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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_2O) 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_2O emissions offset methodologies provided the EFs are evidence based. A meta-analysis was performed using eight individual N_2O emission studies from Australian cotton studies to estimate EFs. Annual N_2O emissions from cotton grown on Vertosols 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}. Seasonal N_2O 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}. A two-component (linear + exponential) statistical model, namely EF (%) = $0.29 + 0.007(e^{0.037N} - 1)/N$, capped at 300 kg N ha^{-1} describes the N_2O 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_2O) is a greenhouse gas with a global warming potential 298-fold higher than that of carbon dioxide (Intergovernment Panel on Climate Change (IPCC) 2013). Agriculture produces approximately 60% of global N_2O emissions, predominantly from emissions after application of nitrogen (N) fertilisers to soils (Reay *et al*. 2012). The rate of N fertiliser applied is the best single predictor of N_2O emissions from agricultural soils (Shcherbak *et al*. 2014).

The current global mean value for fertiliser-induced N_2O 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_2O is estimated to be emitted directly from soil. A 1% emission factor (EF) assumes a linear relationship between N input and N_2O 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 *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_2O 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^{-1}, with as much as 370 kg N ha^{-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_2O and N_2 via denitrification. Chen *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^{-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 *et al*. 2005), based on a limited dataset collected by Grace *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_2O 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. Shcherbak *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_2O 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_2O emissions from cotton soils of Australia in response to N fertiliser applications were determined. Daily estimates of N_2O 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_2O emissions (as a proportion of total N applied), the mean seasonal background N_2O 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_2O from fertiliser is emitted within a month after application, after which emissions decline to a background level (Bouwman 1996), we assumed the background emissions to be equivalent to the lowest emissions consistently recorded during periods that were at least 2 months after fertilisation.

For Narrabri, two of the three datasets had a 0N treatment and we used the site average of 1.01 kg N ha^{-1} for the third dataset; for the two Kingsthorpe datasets, we used the observed site background average of 0.59 kg N ha^{-1}; for the three Dalby datasets on a commercial farm, 0N treatments did not exist, but all the N_2O measurements were from the same or adjacent fields with similar histories and we estimated the background emission at 0.33 kg N ha^{-1} using the method outlined above.

EFs were obtained by subtracting the annual or seasonal N_2O background emissions ($ER_{site,0}$) from each annual or seasonal N_2O emission estimate at a non-zero N application rate ($ER_{site,N}$) for each respective site and divided it by fertiliser application rate (N), as follows:

$$EF_{site,N}\ (\%) = (ER_{site,N} - ER_{site,0})/N \times 100$$

Nitrous oxide emission rates (ER_N), EFs and 95% confidence bounds for both linear and exponential models were calculated using both mean and replicate seasonal emission measurements from across the three sites. The common emissions model is:

$$ER_N = ER_0 + EF \times N$$

A non-linear (exponential) model of N_2O emissions from N application was approximated by a curve of the form:

$$EF_N(\%) = a(e^{bN} - 1)/N$$

where EF_N is EF obtained by the above procedure, N is fertiliser application rate (kg N ha^{-1}) and a and b are constants. EF models (and respective confidence bounds) combining both linear and exponential components using replicate data from each site were also developed. Analysis was performed using Mathematica 9.0.1 (Wolfram Research).

Experiments

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_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^{-1} urea applied as a single application). The 10th treatment was WVC receiving an industry high rate of 300 kg N ha^{-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_W of 8.2. The CC treatment received 140 kg N ha^{-1} on 10 September 2003 as anhydrous NH_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 N_2O 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 pH_W 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 N_2O was conducted at the Agri-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 pH_W 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 N_2O 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 pH_W 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} NH_3^+ 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 N_2O 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 N_2O 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 N_2O emissions from Australia's cotton industry. Annual N_2O 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 N_2O 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 N_2O 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 N_2O-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 N_2O 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 N_2O 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 N_2O 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:

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

This EF is very low for modest N application rates (e.g. 0.29% at 100 kg N ha^{-1} and 0.58% at the current average N application rate for the cotton industry of 250 kg N ha^{-1}). The EF rapidly increases for higher N application rates, reaching 1.08% at 280 kg N ha^{-1}, 1.83% at 300 kg N ha^{-1} and 3.32% at the highest observed N input level of 320 kg N ha^{-1}, past which it becomes an extrapolation and is unlikely to be very reliable. The sharp increase in EF above 280 kg N ha^{-1} is driven by relatively consistent observations at 300 kg N ha^{-1}, but lesser

