Disaggregated N₂O emission factors in China based on cropping parameters create a robust approach to the IPCC Tier 2 methodology

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HIGHLIGHTS

- Disaggregated nitrous oxide emission factors create a more robust IPCC Tier 2 approach.
- Influential cropping factors give consistent emission factors for Chinese agriculture.
- Consistency in emission factors transcended method type, data quality and datasets.

ARTICLE INFO

ABSTRACT

China accounts for a third of global nitrogen fertilizer consumption. Under an International Panel on Climate Change (IPCC) Tier 2 assessment, emission factors (EFs) are developed for the major crop types using country-specific data. IPCC advises a separate calculation for the direct nitrous oxide (N₂O) emissions of rice cultivation from that of cropland and the consideration of the water regime used for irrigation. In this paper we combine these requirements in two independent analyses, using different data quality acceptance thresholds, to determine the influential parameters on emissions with which to disaggregate and create N₂O EFs. Across China, the N₂O EF for lowland horticulture was slightly higher (between 0.74% and 1.26% of fertilizer applied) than that for upland crops (values ranging between 0.40% and 1.54%), and significantly higher than for rice (values ranging between 0.29% and 0.66% on temporarily drained soils, and between 0.15% and 0.37% on un-drained soils). Higher EFs for rice were associated with longer periods of drained soil and the use of compound fertilizer; lower emissions were associated with the use of urea or acid soils. Higher EFs for upland crops were associated with clay soil, compound fertilizer or maize crops; lower EFs were associated with sandy soil and the use of urea. Variation in emissions for lowland vegetable crops was closely associated with crop type. The two independent analyses in this study produced consistent disaggregated N₂O EFs for rice and mixed crops, showing that the use of influential cropping parameters can produce robust EFs for China.

1. Introduction

Nitrous oxide (N₂O) is an important greenhouse gas due to its global warming potential which, over a 100-year period, is 298 times that of carbon dioxide (CO₂), (Myhre et al., IPCC 5th Assessment Report, 2013). Nitrous oxide contributes to stratospheric ozone depletion (Denman et al., IPCC, 2007) and its atmospheric concentrations continue to increase, mostly due to

agriculturally related activities (Bouwman, 1990).

Soil N_2O emission is highly variable in space, associated with heterogeneity in soil properties and agricultural management (e.g. water, nutrient, crop, tillage, and soil texture) (Brown et al., 2001; Velthof and Oenema, 1995). Soil variables influencing the emission of N_2O are soil moisture and readily available nitrogen (N) (Qin et al., 2010; Lu et al., 2006; Linn and Doran, 1984) due to their influence on microbial activity and gas diffusion. The spatial variability of these soil variables results in also spatially variable emissions and uncertainties in overall estimates (IPCC, 2006; Bouwman et al., 2001; Luo et al., 2013).

National inventories employ emission factors (EFs) to determine N_2O emissions. The IPCC Guidelines (IPCC, 2006) treat direct emission (from soil microbial processes) and indirect emission (from volatilization, leaching and runoff) separately. Furthermore, direct emissions due to crop management and from animal-deposited manure have a separate method. This study is concerned with direct soil emission associated with crop management.

In China N_2O emission factors for all agricultural land types are statistically derived from the average values of observed data (National Development and Reform Commission, 2012). The default Tier 1 IPCC methodology (IPCC, 2006) for direct soil N_2O emission is a single EF based method for all types of arable drained agriculture, stating that N_2O emissions are 1% (0.3—3.0% uncertainty) of N applied to soil, and 0.3% (0.0—0.6 uncertainty) for flooded rice fields. This is based on a large and variable dataset, which makes it difficult to obtain accurate estimates (Bouwman et al., 2001; Lesschen et al., 2011). If more specific EFs are produced, the national inventory can use these disaggregated factors in a Tier 2 assessment of emissions (IPCC, 2006); these EFs can be developed for the major crop types by climate zone using country-specific activity data. These specific EFs yield a more accurate emission estimate for a specific region compared to the default IPCC value. The IPCC advises using a separate calculation for N_2O emissions from rice to that from cropland and a consideration of the irrigation regime.

Estimates of N_2O are reasonably consistent at the global scale, but lack of direct measurements in some areas makes national and sub-national estimates highly uncertain (Reay et al., 2012). China is a large contributor of worldwide N_2O emissions due to the country's rank as the top global consumer of N fertilizer. In 2007—2008, China accounted for 31% of global fertilizer N consumption (Heffer, 2013).

Estimates of N_2O emissions in China (Lu et al., 2006) resulted from data collated from measurements from over 60 published experiments between 1982 and 2003. In order to focus on the emission of N_2O resulting from the application of fertilizer, Lu et al. filtered the available data with the following rules: (1) include field studies carried out for more than or close to one year to account for seasonal variation (Bouwman, 1996); (2) exclude N_2O flux data from paddy fields since emission patterns from paddies are different from uplands; (3) exclude measurements taken from unplanted soils and organic soils which have high N_2O emissions and can bias the mean; (4) exclude N_2O emissions from fields growing N-fixing legumes and fields with additional organic N or nitrification inhibitors. The emission factors currently used in China are 0.0074 ± 0.0061 for non-vegetable uplands; 0.0111 ± 0.0099 for rice-upland crop rotation; 0.0030 ± 0.0029 for rice paddy, and 0.0075 (0.00067—0.0284) kgN_2O-N/kgN for vegetable fields and orchards (National Development and Reform Commission, 2014).

A country as large as China will show a large regional variability in emissions as a result of the many climate types (Lu et al., 2006), generally with higher precipitation in East compared to West China. Croplands with high N application rates dominate in East China, whilst grasslands with a lower amount of N applied are common in West China.

Globally 90% of rice land is temporarily flooded (Wassmann et al., 2009). Temporary drainage during the season, for example paddy rice — upland crop rotations, reduces methane emissions but increases N_2O emissions (Jianping and Chaodong, 2007). Zheng et al., (2004) reported regional variation in N_2O emission and showed that 80% of N_2O emitted from the cropland of mainland China in the 1990s was from the humid regions receiving only 65% of the total national N input. Zheng et al. concluded that periodic wetting and drying of the soils due to water management, may greatly increase the N_2O EFs during the drained periods and advice using a separate EF for various cropland categories; their analysis performed better than the default IPCC EF. On mixed cropland, the use of differentiated (Lesschen et al., 2011) or disaggregated (Brocks et al., 2014) EFs accounting for separate crops or regional conditions has also performed better than the IPCC 2006 methodology.

In this paper, two independent data analyses use the preceding ideas of disaggregation and cropland categories to produce N_2O EFs for Chinese agriculture.

