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Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis

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ABSTRACT

Agricultural soils receiving synthetic fertilizers and organic amendments containing nitrogen contribute a large part to anthropogenic nitrous oxide (N_2O) emissions. As a source of nitrate that undergoes reduction to N_2O, organic amendments also change soil C availability and redox potential, which influences the N_2O emission factor (EF) of organically-amended soils. The objective of this study was to conduct a meta-analysis of N_2O EF from agricultural soils receiving organic amendments. A global survey of peer-reviewed literature resulted in the selection of 38 studies including 422 observations at 43 sites in 12 countries. The analysis yielded a global EF for all organic sources, EForg, equal to 0.57 ± 0.30%, which is lower than the IPCC default EF of 1 for synthetic fertilizers. Three groups of organic amendments with similar EFs were identified: the high-risk group including animal slurries, waste waters and biosolids (1.21 ± 0.14%); the medium-risk group including solid manure, composts + fertilizers, and crop residues + fertilizers (0.35 ± 0.13%); and the low-risk group including composts, crop residues, paper mill sludge and pellets (0.02 ± 0.13%). The EF was higher when soils received organic amendments in combination with synthetic fertilizers, such as liquid manures + fertilizers (2.14 ± 0.53%), composts + fertilizers (0.37 ± 0.24%), and crop residues + fertilizers (0.59 ± 0.27%). The EF was modulated by amendment (C/N ratio), soil (texture, drainage, organic C and N) and climatic (precipitation) factors. For example, EFs were on average 2.8 times greater in fine-textured than coarse-textured soils. We recommend site-specific EFs that consider organic amendment chemistry, soil characteristics, climate conditions and whether the organic amendment is applied alone or in combination with synthetic fertilizers.

1. Introduction

Nitrous oxide (N_2O) is an important greenhouse gas, with 298 times the global warming potential of carbon dioxide (CO_2) (Foster et al., 2007). Nitrous oxide emissions are also a major source of ozone-depleting nitrogen oxides (NO and NO_2) in the stratosphere (Ravishankara et al., 2009). Agricultural sources of N_2O make a prominent contribution to the global budget. For example, Syakila and Kroeze (2011) estimated agricultural emissions owing to N fertilizer use and manure management (4.3–5.8 Tg N_2O–N yr^{-1}) represented 23–31% of all global N_2O sources (19 Tg N $year^{-1}$ in 2006). Human population growth and increasing global prosperity demands greater N fertilizer inputs to sustain the global food supply, and also generates more N-rich organic waste that is returned to agricultural soils as organic amendments (OAs). As a result, the N_2O emissions from agricultural soils are predicted to increase in the future, which is cause for concern.

Most N_2O emissions from agricultural soils are the result of nitrification and denitrification of mineral N following application of synthetic fertilizers and OAs. In Canada, 34% of direct soil N_2O emissions are attributed to OAs such as animal manure and crop residues (Rochette et al., 2008). OAs have multiple roles in the microbially-mediated reactions leading to N_2O production, resulting in positive or negative effects. Mineralization of organic N contained in OAs releases ammonium (NH_4^+), with subsequent nitrification (NO_3^-) processes leading to N_2O production. As an organic C substrate for microbial growth, OAs may also stimulate

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microbial N assimilation, which can increase competition for NH_4^+ between heterotrophic microorganisms and autotrophic nitrifiers (Chen et al., 2013), resulting in temporary reduction of N_2O production. In soils with high N availability but low organic C, OAs may stimulate nitrifier denitrification, the oxidation of ammonia to nitrite (NO_2^-) and its subsequent reduction to NO and N_2O by autotrophic ammonia oxidizing microorganisms under low O_2 availability (Butterbach-Bahl et al., 2013). Under anaerobic conditions, organic C provided by OAs enhances denitrification and N_2O production. The ratio of N_2O to N_2 produced during denitrification increases with increasing soil NO_3^- availability, which is influenced by the microbial consumption and production of NO_3^- due to C and N substrate availability in OA-amended soils (Terry and Tate, 1980; Weier et al., 1993; Miller et al., 2008). Finally, OAs such as animal slurries modulate O_2 availability in soil microsites because the labile C input enhances soil respiration; as slurries are mostly water (up to 97% moisture content), their addition saturates soil micropores in the short-term. Given the multiple ways that OAs impact the activity of microorganisms involved in N_2O production, their influence on soil N_2O emissions cannot be predicted from simple measures such as the total N application rate, which is a reasonably good estimator of the EF from synthetic fertilizers (Kim and Dale, 2008).

Although simplified EF values are used in calculating the contribution of agricultural soils to national N_2O inventories following the Tier 1 methodology of the Intergovernmental Panel on Climate Change (IPCC EF_1), they can result in erroneous conclusions. There are four major weaknesses associated with simplified EF_1 values: (1) they assume a linear relationship between total N input and N_2O emissions, not considering that biological thresholds for N_2O emissions might exist (Kim et al., 2013; Shcherbak et al., 2014); (2) the large range of uncertainty that varies from 0.3% to 3%; (3) the dataset used to generate the EF_1 is biased towards mid-latitude and temperate regions (Bouwman et al., 2002a); and (4) the simplified EF_1 values do not account for differences between N inputs from synthetic fertilizer and organic amendments on N_2O emission across soil types, agronomic systems and environmental conditions (Buckingham et al., 2014; Rochette et al., 2008). As signatory countries to the United Nations Framework Convention on Climate Change move to define region- and site-specific EF values (Tier 2 and Tier 3 methodologies) for calculating the N_2O emissions from their agricultural soils, the lack of quantitative information on how OAs contribute to N_2O emissions emerges as a research gap of global significance.

Soil N_2O emissions from agricultural soils receiving OAs can be summarized at global and regional scales using systematic reviews (Bouwman et al., 2002a; Novoa and Tejeda, 2006; Aguilera et al., 2013; Buckingham et al., 2014) or meta-analyses techniques (Liu and Powers, 2012; Chen et al., 2013; Shan and Yan, 2013; Bouwman et al., 2002b). Manure-amended soils had a mean global N_2O EF of 0.8%, i.e. 20% lower than the default IPCC EF_1, with an uncertainty range of −40% to +70% in the N_2O emissions, using Residual Maximum Likelihood (REML)-based models and 846 N_2O cumulative emissions measurements (Bouwman et al., 2002b). In the United-Kingdom, the DNDC mechanistic model generated an EF for manure ranging from +0.01 to +1.53% with an average of $0.43 \pm 0.34\%$ (standard deviation) (Cardenas et al., 2013). A meta-analysis of N_2O emissions from OAs in soils of the Mediterranean region presented an average EF of $0.97 \pm 1.17\%$ for solid OAs (e.g., crop residues, manure, composted municipal solid waste, composted cattle and sheep manure, and composted solid fraction of digested pig slurries), and an average EF of $1.75 \pm 1.34\%$ for liquid manure (Aguilera et al., 2013). Still, another meta-analysis suggested that the EF for pig slurry was similar to EF_1 (Liu and Powers, 2012). Decomposing crop residues generate N_2O emissions, and a global EF of 1.055% was calculated using a simple linear regression of soil N_2O emitted on residue-N applied ($kg\,ha^{-1}$) (Novoa and Tejeda, 2006). However, sensitivity analysis revealed that removing the two highest observations would decrease the EF to 0.6%, indicating the uncertainty of the estimate. A global meta-analysis by Chen et al. (2013) also concluded that crop residues produced comparable or greater N_2O emissions than synthetic fertilizer, whereas Shan and Yan (2013) reported that crop residue addition with synthetic fertilizer inhibited N_2O emissions by 11.7% compared to synthetic fertilizers alone. The variability in EF of agricultural soils receiving OAs warrants more investigation to determine how key factors, such as the OA type and its properties, soil and climate conditions, modulate the EF responsible for soil N_2O emissions.

