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SOIL RESEARCH

Revised emission factors for estimating direct nitrous oxide emissions from nitrogen inputs in Australia's agricultural production systems: a meta-analysis

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ABSTRACT

Context. Agricultural soils are a major source of emissions of the greenhouse gas nitrous oxide (N_2O). **Aim.** Quantify direct N_2O emissions from Australian agricultural production systems receiving nitrogen (N) inputs from synthetic and organic fertilisers, crop residues, urine and dung. **Method.** A meta-analysis of N_2O emissions from Australian agriculture (2003–2021) identified 394 valid emission factors (EFs), including 102 EFs with enhanced efficiency fertilisers (EEFs). **Key results.** The average EF from all N sources (excluding EEFs) was 0.57%. Industry-based EFs for synthetic N fertiliser (excluding EEFs) ranged from 0.17% (non-irrigated pasture) to 1.77% (sugar cane), with an average Australia-wide EF of 0.70%. Emission factors were independent of topsoil organic carbon content, bulk density and pH. The revised EF for the non-irrigated cropping (grains) industry is now 0.41%; however, geographically-defined EFs are recommended. Urea was the most common N source with an average EF of 0.72% compared to urine (0.20%), dung (0.06%) and organo-mineral mixtures (0.26%). The EF for synthetic N fertilisers in rainfed environments increased by 0.16% for every 100 mm over 300 mm mean annual rainfall. For each additional 50 kg N ha^{-1} of synthetic fertiliser, EFs increased by 0.13%, 0.31% and 0.38% for the horticulture, irrigated and high rainfall non-irrigated cropping industries, respectively. The use of 3,4 dimethylpyrazole-phosphate (DMPP) produced significant reductions in EFs of 55%, 80% and 84% for the horticulture, non-irrigated and irrigated cropping industries, respectively. **Conclusions and implications.** Incorporation of the revised EFs into the 2020 National Greenhouse Accounts (NGA) produced a 12% increase in direct N_2O emissions from the application of synthetic N fertilisers. The lack of country-specific crop residue decomposition data is a major deficiency in the NGA.

Keywords: DMPP, emission factors, inventory, meta-analysis, nitrification inhibitors, nitrogen fertiliser, nitrous oxide.

Introduction

Agriculture constitutes 15% of Australia's annual greenhouse gas emissions (Department of Industry, Science, Energy and Resources 2022). Australia is a semi-arid continent of over 750 Mha with an arid heartland (300 Mha) unsuitable for agriculture. Agricultural production is restricted to rainfed farmland (97 Mha) including permanent and perennial pastures, continuous dryland cropping (wheat and sorghum) and phased crop–pasture systems; intensive agriculture (4 Mha) including dairy production, irrigated horticulture and field crops such as cotton; and pastoral rangeland (355 Mha) in semi-arid and northern tropical regions (Angus and Grace 2017).

Nitrous oxide (N_2O) represents 15% of Australia's agricultural emissions. Soils are the primary source of N_2O emissions from Australia agriculture at 12.3 Mt carbon dioxide equivalents (CO_2e) per annum which includes both direct emissions (9.2 Mt CO_2e) from the application of inorganic (26%) and organic nitrogen (5%) fertilisers, crop residue decomposition (36%) and dung and urine from grazing animals (30%), and indirect emissions (3.1 Mt CO_2e). The default aggregated emission factor (EF_1) for N_2O emissions from N input currently recommended by the Intergovernmental Panel on Climate Change (IPCC 2019) is 1% after correction for background (0N) emissions, i.e. for every 100 kg of N input, 1.0 kg of N in the form of N_2O is estimated to be emitted directly from soil. The 1% EF_1 assumes a linear relationship between the mass of N input and N_2O emissions and is indifferent to any biological thresholds that might occur; for example, when the availability of soil inorganic N exceeds crop N demands (Shcherbak *et al*. 2014).

Globally, a growing number of field experiments with multiple N fertiliser rates demonstrate non-linear responses in N_2O emissions 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; Shcherbak *et al*. 2014; Scheer *et al*. 2016; Millar *et al*. 2018; Takeda *et al*. 2021), suggesting that EFs are not constant but increase with N additions. Grace *et al*. (2016) evaluated eight separate field campaigns from the Australian cotton industry with respect to N_2O emissions and the development of linear and/or non-linear models describing EFs in response to exogenous N inputs. Where variable N rate information was explicitly available (i.e. farm or regional methodology or regional inventory data), a two-component (linear + exponential) model was recommended, with EFs capped at a maximum of 1.83% (until additional observational data is available for rates in excess of 300 kg N ha^{-1}). Where only average N application rate information is available, a linear EF of 0.55% was recommended.

The meta-analysis examined the impact of management, soil and climate interactions on N_2O emissions from crop and pasture production systems in Australia receiving externally sourced N inputs, including the use of enhanced efficiency fertilisers (EEFs). The study represents an update of the EFs currently in use in Australia (Shcherbak and Grace 2014) (Table 1) to estimate fertiliser-induced N_2O emissions for inclusion in the National Greenhouse Accounts (NGA) of Australia including EEFs. The analysis also includes a re-assessment of the EFs associated with urine and dung (manure) inputs from grazing animals (specifically EF_3 as designated by the IPCC) and organo-mineral N fertiliser applications.