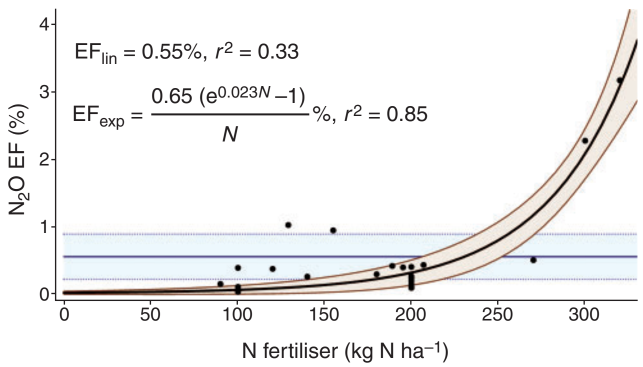

Fig. 1. Linear (EF_{lin}) and exponential (EF_{exp}) models (including 95% confidence intervals) describing N_2O emission factors (EFs) versus N fertiliser application to cotton in Australia using replicated field data from sites outlined in Table 1. One (x, y) data point (300, 4.79) is not shown.

Table 1. Mean (± s.e.m.) N_2O emissions and associated fertiliser-induced emission factors (EFs) in response to N applications to cotton in Australia

Reference	Location	Rotation	N rate (kg ha^{-1})	N_2O-N (kg ha^{-1})	EF (%)
Grace *et al*. (2004)	Narrabri, NSW	Cotton	0	1.07 ± 0.06	–
			100	1.10 ± 0.07	0.03
			200	1.53 ± 0.18	0.23
		Cotton–wheat–vetch	0	1.54 ± 0.26	–
			100	1.92 ± 0.21	0.38
			200	2.34 ± 0.32	0.40
			300	8.33 ± 3.08	2.27
		Cotton–wheat	0	0.69 ± 0.09	–
			100	0.79 ± 0.07	0.10
			200	1.21 ± 0.24	0.26
Grace *et al*. (2006)	Narrabri, NSW	Cotton	140	0.64 ± 0.03	–0.26
Macdonald *et al*. (2015)	Narrabri, NSW	Cotton–faba	0	0.51 ± 0.37	–
			120	0.95 ± 0.49	0.35
			200	0.78 ± 0.04	0.12
			320	10.62 ± 8.34	3.15
Scheer *et al*. (2013)	Kingsthorpe, Qld	Cotton–wheat	200	0.77 ± 0.11	0.09
			200	0.96 ± 0.15	0.19
			200	0.78 ± 0.05	0.10
Scheer *et al*. (2016)	Kingsthorpe, Qld	Cotton	0	0.59 ± 0.14	–
			90	0.72 ± 0.15	0.09
			180	1.11 ± 0.10	0.29
			270	1.94 ± 0.33	0.50
Grace *et al*. (2006)	Dalby, Qld	Cotton	207	1.17 ± 0.30	0.41
Grace *et al*. (2007)	Dalby, Qld	Cotton	129	1.69 ± 0.26	1.05
			189	1.16 ± 0.14	0.44
Grace *et al*. (2008)	Dalby, Qld	Cotton	155	1.83 ± 0.11	0.97
			195	1.33 ± 0.18	0.51

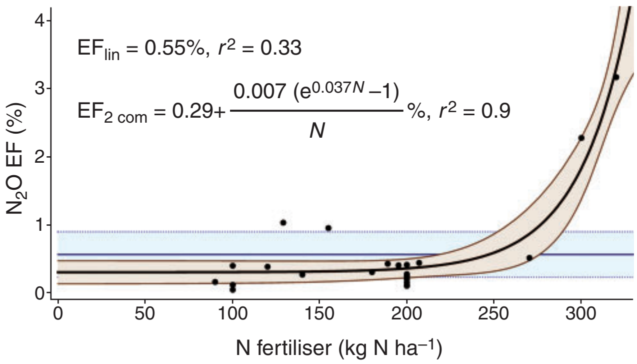

Fig. 2. Linear (EF_{lin}) and two-component (linear + exponential; $EF_{2\,com}$) models (including 95% confidence intervals) describing N_2O emission factors (EFs) versus N fertiliser application to cotton in Australia using replicated field data from sites outlined in Table 1. One (*x*, *y*) data point (300, 4.79) is not shown.

