

Evaluation of the N₂O emissions from N in plant residues as affected by environmental and management factors

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Abstract

A review of the N₂O-N emission from crop residues was conducted based on new data published during the last decade. The result indicated that factors as type of crop, biochemical quality of residues, agricultural management, climate and season of the year, soil properties and soil moisture play a significant role in the rate of N₂O-N emissions. An emission factor (EF) equal to 1.055% of N applied in plant residues – derived from a simple linear regression of emitted N₂O-N (kg ha⁻¹) on N applied in crop residues (kg ha⁻¹) – represent an estimate that explains about 60% of emission variations. However, the EF of N applied in plant residues is not a constant but a variable coefficient that depends on environmental and management variables. The following two linear models – that estimate emitted N₂O-N (kg ha⁻¹) as a function of the variables N (kg ha⁻¹) applied in plant residues (NPR), rain (mm), temperature (°C) and temperature²(°C²) – were fitted to the dataset with 45 observations obtained from the reviewed literature.

$$\text{N}_2\text{O-N} = -4.154 + 0.00955 \text{ NPR} + 1.7278 \text{ ApM} + 0.003996 \text{ Rain} + 0.6242 \text{ Tem} - 0.0230 \text{ Tem}^2$$

and

$$\text{N}_2\text{O-N} = 0.6535 + [-0.0404 + 0.0078 \text{ ApM} + 0.000044 \text{ Rain} + 0.00567 \text{ Tem} - 0.0001975 \text{ Tem}^2] \text{ NPR}$$

Both models provided almost equally good statistical fit to the data, with $R^2=0.832$ and $R^2=0.829$, respectively, and most regression coefficients being significant at $P<0.01$. Because of its internal structure, the second model is more appealing as it represents N₂O-N emission as a transformation that is affected by management and environmental variables. The following expression – that correspond to the quantities in the square bracket at the right hand side of the second model – is the coefficient for the variable N applied in crop residues, and represent the emission factor as a function of application method of plant residues, rain, temperature and temperature².

$$\text{EF} = -0.0404 + 0.0078 \text{ ApM} + 0.000044 \text{ Rain} + 0.00567 \text{ Tem} - 0.0001975 \text{ Tem}^2$$

Standardization of research methodologies and data gathering and reporting, including kind of crop, N content of applied residues, agricultural management, length of the measuring period, climate, soils properties, soil temperature and water content, would facilitate further advances in studies oriented to increase the precision of N₂O-N emission estimates.

Introduction

Organic residues of plant materials are decomposed by the soil microorganisms and the organic nitrogen (N) and other reduced forms of N are nitrified to NO_3^- . However soil NO_3^- can be denitrified to N_2 . Nitrous oxide (N_2O) is formed in soils during nitrification and denitrification processes, which can occur simultaneously. They are driven by soil microorganisms, oxygen, temperature, water content and others factors.

Crop residues, cover crops or green manure can be important sources of N_2O emissions from agricultural soils (Goodroad et al., 1984; Baggs et al., 1994; Flessa and Beese, 1995; Intergovernmental Panel on Climate Change (IPCC), 1997; Wagner-Riddle et al., 1997; Kaiser et al., 1998b; Baggs et al., 2000a, b; IPCC, 2000; Shelp et al., 2000; Aulakh et al., 2001; Aulakh and Doran, 2002; Harrison et al., 2002; Baggs et al., 2003; Millar et al., 2004). However, information on the fate of N from crop residues, applied to agricultural lands, is limited (Mosier and Kroeze, 1998).

The N content from crop residues returned to the soils (kg N yr^{-1}) or FCR, in IPCC terminology, is calculated on the basis of crop biomass and its N content. Residue biomass is calculated from crop yield data and residue/crop product ratios. Two different N contents are proposed by IPCC. FracNCR0 is the fraction of N for non-N-fixing crops, (kg N kg^{-1} of biomass dry matter) and FracNCRBF is the fraction of N for N-fixing crops, (kg N kg^{-1} of biomass dry matter). Proposed default values of N content, for each of these fractions, are 0.015, and 0.03, respectively. N content in crop residues can also be obtained from animal feed tables that summarize approximate analysis of plant materials (Committee on Animal Nutrition, 2001; Cullison and Lowery, 1987). Roots biomass remaining in the soil and residues removed to feed animals, to be used in craftworks or residues mixed with mud for construction of house walls are not considered in some countries whereas climate, soil type, soil moisture, soil pH, soil and crops management, and other factors are also not considered. However the quest for realism needs to be weighed against data requirement as was pointed out by Dobbie and Smith (2003).