Materials and methods

Estimates of N_2O emissions from mineral and organic N fertilisers (and combined additions), crop residues, and urine and dung by grazing animals were obtained directly from peer-reviewed publications and federal government reports. The majority of the data was sourced from published field-based experimental studies within four major research networks funded by the Australia federal government since 2009, i.e. the Nitrous Oxide Research Program (NORP) (2009–2012), the National Agricultural Nitrous Oxide Research Program (NANORP) (2012–2016), the National Adaptation and Mitigation Initiative (NAMI) (2009–2012); and outputs from multiple projects funded through the Action on the Ground Program (2012–2016). The purpose of these programs was to baseline N_2O emissions from common practices and develop N_2O mitigation strategies which supported the environmentally sustainable productivity and profitability of Australia agriculture.

Studies were grouped by industry-based categories (i.e. production systems) which aligned with the NGA, i.e. non-irrigated (grain) crop, irrigated (grain) crop, non-irrigated pasture, irrigated pasture, sugar cane, cotton and horticulture. Additional data in the analysis included climate (e.g. mean annual rainfall (MAR)), agronomic management (e.g. irrigation, tillage, fertiliser product), soil properties (e.g. soil organic carbon, bulk density, soil type, cation exchange capacity) and experimental design. In the case of pastures, the EFs associated with the addition of urine and dung by grazing animals were also calculated as these are also included in the Agricultural Soils category (3.D) of the NGA.

With respect to the non-irrigated cropping category (which is dominated by rainfed grain production), we also examined two contrasting approaches to determine EFs, i.e. climatic versus geographic delineation of observations. With respect to climate, after a preliminary scan of N_2O emissions and a variety of climatic variables and indices (e.g. precipitation/evaporation ratio) we chose to disaggregate the Australian grain production regions (West, South and North) on the basis of what is nominally considered to be high and low annual rainfall areas, with 600 mm MAR the chosen point of differentiation. These areas were accurately quantified in ARC GIS by overlaying a map of the Grains Research and Development Corporation (GRDC) agro-ecological zones with a Bureau of Meteorology contour map of average annual rainfall (1991–2020). For the geographic delineation, climatic conditions were irrelevant, and we calculated a separate EF for the Western Region (which is dominated by coarse textured soils) from the rest of the non-irrigated grains industry (South and North) of Australia. The three regions are geographically contained within state boundaries, i.e. the Western Region is solely within the state of Western Australia, the Southern Region encompasses south-eastern Australia and includes the states of South Australia, Victoria and Tasmania, and the Northern Region is within the states of Queensland and Victoria.

Emission factors were calculated by subtracting seasonal N_2O background emissions ($ER_{site,0}$) from each seasonal N_2O emission at a non-zero N application rate ($ER_{site,N}$) for each respective site, then dividing the calculated net emission by the fertiliser application rate (N):

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

The background N_2O emissions were estimated from measurements for the same year, crop, management and

Table 1. Revised nitrous oxide emission factors (EFs) for major production systems of Australia based on a meta-analysis of 292 field observations (2003–2021).

Production system	Treatments	Mean N Rate and range (kg ha^{-1})	Revised EF (%)	s.e.	Current EF (%)
Non-irrigated crop	111	88 (20–240)	0.56[A]	0.06	
Low-rainfall crop (≤ 600 mm)	(51)	78 (20–160)	0.29	0.08	0.05
High-rainfall crop (>600 mm)	(60)	96 (30–240)	0.80	0.09	0.84
Non-irrigated crop (climatic)[B]	111	88 (20–240)	0.41		0.2[C]
Non irrigated crop – only WA[D]	(15)	76 (20–100)	0.04	0.01	
Non irrigated crop – excl. WA	(96)	90 (30–240)	0.65	0.07	
Non-irrigated crop (geographic)	111	88 (20–240)	0.41		
Irrigated crop	17	132 (20–300)	0.62	0.17	0.85
Irrigated pasture	11	271 (48–485)	0.59	0.18	0.39
Non-irrigated pasture	10	363 (100–939)	0.17	0.05	0.21
Cotton	22	182 (90–320)	0.53	0.16	0.55
Sugar cane (excluding acid sulphate soils)	26	142 (75–250)	1.77	0.24	1.99
Horticulture	24	210 (35–592)	0.63	0.19	0.85
Non-irrigated pasture (urine)	32	793 (140–2000)	0.20	0.03	0.4
Non-irrigated pasture (dung)	16	372 (152–448)	0.06	0.01	0.4
Organo-mineral N fertiliser	23	248 (96–907)	0.26	0.06	

[A]Aggregated average.
[B]Mean Annual Rainfall (MAR) ≤600 mm equivalent to 77% of total non-irrigated cropping area of Australia based on overlaying Bureau of Meteorology MAR 1991–2020 spatial grid on GRDC regions.
[C]Current area weighted EF in 2020 National Greenhouse Accounts of 0.2% is an EF of 0.05% for low rainfall cropping (MAR < 600 mm) (80% of non-irrigated area of Australia) and 0.84% for high rainfall cropping (20% of non-irrigated crop area).
[D]Western Australia (WA) is 39% of non-irrigated crop area of Australia (ABS 7121.0 Agricultural Commodities 2012/2013–2001/2022).

field as the N_2O emissions induced by the external N inputs. On the single occasion where this background data was not explicitly available, i.e. the high temporal frequency N_2O data of Scheer *et al.* (2013) measured using the fully automated chambers described in Grace *et al.* (2020), we assumed that the daily background N_2O emissions were equivalent to the lowest emissions consistently recorded at least 2 months after the addition of the N source. We based this assumption on Bouwman (1996) who reported that most of the N_2O from fertiliser is emitted within a month after N application, after which N_2O emissions decline to a background level.