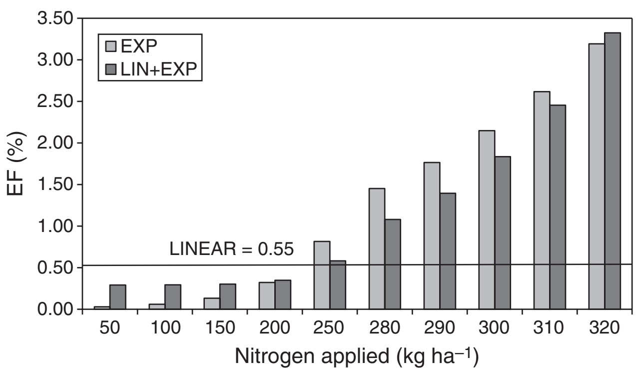

Fig. 3. Modelled emission factors (EFs) in response to nitrogen fertiliser application as predicted by linear, exponential (EXP) and two-component (linear and exponential; LIN + EXP) statistical models using replicated treatment data for irrigated cotton in Australia.

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_2O 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_2O 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_2O 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}.

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References

Bouwman A (1996) Direct emissions of N_2O from agricultural soils. *Nutrient Cycling in Agroecosystems* **46**, 53–70. doi:10.1007/BF00210224

Braunack M (2013) Cotton farming systems in Australia: factors contributing to change yield and fibre quality. *Crop and Pasture Science* **64**, 834–844.

Chen DL, Freney JR, Mosier AR, Chalk PM (1994) Reducing denitrification loss with nitrification inhibitors following presowing applications of urea to a cottonfield *Australian Journal of Experimental Agriculture* **34**, 75–83. doi:10.1071/EA9940075

Department of Environment (2015) 'The emissions reduction fund – what it means for you.' (Commonwealth of Australia: Canberra)

Galbally I, Meyer M, Bentley S, Weeks I, Leuning R, Kelly K, Phillips F, Barker-Reid F, Gates W, Baigent R, Eckard R, Grace P (2005) A study of environmental and management drivers of non-CO_2 greenhouse gas emissions in Australian agro-ecosystems. *Environmental Sciences* **2**, 133–142. doi:10.1080/15693430500395396

Grace P, Weier KL, Rochester I (2004) 'Baseline assessment of greenhouse gas emissions in cotton based farming systems (GCRC3C). Final report.' (Cotton Research and Development Corporation: Narrabri)

Grace P, Rowlings D, Rochester I (2006) 'Reducing nitrogen losses from cotton rotation systems (GCRC4C). Final report.' (Cotton Research and Development Corporation: Narrabri)

Grace P, Rowlings D, Rochester I (2007) 'Benchmarking and reducing greenhouse gas emissions and improving resource use efficiency (QUT2) progress report November 2007.' (Cotton Research and Development Corporation: Narrabri)

Grace P, Rowlings D, Rochester I (2008) 'Benchmarking and reducing greenhouse gas emissions and improving resource use efficiency (QUT2) progress report November 2008.' (Cotton Research and Development Corporation: Narrabri)

Grace P, Rowlings D, Rochester I, Kiese R, Butterbach-Bahl K (2010) Nitrous oxide emissions from irrigated cotton soils of northern Australia. In 'Proceedings of the 19th World Congress of Soil Science. Congress Symposium 4: Greenhouse Gases from Soils'. (Eds RJ Gilkes, N Prakongkep) pp. 179–182. (International Union of Soil Sciences: Brisbane)

Hoben JP, Gehl RJ, Millar N, Grace PR, Robertson GP (2011) Nonlinear nitrous oxide (N_2O) response to nitrogen fertiliser in on-farm corn crops of the US Midwest. *Global Change Biology* **17**, 1140–1152. doi:10.1111/j.1365-2486.2010.02349.x

Intergovernment Panel on Climate Change (IPCC) (2006) N_2O emissions from managed soils, and CO_2 emissions from lime and urea applications. In '2006 IPCC guidelines for national greenhouse gas inventories, volume 4, agriculture forestry and other land use'. (Eds HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe) pp. 11.1–11.54. (Institute for Global Environmental Strategies: Hayama)