To estimate N_2O emissions, the IPCC methodology uses a single emission factor (EF) equal to 1.25% for fertilizer N, biological fixed N and N

from crop residues (IPCC, 1997). The numerical value of the EF is based on a compilation made by Bouwman (1996).

Significant correlations were found between N_2O emissions and soil NO_3^- as well as between N_2O production and potential N mineralization, probably due to denitrification (Baggs et al., 2000b). On the other hand, no significant correlation between N_2O emission and available soil N was found throughout the experimental period by Baggs et al. (2003). In addition, contrary to Bouwman (1996) results, when the data set was composed of measurements carried out during one or more years, no clear relationship between application rates of N and measured N_2O or NO emissions was reported (FAO, 2004), as illustrated in Figure 1

EFs for residues of oats, peas and beets, estimated from quantities of N measured in the incorporated plant residues, were found to be lower than the IPCC default value of 1.25% (Harrison et al., 2002). The measured emissions were 0.62% of the applied N, value that is lower than those used as the basis for the current IPCC adopted EF. This might be possible because spring/early summer temperatures in SE Scotland are lower than those prevailing where the other data were obtained (Smith et al., 1998b). The N_2O emissions were found to be overestimated by the IPCC methodology when compared with actual emissions. However, others authors have found EFs ranging 0.016–0.028, being higher than the IPCC value (Kaiser et al., 1998a; Kasimir-Klemedtsson and Klemedtsson, 2002; Petersen et al., 2003; Vinther et al., 2003; Millar et al., 2004).

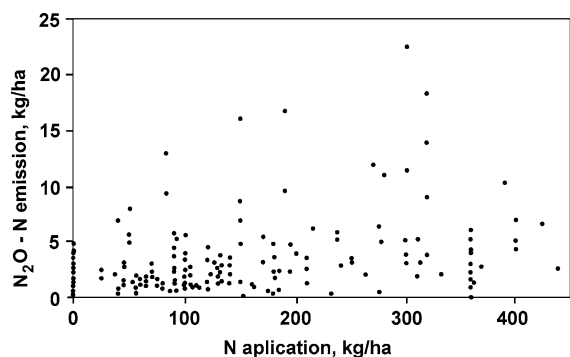


Figure 1. NO_2 emissions and N fertilizer applications rates, FAO, 2004.

Moreover, a reassessment of 54 direct N₂O EFs in croplands of China showed a huge uncertainty ($-78 \pm 15\%$ to $129 \pm 62\%$), (Zheng et al., 2004).

The IPCC methodology assumes a simple linear relationship between N₂O emission and total soil N from fertilizers, biological N fixation, and crop residues. Abiven et al. (2002) found a linear relationship between the amount of N from various plant residues mineralized after 60 days and their initial organic N content, the correlation being lower for roots ($r^2=0.7$) than for leaves ($r^2=0.93$) or stems ($r^2=0.91$). These authors hypothesized that the suberin content of roots can explain their lower decomposition. Nevertheless, the use of simple linear models linking N mineralization to biochemical residue characteristics did not allow them to represent the actual data.

Other authors have found large temporal changes in the N₂O emission rates and their data were approximately log-normally distributed (Kaiser et al., 1998a, b). Moreover, log_e (Ln) transformation of N₂O emissions were positively correlated ($r=0.93$; $P<0.05$) with N content in plant residues (Millar et al., 2004). Also, N₂O and NO emissions from fertilizers were found to follow a non linear response to the amount of applied N (FAO, 2004). FAO (2004) developed a residual maximum likelihood model to predict N₂O and NO emissions from fertilizers, and proposed the following expression:

$$\text{Ln}(\text{emissions}) = \sum_n^1 \text{kind factors } (n)$$

The reverse transformation estimates the emission in kg N ha⁻¹. In this case the resulting emission summarizes the effect of various factors. The factors involved are: kind of fertilizer (the EF for fertilizers is multiplied by the N application rate under consideration), crop specie, soil texture, C content of soil (%), soil drainage (poor, good), soil pH, climate (FAO taxonomy), length of measurement period (days) and frequency of measurements. A table of values of constants and factor classes in the models for N₂O and NO is provided. The logarithmic transformation was used to decrease the influence of extreme values.