The aim of this study was to provide a comprehensive and quantitative analysis of a dataset containing 422 EFs reported in 38 studies that measured soil N_2O emissions after OA addition in perennial and annual cropping systems. The analysis was done using (1) a systematic review and (2) a REML model. These two approaches allowed us to compare EF for OAs and OAs combined with synthetic fertilizers, to categorize the global EF according to OA types and properties, and to determine how the global EF for OAs was influenced by environmental and management-related factors.

2. Material and methods

2.1. Global database

The systematic review summarises the results of publications relevant to the objectives, while minimizing publication bias (i.e., bias towards particular publication journals, authors or study type) as much as possible by following six main steps: (1) determination of search terms, (2) conducting searches and obtaining literature, (3) development of screening criteria, (4) extraction and data assimilation protocol, (5) quality assurance and (6) post extraction data summary and analysis (Buckingham et al., 2014).

A detailed review of literature was carried out until June 13, 2014 with Scopus (1960–2014) and *CAB Abstracts* (1910–2014) research databases using the key words listed in Tables S1 combined with Boolean Operators. It retrieved 1064 papers published in peer-reviewed journals (Fig. S1). The following inclusion criteria were applied to screen studies in a standardized manner; which resulted in the retention of 38 studies:

- N_2O fluxes were measured from agricultural soils for at least 30 d (modelling outputs excluded, grazing pasture and paddy soils excluded).
- Unamended soils that received no fertilizer/amendment addition were used as control.
- Soils were amended with organic by-products with or without synthetic fertilizers.
- Information on chemical properties of amendments and application rates was available to estimate the relative contribution of the applied materials (e.g., total N input) to cumulative N_2O fluxes.

We retained field experiment data only and excluded experiments done under controlled conditions such as disturbed soil and undisturbed soil column incubations. Studies without spatial replication or no replicates reported were excluded from the analysis. Three studies against the selected 38 used micrometeorological instrumentation (Sharpe and Harper, 1997, 2002; Merbold et al., 2014) and were excluded because not in a relatively large number to adequately sub-group the meta-analysis considering methodological aspects in N_2O measurements (Borenstein et al., 2009). Using these criteria, the selected 38 studies reported

537 observations from closed chamber experiments that were used to create the metafile with 422 observations from amended plots and 115 observations from control plots.

For each observation from amended plots, cumulative N_2O emissions were entered into the database and EF were calculated as another response variable following Eq. (1):

$$EF = \frac{\boldsymbol{N_2O - N_{fertilized} - N_2O - N_{unfertilized}}}{\boldsymbol{N_{input_{fertilized}} - N_{input_{unfertilized}}}} \quad (1)$$

Where $N_2O - N_{fertilized} - N_2O - N_{unfertilized}$ is the difference between cumulative N_2O emissions from the fertilized plot and the unfertilized control plot and $N_{input_{fertilized}}$ is the total amount of N applied in the fertilized plot, and $N_{input_{unfertilized}}$ is zero. Where cumulative N_2O emissions were not reported, the value was estimated by linear integration of the average daily fluxes over the measurement period. Graphical data (means and variation estimates) were digitized using the Datathief III software (v. 1.5).

Standard deviations (*SD*) of EF were rarely provided and variance of EF (V_{EF}) V_{EF} :V_{EF} : variance of EF V_{EF} :V_{EF} : variance of EF (V_{EF}) was calculated from *SD* of cumulative N_2O fluxes and number of replicates (n) following Eq. (2):

$$\boldsymbol{V}_{EF} = \left(100/\boldsymbol{N}_{input_{fertilized}}\right)^2 \times \left(\boldsymbol{SD_f}^2/\boldsymbol{n_f} + \boldsymbol{SD_c}^2/\boldsymbol{n_c}\right) \quad (2)$$

Where SD_f and SD_c are the standard deviations of cumulative N_2O emissions from the fertilized and the control plots, respectively, and n_f and n_c are the number of replicates of the fertilized and control plots, respectively. Missing values of EF variance (25% of the datasets) were not approximated, as they were not at random and imputation techniques may lead to underestimation of the effect (Uijl et al., 2012).

Selected explanatory variables (Table S2) were included in the database to explain the variation in N_2O emissions due to amendment additions. Studies were grouped according to their cropping system (grassland *vs.* cropland). Methodological aspects (e.g., study duration, sampling events, number and surface of closed chambers) and results from the variance analysis (e.g., number of replicates, variability estimate and degree of freedom) were used to identify the weighting procedure appropriate for the meta-analysis of global N_2O EF with more weight given to study with more precise EF estimates. Those steps produced a robust dataset with minimal bias that was suitable to evaluate the response of EF to OAs and other relevant factors with a systematic review and a quantitative approach using a REML model.

2.2. Systematic review

First, the OA effects on cumulative fluxes of N_2O and EF were studied using a general matrix containing results from the 38 selected studies (Table S3). The box plot representation was selected for raw data illustration because this non-parametric tool does not require any assumptions of the underlying statistical distribution. Box plots graphically appraised the degree of dispersion and skewness in the data, and showed outliers of cumulative N_2O flux and EF in a transparent manner, through their quartiles. Fertilizer type was grouped (Table S2) into: (i) organic (O), (ii) organic combined with synthetic (OS), and (iii) synthetic (S), hereafter referred to as “FertiType”. The FertiType S does not exhaustively represent global soil N_2O emissions following synthetic fertilizer application since the observations came from studies where soil N_2O emissions were measured on sites where OAs and synthetic fertilizer effects were jointly assessed. Then, FertiType was sub-divided in categories, “FertiClass”, according to the nature of amendments (Table 1).

Table 1
Global estimates of N_2O emission factors (*N_2O EF*) according to fertilization type.

Fertilization			Acronyms	Descriptive parameters				N_2O EF, (% N applied)							
				Representativeness			N rate	Raw Data		REML[a]					
				total #			(kg N/ha)			Unweighted[b]			Weighted[c]		
				Obs.	Site	Study	median	mean	median	mean	sem	$Pr > \|t\|$[d]	mean	sem	$Pr > \|t\|$[d]
FertiTypeS	Organic sources		**O**	**251**	**41**	**35**	**154**	**0.82**	**0.42**	**0.84 a**	**0.22**	*<0.001*	**0.57 b**	**0.30**	*<0.001*
	Organic and synthetic sources		**OS**	**72**	**13**	**13**	**150**	**1.50**	**0.87**	**1.30 a**	**0.3**	*<0.001*	**1.15 ab**	**0.31**	*ns*
	Synthetic sources		**S**	**99**	**32**	**26**	**130**	**1.34**	**0.57**	**1.30 a**	**0.29**	*<0.001*	**1.76 a**	**0.42**	*<0.001*
FertiClasses		All high-risk						1.20	0.67	1.13 A	0.21	*<0.001*	**1.21 A**	**0.13**	*<0.001*
	High risk	Liquid manure + S	LM-S	31	5	6	130	2.44	1.72	1.81 a	0.48	*<0.001*	2.14 a	0.53	*<0.001*
		Biosolid, CR + S	BSD-CR-S	6	1	1	131	1.64	1.54						
		Biosolid + S	BSD-S	6	4	4	145	1.16	0.88	0.39 bcd	0.55	*ns*	0.89 abcd	0.45	*<0.05*
		Waste water	WW	8	2	2	161	1.15	0.45						
		Liquid manure	LM	149	24	20	148	0.96	0.56	1.11 ab	0.23	*<0.001*	1.12 ab	0.18	*<0.001*
		Biogas residues	BR	10	2	1	360	0.92	0.49						
		Solid manure + S	SM-S	3	2	2	240	0.78	0.85						
	Medium risk	All medium-risk						**0.75**	**0.43**	**0.74 A**	**0.21**	*<0.001*	**0.35 B**	**0.13**	*<0.01*
		Solid manure	SM	29	13	11	170	0.97	0.24	1.01 abc	0.28	*<0.001*	0.35 c	0.18	*<0.05*
		Compost + S	CMPT-S	14	4	5	150	0.54	0.45	0.52 cd	0.26	*<0.05*	0.37 cd	0.24	*ns*
		Crop residues + S	CR-S	12	3	3	210	0.46	0.33	0.66 cd	0.30	*<0.05*	0.59 bc	0.27	*<0.05*
	Low risk	All low-risk						**0.23**	**0.14**	**0.33 B**	**0.21**	*ns*	**0.02 C**	0.13	*ns*
		Paper mill sludge + CR	PMS-CR	6	1	1	231	0.28	0.13						
		Compost	CMPT	29	8	8	200	0.27	0.17	0.43 d	0.24	*ns*	0.00 *d*	0.17	*ns*
		Pellets	PLTS	5	1	1	508	0.25	0.24						
		Crop residues	CR	8	3	3	83	0.19	0.08						
		Liquid manure + CR	LM-CR	1	1	1	178	0.07	0.07						
		Paper mill sludge	PMS	6	1	1	519	0.03	0.01						