Statistical analyses were performed in the R environment (R Core Team 2021). Analysis of groups of site-years was performed to determine mean and standard error of EFs associated with fertiliser-induced N_2O emissions for each production system.

The efficacy of specific EEFs within a production system was tested using pairwide comparisons of N rate for the same site-year and a one-tailed *t*-test.

Both simple linear and linear mixed-modelling approaches were applied to test the response of EF to MAR in non-irrigated agricultural systems, and the response of mineral fertiliser nitrogen applications in horticultural cropping systems, as well as in both irrigated and non-irrigated cropping sectors. The linear mixed-modelling approach included the year of experimentation, location and duration of the measurement periods as random effects. These variables were treated as random effects to account for potential variability across different experiments. If no significant difference was observed between the simple linear regression and the linear mixed-model approach, the simpler model (i.e. simple linear regression) was used. The linear mixed models were evaluated with the marginal R^2 (R^2LMM(m)), which represents the proportion of variance explained by the fixed effects of the model, ignoring the contribution of any random effects (Nakagawa and Schielzeth 2013), using the R package MuMIn (Bartoń 2023).

Results and discussion

A total of 419 individual EFs were identified with one-third being in irrigated crop and pasture systems, as well as 108 EFs for treatments where EEFs had been applied. Negative EFs were included in our analysis. The majority of studies utilised fully automated greenhouse gas monitoring systems as described by Grace *et al.* (2020) with eight discrete measurement periods per day and *in situ* measurement of N_2O using in line gas chromatograph. Data was collected from 50 separate trial sites across Australia covering the seven major production systems outlined in the NGA (Fig. 1). The average measurement period was 222 days

(30–900 days) with two-thirds of the experiments (n = 283) exceeding 150 days. The shorter measurement periods (<100 days) were only utilised in the intensively managed horticulture and pasture systems where multiple N applications or multiple crops within a single year are the norm. In contrast, the longest measurement periods (average 314 days) were found in the sugar cane industry (n = 36). Over one-third of the EF dataset (n = 148) was collected from 20 locations with non-irrigated grain experiments (average 254 days) with the majority of the non-irrigated grain experiments on the heavier textured soils of eastern Australia. For non-irrigated pastures (n = 99), six locations were utilised with an average measurement period of 172 days. The non-irrigated pasture sites were mainly under dairy production with the majority of these measurements at Terang (n = 56) in the higher rainfall region of southern Australia.

Consistently high EFs in the sugarcane data (Denmead *et al.* 2010; Wang *et al.* 2016; Westermann 2017; Salazar Cajas 2019) (n = 8) on acid sulfate soils (ASS) were excluded. Anomalies in the non-irrigated crop data for Hamilton in 2012 (Harris *et al.* 2016) and Hart in 2015 (Poole 2017) (n = 4) were excluded after identification of potential sampling and analysis errors. Studies by Jamali *et al.* (2016), Schwenke *et al.* (2015) and Muller *et al.* (2023) (n = 13) were also excluded as no background emissions data was available or reasonably estimated.

Nitrogen fertilisers

Of the 394 valid EFs included in the final analysis, there were 292 non-EEF treatments which included synthetic fertiliser,