The main objective of this study was to review recent publications on N₂O emission from crop residues in order to (a) assess the present state of development of the subject, and, (b) to collect published data on observed N₂O emissions and

related environmental and management variables to estimate quantitative relationships among them.

Material and methods

Review of recent literature

Published articles on N₂O emissions from crop residues were searched in CAB, Agris and Agricola data bases and on the Internet. The purpose was to review and evaluate the most recent published findings on this topic and to collect published data to build a data set on measured N₂O emissions and associated environmental and management variables. Most collected information has been published during the last 10 years and was selected for its direct relation with measured N₂O fluxes. Main results found in the bibliographic review and a discussion and recapitulation of important issues are presented in subsequent sections.

The collected numerical dataset, crop specie and bibliographical reference are shown in Table 1. Net cumulative N₂O emitted from N in crop residues, total N in crop residues, C/N ratios of the residues, method and length of the emission measuring period, method of residues application, soil texture, soils clay content, total rain and average temperature during the experiments were obtained from tables, figures and texts in the reviewed publications. In three cases when the C/N was not reported the values for the same crops reported elsewhere were used. The average clay content corresponding to the reported soil texture class was used as a substitute when the clay percentage was not provided by the authors. When rain and temperature was not reported (Baggs et al., 2000b, 2003), the data was obtained from UK Meteorological Office reports for meteorological stations near the experimental sites. All measurements were done in the field except those of Fleesa and Beese (1995) that were not included in the statistical analysis. The crop residue induced emissions were calculated as the difference between the emissions from plots receiving residues minus control plots or from plots receiving residues plus fertilizers minus plots receiving only fertilizer. Emissions factors calculated and published by some of the authors in reviewed publications are in Table 1.

Table 1. N₂O emissions from plant residues and related data from reviewed literature.

Ob. Num	Plant residue	Measuring N ₂ O-N			N in plant residues			Environmental factors			References	
		Total N ₂ O-N emitted (kg ha ⁻¹)	Meas. period days	Meas. Meth ⁹	N content (%)	C/N	Total N applied (kg/ha)	App. Meth ⁸	Rain ⁷ (mm)	Aver. T (°C)		Clay (%)
1	Sesbania ses. + Macroptil. atropur.	3.890	84	a	2.9	14.5	214.60	0	421	23	20	Millar et al. (2004)
2	Sesbania sesban	1.710	84	a	3.2	13.9	115.20	0	421	23	20	Millar et al. (2004)
3	Crotalaria grahamiana	1.630	84	a	2.5	16.6	287.50	0	421	23	20	Millar et al. (2004)
4	Macroptilium atropurpureum	1.400	84	a	2.5	16	360.00	0	421	23	20	Millar et al. (2004)
5	Natural fallow (broad leaved weeds and grasses)	0.000	84	a	1.6	24.5	121.60	0	421	23	20	Millar et al. (2004)
6	Sesbania sesban	0.230	61	a	2.3	22.3	128.80	0	421	23	20	Millar et al. (2004)
7	Sesbania ses. + Macroptil. atropur.	0.160	61	a	2.4	17.6	115.20	0	421	23	20	Millar et al. (2004)
8	Triticum aestivum. Straw ³	2.000	183	b	0.48	94.0	28.80	0	700	15.1	5	Aulakh and Doran (2002), Aulakh et al. (2001)
9	Oryza sativa. Straw	0.000	183	b	0.71	63.0	42.60	0	55	21	5	Aulakh and Doran (2002), Aulakh et al. (2001)
10	Sesbania aculeata	6.000	183	b	2.2	18.0	176.00	0	700	13.6	5	Aulakh and Doran (2002), Aulakh et al. (2001)
11	Vicia faba. Field bean ⁴	2.269	65	a	3.4	12.0	180.20	1	117	20	15	Baggs et al. (2003)
12	Vicia faba. Field bean ⁵	0.808	65	a	3.4	12.0	180.20	0	117	20	15	Baggs et al. (2003)
13	Triticum aestivum. Wheat ⁴	3.456	79	a	0.6	68.0	36.00	1	90	16	15	Baggs et al. (2003)
14	Triticum aestivum. Wheat ⁵	0.361	79	a	0.6	68.0	36.00	0	90	16	15	Baggs et al. (2003)
15	Secale cereale. Rye ⁴	3.230	65	a	1.1	41.0	42.90	1	117	20	15	Baggs et al. (2003)
16	Secale cereale. Rye ⁵	0.364	65	a	1.1	41.0	42.90	0	117	20	15	Baggs et al. (2003)
17	Vicia faba. Field bean ⁴	0.478	65	a	3.4	12.0	180.20	1	117	20	15	Baggs et al. (2003)
18	Vicia faba. Field bean ⁵	0.564	65	a	3.4	12.0	180.20	0	117	20	15	Baggs et al. (2003)
19	Triticum aestivum. Wheat ⁴	1.891	79	a	0.6	68.0	36.00	1	90	16	15	Baggs et al. (2003)
20	Triticum aestivum. Wheat ⁵	0.129	79	a	0.6	68.0	36.00	0	90	16	15	Baggs et al. (2003)
21	Secale cereale. Rye ⁴	0.363	65	a	1.1	41.0	42.90	1	117	20	15	Baggs et al. (2003)
22	Secale cereale. Rye ⁵	-0.068	65	a	1.1	41.0	42.90	0	117	20	15	Baggs et al. (2003)
23	Secale cereale. Rye	-0.038	19	a		15.5	13.85	0	47	9	10	Baggs et al. (2000b)
24	Brassica napus var. Olerifera.	-0.022	19	a		24.7	7.38	0	47	10	10	Baggs et al. (2000b)
25	Pisssum sativum. Winter Peas	-0.030	19	a		16.4	10.85	0	47	10	10	Baggs et al. (2000b)
26	Hordeum sativum. Winter barley	-0.034	19	a		22.0	8.07	0	47	10	10	Baggs et al. (2000b)
27	Triticum aestivum. Winter wheat	-0.017	19	a		32.6	5.53	0	47	10	10	Baggs et al. (2000b)
28	Sinapsis alba. White mustard	-0.030	19	a		17.8	10.15	0	47	10	10	Baggs et al. (2000b)
29	Trifolium repens. White clover	0.050	53	a		9.0	13.30	0	78	9	10	Baggs et al. (2000b)
30	Lotus corniculatus. Birdsfoot trefoil	0.227	53	a		11.5	12.00	0	78	9	10	Baggs et al. (2000b)
31	Medicago lupulina. BlacB medic.	0.086	53	a		14.2	12.00	0	78	9	10	Baggs et al. (2000b)