Means sharing a small bold letter are not significantly different within FertiTypes by a LSD test ($P < 0.05$). Means sharing a small letter are not significantly different within FertiClasses by a LSD test ($P < 0.05$). Means sharing a capital letter are not significantly different within low-, medium-, and high-risk Ferticlasses by a LSD test ($P < 0.05$).
[a] REML,Residual Maximum likelihood model.
[b] Unweighted procedure: an equal weight for each EF reported in the dataset.
[c] Weighted procedure with the N_2O coverage factor (Table S2).
[d] $Pr > |t|$ refers to at test to test the null hypothesis that the associated population quantity equals zero.

Because OAs applied to agricultural soils depend upon national, regional and local factors (type and scale of farming systems, farm storage facilities and equipment, livestock production with manure availability, availability of non-manure-based amendments (Thangarajan et al., 2013), the database was expanded to include explanatory variables that might influence the EFs for soil N_2O such as climate, soil properties and cropping systems with their common management practices (Table S2). Soil texture classes were fine-, medium- and coarse-textured soils (Shirazi and Boersma, 1984; CRAAQ, 2010) criteria. The modulation of soil N_2O emissions by EFs at FertiType and FertiClass levels could then be evaluated while considering the variation induced by environmental and management-related factors when sufficient data were available.

2.3. The residual maximum likelihood (REML) approach

Meta-analysis was performed with the Residual Maximum Likelihood (REML) approach which is appropriate for analysis of global meta-data related to soil N_2O emissions and EFs (Bouwman et al., 2002b). The REML approach has four main advantages: (1) it provides efficient estimates of treatment effects in unbalanced designs; (2) the interdependency of EFs obtained from the same study is taken into account; (3) all observations of the database are included in the analysis, (4) different weighting schemes can be tested.

In this study EF was selected as response variable following Eq. (1). A linear mixed-effects model was performed using the "Proc Mixed" procedure of the SAS software, version 9.2 (SAS Institute, Cary, NC, USA). The fertilizer type variable (FertiClass) was the fixed-effect component of the model. The unique study and site identifiers (IDstudy, IDsite), as well as FertiClass or FertiType, appeared in the random-effect component to account for the dependency of several effect sizes reported in the same study (Bouwman et al., 2002b; Sauvant et al., 2008). Once model parameters were estimated, the homogeneity of variance and normality of the residuals were analyzed graphically. Normality tests (Shapiro-Wilk and Kolmogorov-Smirnov) were also performed. No power transformation using Box Cox transformation improved data distribution, yet heterogeneity was corrected by controlling the covariance structure (compound symmetry or heterogeneous compound symmetry) imposed upon the residuals or errors using the REPEATED statement. In particular, the GROUP = optional statement permitted different categories of fertilization effect to have different structure parameters with the smallest value of the Akaike Information Criteria being considered as the best model. Statistical results were considered to be significant at the 0.05 α level. Statistical significance of selected explanatory factors was tested separately, as datasets were not complete for every explanatory factor.

Weighting based on variance could bias the analysis towards situations with low N_2O emissions because V_{EF} tends to scale with EF and variability scaled with cumulative N_2O emissions (Fig. S2). Moreover, the REML procedure using the inverse of variance in weighting procedure provided identical EF estimates to those obtained with a fixed-effect meta-analysis model (no between-study variance) (data not shown), which is not recommended by Borenstein et al. (2009) for biological and environmental studies such as EF from agricultural soils receiving OAs and other fertilizers. Therefore, we used the REML weighted procedure to account for the spatiotemporal coverage of N_2O emissions (number of sampling days, "SamplingEvent", and total surface of gaseous measurements, "GasSurface" as a product of the total number of chambers and the chamber surface). Indeed, cumulative N_2O emissions are disproportionately influenced by a few 'hot events' during the growing season. Molodovskaya et al. (2012) demonstrated that up to 51% of cumulative annual N_2O emissions are caused by short-term events (rainfall) that promote high sporadic pulses of N_2O with large variance (<7% of the total observation time). Even automated measurement approaches, which provide better temporal coverage than periodic sampling, are susceptible to i) underestimate N_2O emissions because integration of point-in-time observations missed a number of transient high-flux events (Scott et al., 1999), and ii) overestimate N_2O emissions because they neglect temperature-dependent diurnal variations (Yao et al., 2009) when integrating transient high-flux events. Given the high spatiotemporal variability in soil N_2O emissions, assigning more weight to studies with larger spatiotemporal coverage of N_2O emissions favors more accurate estimates of N_2O EF. Moreover, 100% of the studies reported the methodological aspects of N_2O measurements, which maximizes the statistical power of the model that includes the entire dataset. We compare three weighting schemes:

- the unweighted procedure (equal weight for each observation) according to Bouwman et al. (2002b);
- the new weighted procedure using the N_2O coverage weight (N_2O_{cov}Weight) for each observation *i*, according to Eq. (3), as follows;

$$N_2O_{cov}Weight_i = Sampling\ Event_i \times Gas\ Surface_i \quad (3)$$

- a revised-N_2O coverage weighting procedure that tests the influence of superior weight studies defined as studies whose weight of N_2O observations was twice greater than the average weight of all N_2O observations (0.24%), according to Eq. (4);

$$revised-Weight_i = N_2O_{cov}Weight_{max} \times [1 + (N_2O_{cov}Weight_i/N_2O_{cov}Weight_{max})/1000] \quad (4)$$

Where $N_2O_{cov}Weight_{max}$ is equal to 885600, the maximum weight of a non-superior weight study in the dataset.

All weighting schemes were automatically rescaled so that their sums equaled 1 ($\sum_i Weight_i = 1$), resulting in expressions of dispersion in the same scale as the original data (Fig. S3).

3. Results and discussion

3.1. Systematic review

3.1.1. Database

The selected studies (n = 38) provided N_2O measurements from 43 sites located in 12 countries (Table S3). Europe contributed 48% (n = 201) of the 422 observations, North America 32% (n = 137), Asia 13% (n = 55), South America 6% (n = 24), and Australia 1%, (n = 5). In Europe, more than 70% of reported EFs came from agricultural soils receiving OA application only, hereafter referred to as FertiType O. A similar trend was observed in North America (62%) but not in Asia and South America where FertiType O measurements represented 18% and 33%, respectively, of the total EFs. In Australia, four out of five of the EFs were for FertiType O and no observations were available for FertiType OS. Germany, Brazil and United-Kingdom provided 100% of N_2O EF for biogas residue (BR), biosolids applied with crop residues and S (BSD-CR-S), and paper mill sludge combined or not with S (PMS $\pm$ S), respectively. While more than 90% of the N_2O EF for liquid manure (LM) came from studies in Europe and North America, 92% of the N_2O EF for crop residues alone was determined in China. This is evidence of the interdependency between types of fertilization and geographical areas providing N_2O EF, which may create bias in the interpretation of results, as discussed later.

