datasets relevant to N\(_2\)O emissions from cotton cropping are from Australia. Based on eight studies with 27 individual treatments across the cotton industry of Australia, a two-component (linear + exponential) statistical model describes fertiliser-induced N\(_2\)O emissions at the lower N rates better than an exponential model, and aligns with the EF using a traditional linear regression model. Where variable N rate information is explicitly available (e.g. farm or regional emissions reduction methodology or regional inventory data) the two-component (linear + exponential) model is recommended but should be capped at an EF of 1.83% until additional observational data are available for rates in excess of 300 kg N ha\(^{-1}\).

Acknowledgements

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