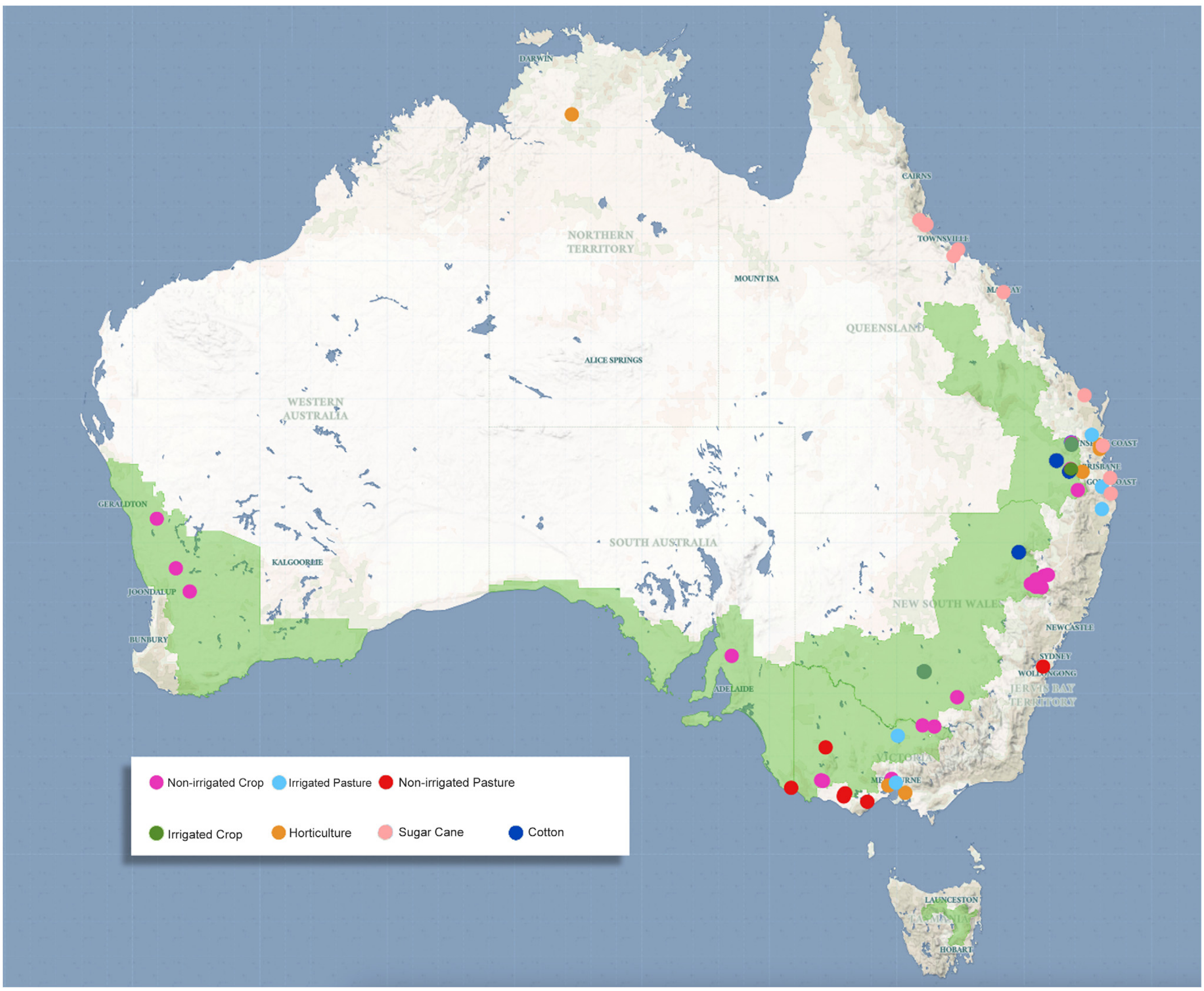

Fig. 1. Location of historical nitrous oxide measurement trials in Australia and their relationship to the production systems listed in the National Greenhouse Accounts. Green shading indicates the extent of grain cropping systems as determined by the Grains Research and Development Corporation (GRDC).

urine, dung and organo-mineral mixtures returning an Australian average EF of 0.57%. Synthetic N fertilisers were exclusively applied in 221 cases returning an average EF of 0.70%. This EF is significantly lower than the aggregated EF_1 value of 1% for synthetic N fertilisers (and N inputs generally) recommended by the IPCC (IPCC 2019). The IPCC also provide disaggregated EFs by differentiating wet and dry climates. By excluding the individual EFs from the Australian 'wet climate' sugar cane industry, the average 'dry climate' EF for Australia of 0.56% (n = 195) is higher than the IPCC's disaggregated EF_1 recommendation of 0.50% for N fertiliser application in dry climates. The Australian 'wet climate' EF of 1.77% (i.e. the sugar cane industry) is also higher than the 1.6% recommended by the IPCC but it does fall within the confidence limits reported by the IPCC for wet climates. It should be noted that the IPCC EF_1 does not distinguish between irrigated and non-irrigated systems; however, by excluding N_2O date for irrigated systems from the 'dry climate' returns an EF of 0.53% (n = 121).

Urea was the most commonly used N fertiliser in the dataset with 213 observations, with an average EF of 0.72%, well above the average EF of urine (0.20%), dung (0.06%) and organo-mineral mixtures (0.26%) (Table 1). Whilst the revised EF for urine is consistent with the IPCC EF_3 recommendation for 'dry climates' (0.2%) (IPCC 2019), the revised EF for dung is significantly lower. The revised EFs for both urine and dung are also significantly lower compared to the current EF used for both N inputs in the NGA, i.e. 0.4%, which is based on the aggregated EF_3 value recommended by the IPCC. Separate EFs for urine and dung is consistent with approaches taken by New Zealand (van der Weerden *et al.* 2011) and the United Kingdom (Chadwick *et al.* 2018) where animal based N inputs and N_2O emissions have been extensively researched.

The revised EF for organo-mineral mixtures (0.26%) is significantly lower than the recommended IPCC EF_1 value (0.5%) for dry climates and well below the average EF of 1.5% reported in the meta-analysis by Charles *et al.* (2017); however, the majority of Australian studies were in irrigated horticulture (e.g. De Rosa *et al.* 2016, 2018) with a precision budgetting approach to N management which limits N_2O emissions. Also, there are no definitive EFs for above and belowground crop residue decomposition in Australia except for the observations of Schwenke *et al.* (2015) which range from 0.12% to 0.62% (average 0.32%) but are not corrected for background emissions and therefore overestimate N_2O emissions from crop residues. The EF for crop residues used in the 2020 NGA is 1.0% based on the aggregated EF_1 value recommended by the IPCC in 2006 (IPCC 2006); however, the IPCC (2019) 'dry climate' EF_1 is 0.5% which still exceeds the uncorrected EF values reported by Schwenke *et al.* (2015). The global meta-analysis of Charles *et al.* (2017) reported an average EF of 0.19% across eight crop residue studies. A recent global meta-analysis of N_2O emissions from crop residues by Abalos *et al.* (2022) reported a large range in residue-based N_2O emissions but no useable data on surface residue decomposition in dry climates which is the norm for Australian no-till non-irrigated grain cropping systems.

The average EF for irrigated (crop and pasture) systems receiving synthetic N fertilisers (excluding EEFs) was 0.67% (n = 79) with 201 kg N ha^{-1} applied on average during the growing season. The EF for rainfed (crop and pasture) systems receiving synthetic N fertiliser (excluding EEFs) was 0.75% (n = 142) with an average N application of 113 kg ha^{-1}. A highly significant linear relationship was found in rainfed systems between the EF associated with the application of urea and MAR (Fig. 2) with the EF increasing by 0.16% for each 100 mm over 300 mm MAR.