Our dataset is particularly strong in reporting EF for OAs, with 60% of the EF reported for FertiType O (n = 251), 17% for FertiType OS (n = 72), and 23% for FertiType S (n = 99) (Table 1). This is five times more information on OAs since the last global meta-analysis conducted by Bouwman et al. (2002b) that reported 45 and 25 EFs in FertiTypes O and OS, respectively. More observations permit us to detail the EFs by "FertiClasses", listed in Table 1. The LM FertiClass represented 35% of all EFs, about five times more than solid manures (SM) or composts (CMPT) and two-fold more than the FertiClass OS. The dominant OAs were LM in 53% of studies, SM in 29% of studies and CMPT in 21% of studies. A smaller proportion of studies concerned the use of LM-S (16%) and CMP-S (13%), BSD-S (10%), crop residues (CR) (8%) and of remaining amendments (≤5%). Proposing a global EF for FertiType O from the current database would be biased towards EFs from the N-rich, wet LM and barely consider EFs from moderately decomposed, drier CMPT and Pellets.

Most observations (n = 393) in the database came from regions with a temperate climate, so present a similar bias towards temperate climates as Bouwman et al. (2002a). While 67% (n = 198) of the EFs from FertiType O were derived from studies in cool and moist conditions, the EFs from FertiType OS were studied under warm and dry conditions (n = 31) with all EFs from LM addition alone occurring in a cool temperate moist climate (n = 23). Therefore, the impact of FertiType is partly confounded with that of climate.

3.1.2. Emission factors

Global EF averaged 0.82% for the FertiType O, 1.50% for FertiType OS and 1.34% for FertiType S (Table 1). FertiType medians were roughly two times lower than means, indicating the presence of outlier observations in a positive skew distribution of EF (Fig. 1). Global EFs ranged from −0.99 to 12.80% of N applied (Fig. 1), and both extreme values were measured following the application of ammonium nitrate (Ball et al., 2004; Dittert et al., 2005). Similarly, Bouwman et al. (2002b) reported minimum and maximum EF values of −1.71% and 14.7% following the application of synthetic N fertilizers.

Risk grouping of Ferticlasses generated three groups identified in Table 1 as follows: the high-risk group with EF around 1.20%, the medium-risk group with EF around 0.75%, and a low-risk with EF around 0.23%. The high-risk group included reactive OAs with higher water content (dry matter equal to 5%), C:N ratio lower than 5, and higher mineral N content (10% d.w. basis), whereas the medium- and low-risk groups included more stabilized products with higher C:N ratio (average of 28 and 18, respectively) and higher dry matter content (average of 51 and 47%, respectively). Boxplot analyses suggest EF_1 should be revised according to the type (organic, synthetic, both) and the nature of fertilization. Distribution of the EF population among percentile categories at the FertiType and FertiClass levels led to visualization and identification of FertiClasses that to deviate from the central tendency with regards to N_2O EFs (Fig. 1).

In the FertiType O group, 74% of the reported EF estimates (n = 251) were smaller than 1%, the IPCC EF_1 value. LM represented more than 70% of the EFs superior to the 90th percentile of the FertiType O (2.27% of N applied), but less than 30% were inferior to the 10th percentile (0.04% of N applied). Conversely, more-stabilized amendments such as CMPT, CR, and PMS ± CR did not promote any EF superior to the 90th percentile but yielded more than 58% of the EF inferior to the 10th percentile of the FertiType O.

In FertiType OS, approximately half of the observations were below EF_1. At the FertiClass level, 80% of the observations from agricultural soils amended with CMPT and CR combined with fertilizers had global EFs lower than EF_1. In contrast, 68% of the observations from agricultural soils receiving LM-S had global EFs greater than EF_1 (data not shown). In FertiType OS, the combined application of OA and synthetic N fertilizer increased the EF quartiles by 2.2-fold. Based on the nine studies that simultaneously compared both FertiTypes O and OS (since there were an unequal number of studies from fine-textured (53%) and coarse-textured

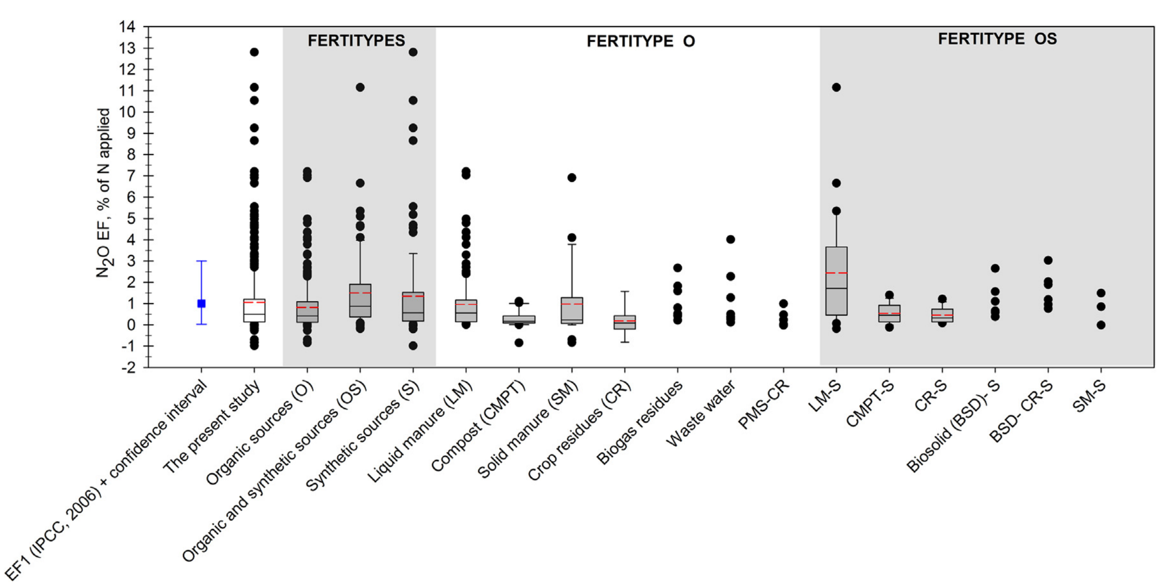

Fig. 1. Global estimates of N_2O emission factors according to the type of fertilization. Vertical point plots were used for the graphical presentation of data when ten observations or less were reported in a category of fertilization. Box plots were represented when the number of observations per category of fertilization exceeded ten. The boundary of the box closest to zero (Y axis) indicates the 25th percentile and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. The solid line within the box marks the median and the dashed red line marks the mean. Outlying points are represented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(27%) soils), it was found that the combined application of OA and synthetic N fertilizers increased the EF quartiles by a factor of 1.8.

3.2. Meta-analysis

3.2.1. Comparison of the unweighted REML with the weighted REML approach

The REML model confirmed the significant impact of fertilization sources on global N_2O emissions (Table 2). At the FertiType level, EF estimates of the unweighted REML were closed to raw means and no significant differences were detected between FertiTypes (Table 1). Conversely, EF estimates of the weighted REML ranged between the mean and the median of raw data (Table 1) and the FertiType O (0.57%) was significantly lower than FertiTypes S (1.76%). Interestingly, synthetic sources were attributed an estimate 1.3 times greater than the raw mean with the new N_2O coverage weighted procedure of the REML. Even if FertiType S does not exhaustively represent global N_2O EF following fertilizer application, this weighted REML procedure strongly indicated higher EF were measured after synthetic fertilizer application in studies with better spatiotemporal coverage of soil N_2O emissions.