The study collated N_2O emissions data together with environmental data, including details of the duration of measurement of GHG emissions from experiments conducted in China and published in the last 30 years. The two different analyses of the data were used to examine how GHG emissions vary with different cropping systems. Rice was analysed separately from other crops, and in the context of different irrigation regimes.

The two analyses differ in methodology and in the quality threshold for data accepted, especially in the duration of N_2O flux measurement. We wanted to determine if the use of cropping parameters can produce a robust framework that will result in reasonably comparable EFs for Chinese agriculture despite the differences in analyses. The most influential parameters to N_2O emission for Chinese agriculture and the highest and lowest N_2O EFs were determined, and a regional analysis made.

2. Materials and methods

Two methods of analysis were applied to derive EFs for mixed crops and rice using N-input sources and environmental factors. The first analysis (non-transformed data analysis) was based on good practise for emission calculation plus rules used in the literature (IPCC, 2006; Lu et al., 2006; Zheng et al., 2004; Lesschen et al., 2011). The second analysis (transformed data analysis) was based on good practise plus the back transformation correction of log transformed emission data (Finney, 1941; Sichel, 1966). These two methods contrast in showing different thresholds for data quality. Using a large dataset, the non-transformed data analysis sets a high quality threshold for the data at the risk of eliminating a large proportion of data, whereas the transformed data analysis uses the majority of the experimental data that it collates from the literature, which produces averages from the large dataset used.

For each method of analysis, two datasets were compiled, one for rice cropping and the other for mixed cropping (see supporting information Tables S1—S5 for the most influential cropping factors). The transformed data analysis comprised two separate categories of upland mixed crops (comparable with the non-transformed mixed cropping) and lowland vegetable crops, referred to as lowland horticulture. The datasets originate from Chinese agricultural emissions research collated from the literature over the last 30 years. Parameters included in the mixed crops dataset are amount of fertilizer applied, N_2O flux, number of days of measurements, fertilizer type, annual precipitation, annual temperature, location, SOC, pH, total N content, crop type, organic N type, soil texture and the reference for the experiment. Parameters included in the rice dataset are amount of fertilizer applied, N_2O flux plus number of days of measurements, fertilizer type, annual precipitation, annual

temperature, location, SOC, pH, total N content, organic N type, rice type and water regime.

For mixed crops, 43 experimental studies were collated from the literature for the non-transformed data analysis, and 23 studies were collated for the transformed data analysis. For rice cropping systems 32 experimental studies were collated from the literature for the non-transformed data analysis, and 15 studies of rice were collated for the transformed data analysis. The non-transformed data analysis collated a greater number of experimental studies than the transformed data analysis, but it reduced the datasets used because not all met the data quality requirements.

In both crop and rice analyses, a N_2O EF was calculated as N_2O emission from a fertilized plots minus the emission from an unfertilized plot (all other conditions being equal) expressed as a percentage of N applied. If the emission from a similar unfertilized plot was not available, we used the slope of the linear response of N_2O flux as a function of several application rates of N fertilizer. In a number of cases the experimental data could not be used due to a lack of emission data from unfertilized plots, plus a lack of emission data at different application rates of N.

2.1. Non-transformed data analysis

When considering countrywide emissions from mixed agricultural systems, it is not appropriate to use simple relationships between fertilizer N application rates and emissions (Bouwman et al., FAO report, 2001) due to the influence of differing climate, soil, crop and management conditions. The FAO report advises a different approach whereby the data set is summarized based on the factors that regulate N_2O emissions. The factors selected by FAO include: climate, crop type, fertilizer type, application rate, soil pH, soil texture and drainage, measurement technique, and length of the measurement period. The non-transformed data analysis adhered to this recommendation and used this data, using annual precipitation and annual temperature for the climate parameters. IPCC methodology and the FAO report also advise taking N_2O measurements for a year to account for seasonal variation. This advice was taken into consideration, together with the wide range of measurement periods in the peer-reviewed literature, and the most suitable threshold period of measurement was determined with which to eliminate datasets. A hierarchical cluster analysis (Payne et al., 2014) was applied to the data to determine a representative number of days of N_2O measurement required for the analysis.

Two- and three-factor linear regression analyses of flux versus all other environmental parameters were carried out to determine the most significant factors driving the emissions for both mixed crops and rice. ANOVA and REML (mixed model) (Payne et al., 2014) with a Bonferroni analysis were used to check if separate groups could be determined. Multiplication of the factors produced group means that were tested for similarities using a hierarchical cluster. The cluster analysis was used to determine separation between groups by classifying the groups for similarity, based on Euclidean distance between each pair of objects. The matrix from the cluster analysis produced a dendrogram (using average link criterion) which displays the agglomeration of group means as related to one another over an axis representing the percentage of multivariate similarity. The groups were assessed for 70, 90 and 95% similarity. The same procedure was carried out for both mixed crops and rice datasets. From a visual check of the resulting dendrograms, a level of 95% similarity was chosen.

For each combined group the corresponding EF was calculated by subtracting the N_2O flux produced from the treatment minus the background flux (no N applied) for the same experiment and dividing by the total amount of N applied. The resulting EFs (expressed in % N_2O per N applied) were used to calculate the mean for each dendrogram similarity group.

The statistical package used for the non-transformed data analysis was Genstat version 17 (VSN International, 2014).

2.2. Transformed data analysis

In this analysis, the crop specific or overall EF for upland crops, vegetable crops and rice paddy, and their sub-groups were calculated based on a common influencing factor to N_2O emission.

Dependence of N_2O emissions on soil N inputs was estimated by using the arithmetic mean (AM) and geometric mean (GM) of EFs. The group means were estimated to obtain the original data's AM as a reference value.

A GM, unlike an AM, tends to dampen the effect of very high or low values, which might bias the mean if AM were calculated. If data is highly skewed the extreme observations have a large influence on the arithmetic mean, making it more prone to sampling error. Lessening this influence is one advantage of using transformed data. The frequency distribution of EFs for paddy fields, upland crops and vegetables are not normally distributed so we transformed the EF data by taking the natural log of EF. Then the group means were estimated to obtain the log transformed data's GM. The results from log transformed data (GM) were then back transformed by taking the antilog ($Y = \exp^{GM}$) and reported as uncorrected GM (GMuncorr). However, reporting the antilog of the estimated mean for the log transformed data without considering the bias gives a very low value as it is the geometric mean rather than the arithmetic mean. To allowing for bias incurred in back-transformation, we need to convert the geometric mean to an arithmetic mean for the log transformed data, and for this we use Sichel's t estimator, or the Finney formula (Sichel, 1966; Finney, 1941). An adjustment to the GM was done by adding half the variance of the transformed values to the GM before back-transformation ($\exp^{GM+0.5Variance}$). This was reported as the corrected GM (GMcorr). After an initial comparison of AM, GMuncorr and GMcorr, simply the AM and GMcorr were reported.