The industry-based EFs in response to applying synthetic N fertilisers (excluding EEFs) ranged from 0.17% (non-irrigated pasture) to 1.77% (sugar cane) (Table 1), with an average EF value of 0.71% across all observations. The irrigated and rainfed crop categories exclude cotton, horticulture and sugar cane, as they represent separate categories in the NGA. In all categories except cotton (revised EF = 0.53%), there were significant changes in the EF compared to those used in the NGA for 2020 (Department of Industry, Science, Energy and Resources 2022). This is due to the inclusion of 72 additional non-EEF fertiliser observations to complement the previous EF meta-analysis (of 148 studies) of Shcherbak and Grace (2014). In addition, some of the previous inclusions were either recalculated or reclassified. The majority of the additional data were in low rainfall (≤600 mm MAR) non-irrigated crop (n = 27), horticulture (n = 18) and sugar cane (n = 14) categories.

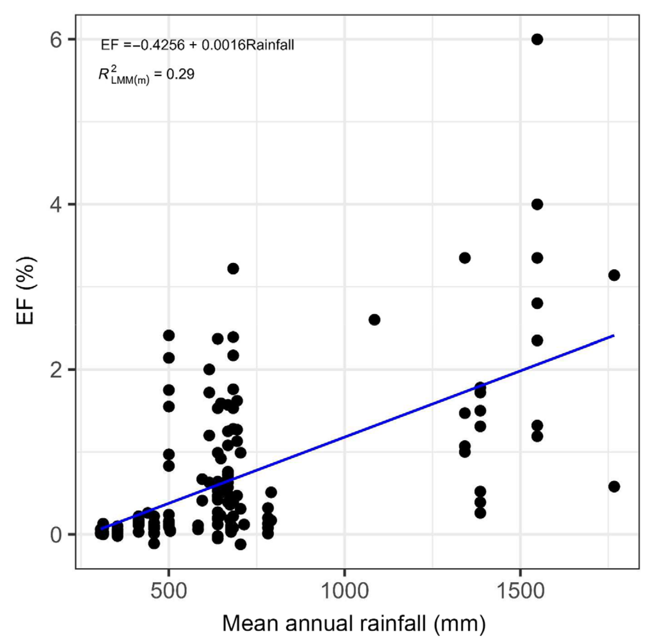

Fig. 2. Nitrous oxide emission factors (%) in response to N fertiliser addition in non-irrigated agricultural systems and their relationship to mean annual rainfall in Australia. Excluding enhanced efficiency fertilisers. Year, location and duration of measurement were included as random effects in the linear mixed-modelling approach.

The revised EF for irrigated pasture (0.59%) is triple the revised EF value for non-irrigated pasture (0.17%). The latter EF is similar to the current EF value of 0.21% for non-irrigated pastures in the NGA for 2020 whilst the revised EF for irrigated pastures is double the current EF value in the NGA. The revised EFs for irrigated crops and horticulture are 0.62% and 0.63%, respectively, which are significantly lower than their current EF value (0.85%) in the NGA. The revised EFs for irrigated crops and horticulture are now similar to the EF of the cotton industry which has collected N_2O emissions data for irrigated systems only.

Differentiating the non-irrigated cropping area of Australia into low (≤600 mm MAR) and high rainfall (>600 mm) MAR regions (the latter representing 23% of the non-irrigated cropping area of Australia) returned revised EFs of 0.29% and 0.80%, respectively, with a weighted climatic average EF of 0.41%, double the current EF in the NGA for non-irrigated crops using a similar climate-centric calculation. This change was mainly due to a significant increase in the EF for the low rainfall region, from 0.05% to 0.29%, based on a significant number of additional observations. The geographic differentiation of the non-irrigated crop category returned a revised EF of 0.04% for the Western Region compared to an average revised EF of 0.65% for the Northern and Southern Regions of grain production in Australia. With 39% of Australia's non-irrigated grain crop grown in the Western Region (Australian Bureau of Statistics), the weighted geographic average EF was 0.41%, the same as the revised EF based on a weighted climatic average. The use of a weighted average climatic EF in the current NGA is problematic considering changes in both annual and seasonal rainfall linked to global warming. Nitrous oxide studies in the Western non-irrigated cropping region (dominated by the coarse-textured sands of Western Australia) have consistently returned low EFs (Barton *et al.* 2008, 2010, 2013, 2016). Considering regional N fertiliser usage data is readily available and embedded in the NGA calculation, we recommend that the weighted average climatic approach to the EF for non-irrigated cropping in the NGA be discontinued and be replaced by geographically-distinct EFs of 0.04% and 0.65% for the Western and North/South Regions of grain production, respectively.

Sugar cane production systems (excluding those on ASS) returned the highest revised EF (1.77%) of all production systems. Whilst this EF is slightly lower than the current EF value (1.99%) in the 2020 NGA for sugar cane, the revised EF calculation includes five new observations in irrigated cane (average EF = 0.81%). The EF in irrigated sugar cane is significantly lower than the current EF for sugar cane which is based solely on rainfed systems and there may be justification for separate EFs for irrigated and rainfed sugar cane similar to crop and pasture systems in the NGA. There is also growing evidence that the very high EFs in sugar cane that we excluded from this and previous analyses (Shcherbak and Grace 2014) are consistent with the reducing conditions in the sub-layers of ASS inducing N_2O production through abiotic chemo-denitrification