32	Pisum sativum. Forage peas	0.182	53	a	13.2	12.00	0	78	9	10	Baggs et al. (2000b)
33	Avena sativa. Oats	0.100	53	a	38.1	12.00	0	78	9	10	Baggs et al. (2000b)
34	Sinapsis alba. White mustard	0.072	53	a	30.3	11.40	0	78	9	10	Baggs et al. (2000b)
35	Lolium peren. + Fescue prat. Low N	0.400	92	c	1.15	348.45	1	104	16	70	Larsson et al. (1998)
36	Lolium peren. + Fescue prat. High N	6.000	92	c	2.12	483.36	1	104	16	70	Larsson et al. (1998)
37	Medicago sativa. Alfalfa	13.000	92	c	4.33	1004.56	1	104	16	70	Larsson et al. (1998)
38	Groundnut	0.132	72	a	2.68	70.00	1	188	28	17	Khalil et al., (2002)
39	Maize	0.314	48	a	1.57	72.00	1	183	26	17	Khalil et al., (2002)
40	Hordeum sativum. Barley ²	0.628	186	a	22*	51.00	0	385	8.1	17	Harrison et al. (2002)
41	Pisum sativum. Peas. cv. Eiffel	0.743	186	a	15*	56.00	0	385	8.1	17.0	Harrison et al. (2002)
42	Beta vulgaris. Sugar beets	0.715	133	a	42*	140.00	0	208	7.0	17.0	Harrison et al. (2002)
43	Pea –barley/grass	3.400	140	a	31.0	58.00	0	269	14.2	8.8	Vinther et al. (2003)
44	Grass clover	3.100	140	a	30.0	190.00	0	269	14.2	8.8	Vinther et al. (2003)
45	Pea –barley	2.700	140	a	43.0	16.00	0	269	14.2	8.8	Vinther et al. (2003)
46	Winter wheat/grass	2.700	140	a	34.0	27.00	0	269	14.2	8.8	Vinther et al. (2003)
47	Hordeum sativum. Spring Barley ²	0.673	139	a			0	281	6.6	17.0	Harrison et al. (2002)
48	Pisum sativum. Peas. cv. Eiffel	0.839	139	a			0	281	6.6	17.0	Harrison et al. (2002)
49	Beta vulgaris. Sugar beets	1.902	134	a			0	281	6.6	17.0	Harrison et al. (2002)
50	Beta vulgaris. Sugar beets	0.915	55	a			0	88	5.4	17.0	Harrison et al. (2002)
51	Hordeum sativum. Barley	0.390	199	a			0	315	9.1	17.0	Harrison et al. (2002)
52	Hordeum sativum. Spring Barley	0.251	139	a			0	208	7.0	17.0	Harrison et al. (2002)
53	Pisum sativum. Peas. cv. Eiffel	0.452	199	a			0	315	9.1	17.0	Harrison et al. (2002)
54	Pisum sativum. Peas. cv. Eiffel	0.365	139	a			0	208	7.0	17.0	Harrison et al. (2002)
55	Beta vulgaris. Sugar beets	0.239	43	a			0	76	5.7	17.0	Harrison et al. (2002)
56	Raphanus sativus. Fodder radish		19	a	18.4	9.69	0	47	10	10	Baggs et al. (2000b)
57	Trifolium pratense. Red Cover		53	a	10.3	13.00	0	78	9	10	Baggs et al. (2000b)
58	White clover + Wild flower		53	a	28.1	12.00	0	78	9	10	Baggs et al. (2000b)
59	Sugar Beets (Beta vulgaris)		45	a		113.00	0				Flessa and Beese (1995)
60	Stubble of Winter Wheat ⁶	2.600	124	a			0	269	14.2	2.80	Vinther et al. (2002)
61	Stubble of Pea –barley ⁶	2.600	124	a			0	269	14.2	1.90	Vinther et al. (2002)
62	Grass –clover ⁶	2.700	124	a			0	269	14.2	1.90	Vinther et al. (2002)
63	Pea –barley + rye grass ⁶	3.300	124	a			0	271	14.2	2.80	Vinther et al. (2002)