The statistical package used for the transformed data analysis was IBM SPSS Statistics edition 19.0 (IBM, 2010).

3. Results

3.1. Non-transformed data analysis

3.1.1. Three-factor groups and dendrograms
A hierarchical cluster analysis determined that 120 and 200 days of data measurement period were representative thresholds of data acceptance for rice and mixed crops, respectively. The dataset was filtered accordingly.

Multiple regression determined influencing factors on the N_2O flux. Data for rice (n = 63) showed variation in flux is associated with 3 statistically significant factors in combination: fertilizer type ($R^2 = 0.320$; $p < 0.001$); fertilizer type and water regime ($R^2 = 0.406$; $p < 0.001$); fertilizer type, water regime and crop type ($R^2 = 0.460$; $p < 0.001$). Data for mixed crops (n = 68) showed variation in flux is associated with 3 statistically significant factors in combination: fertilizer type ($R^2 = 0.297$; $p < 0.001$); fertilizer type and soil texture ($R^2 = 0.597$; $p < 0.001$); fertilizer type, soil texture and crop type ($R^2 = 0.727$; $p < 0.001$). We produced 28 × 3-factor combined groups of data for rice, and 109 × 3-factor combined groups for mixed crops.

The resulting dendrograms of rice and mixed crops from the cluster analysis of 3-factor combinations are shown in Figs. 1a,b and 2a,b,c, respectively. At 95% similarity there are 8 groups of 3-factor combinations, listed along the dendrogram axis. Knowing these
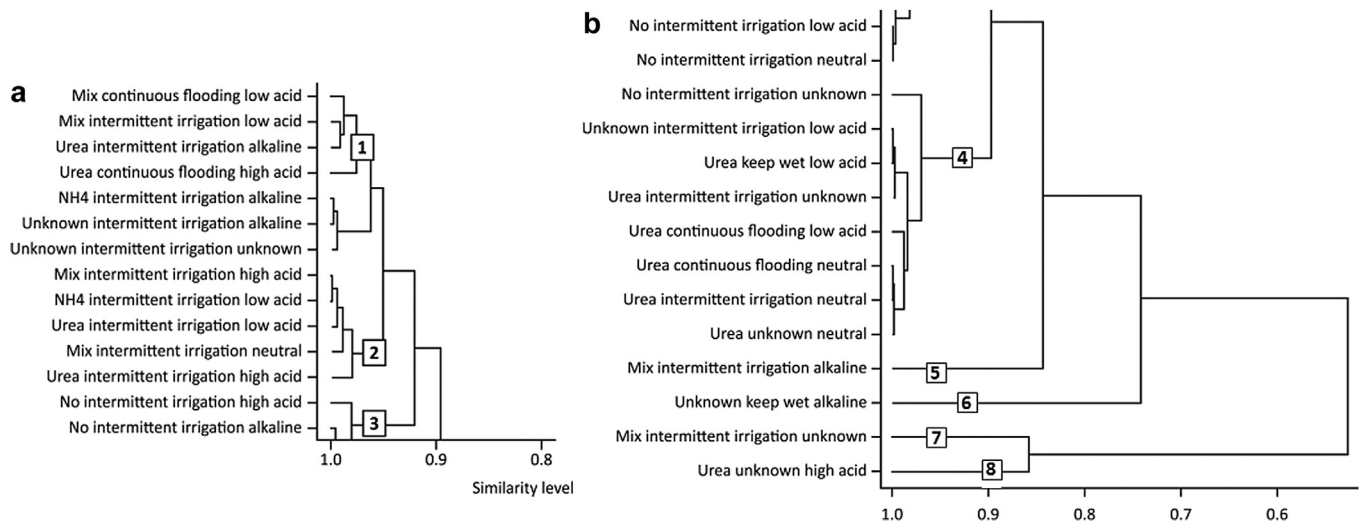
Fig. 1. a and b. Dendrogram of rice 3-factor groups (non-transformed data). 1a shows dendrogram groups 1–3 and 1b shows groups 4–8. Dendrogram numbers relate to dendrogram numbers in Table 1. Group names arranged in order of fertilizer–irrigation–soil. 'No' in factor descriptors refers to none, e.g. no fertilizer.

factors are influential for N$_2$O emissions, and have similarity within their dendrogram group, the EFs calculated from available data can then be extrapolated to within-dendrogram combined factors.

The calculated N$_2$O EFs for dendrogram groups are shown in Tables 1 (rice) and 2 (mixed crops). Some groups had no data available and some groups had only emissions data for zero N, so EFs could not be determined. Some groups had two sources of emission factor data: calculated from fertilizer minus background emission, or obtained from a regression of same-experiment emissions from differing N applications.

For rice, the dendrograms 1–8 in Fig. 1a and b are to be viewed in conjunction with the EFs for dendrograms 1–8 shown in Table 1. For mixed crops, the dendrograms 1–8 in Fig.. 2a, b and c are to be viewed in conjunction with the EFs for dendrograms 1–8 shown in Table 2.

3.1.2. N$_2$O EFs for rice

For rice, EFs ranged from 0.15% to 1.0% of applied N fertilizer (Table 1), but the extremes of 0.15% (from continuously flooded soil) and 1.0% (with intermittent irrigation) were from single experiments of differing N application. The majority of rice emissions were between 0.37% and 0.66%, with suppressed emission from continuously flooded soil from 0.15% to below 0.37%. The higher EF of 0.66% (dendrogram no. 2) was populated by ammonium or compound fertilizers or highly acid soils. The lower EF of 0.37 (dendrogram no. 4), was populated by urea and continuously flooded soils.

3.1.3. N$_2$O EFs for crops

Mixed crop EFs ranged from 0.4% to 1.4% of applied N fertilizer (Table 2). The lowest EF was from the combined groups in the same dendrogram as urea applied to wheat on a sandy loam soil (dendrogram no. 3 in Table 2 and Fig. 2b). This finding is supported by findings of low EFs from applied urea in the transformed data analysis for mixed crops, and is expected in the case of a freely draining soil. Two different dendrogram groups had a high EF of 1.4%. One group encompassed similarity groups to urea applied to corn on clay soils (dendrogram no. 2 in Table 2 and Fig. 2b). Clay and corn have been reported as influential factors on higher N$_2$O emissions (Crutzen et al., 2007; Bouwman et al., 2001). A more surprising similarity group in dendrogram no. 2 is urea applied to wheat to a silty-sand soil, since sandy soil is free draining, although

it is difficult to know the proportion of sand from experiments in the literature. The other high EF of 1.4% was the combination of urea applied to a clay soil growing maize (dendrogram no. 8 in Table 2 and Fig. 2c). This combination of factors appears very similar to the other high EF combination in dendrogram no. 2 (corn, i.e. maize, grown on a clay soil), but some experimental data was labelled 'corn' and some 'maize', and when assessed for effects on N$_2$O emission the multi-factor group cluster analysis determined them as statistically separate groups.