3.2.2. In-depth testing of the N_2O coverage REML-weighted function

Three superior weight studies were identified in the N_2O coverage weighted REML and reported measurements from the highest surfaces reported in the selected literature (i.e., between 1 and 1.5 m square of total monitored surface per treatment). Two studies used automated closed chamber system. Thornton et al. (1998) roughly accounted for 20.6% of the entire database (sum of all weights equal to 100%) with a reported EF of 0.73% following application of 336 kg N/ha of urea on a silty clay loam (Fig. S3). Ball et al. (2004) was attributed on average 4.83 times more weight than other studies, including two outliers (12.80% and −0.18% of N applied) of equal weight (around 1.7%) measured after application of 120 N kg/ha of NH_4NO_3 on a clay loam (Fig. S3). In Parnaudeau et al. (2009) study, eight chambers were installed on two replicates of each treatment allowing 2.3 times more weight than average for waste water EFs.

Sensitivity analyses were conducted to test the robustness of the weighted REML procedure and the potential gains of the N_2O coverage weighted function (Table 3). In absence of superior weight studies (31 observations deleted), the global EF estimate for OAs still fall within the range of those proposed by Bouwman et al. (2002b) with a 24.6% increase recorded that reached 0.71%. FertiType S estimate was not significantly different from the FertiType O and fell in accordance with the IPCC EF_1 reaching 1.01% (Table 3). Additional analyses conducted separately on the three superior weight studies (data not shown) concluded (1) Thornton's study leverage was strongly negative on FertiType S estimate and set down the estimate from 3.85% to 1.76%; (2) Ball's study leverage was strongly positive on FertiType S estimate and rise the estimate from 1.01 to 1.76%; (3) Parnaudeau's study leverage was strongly negative on FertiType O and set down the estimate from 0.83% to 0.57%.

In a second sensitivity analysis, we revised the N_2O coverage factor to moderate the influence of superior weight studies whose weight of N_2O observations was twice greater than the average weight of all N_2O observations. The revised N_2O coverage weighted function pointed out the EF estimate for organic sources (0.57%) was quite consistent with the N_2O coverage weighted REML procedure (0.64%) (Table 3).

Thus, the N_2O coverage weighting function of the REML procedure appeared as appropriate for proposing a global EF for OAs applied to agricultural soils. Sensitivity analyses pointed out more variability in the EF estimates for organic sources combined with synthetic sources (0.88–1.15%). Thus, the use of FertiClasses appeared as more appropriate for proposing EF estimates for organic sources jointly applied to agricultural soils with synthetic sources.

3.2.3. New insights with the N_2O coverage weighted REML procedure

Interestingly, the N_2O coverage weighted REML pointed out lower EF following CMPT, CMPT-S and SM application in studies with better spatiotemporal coverage of emissions (Table 1). CMPT and CMPT-S were respectively attributed a global EF equal to 0.00 ± 0.17% and 0.37 ± 0.24% (Table 1), that were consistent with the N_2O coverage weighted REML procedure (Table 3). At *t* test revealed addition of CMPT would not affect soil N_2O emissions ($Pr > 0.05$). Higher EF were measured following LM-S application in studies with better spatiotemporal coverage of emissions (Table 1). Sensitivity analyses pointed out the large EF estimates for LM-S was quite consistent among weighted REML procedures (1.79–2.14%).

3.3. Proposition of global EFs with the N_2O coverage weighted REML procedure

Our proposition for a global EF for OAs applied to agricultural soils are based on the N_2O coverage weighted REML. The global EF for OAs, hereafter referred to as "EF_{org}", was equal to 0.57 ± 0.30%. This is lower than the EF_{org} of 0.8% proposed by Bouwman et al. (2002b) probably because (1) our database contained five times more information on OAs, and because (2) the new N_2O coverage weighted function of the REML allowed considering the intrinsic spatio-temporal variability of N_2O emissions from agricultural soils receiving OAs. No global EF is proposed for organic sources combined with synthetic fertilizers because the dataset was biased toward LM-S application, which represented most of the OA plus synthetic fertilizer observations.

At the FertiClass level, the following EFs were estimated for OA combined with synthetic fertilizer: LM-S had an EF of 2.14% ± 0.53, CMPT-S had an EF of 0.37% ± 0.24 and CR-S had an EF of 0.59% ± 0.27. The CR-S estimate is consistent with Novoa and Tejeda (2006) whose meta-analysis involved unamended plots as control that were unfertilized or fertilized with synthetic N fertilizer. FertiRiskClasses allowed generating new EFs for under-represented FertiClasses (BSD-CR-S, WW, BR, SM-S, PMS-CR, PLTS, CR, LM-CR and PMS) that could not be included at first in the modeling process (Table 1). Considering the three FertiRiskClasses of OAs led to estimates of EFs equal to 1.21% ± 0.13 for the high-risk class, 0.35% ± 0.13 for the medium-risk class, and 0.02% ± 0.13% for

Table 2
Significance of fertilization sources on global N_2O emission factors with the unweighted and weigthed REML approaches.

	N₂OEF,(% N applied)							
	REML model[a]							
	Unweighted[b]				Weighted[c]			
	n	F	$Pr > F$	df	n	F	$Pr > F$	df
Fertilization								
FertiType	422	3.57	<0.05	376	314	14.89	<0.0001	24
FertiClass	422	2.25	<0.01	362	422	4.04	<0.0001	362
FertiRiskClass	323	8.06	<0.001	277	323	152.66	<0.0001	277

FertiType, type of fertilization: organic, synthetic fertilizers, organic and synthetic fertilizers. FertiClass, nature of organic sources ± synthetic sources (Table 1). FertiRiskClass (high, medium or low), N_2O risk grouping of FertiClasses (Table 1). n, total # of observations used in the analysis. df, degree of freedom. Differences in df are due to differences in n and to the random effect adjustment in the proc mixed procedure for the best model performance.

[a] REML, Residual Maximum likelihood model.

[b] Unweighted procedure: an equal weight for each EF reported in the dataset.

[c] Weighted procedure with the N_2O coverage factor (Table S2).

Table 3
Sensitivity analyses of the REML approach using spatial and temporal N_2O coverage information in weighing procedures.