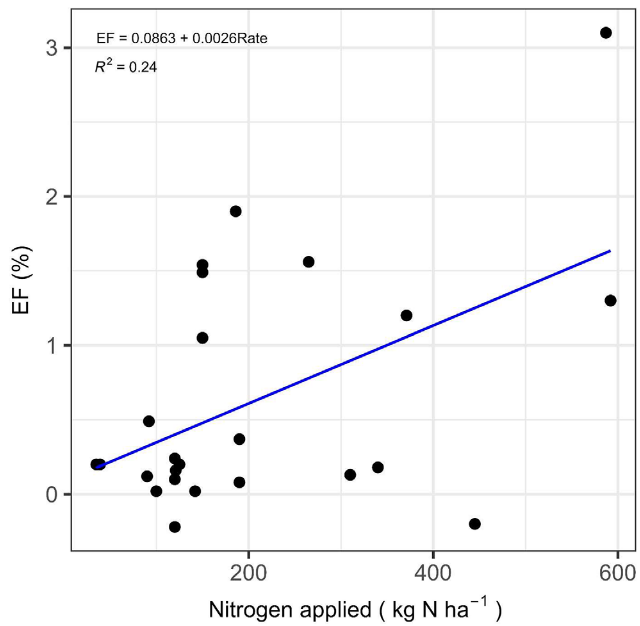

Fig. 3. Nitrous oxide emission factors (EF; %) in response to mineral fertiliser nitrogen applications in the horticulture sector of Australian agriculture. Excluding enhanced efficiency fertilisers. Year, location and duration of measurements were included as random effects in the linear mixed-modelling approach.

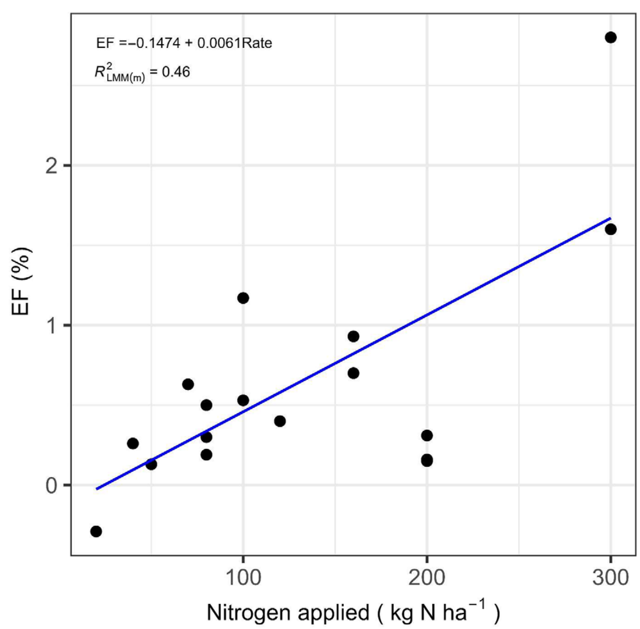

Fig. 4. Nitrous oxide emission factors (EF; %) in response to mineral fertiliser nitrogen applications in the irrigated cropping sector of Australian agriculture. Excluding enhanced efficiency fertilisers. Year, location and duration of measurements were included as random effects in the linear mixed-modelling approach.

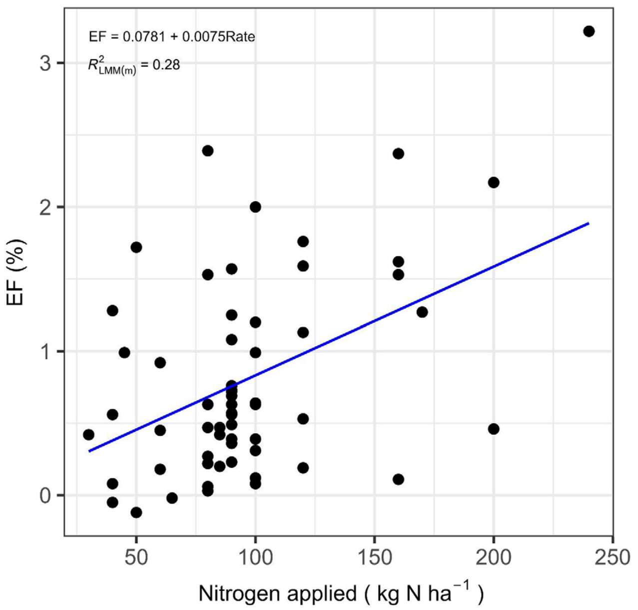

Fig. 5. Nitrous oxide emission factors (EF; %) in response to mineral fertiliser nitrogen applications in the non-irrigated cropping sector of Australian agriculture. Excluding enhanced efficiency fertilisers. Year, location and duration of measurements were included as random effects in the linear mixed modelling approach.

(Chalk and Smith 1983; Wang *et al.* 2008). A preliminary estimate by the Department of Environment and Science in the State of Queensland (the major region of sugar production in Australia) indicates that approximately 5% of cane is grown on ASS. A separate (relatively high) EF exceeding 10% may be required for estimating N_2O emissions from sugar cane production on ASS.

We analysed each of the industry-based datasets to determine if linear or non-linear (i.e. exponential) models for EFs could be developed to relate N_2O emissions to N fertiliser application rate (as per Shcherbak *et al.* 2014). Emission factors with a significant linear response to N rate were identified in the horticulture industry (Fig. 3), irrigated cropping (Fig. 4) and the high rainfall (>600 mm MAR) non-irrigated cropping systems (Fig. 5). The latter is geographically analogous to the grains region of eastern Australia. For each additional 50 kg N ha^{-1} of N fertiliser, EFs increased by 0.13%, 0.31% and 0.38% for horticulture, irrigated cropping and high rainfall non-irrigated cropping categories, respectively. The industries with the highest degree of statistical confidence for an exponential response in EF to N rate were cotton and to a lesser extent irrigated cropping. A two-component EF model (with both linear and exponential components) has been developed and published for cotton (Grace *et al.* 2016).