Dendrogram similarity groups to compound fertilizer applied to a clay soil for a wheat crop gave a higher EF of 1.0%. Dendrogram similarity groups to urea applied to a clay soil for a rape crop gave a lower EF of 0.8%. These findings are supported by the transformed data analysis. This analysis set high quality data acceptance thresholds which eliminated so much data that only not all dendrogram groups could be distinguished but the dendrograms available encompass the majority of crop and environmental data.

3.2. Transformed data analysis

3.2.1. N$_2$O EFs for rice

The EF for rice (Table 3) was calculated initially in three ways, using the reference value of AM, with GMuncorr and GMcorr. The AM using original data was 0.34%. Using normalized data for the EF, GMuncorr was only 0.18%, but GMcorr was 0.39%. In initial results, not shown, for rice, upland crops and lowland horticulture, GMuncorr was consistently much lower than the reference AM, and GMcorr was similar to the AM. Therefore after the initial analysis for rice, only the AM and GMcorr for each crop sector are reported.

Transformed data analysis EF for rice overall was between 0.24% and 0.44% (AM), or between 0.29% and 0.52% (GMcorr).

3.2.2. Influencing factors of N$_2$O EF for rice

In a statistical F-test for influencing factors, location had no significant association with rice N$_2$O EFs ($F_{(2, 70)} = 0.167$; $p = 0.847$), whereas water regime was significantly associated with rice N$_2$O EFs ($F_{(1,53)} = 6.187$; $p = 0.001$). This is supported by Zou et al. (2005) who concluded that N$_2$O emissions from rice paddy mainly depend on water management. Various water management patterns currently practiced in China's rice paddies are continuous flooding (CF), flooding-midseason drainage-flooding, otherwise termed here intermittent saturation (IS), and flooding–midseason
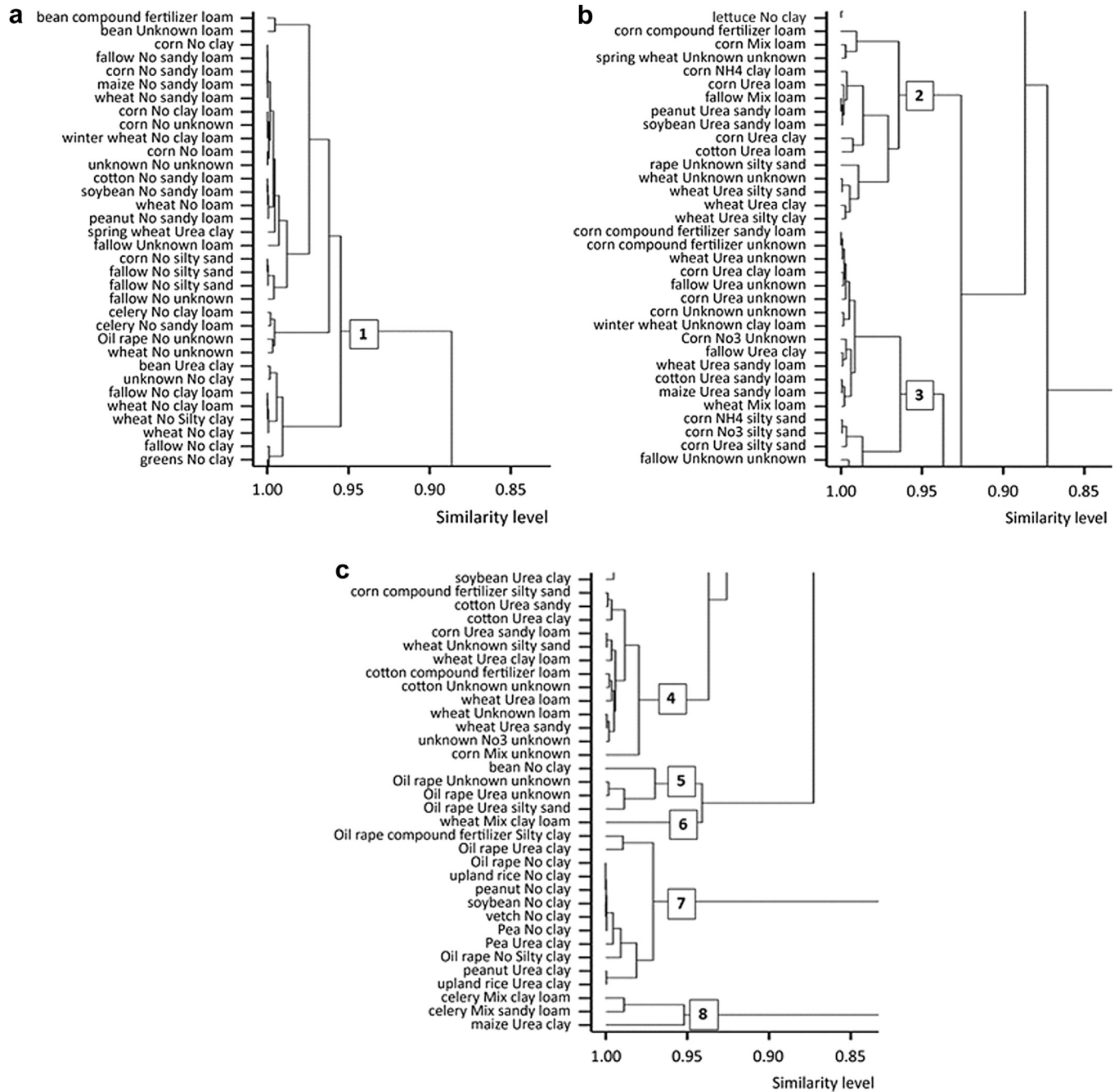
Fig. 2. a, b and c. Dendrogram of mixed crops 3-factor groups (non-transformed data). 2a shows dendrogram group 1, 2b shows groups 2–3, 2c shows groups 4–8. Dendrogram numbers relate to dendrogram numbers in Table 2. Group names arranged in order of crop–fertilizer–soil.

drainage–flooding–moist intermittent irrigation but without water logging, termed here intermittent irrigation (IM) (Huang et al., 2004; Zou et al., 2007). Water regime specific N_2O EFs were calculated based on 73 paired data for fertilized and background measurements (Table 4). EFs calculated by normalizing distribution and bias correction (GMcorr) were higher under IM (0.29%) and IS (0.64%) water regimes than CF (0.12%). N_2O emission gave a weak relationship with applied N for CF (n = 36; R^2 = 0.382; p = 0.019). N_2O emission was significantly associated with N fertilizer input (n = 66, 30; R^2 = 0.502, 0.614; p < 0.005) for the emissions of IM and IS, respectively. Since the 1980s, about 12–16%, 77% and 7–12% of paddy fields have been under the water regimes of CF, IM and IS, respectively.