Fertilization			Acronyms	Global estimates of N_2O emission factors, (% N applied)										
				Raw Data		REML[1]								
						N_2O coverage weight			revised N_2O coverage weight			weighted without superior weight studies*		
				mean	median	mean	sem	$Pr > \|t\|^{\chi}$	mean	sem	$Pr > \|t\|^{\chi}$	mean	sem	$Pr > \|t\|^{\chi}$
FertiTypes	Organic sources		**O**	**0.82**	**0.42**	**0.57 b**	**0.30**	*<0.001*	**0.64 a**	**0.15**	*<0.001*	**0.71 A**	**0.17**	*<0.001*
	Organic and synthetic sources		**OS**	**1.50**	**0.87**	**1.15 ab**	**0.31**	*ns*	**0.88 a**	**0.19**	*<0.001*	**1.16 A**	**0.26**	*<0.001*
	Synthetic sources		**S**	**1.34**	**0.57**	**1.76 a**	**0.42**	*<0.001*	**1.62 a**	**0.32**	*<0.001*	**1.01 A**	**0.22**	*<0.001*
FertiClasses	High risk	All high-risk				**1.21 A**	**0.13**	*<0.001*	**1.86 A**	**0.37**	*<0.001*	**1.79 A**	**0.37**	*<0.001*
		Liquid manure + S	LM-S	2.44	2.14 a	2.14 a	0.53	*<0.001*	1.79 a	0.31	*<0.001*	1.84 a	0.50	*<0.001*
		Biosolid, CR + S	BSD-CR-S	1.64										
		Biosolid + S	BSD-S	1.16	0.89 abcd	0.89 abcd	0.45	<0.05	1.00 abcd	0.56	*ns*	0.73 ab	0.44	ns
		Waste water	WW	1.15										
		Liquid manure	LM	0.96	1.12 ab	1.12 ab	0.18	<0.001	0.95 b	0.16	*<0.0001*	0.93 ab	0.18	<0.0001
		Biogas residues	BR	0.92										
		Solid manure + S	SM-S	0.78										
	Medium risk	All medium-risk			**0.35 B**	**0.35 B**	**0.13**	*<0.01*	**0.95 AB**	**0.43**	*<0.05*	**1.41 AB**	**0.43**	*<0.05*
		Solid manure	SM	0.97	0.35 c	0.35 c	0.18	*<0.05*	0.69 bc	0.29	*<0.05*	0.86 ab	0.30	*<0.01*
		Compost + S	CMPT-S	0.54	0.37 cd	0.37 cd	0.24	*ns*	0.25 cd	0.33	*ns*	0.39 b	0.39	*ns*
		Crop residues + S	CR-S	0.46	0.59 bc	0.59 bc	0.27	*<0.05*	0.49 bcd	0.43	*ns*	0.53 b	0.39	*ns*
	Low risk	All low-risk				**0.02 C**	**0.13**	*ns*	**0.49 B**	**0.38**	*ns*	**0.97 B**	**0.65**	*ns*
		Paper mill sludge + CR	PMS-CR	0.28										
		Compost	CMPT	0.27	0.00 *d*	0.00 *d*	0.17	*ns*	−0.03 d	0.22	*ns*	0.31 b	0.41	ns
		Pellets	PLTS	0.25	0.24									
		Crop residues	CR	0.19	0.08									
		Liquid manure + CR	LM-CR	0.07	0.07									
		Paper mill sludge	PMS	0.03	0.01									

[1]Residual Maximum likelihood analysis, weighting procedure with spatial and temporal N2O coverage (Table S2). Means sharing a small bold letter are not significantly different within FertiTypes by a LSD test ($P < 0.05$). Means sharing a small letter are not significantly different within FertiClasses by a LSD test ($P < 0.05$). Means sharing a capital letter are not significantly different within low-, medium-, and high-risk Ferticlasses by a LSD test ($P < 0.05$). $^{\chi}$ $Pr > |t|$ refers to a *t* test to test the null hypothesis that the associated population quantity equals zero. * Superior weight studies are defined as studies whose weight of N2O observations was twice greater than the average weight of all N_2O observations (0.24%).

the low-risk class (Table 1). We are not aware of any other attempt to estimate the EFs for OAs based on risk classes, but note that the EF for the low-risk class was about one thirtieth of the global EF for OAs, implying that use of the global EF for OAs would greatly overestimate the N_2O emissions from agricultural soils that received Pellets (sewage sludge),CMPT (animal, vegetal, and municipal wastes), PMS, CR (maize or barley straw, lettuce or calabrese residues), PMS-CR, and even LM-CR.

3.4. Emission Factors and Controlling Factors

3.4.1. Physico-chemical Properties of Organic Amendments

Pig slurries that contained greater mineral N content (>10% d.w.), more water content (>95%) and low C/N ratio (<5) had larger EFs than more viscous animal slurries (dry matter range of 5–15%), SM (dry matter >15%) or more stabilized products (C/N ratio >30) (Table 1 and S4). These findings agree with other reports (Velthof et al., 2003; Chantigny et al., 2010; Senbayram et al., 2012). For instance, pig slurry contains high amounts of NH_4 and easily decomposable organic C that can, in concert, directly stimulate soil denitrifiers and decrease O_2 concentration; thereby further stimulating N_2O production through denitrification (Velthof et al., 2003; Chantigny et al., 2010). Senbayram et al. (2012) pointed out that application of OAs with high contents of labile C may trigger denitrification-derived N_2O emission in N-fertilized agricultural soils, coupled with a substantial increase of $N_2O/(N_2O + N_2)$ product ratio of denitrification in presence of large amount of nitrate from synthetic sources.

Chemical properties of OAs such as the mineral N content and C/N ratio were evidently important in predicting their N_2O EF. More than 90% of OAs containing less than 0.3% d.w. of mineral N yielded EFs below the range proposed for the IPCC EF_1 (0.3 to 3% of N applied) (Fig. S4). Conversely, the OAs with greater mineral N content tended to have EFs above the maximum EF_1 value. For organic amendments whose mineral N content is less than 0.3% d.w, 10 of the 28 the EF estimates below 0.3% concerned surface application of cattle/co-fermented slurries and 13 of the 28 the EF estimates below 0.3% concerned compost application. For organic amendments (±synthetics) containing more than 25% d.w. of mineral N, 100% of out of range EF_1 above 3% are attributed to the injection of pig slurry combined with synthetic fertilizers (Table S4). Thus, mineral N alone cannot depict differences in composition between animal manures, due to litter type, and animal species and nutrition. Animal litter is a mixture of bedding material, excreta, and waste feed generated during animal production (Cabrera et al., 1994). Manure showed contrasting N-mineralization patterns where N concentration varied among biochemical fractions (Tremblay et al., 2010). The manure-N mineralization increased in the presence of low-molecular-weight compounds such as sugar, starch, protein, uric acid N, and water-soluble organic N and decreased with lignin and polyphenol content (Morvan et al., 1997; Pansu et al., 2003). In general, the degradability of organic C and N of cattle manure is lower than that of pig and poultry manure (Chadwick et al., 2000).

We conducted linear regressions based on log-transformed EF data to predict the N_2O EFs of crop residues from their C/N ratio with 78.4% of variance in EF explained by the model (Fig. 2). According to the model, CRs with C/N higher than or equal to 21.3 would not significantly increase soil N_2O emissions following their addition. More generally, the EFs of the Fertitype O and OS decreased as the C/N ratio of OAs decreased (Fig. 2), which agrees with controlled laboratory studies on N_2O emissions from soils receiving OAs (Rizhiya et al., 2011). According to higher N_2O observations reported in the literature (Fig. 2), OAs with C/N higher than or equal to 45.9 would not significantly increase soil N_2O emissions following their addition. For OAs with C/N lower than 25,