Enhanced efficiency fertilisers

A total of 108 EEF observations were identified, with six discarded as anomalies (Table 2). The average EF across all production systems, N sources and EEFs was 0.20% ($n = 102$) with 60 observations returning an EF < 0.15% (Table 3). Nearly one-half of all EEF studies (n = 46) applied 3,4 dimethylpyrazole-phosphate (DMPP) (EF = 0.20%), with the non-irrigated cropping (n = 20) and horticulture (n = 13) categories both returning an average EF of 0.15%. Pairwise comparisons of DMPP and urea applications returned significant reductions in the EF of non-irrigated cropping systems (n = 17) of 80% ($P < 0.01$), 55% ($P < 0.05$) in horticulture ($n = 9$) and 84% ($P < 0.05$) in irrigated cropping ($n = 4$). The efficacy of DMPP to reduce N_2O emissions in Australian

Table 2. Total number of observations and average nitrogen fertiliser, urine and dung application rates (kg N ha^{-1}) (in parentheses) used to determine nitrous oxide emission factors of enhanced efficiency fertilisers (EEF) for major agricultural production systems of Australia based on a meta-analysis of 102 field studies (2003–2021).

Production system	EEF[A]						
	DMPP	NBPT	3MP + TZ	Nitrapyrin	DCD	PCU	Alzon
Non-irrigated crop	20 (95)	4 (85)	–	1 (170)	–	2 (130)	–
Irrigated crop	4 (130)	–	–	–	–	–	–
Irrigated pasture	2 (323)	1 (485)	–	–	2 (1000)[B]		–
Non-irrigated pasture (fert.)	5 (188)	6 (197)	–	–	3 (180)	1 (250)	–
Cotton	–	–	–	–	–	–	–
Sugar cane	2 (115)	–	–	–	–	1 (80)	–
Horticulture	13 (276)	–	3 (490)	–	2 (123)	–	1 (125)
Non-irrigated pasture (urine)	–	–	–	9 (844)	11 (963)		–
Non-irrigated pasture (dung)	–	–	–	9 (360)	–		–
Total	46 (174)	11 (182)	3 (490)	19 (589)	18 (739)	4 (148)	1 (125)

[A]DMPP, 3,4 dimethylpyrazole-phosphate; NBPT, N-(n-Butyl) thiophosphoric triamide; 3MP + TZ, 3-methylpyrazole 1,2,4-triazole; Nitrapyrin, 2-chloro-6 (trichloromethyl) pyridine; DCD, dicyandiamide; PCU, polymer-coated urea; Alzon, 2-cyanoguanidine and 1,2,4-triazole.
[B]Bovine urine.

Table 3. Nitrous oxide emission factors (%) (mean and standard error (s.e.) in parentheses) of enhanced efficiency fertilisers (EEF) for major agricultural production systems based on a meta-analysis of 102 field experiments (2003–2021).

Production system	EEF[A]						
	DMPP	NBPT	3MP + TZ	Nitrapyrin	DCD	PCU	Alzon
Non-irrigated crop	0.15 (0.05)	0.15 (0.04)	–	0.83 (–)	–	0.34 (0.03)	–
Irrigated crop	0.11 (0.05)	–	–	–	–	–	–
Irrigated pasture	0.41 (0.29)	0.7 (–)	–	–	0.32 (0.02)[B]		–
Non-irrigated pasture (fert.)	0.12 (0.05)	0.15 (0.11)	–	–	0.12 (0.07)	0.07 (–)	–
Cotton	–	–	–	–	–	–	–
Sugar cane	1.2 (0.01)	–	–	–	–	2.8 (–)	–
Horticulture	0.15 (0.08)	–	0.18 (0.06)	–	0.16 (0.01)	–	0.16 (–)
Non-irrigated pasture (urine)	–	–	–	0.09 (0.04)	0.18 (0.04)	–	–
Non-irrigated pasture (dung)	–	–	–	0.03 (0.01)	–	–	–
Average (s.e.)	0.20 (0.05)	0.15 (0.06)	0.15 (0.05)	0.10 (0.04)	0.18 (0.03)	0.89 (0.64)	0.16 (–)

[A]DMPP, 3,4 dimethylpyrazole-phosphate; NBPT, N-(n-Butyl) thiophosphoric triamide; 3MP + TZ, 3-methylpyrazole 1,2,4-triazole; Nitrapyrin, 2-chloro-6 (trichloromethyl) pyridine; DCD, dicycandiamide; PCU, polymer-coated urea; Alzon, 2-cyanoguanidine and 1,2,4-triazole.
[B]Bovine urine.

croplands and horticulture is far higher than the EF reported by Gilsanz *et al.* (2016) who only had a total of 22 observations globally, with a high proportion in grasslands. Fan *et al.* (2022) reported the 'exceptional' performance of DMPP at lowering both N_2O and EF in their meta-analysis which included 82 DMPP observations. They attributed the efficacy of DMPP to its reduced mobility, lower water solubility, higher resistance to biodegradation and longer residence time in soil compared with other products.