N fertilizer type was significantly associated with the N_2O EF of rice (F(1,3) = 23.367; p = 0.001). Table 5 shows N fertilizer type, water regime and pH specific N_2O EF for rice. The highest EF of 1.79% (GMcorr) came from an application of mixed or compound fertilizer in a neutral pH soil, but the irrigation scheme was unknown and could therefore have been a contributory factor. The lowest EF of 0.13% (GMcorr) was observed with urea application in low pH soil and also with AS in neutral pH soil, both under the IS irrigation regime (i.e. flooding-midseason drainage-flooding).

3.2.3. N_2O EFs for upland crops

N_2O EFs for all upland crops were calculated (Table 6) using AM and GMcorr. The AM using original data was 0.77% with a

Table 1
Emission factors (EF) for rice (non-transformed data).

Dendrogram group (95% similarity)	Results of 3 factor group data			
	Fertiliser	Water regime	Acidity–alkalinity	EF, %
1	Mix	Continual flood	Low acid	Insufficient quality data
2	Mix	Int irrigation	High acid	0.66
	NH4	Int irrigation	Low acid	
	Urea	Int irrigation	Low acid	
	Mix	Int irrigation	Neutral	
	Urea	Int irrigation	High acid	
3	No fertilizer	Int irrigation	High acid	Control data (zero N)
4	Unknown	Int irrigation	Low acid	0.37
	Urea	Keep wet	Low acid	
	Urea	Int irrigation	Unknown	
4	Unknown	Int irrigation	Low acid	1.00[a]
4	Urea	Keep wet	Low acid	0.15[a]
5	Mix	Int irrigation	Low acid	Insufficient quality data
6	Unknown	Keep wet	Alkaline	Insufficient quality data
7	Mix	Int irrigation	Unknown	Insufficient quality data
8	Urea	Unknown	High acid	Insufficient quality data

Int irrigation = Intermittent irrigation.

[a] No zero N data, so emission factor calculated from intercept of regressions.

Table 2
Emission factors (EF) for mixed crops (non-transformed data).

Dendrogram group (95% similarity)	Results of 3-FACTOR data available			
	Crop	Fertiliser type	Soil texture	EF, %
1	Wheat	No fertilizer	Clay loam	All exptl. data has zero N application
2	Corn	Urea	Clay	1.4
	Wheat	Urea	Silty sand	
	Wheat	Urea	Clay	
	Wheat	Urea	Silty clay	
2	Wheat	Urea	Silty clay	0.71[a]
3	Wheat	Urea	Sandy Loam	0.4
	Soybean	Urea	Clay	
4	Wheat	Urea	Loam	Insufficient quality data
5	Rape	Urea	Silty sand	Insufficient quality data
6	Wheat	Mix	Clay loam	1.0
7	Rape	Urea	Clay	0.8
8	Maize	Urea	Clay	1.4

[a] No zero N data, so emission factor calculated from intercept of regressions.

Table 3
Overall N_2O emission factor (EF) for rice (transformed data).

Metric used	Method of analysis	Emission factor (% of applied N)	CI_L %	CI_U%
Arithmetic mean (AM)	Reference data	0.34	0.25	0.44
Geometric mean uncorrected (GMuncorr)	Data transformed (y = ln(X)) GM without adjustment for bias	0.18	0.13	0.24
Geometric mean corrected (GMcorr)	Data transformed (y = ln(X)) GM with adjustment for bias	0.39	0.29	0.52

Abbreviation: CI_L – 95% confidence interval lower limit; CI_U – confidence interval upper limit.

Table 4
Water regime specific N_2O emission factors (EF) for rice (transformed data).

Water regime	EF (% of applied N)	
	AM	GMcorr
CF	0.11	0.12
IM	0.27	0.29
IS	0.53	0.64
UN	0.56	0.60

Abbreviation: Water regime: CF – continuously flooded; IM – Intermittent irrigation; IS – Intermittent saturation; UN – unknown.

confidence limit of 0.01–3.63. Mean GMcorr EF for mixed crops was 0.92% with a narrower confidence limit of 0.56–1.54.

Transformed data EF for upland crops was between 0.01 and

3.63 (AM), and between 0.56% and 1.54% (GMcorr).

3.2.4. Influencing factors of EF for upland crops

The N_2O emissions data for upland crops is based on 104 experiments from the central south, east, north, northeast and northwest regions of China. Predominant crops were maize, wheat, rape, soybean and upland rice. The regional N_2O EFs (GMcorr), showed significant variation (Fig. 3) with the highest EF of 1.8 from the northwest region followed by 1.3 for the east region and the lowest EF of 0.2 from the central south region. With data from only 2 experiments from the northeast, the N_2O EF for northeast region showed the highest uncertainty. The collated dataset contained no experiments located in the south-west.

Wheat and maize were predominant, with 38 experiments for maize and 48 experiments for wheat, sufficient to assess regional variation. Wheat showed significant regional variation

Table 5
Nitrogen type, water regime and pH class specific N_2O emission factors (EF) for rice (transformed data).

N type	EF (% of applied N)											
	AB	AS			Mix	Urea						
Water regime	IS	IS			UN	CF		IM	IS			UN	
pH class	N	N	L	N	H	N	N	H	N	L	H	N
AM	0.79	0.12	0.16	1.77	0.15	0.03	0.63	0.18	0.27	0.11	0.13	0.52
GMcorr	0.82	0.13	0.28	1.79	0.16	0.03	0.72	0.22	0.31	0.13	0.14	0.53

Abbreviation: nitrogen type − AB: ammonium bicarbonate; AS: ammonium sulphate; mix: compound fertilizer. Water regime − IM: intermittent irrigation; IS: intermittent saturation of soil; CF: continuous flooding; UN: unknown. pH class − H: high acid; N: neutral; L: low acid.

Table 6
Overall N_2O emission factor (EF) for upland crops of China (transformed data).

Metric used	Method of analysis	EF (% of applied N)	CI_L %	CI_U %
AM	Reference data	0.77	0.01	3.63
GMcorr	Data transformed (y = ln(X)) GM with adjustment for bias	0.92	0.56	1.54

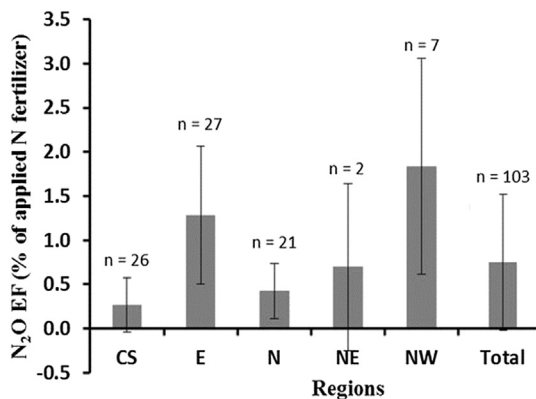Abbreviation: CI_L − 95% confidence interval lower limit; CI_U − confidence interval upper limit.