Intergovernment Panel on Climate Change (IPCC) (2013) Anthropogenic and natural radiative forcing. In 'Climate change 2013: the physical science basis. Working Group I contribution to the fifth assessment

report of the Intergovernmental Panel on Climate Change'. (Ed. TF Stocker) pp. 659–740. (Cambridge University Press: Cambridge)
Isbell R (2002) 'The Australian soil classification.' (CSIRO Publishing: Melbourne)
Kim DG, Hernandez-Ramirez G, Giltrap D (2013) Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: a meta-analysis. *Agriculture, Ecosystems & Environment* **168**, 53–65. doi:10.1016/j.agee.2012.02.021
Liu C, Zheng X, Zhou Z, Han S, Wang Y, Wang K, Liang W, Li M, Chen D, Yang Z (2010) Nitrous oxide and nitric oxide emissions from an irrigated cotton field in Northern China. *Plant and Soil* **332**, 123–134. doi:10.1007/s11104-009-0278-5
Ma BL, Wu TY, Tremblay N, Deen W, Morrison MJ, McLaughlin NB, Gregorich EG, Stewart G (2010) Nitrous oxide fluxes from corn fields: on-farm assessment of the amount and timing of nitrogen fertiliser. *Global Change Biology* **16**, 156–170. doi:10.1111/j.1365-2486.2009.01932.x
Macdonald BCT, Rochester IJ, Nadelko A (2015) High yielding cotton produced without excessive nitrous oxide emissions. *Agronomy Journal* **107**, 1673–1681. doi:10.2134/agronj14.0369
Mahmood T, Ali R, Iqbal J, Robab U (2008) Nitrous oxide emission from an irrigated cotton field under semiarid subtropical conditions. *Biology and Fertility of Soils* **44**, 773–781. doi:10.1007/s00374-008-0276-4
McSwiney CP, Robertson GP (2005) Nonlinear response of N_2O flux to incremental fertiliser addition in a continuous maize (*Zea mays* L.) cropping system. *Global Change Biology* **11**, 1712–1719. doi:10.1111/j.1365-2486.2005.01040.x
Millar N, Robertson GP, Grace P, Gehl R, Hoben J (2010) Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (maize) production: an emissions reduction protocol for US Midwest agriculture. *Mitigation and Adaptation Strategies for Global Change* **15**, 185–204. doi:10.1007/s11027-010-9212-7
Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, Crutzen PJ (2012) Global agriculture and nitrous oxide emissions. *Nature Climate Change* **2**, 410–416. doi:10.1038/nclimate1458
Rochester IJ (2003) Estimating nitrous oxide emissions from flood-irrigated alkaline grey clays. *Soil Research* **41**, 197–206. doi:10.1071/SR02068
Rochester I (2011) Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. *Nutrient Cycling in Agroecosystems* **90**, 147–156. doi:10.1007/s10705-010-9418-9
Roth Rural (2013) 'Cotton growing practices 2013: findings of CRDC's survey of cotton growers.' (Cotton Research and Development Corporation: Narrabri)
Scheer C, Wassmann R, Butterbach-Bahl K, Lamers JP, Martius C (2008) The relationship between N_2O, NO, and N_2 fluxes from fertilized and irrigated dryland soils of the Aral Sea Basin, Uzbekistan. *Plant and Soil* **314**, 273–283. doi:10.1007/s11104-008-9728-8
Scheer C, Grace P, Rowlings D, Payero J (2013) Soil N_2O and CO_2 emissions from cotton in Australia under varying irrigation management. *Nutrient Cycling in Agroecosystems* **95**, 43–56. doi:10.1007/s10705-012-9547-4
Scheer C, Rowlings DW, Grace PR (2016) Non-linear response of soil N_2O emissions to nitrogen fertiliser in a cotton–fallow rotation in sub-tropical Australia. *Soil Research* **54**, 494–499. doi:10.1071/SR14328
Shcherbak I, Millar N, Robertson GP (2014) A global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertiliser nitrogen. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 9199–9204. doi:10.1073/pnas.1322434111
Signor D, Cerri CEP, Conant R (2013) N_2O emissions due to nitrogen fertiliser applications in two regions of sugarcane cultivation in Brazil. *Environmental Research Letters* **8**, 015013. doi:10.1088/1748-9326/8/1/015013
Wang W, Park G, Reeves S, Zahmel M, Heenan M, Salter B (2016) Nitrous oxide emission and fertiliser nitrogen efficiency in a tropical sugarcane cropping system applied with different formulations of urea. *Soil Research* **54**, 572–584. doi:10.1071/SR15314
Watts DB, Runion GB, Smith Nannenga KW, Torbert HA (2015) Impacts of enhanced-efficiency nitrogen fertilizers on greenhouse gas emissions in a coastal plain soil under cotton. *Journal of Environmental Quality* **44**, 1699–1710. doi:10.2134/jeq2015.01.0036