The use of dicycandiamide (DCD) ($n = 14$) and 2-chloro-6 (trichloromethyl) pyridine (Nitrapyrin) ($n = 18$) was prolific in non-irrigated pastures returning EFs of 0.17% and 0.06%, respectively. Pairwise comparisons ($n = 9$) found no significant reduction in the N_2O EF when Nitrapyrin was applied with either urine or dung but a 58% reduction in the EF ($P < 0.01$) when DCD was applied with urine ($n = 11$). The latter is consistent with observations by Soares *et al.* (2023). The use of the urease inhibitor N-(n-Butyl) thiophosphoric triamide (NBPT) was reported in 11 studies with an average EF of 0.20%. Pairwise comparisons ($n = 7$) found no significant reduction in EF through the use of NBPT.

National inventory

On average, between 2014 and 2020 there was 1.4 Mt of N fertiliser applied to Australian agricultural production systems per annum (Australian Government Emissions Information System 2023). This was mainly in the form of urea which is the primary N fertiliser used in the development of EFs for determining total N_2O emissions from Australian agriculture. The most recent NGA (Department of Industry, Science, Energy and Resources 2022) includes the use of 1514 kt N

Table 4. Nitrous oxide emissions (Mt CO_2e) from synthetic nitrogen fertilisers in the 2020 National Greenhouse Accounts (3.D.A.1) of Australia compared to an assessment using revised emission factors (EF) based on a meta-analysis of 221 field observations (2003–2021).

Production system	N fertiliser[A] (kt)	NGA EF (%)[B]	N_2O emitted (t N)	N_2O emitted (kt CO_2e)[C]	Revised EF (%)	N_2O emitted (t N)	N_2O emitted (kt CO_2e)[C]
Non-irrigated crop	522	0.20	1044	489	0.41	2140	1002
Irrigated crop	24	0.85	207	97	0.7	171	80
Irrigated pasture	50	0.39	196	92	0.59	300	139
Non-irrigated pasture	764	0.21	1604	751	0.18	1375	644
Cotton	17	0.55	95	45	0.53	92	43
Sugar cane	76	1.99	1503	704	1.77	1337	626
Horticulture	61	0.85	517	242	0.64	389	182
Total	1514		5165	2419		5799	2706

[A]AGEIS activity table-1990–2020-agriculture-fertiliser (ageis.climatechange.gov.au).
[B]Current EF in 2020 National Greenhouse Accounts (NGA) Table 5.23.
[C]UNFCCC AR4 GWP (N_2O = 298).

fertiliser in agriculture in 2020, with 50% being applied in non-irrigated pasture and 34% in non-irrigated cropping systems (Table 4). Using the EFs provided in the 2020 NGA, a total of 5165 t N_2O-N was estimated to be directly emitted from N synthetic fertilisers in that year. This is equivalent to 2419 kt CO_2e using a Global Warming Potential of 298 for N_2O as stated in the 2020 NGA. Invoking the revised EFs and using 2020 N fertiliser data would result in 2716 kt CO_2e being emitted, a 12% higher estimate in national N_2O emissions from N fertilisers applied in the agricultural sector. The main contributor to this increase in N_2O emissions using revised EFs was non-irrigated cropping systems with an additional 513 kt CO_2e. Effectively, a doubling of N_2O emissions from synthetic fertilisers compared to the EFs used in the official 2020 NGA. Nitrous oxide emissions from irrigated pastures would also increase by 51% or 47 kt CO_2e. Significant reductions in N_2O emissions were evident in the non-irrigated pasture category (107 kt CO_2e), sugar cane (78 kt CO_2e), horticulture (60 kt CO_2e) and irrigated cropping (26 kt CO_2e). Hypothetically, complete adoption of DMPP across the entire non-irrigated cropping (grains) sector of Australia, would potentially result in a saving of 802 kt CO_2e based on an 80% reduction in the revised EF of the non-irrigated cropping EF using the total N fertiliser applied as outlined in the NGA for 2020.

Conclusions

The majority of the revised EFs are not consistent with the 2019 IPCC Refinement for N_2O Emissions from Managed Soils, the current NGA and global meta-analyses, which is further evidence that in developing national greenhouse gas inventories, country-specific data must be paramount. The derivation of a single weighted average EF for non-irrigated cropping should potentially be discontinued and replaced by geographically-defined EFs. Reductions in EFs have been identified in irrigated cropping and horticulture, but these changes do not offset the national increase in N_2O emissions primarily from non-irrigated cropping and irrigated pastures. Separate EFs for irrigated and rainfed sugar cane, as well as cane on ASS should be considered, but may require additional observations for validation. There is no useable data for estimating N_2O emissions from crop residue decomposition in Australia and there is every indication that the recommended IPCC default (aggregated and disaggregated) EFs are too high for Australia and overestimating N_2O emissions from that source. Overcoming this specific deficiency in N_2O emissions data from agriculture should be a research priority considering that crop residues are 36% of the official national account of direct N_2O emissions from Australia's agricultural soils. Enhanced efficiency fertilisers such as DMPP and DCD provide significant opportunities for reducing N_2O emissions from cropping and horticultural systems and confirm international observations of their efficacy. Using EEFs does come at an increased cost to agricultural producers both financially, and in some cases, the health of the broader community if you consider application of DCD in New Zealand (Ray *et al.* 2023). Rose *et al.* (2018) argue that the agronomic efficiency of inhibitors is underestimated and reductions in the application rates (and therefore cost) as well as N_2O emissions can be realised without negatively impacting agricultural production. To increase the adoption of EEFs in the agricultural market place at scale, fertiliser companies could be incentivised through the carbon credit market to produce EEFs at a reduced cost.

Supplementary material

Supplementary material is available online.

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