Fig. 3. Region specific N_2O Emission Factors (EF) for upland crops (transformed data). Abbreviation: CS − Central south including 4 provinces (Guangdon, Henan, Hubei, Hunan), E − East including 4 provinces (Jiangsu, Jiangxi, Shandong, Shanghai), N − North including 4 provinces (Beijing, Hebei, Inner Mongolia, Shanxi), NE − Northeast including 2 provinces (Heilongjiang, Liaoning), NW − Northwest including 1 province (Shaanxi).
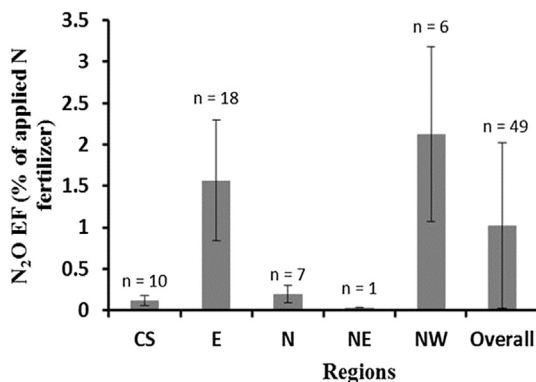

Fig. 4. Region specific N_2O Emission Factors (EF) for wheat (transformed data). Abbreviation: CS − Central south including 4 provinces (Guangdon, Henan, Hubei, Hunan), E − East including 4 provinces (Jiangsu, Jiangxi, Shandong, Shanghai), N − North including 4 provinces (Beijing, Hebei, Inner Mongolia, Shanxi), NE − Northeast including 2 provinces (Heilongjiang, Liaoning), NW − Northwest including 1 province (Shaanxi).

$(F_{(5,94)} = 18.532; p = 0.005)$ with the highest GMcorr EF of 2.2% from the northwest region followed by 1.6 for the east region, and the lowest EF of 0.2% from the northeast region (Fig. 4). Unlike

wheat, N_2O EF for maize did not show significant regional variation $(F_{(4, 71)} = 1.752; p = 0.154)$; maize data are not shown.

Countrywide EFs were determined (Table 7) for different crops combined with N fertilizer type and soil texture (determined by analysis as the most influential variables on EFs). EFs for upland crops varied significantly with soil texture, the highest GMcorr EF (1.76%) being from a silty clay soil. The lowest overall N_2O EF was from sandy loam.

3.2.5. N_2O EFs for lowland horticulture

Regressions of N_2O emission from lowland horticulture (vegetable crops) showed significant association with N fertilizer application rate $(n = 26; R^2 = 0.58; p < 0.05)$. EFs for these crops (Table 8) were calculated using AM and GMcorr methods. The AM using original data was 0.93% of applied N fertilizer. The GMcorr EF using normalized data was 0.96% of applied N fertilizer.

Transformed data analysis showed that the EF for lowland horticulture was between 0.69 and 1.17 (AM), and between 0.74 and 1.26 (GMcorr).

Comparing crops, N_2O EFs (GMcorr) were highest for Chinese cabbage (1.23%) and lowest for tomato (0.29%), see Fig. 5.

For an overall view of all crop sectors' EFs, Tables 3, 6 and 8 give the confidence limits for the main countrywide disaggregation by rice, upland crops and lowland horticulture.

4. Discussion

4.1. Rice

We compared our results with published emission factors. Under IPCC (2006) guidelines the uncertainty range for EFs for rice grown in a standard flooded soil is 0.0−0.6%. Akiyama et al. (2005) report N_2O EF during the rice-cropping season as 0.22% for fertilized fields continuously flooded, 0.37% for fertilized fields with mid-season drainage, and 0.31% for all water regimes. Gao et al. (2011) report an EF of 0.41% for paddy fields. Zheng et al. (2004) report an EF of 0.75% for paddy rice during the growing season. The literature gives a range of values which support our findings. From these results we confirm that it is important to use a water regime specific N_2O EF for an accurate assessment of national N fertilizer induced N_2O emission from rice paddies (Jianping and Chaodong, 2007; Lu et al., 2006).

N_2O emission varies significantly with the type of N fertilizer. Using the transformed dataset, in 85% of cases urea was the N

Table 7
Crop, nitrogen fertilizer type and soil texture specific N_2O emission factor (EF) for upland crops (transformed data).

Crop	Fertilizer	Soil Texture	AM EF	GMcorr EF
Peanut	Urea	UN	0.33	0.33
Maize	AS,Mix,NO$_3$,UN	UN	0.32, 0.22, 0.10, 1.37	0.32, 0.22, 0.11, 1.37
	Urea	CL, L, SL, SiL	0.77, 0.21, 0.57, 0.47	0.77, 0.23, 0.59, 0.48
	Urea	UN	0.25	0.32
Pea	Urea	UN	0.25	0.25
Rape	UN	UN	1.67	2.17
	Urea	SL, UN	0.45, 0.09	0.46, 0.09
Soybean	Urea	UN	0.64	0.64
Upland rice	Urea	UN	0.13	0.13
Wheat	Mix	SL	0.60	0.60
	UN	UN	0.58	0.86
	Urea	CL, SL, SC, SiL	0.14, 0.12, 1.76, 0.75	0.14, 0.12, 1.76, 1.30
	Urea	UN	1.15	2.35
Wheat-Maize	UN	SL	1.24	1.25
	UN	UN	0.98	0.99
Average of upland EF			0.77	0.92

Abbreviation: fertilizer nitrogen type − AB: ammonium bicarbonate; AS: ammonium sulphate; NO$_3$: ammonium nitrate; mix: compound fertilizer. Soil texture − SC: silty clay; CL: clay loam; SiL: silty loam; L: loam; SL: sandy Loam; UN: unknown.

Table 8
Overall N_2O emission factor (EF) for lowland horticulture in China (transformed data).