*Values taken from published data for the same crops in this work and Neeteson and Whitmore (2005), for sugar beets.

¹ N after deduction of emissions from bare ground or controls.

² N net cumulative averaging values from Figures 1 and 2 of Harrison et al. (2002).

³ Wheat straw N content estimated from the C:N ratio and assuming a C content of 45 % in the biomass.

⁴ No tillage.

⁵ Conventional tillage.

⁶ EF calculated on the basis of mineralized N; they are EF for soil organic matter.

⁷ Accumulated during the experiment.

⁸ Application method, 0: Incorporated, 1: Mulch

⁹ (a) static chamber, (b) acetylene inhibition –soil core technique, (c) dynamic chamber.

¹⁰ % of N applied in crop residues.

Statistical treatment of the data

The objective of the statistical analysis was to test the assumption that in the case of plant residues applied to the soil, the N₂O emission is a variable coefficient related to the content of N in the residues and also to other site characteristics, rather than a constant fraction of the content of N in the residues. The N₂O emission is primarily the result of the de-nitrification process, and the hypothesis is that the N₂O emission is quantitatively related not only to total N but also to the value of some of the site characteristics that affect such process. The objective of the model building procedure was first to identify the variables that are related to N₂O emissions and second, to find out whether a statistical model can be established to describe the relationships between N₂O emission and specific values of site variables.

A matrix of correlation coefficients was calculated and used to gain initial information on the degree of association between N₂O emissions and potential explanatory variables, and on the degree of association among the potential explanatory variables themselves. Perfect correlation between explanatory variables or multicollinearity violates a basic assumption underlying the regression analysis hence parameters of the regression model cannot be estimated. In the less extreme case when some of the explanatory variables are highly but not perfect collinear, the resulting statistical models may not provide the best representation of the situation being studied (Johnston, 1972). One of the proposed solutions is to eliminate from the regression analysis being made one of the variables responsible for multicollinearity (Greene, 1998).

On the basis of the results from the correlation analysis, an initial multivariable additive linear model relating N₂O emissions to potential explanatory variables was proposed to be tested with the data. The final set of explanatory variables was selected on the basis of successive regression analysis conducted according to the Backward Selection procedure (Draper and Smith, 1981). In a subsequent step, the mathematical form of the model was modified to obtain a closer representation of the mechanisms of N₂O emission as affected by the selected variables.