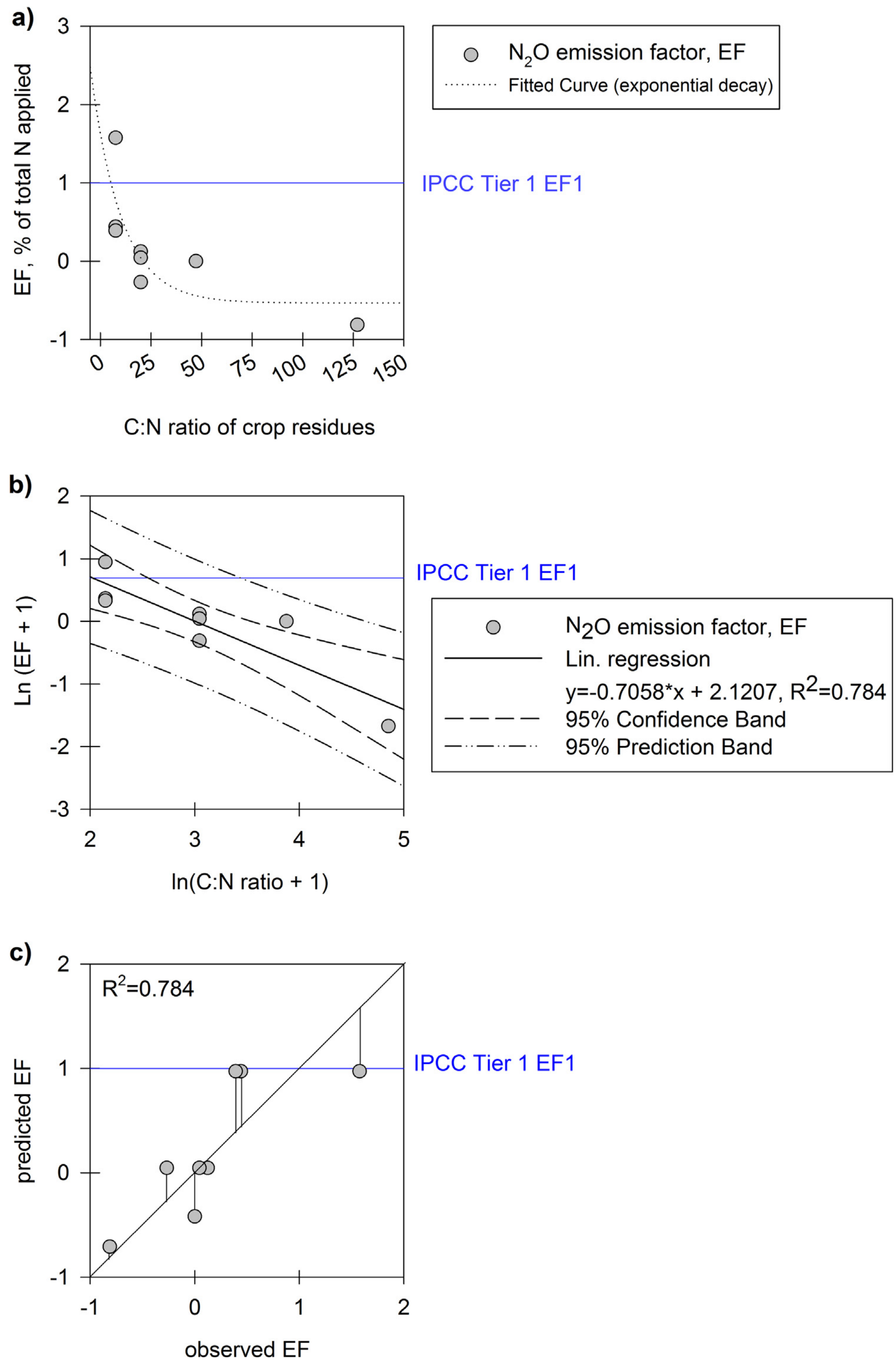

Fig. 2. Nitrous oxide emission factors of crop residues as a function of C:N ratio. a) Observed N_2O emission factors as a function of crop residues C:N ratios. b) Linear regression analysis of log-transformed crop residue variables. c) Predicting N_2O emission factors of crop residues from their C:N ratio.

the C/N of OAs explained only a part of the variations in EF, suggesting the influence of other environmental and management-related factors (Fig. S5).

3.4.2. Climate

Climate type and annual mean air temperature (MAT) had no significant effect of on global EF (Table 4), probably because our database is biased toward temperate climates and under-represented tropical and arid climates. There was a significant effect ($P < 0.001$) of total annual precipitation (TAP) on global EF, where the EF estimate from FertiType O increased by a factor of 5 as TAP increased from 0 to 250 mm to 500–1000 mm (Table 4). This is consistent with the fact that soil moisture generating temporary anoxic conditions is a major driver of N_2O production from

Table 4
Significance of environmental and management-related factors on global N_2O emission factors with the weighted REML approach.

	FertiType O				—	**FertiType O and OS**					**FertiType S**				
	n	Raw mean	*Pr > F* mean	df (sem)		n	Raw mean	*Pr > F* mean	df (sem)		n	Raw mean	*Pr > F* mean	df (sem)	
Climate															
Climate type[1]	251	0.81	ns	197		323	0.96	ns	249		99	1.34	ns	68	
TAP[2], (mm)	229	0.80	***	173		296	0.97	***	221		91	1.37	ns	58	
0–250	42	0.20	0.21	(0.33)	*b*	51	0.21	0.29	(0.31)	*b*	12	0.48	–	–	
250–500	26	0.94	0.59	(0.47)	*ab*	45	0.78	0.61	(0.36)	*ab*	14	1.34	–	–	
500–1000	96	0.92	1.05	(0.18)	*a*	105	0.90	1.16	(0.21)	*a*	42	1.38	–	–	
>1000	65	0.96	0.50	(0.19)	*b*	95	1.54	0.63	(0.21)	*b*	23	1.83	–	–	
MAT[2], °C	167	0.82	ns	132		70	1.40	ns	170		70	1.40	ns	48	
Cropping Systems															
Land-use type	251	0.81	ns	196		323	0.96	ns	248		99	1.34	ns	67	
Crop type[3]	109	0.64	ns	87		116	0.65	ns	100		34	1.56	ns	67	
Soil Management															
Soil tillage	127	1.02	ns	100		184	1.20	ns	142		57	1.22	ns	35	
Incorporation[4]	207	0.72	ns	63		–	–	–	–	–	–	–	–	–	
Soil Properties															
Drainage	115	0.81	***	102		117	0.81	***	104		34	1.93	**	24	
Poor	49	1.10	1.02	(0.16)	*a*	49	1.11	1.02	(0.16)	*a*	15	3.70	5.34	(1.46)	*a*
Well	66	0.59	0.34	(0.03)	*b*	68	0.59	0.34	(0.03)	*b*	19	0.52	0.72	(0.13)	*b*
Texture	221	0.89	***	129		281	1.06	*	214		90	1.41	ns	61	
Fine	49	1.33	1.52	(0.38)	*a*	81	1.77	1.42	−0.26	*a*	24	3.01	2.85	(1.43)	*a*
Medium	44	0.96	0.82	(0.18)	*a*	56	0.91	0.71	−0.26	*b*	21	0.93	0.7	(1.86)	*a*
Coarse	128	0.67	0.49	(0.18)	*b*	144	0.73	0.59	−0.21	*b*	45	0.79	0.66	(3.00)	*a*
Organic C, (%)	193	0.8	**	151		252	0.96	**	194		86	1.03	***	59	
<1	31	0.64	0.47	(0.22)	*b*	56	0.61	0.44	(0.21)	*b*	20	0.71	1.09	(0.73)	b
1–3	105	0.83	0.48	(0.18)	*b*	116	0.80	0.46	(0.18)	*b*	35	0.78	−0.71	(0.66)	b
3–6	35	0.77	1.47	(0.29)	*a*	53	1.74	1.46	(0.26)	*a*	23	1.68	3.83	(0.72)	a
>6	22	0.84	0.72	(0.84)	*ab*	27	0.85	0.72	(0.84)	*ab*	8	1.07	1.21	(2.27)	ab
Nitrogen, (%)	165	0.88	**	140		225	1.04	***	177		81	1.04	ns	58	
<0.1	18	0.84	0.57	(0.35)	*b*	45	0.63	0.48	(0.22)	*b*	–	–	–	–	
0.1–0.2	117	0.72	0.50	(0.17)	*b*	124	0.72	1.69	(0.36)	*a*	–	–	–	–	
>0.2	30	1.54	1.66	(0.31)	*a*	56	2.08	0.59	(0.16)	*b*	–	–	–	–	
Soil C/N ratio	165	0.88	ns	140		229	1.04	***	178		85	1.12	**	61	
<10	18	0.85	0.66	(0.27)	*a*	41	0.54	0.81	(0.31)	*a*	19	1.11	1.40	(0.57)	*ab*
10–14	117	0.72	0.80	(0.19)	*a*	90	1.51	1.16	(0.23)	*a*	26	1.79	2.55	(0.71)	*a*
>14	30	1.54	0.55	(0.24)	*a*	98	0.83	−0.17	(0.27)	*b*	40	0.69	0.04	(0.49)	*b*
pH	184	0.87	1.76	ns		254	1.04	ns	194		90	1.13	ns	60	