Metric used	Method of analysis	Emission factor (% of applied N)	CI_L %	CI_U %
AM	Reference data	0.93	0.69	1.17
GMcorr	Data transformed (y = ln(X)) GM with adjustment for bias	0.96	0.74	1.26

Abbreviation: CI_L − 95% confidence interval lower limit; CI_U − confidence interval upper limit.
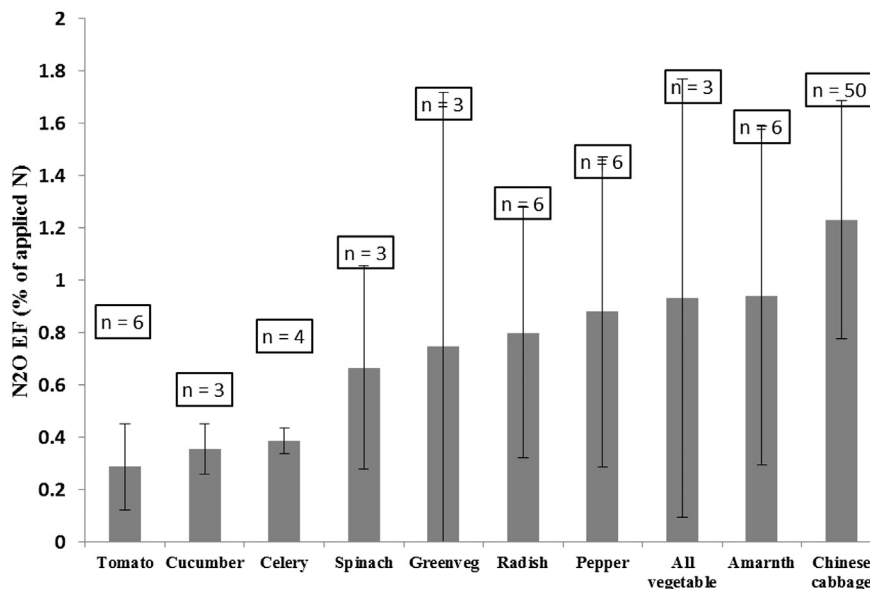
Fig. 5. Crop specific N_2O Emission Factors (EF) for vegetable crops (transformed data).

fertilizer. Mixed N fertilizer, ammonium sulphate (AS) and ammonium bicarbonate (AB) was used in 2.8%, 10% and 4% of cases, respectively. Although having limited data, our analysis gave higher emissions from mixed fertilizer, e.g. compound fertilizer as basal and urea as top dressing. Lower emissions were observed from applications of AS or urea. These results are supported by the findings using the non-transformed data. Since a low number of cases use mixed fertilizer, commonly listed with unknown irrigation and soil texture parameters, it is not possible to tell from the experiments if mixed fertilizer is responsible for higher EFs or if there are other contributing factors.

4.2. Mixed crops

Zhang et al. (2010) report high N_2O emissions mainly concentrated in the North China Plain and Sichuan Basin (central-south). However, provinces with high N_2O emissions per unit arable land area were mainly in the North China Plain and the Southeast coastal area. Gao et al. (2011) report provinces with high emissions predominantly in the eastern region and advised using region specific EFs if sufficient data is available. Our analysis has found higher emissions, generally in crops, and specifically for wheat, in the east and north. Higher northern EFs may reflect flood irrigation on

wheat, a common practise on the North China plain (Cui et al., 2012). Higher eastern EFs may reflect the higher population and higher N application (Lu et al., 2006), and being located in the humid climate region which has a bearing on higher N_2O emission (Zheng et al., 2004). Soil, climate and traditional management vary spatially in a large country like China, the use of crop specific and region specific EFs can significantly decrease the uncertainty in estimated EFs.

Gao et al. (2011) reported the EF for upland crops to be 1.05%. Lu et al. (2006) reported the EF for mixed crops to be 0.92%. Zhang et al. (2004) reported the EF for wheat as 0.26%–0.34%. The estimates for Gao et al. and Lu et al. fall in the middle of our non-transformed and transformed corrected values. A 4-year study of vegetable cultivation in the Yangtze River delta reported emission factors of 0.59–4.98%, with a mean of 2.88% (Mei et al., 2011). Our lowland horticulture values fall within the limits of these estimates with a smaller maximum value.

We collated all the environmental factors common to the experimental data and assessed them for influence on N_2O emissions. There are reports of other factors influencing variation in EFs. Bouwman et al. (2001) report major factors controlling N_2O emissions include N application rate and climate. Lu et al. (2006) reported that N input and precipitation were largely responsible for temporal and spatial variability in the EFs they measured. In our study, analyses carried out separately using non-transformed and transformed data both found only minor associations with annual precipitation and annual temperature.

Our results for the different crop types and conditions show that, despite the analyses using different datasets, having different methodologies and different thresholds of data quality acceptance, they gave similar values for EFs in the range of other published studies, giving confidence that our results can be used to improve the estimate of emissions in China. Generally, for rice our EFs are similar to the values currently used to compile the greenhouse gas inventory in China; for mixed crops, values are also similar to those used in China but looking at the ranges, our lower values (0.4 and 0.56%) are greater than currently used values (0.13%). For vegetables our results are generally smaller than those currently used in the inventory under vegetables (National Development and Reform Commission, 2014).

5. Conclusion

To summarize our overall findings, between the two analyses transformed data has a low threshold for data quality acceptance (short-term experiments can be included), and the non-transformed data has a high threshold for data quality acceptance (rice emission measurements need to be over a third of a year and mixed crops emission measurements for over a half year). For mixed crops, the non-transformed data method determined that fertiliser type, soil texture and crop type are influential, and the method reported high EFs for clay soil or maize crops. The transformed data was split into upland mixed crops (predominantly wheat and maize) and lowland horticulture. The transformed data method determined that for upland crops location is an influential factor, and reported high EFs in north-west and east China. It determined that, for lowland horticulture, fertiliser rate and crop type are important, and it reported high EFs for Chinese cabbage. For rice, both methods determined that the water regime and fertiliser type are influential factors, and reported higher EFs for irrigation with longer periods of drained soil and compound fertilizer (only on drained soil). For the transformed data method the amount of fertiliser was also influential but not for continuously flooded paddy fields.

The N_2O EF from lowland horticulture is slightly higher (transformed data analyses gave between 0.74% and 1.26% countrywide) than upland crops (non-transformed and transformed data analyses gave 0.40% and 1.54%), and EFs for both lowland horticulture and upland crops are significantly higher than those for rice (non-transformed and transformed data analyses gave values from 0.29% to 0.66% on temporarily drained soils, and 0.15%–0.37% on un-drained soils).

We conclude that the two independent analyses in this study produced consistent disaggregated N_2O EFs for rice and mixed crops, and support the use of the most influential cropping parameters on emissions to robust EFs for China.

Experimental studies covering longer measurement periods and including a control with no N application will help to increase the accuracy of these EFs.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.09.054.

References

Akiyama, H., Yagi, K., Yan, X., 2005. Direct N_2O emissions from rice paddy fields: summary of available data. Glob. Biogeochem. Cycles 19 (GB1005), 10. http://dx.doi.org/10.1029/2004GB002378.

Bouwman, A.F., 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman, A.F. (Ed.), Soils and the Greenhouse Effect. JohnWiley & Sons, Chichester, UK, pp. 61–127.