As a final step in the statistical analysis, an examination of the residuals of the selected regression models was conducted. The objective

was to uncover the presence of individual observation points not having the same sampling properties as the rest of the observations. This kind of observations may have negative effects in the models being built and are known as outliers. The removal of outliers from the dataset was analyzed using specific statistical procedures (Daniel and Wood, 1980; Janke and Tinsley, 2005).

As indicated before, the dataset was developed on the basis of information present in the reviewed literature. The data set contains 46 observations with complete information on N₂O emissions from plant residues and on a group of associated environmental and management variables (Table 1). This data was used in the subsequent analysis. All statistical analysis were done using the MINITAB (1996) statistical programs.

Results and discussion

N₂O emissions as affected by environmental and management variable factors

The IPCC approach estimates N₂O emissions from crop residues on the basis of only one factor, their total N content. Many experiments, however, have found evidences that N₂O emissions increase when the N content of the biomass increases: total N₂O losses during the winter increased with decreasing dry matter/N content ratio and C/N ratio of plant residues incorporated into the soil (Kaiser et al., 1998a). Cumulative denitrification losses were maximal with green manure (N = 26.8 g kg⁻¹; C/N = 14), followed by poultry manure (N = 19.5 g kg⁻¹; C/N = 12), pressmud (N = 17.4 g kg⁻¹; C/N = 22), and cattle manure (N = 6 g kg⁻¹; C/N = 35), showing an increase in denitrification with increasing N content and decreasing C/N ratio of manure (Aulakh et al., 2000). Comparatively large emissions were measured after incorporation of material with low C/N ratios (Baggs et al., 2000a). Nevertheless, various others factors discussed below are known to change the N₂O emission.

Type of crop and biochemical composition of crop residues

As it was pointed out before, the IPCC methodology differentiates between fixing and non-fixing

crops, on the basis of their N content. The type of crop has a significant influence on N₂O emissions (Kaiser et al., 1998b). The rate of residue decomposition changes with crop type: e.g., wheat straw decomposes more slowly than pea straw (Soon and Arshad, 2002). So, differences in EF between various types of crops should be taken into account when compiling N₂O inventories (Smith et al., 1998b; Dobbie and Smith, 2003).

Under controlled conditions, incorporation of various plant parts into three different types of soil led to various soil mineral N dynamics. Two plant residues, alfalfa shoots and rape leaves, out of 47 types, caused a net N mineralization immediately upon their incorporation, whereas all others induced a net N immobilization (1–33 g N kg⁻¹ of added C). Mineral N dynamics are related mainly to the organic N concentration of the residues and to their C/N ratio. After 168 d, only residues with a C/N ratio < 24 induced a surplus of mineral N as compared to the control soil. The N concentration or C/N ratios of the residues are sufficient to predict the net effect of crop residues on soil mineral N dynamics (Trinsoutrot et al., 2000). Immobilization of N has been reported in several cases (Baggs et al., 2000b; Khalil et al., 2002). On the other hand incorporation of green manure, i.e., white clover, reduced N₂O emissions from a bare soil even with C/N ratios as low as 9, and incorporation of green manure residues with C/N ratios of 38, i.e., oats, did not reduce the emissions. Also, emissions of N₂O were lower after incorporation of cover crops (winter peas, forage rape, with mustard, winter barley, grazing rye) except wheat (Baggs et al., 2000b).

Low-N corn residues (cobs, husks, and stems) all immobilized some N. However, such immobilization has always been counterbalanced or exceeded by N release of other residues. Therefore, no net N immobilization was observed when all residues are considered together. Nitrogen dynamics were related to how easy is the decomposition of residues as well as to their initial N content, being thus influenced by their physical and chemical characteristics as well as by environmental conditions. Cobs with very low initial N content and a C/N ratio of 149 decompose slowly and seem to limit microbial N needs at any given time. As a result, net amounts of N immobilized were small (Burgess et al., 2002).

It is questioned whether different plant parts should be considered separately when studying decomposition. There is also a need to develop other methods of characterization of residue quality in order to improve the prediction of residue decomposition (Abiven et al., 2002). The presence of polyphenols in plant tissues was found to influence N dynamics, at the start of incubation, showing the need to include the biochemical quality of crop residues in any C and N transformation model describing decomposition (Trinsoutrot et al., 2000).