[1]Climate types reported in the database: cool temperate dry/moist, tropical dry/moist, warm temperate dry/moist. [2]FertiType, type of fertilization: organic (O), synthetic fertilizers (S), organic and synthetic fertilizers (OS). [1]TAP, Total annual precipitation. [2]AMAT, Annual mean air temperature. [3]Crop type, type of crops (legume, grass, legume + grass) in grassland only. [4]Incorporation, incorporation depth (cm) of organic amendments only. n, total # of observations used in the analysis. *Pr* > F refers to a *F*-test used for comparing the soil factors of the total deviation.Df, degree of freedom. Significance of the effect: $Pr < 0.001^{***}$, $Pr < 0.01^{**}$ and $Pr < 0.05^{*}$, ns = non-significant.Means sharing a letter are not significantly different within soil factor by a LSD test ($P < 0.05$).

denitrification in microsites where a high oxygen demand from intense respiratory activity exceeds the oxygen supply (Parkin, 1987; Linn and Doran, 1984). It is notable that the EF estimates declined by a factor of 2 when TAP exceeded 1000 mm (Table 4), suggesting that N_2 was the end product of denitrification in agricultural soils receiving OAs under these conditions of higher soil moisture. When TAP exceed 1000 mm, 100% of the EF estimates was measured under moist climates (tropical or temperate). A function relating EF to the “TAP to potential evapotranspiration (PET)” ratio would correct this bias (Rochette et al., 2008). However, PET was rarely reported (Meijide et al., 2009).

3.4.3. Soil properties

3.4.3.1. Texture and drainage. Soil texture modulates soil N_2O emissions in agricultural soils receiving OAs and synthetic fertilizers (Pelster et al., 2012). Similar to Bouwman et al. (2002b), our results showed that N_2O emissions were greater in fine-textured than coarse-textured soils (Table 3). In FertiType O, the EF increased by a factor of 2.8 in fine-textured than coarse-textured soils (Table 4). In FertiType OS, the EFs differed significantly between fine-textured and medium-textured soils. This may be a function of mineral N availability for microbially-mediated denitrification since the magnitude of EF response to increasing mineral N content of soil amendments is regulated by soil texture (Fig. 3), with greater EF estimates occurring in situations where mineral N content of fertilizer inputs was higher in fine-textured than in medium- and coarse-textured soils. When LM was injected with synthetic fertilizers, the EF estimates were >3% (Chantigny et al., 2010; Wei et al., 2010; Senbayram et al., 2014), exceeding the IPCC EF_1 value.

Soil drainage was another significant modulator of EFs in agricultural soils receiving OAs and synthetic fertilizers (Table 4). The effect of soil drainage is related to texture because fine-textured soils hold water, while coarse-textured soils allow water to pass through quickly. The effect of soil drainage is also

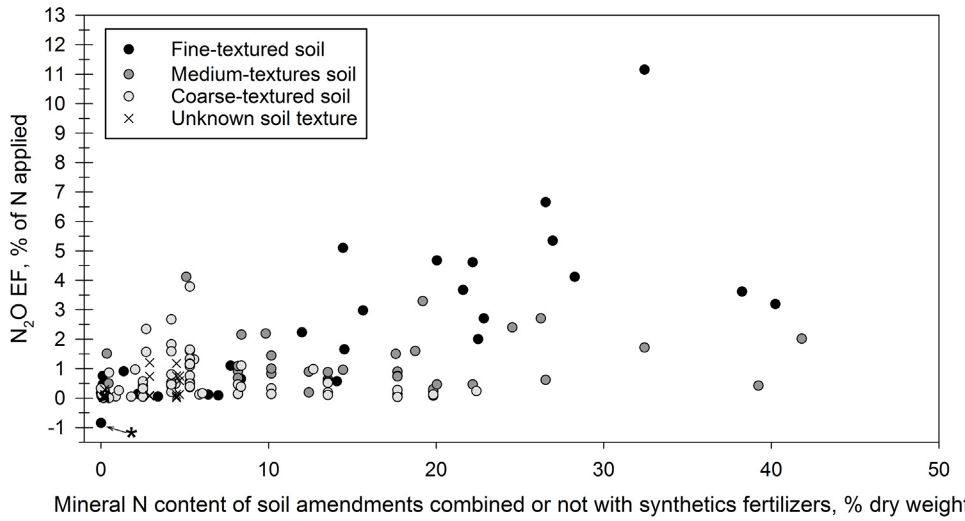

Fig. 3. Modulation of global N_2O emission factors by mineral nitrogen content of inputs organic sources, alone and combined with synthetic inputs, and soil texture. *Emission factor reported by Dalal et al. (2010) after green waste compost application on a sorghum crop cultivated on a Vertisol (Udic Haplustert, USDA, 1975) under a subtropical climate (Australia).

influenced by climate conditions and the presence of controlled drainage structures. The attribution of a drainage class (poor, well, n/a) to reported EFs was based on explicit details provided by authors in selected studies. The EFs in poorly drained soils were two times larger than in well-drained soils in presence of OAs. For the FertiType S, the EFs were 7-fold greater in poorly drained than in well-drained soils. These differences reflect the impact of soil oxygen and moisture status on N_2O production and diffusion/emission in agricultural soils, which was also noted by Bouwman et al. (2002b).

3.4.3.2. Soil organic carbon and nitrogen. Soil organic carbon (SOC), is another soil parameter implicated in soil N_2O emissions (Giles et al., 2012) that was considered in this study (Table S2). Regardless of the FertiType applied, SOC had a significant effect on EF (Table 4) and this was more important in FertiType S ($P < 0.001$) than FertiType O and OS ($P < 0.01$), which corroborates previous findings (Pelster et al., 2012) stating that N_2O emissions are often limited by soil C availability. In synthetically fertilized soils, the SOC could be an indicator of the concentrations of C substrates accessible to nitrifying and denitrifying microorganisms that produce N_2O. The soil C/N ratio was also related to the EFs in synthetically fertilized soils (Table 4), which is consistent with findings reported by Wei et al. (2010). In contrast, the C/N ratio or organic C content of OAs is a better representation of the C substrate availability because the labile C substrates that originate from OAs are more readily metabolised than those that originate from the native SOC, since a large proportion of the SOC is physically protected and associated with soil minerals (see Table S5).

4. Conclusion

The REML approach was able to distinguish and estimate EF for soil N_2O emissions from OAs, alone and combined with synthetic fertilizers. The weighted REML model could account for the intrinsic spatio-temporal variability of N_2O emissions from agricultural soils receiving OAs using the N_2O coverage weighted function. In estimating the EFs for N_2O emissions from agricultural soils, we demonstrated that the IPCC EF_1 value was too high when considering the N_2O contribution from agricultural soils amended with composts, but too low to represent the EF of N_2O in agricultural soils receiving liquid manure (mostly pig slurry) combined with synthetic fertilizers. We propose a global default EF for organic sources, EF_{org}, equal to $0.57 \pm 0.30\%$ and encourage the use of FertiClasses or FertiRiskClass categories to account for the N_2O emissions from specific OA sources or groups of OAs with similar characteristics. Finally, we confirm that variations in N_2O EFs in OA-amended soils are influenced mainly by the mineral N content and the C/N ratio of OAs, rainfall (expressed as TAP), soil texture and drainage. The database assembled and the approach followed in this study could therefore be used to update the IPCC EFs for soil N_2O emissions resulting from the application of OAs to agricultural soils.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.11.021.

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