Bouwman, A.F., 1996. Direct emission of nitrous oxide from agricultural soils. Nutr. Cycl. Agroecosyst. 46, 53–70.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land. In: Food and Agriculture Organisation Report, ISBN 92-5-104698-1. International Fertilizer Industry Association and Food and Agriculture. Organization of the United Nations, City Rome.

Brocks, S., Jungkunst, H.F., Bareth, G., 2014. A regionally disaggregated inventory of nitrous oxide emissions from agricultural soils in Germany — a GIS-based empirical approach. Erdkunde 68, 125–144.

Brown, L., Brown, S.A., Jarvis, S., et al., 2001. An inventory of nitrous oxide emissions from agriculture in the UK using the IPCC methodology: emission estimate, uncertainty and sensitivity analysis. Atmos. Environ. 35, 1439–1449.

Cui, F., Yan, G., Zhou, Z., Zheng, X., Deng, J., 2012. Annual emissions of nitric oxide from a wheat-maize cropping system on a silt-loam calcareous soil in the North China Plain. Soil Biol. Biochem. 48, 10–19.

Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2007. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys. 8, 389–395.

Denman, K.L., Brasseur, G., Chidthaisong, A., 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon, S., Qin, D., Manning, M., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Finney, D.J., 1941. On the distribution of a variate whose logarithm is normally distributed. Suppl. J. R. Stat. Soc. 7, 155–161.

Gao, B., Ju, X.T., Zhang, Q., Christie, P., Zhang, F.S., 2011. New estimates of direct N_2O emissions from Chinese croplands from 1980 to 2007 using localized emission factors. Biogeosciences 8, 3011–3024. http://dx.doi.org/10.5194/bg-8-3011-2011.

Heffer, P., 2013. Assessment of Fertilizer Use by Crop at the Global Level 2010-2010/11. International Fertilizer Industry Association, Paris. http://www.fertilizer.org/imis20/images/Library_Downloads/AgCom.13.39%20-%20FUBC%20assessment%202010.pdf?WebsiteKey=411e9724-4bda-422f-abfc-8152ed74f306&=404%3bhttp%3a%2f%2fwww.fertilizer.org%3a80%2fen%2fimages%2fLibrary_Downloads%2fAgCom.13.39++FUBC+assessment+2010.pdf (accessed 10.02.15. accessed 09.02.15.).

Huang, Y., Zhang, W., Zheng, X., Li, J., Yu, Y., 2004. Modeling methane emission from rice paddies with various agricultural practices. J. Geophys. Res. 109, D08113.

IBM Corp, 2010. IBM SPSS Statistics for Windows, Version 19.0. Armonk, NY.

IPCC, 2006. IPCC guidelines for national greenhouse gas inventories. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, p. 2006.

Jianping, G., Chaodong, Z., 2007. Greenhouse gas emissions and mitigation measures in Chinese agro-ecosystems. Agric. Forest Meteorol. 142, 270–277.

Lesschen, J.P., Velthof, G.L., de Vries, W., Kros, J., 2011. Differentiation of nitrous oxide emission factors for agricultural soils. Environ. Pollut. 159, 3215–3222.

Linn, D.M., Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Sci. Soc. Am. Proc. 48, 1267–1272.

Lu, Y., Huang, Y., Zou, J., Zheng, X., 2006. An inventory of N_2O emissions from agriculture in China using precipitation-rectified emission factor and background emission. Chemosphere 65, 1915–1924.

Luo, G.J., Kiese, R., Wolf, B., Butterbach-Bahl, K., 2013. Effects of soil temperature and moisture on methane uptake and nitrous oxide emissions across three different ecosystem types. Biogeosciences 10, 3205–3219. http://dx.doi.org/10.5194/bg-10-3205-2013.

Mei, B., Zheng, X., Xie, B., 2011. Characteristics of multiple-year nitrous oxide emissions from conventional vegetable fields in southeastern China. J. Geophys. Res. 116, D12113. http://dx.doi.org/10.1029/2010JD015059.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

National Development and Reform Commission, 2012. Second National Communication on Climate Change of the People's Republic of China. Beijing. http://unfccc.int/essential_background/library/items/3599.php?rec=j&priref=7666#beg (accessed 25.08.15.).

National Development and Reform Commission, 2014. Department of Climate Change, (Ed), The People's Republic of China National Greenhouse Gas Inventory. China Environmental Science Press, p. 409.

Payne, R., Murray, D., Harding, S., Baird, D., Soutar, D., 2014. Introduction to GenStat® for Windows, seventeenth ed. VSN International, Hemel Hempstead, UK.

Qin, Y., Liu, S., Guo, Y., Liu, Q., Zou, J., 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. Biol. Fertil. Soils 46, 825–834.

Reay, D.S., Davidson, E.A., Smith, K.A., Smith, P., Melillo, J.M., Dentener, F., Crutzen, P.J., 2012. Global agriculture and nitrous oxide emissions. Nat. Clim. Change 2, 410–416.

Sichel, H.S., 1966. The estimation of means and associated confidence limits for small samples from lognormal populations. In: Proceedings of the Symposium on Mathematical Statistics and Computer Applications in Ore Valuation. Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 106–122.

Velthof, G.L., Oenema, O., 1995. Nitrous oxide fluxes from grassland in Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. Eur. J. Soil Sci. 46, 541–549.

VSN International, 2014. GenStat for Windows 17th Edition. VSN International, Hemel Hempstead, UK.

Wassmann, R., Hosen, Y., Sumfleth, K., 2009. Reducing Methane Emissions from Irrigated Rice. International Food Policy Research Institute, Washinmgton DC. http://www.asb.cgiar.org/PDFwebdocs/focus16_03.pdf (accessed 09.02.15.).

Zhang, Y.M., Chen, D.L., Zhang, J.B., Edis, R., Hu, C.S., Zhu, A.N., 2004. Ammonia volatilization and denitrification losses from an irrigated maize-wheat rotation field in the North China Plain. Pedosphere 14, 533–540.

Zhang, Q., Ju, X.-T., Zhang, F.-S., 2010. Re-estimation of direct nitrous oxide emission from agricultural soils of China via revised IPCC 2006 guideline method. Chin. J. Eco Agric. 18, 7–13.

Zheng, X., Han, S., Huang, Y., Wang, Y., Wang, M., 2004. Re-quantifying the emission factors based on field measurements and estimating the direct N_2O emission from Chinese croplands. Glob. Biogeochem. Cycles 18 article number GB2018.

Zou, J., Huang, Y., Lu, Y., Zheng, X., Wang, Y., 2005. Direct emission factor for N_2O from rice-winter wheat rotation systems in southeast China. Atmos. Environ. 39, 4755–4765.

Zou, J., Huang, Y., Zheng, X., Wang, Y., 2007. Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmos. Environ. 41, 8030–8042.