Suberin and secondary metabolites of plant tissues as well as lignin will no doubt slow down the decomposition rate of plant residues and mineralization of organic N. The concentration of different polymers in plant tissue is the most important factor influencing decomposition of crop residues when the process is not controlled by N availability (Trinsoutrot et al., 2000).

Management practices

Soil tillage or the use of nitrification inhibitors can change the N₂O emission (Dobbie and Smith, 2003). Nitrification inhibition of applied fertilizer N in both arable crops and flooded rice systems could highly minimize N losses (Aulakh and Singh, 2001). The magnitude and pattern of emissions was found to be strongly influenced by cultivation technique. So, management practices can increase N-use efficiency and reduce N₂O emissions (Baggs et al., 2000b). Heavy soil compaction increased N₂O emissions more than light or zero compaction after fertilizer application or incorporation of residues. Nitrogen availability together with low gas diffusivity and less air-filled porosity make heavily compacted soils more anaerobic and likely susceptible to denitrification than no or lightly compacted soils (Ball et al., 1999).

Comparison of three different tillage systems – conventional (CT), reduced (RT) and zero tillage (ZT) showed that N₂O emissions were similar among the three systems (Elmi et al., 2003). A significant interaction between type of residue and cultivation technique with respect to N₂O emissions was found. Higher emissions were measured from ZT rye-treatments than from ZT bean-treatments, however higher emissions were found

from CT bean-treatments than from CT rye-treatments. This was attributed to a rapid release of N following incorporation of bean residues in the conventionally tilled soil, and to the availability of readily degradable C from the rye in the presence of anaerobic conditions under the mulch in the zero tilled soil. Also, measurement of ^{15}N - N_2O emission following application of ^{15}N -labelled fertilizer to microplots indicated that surface mulching of residues in zero till treatments resulted in a greater proportion of fertilizer N being lost as N_2O than with incorporation of residues. Combined applications of ^{15}N fertilizer and bean residues resulted in higher or lower emissions, depending on cultivation technique, when compared with the sum of N_2O from single applications (Baggs et al., 2003).

Also, N_2O emissions were found to be higher when residues were incorporated by plowing ($349 \text{ g N}_2\text{O-N ha}^{-1}$) than with a rotovator ($248 \text{ g N}_2\text{O-N ha}^{-1}$), but NO emissions were higher when a rotovator was used (Harrison et al., 2002).

Alfalfa incorporation in the fall leads to high spring emissions, while the presence of plants as in the case of alfalfa or grass can result in negligible emissions during thaw (Wagner-Riddle and Thurtell, 1998). Moreover, the particle size of residues influences the N_2O emissions. Higher N_2O losses were found with alfalfa particles 5 cm than with alfalfa ground to $< 1 \text{ mm}$ (Shelp et al., 2000).

Residual N from applied fertilizer to the previous crop can be substantial. In a spring barley long-term experiment at Rothamsted, between 28 and 39% of ^{15}N remained in the soil (0–70 cm) and stubble at harvest, mostly in organic form and a small amount of 'residual' ^{15}N was recovered in the following two spring barley crops; 8% in the first and 3% in the second one (Glendining et al., 2001). Moreover, 50–52% of the applied ^{15}N remained in the soil after rice harvest, mainly in the upper 0–5 cm layer. The unaccounted for ^{15}N was probably lost by gaseous N emissions ranging from 27 to 33% of the applied N and was unaffected by residue treatment (no residue, burned residue or untreated rice crop residue). Only 4–5% of the initial ^{15}N -labelled urea applied during the dry season to the rice crop was taken up by the succeeding rice crop to which no additional N fertilizer was applied (Phongpan and Mosier, 2002). The residual N effect should be accounted

for when two crops are sown in the same year, to prevent double counting the annual N_2O emission.

From the above, it is clear that the estimates of regional N_2O emissions based on a fixed proportion of applied N may be tenuous since the N_2O emission varies widely depending on straw and fertilizer management practices, as it is also indicated by Hao et al. (2001).

Climate and season of the year

Temperature and rainfall influences N_2O emissions from residues since the activity of soil microorganisms and plant roots are affected by these factors.

In a field study at Bushland, Texas, residue decomposition of four small grains, winter and spring wheat, winter barley, and spring oat, was studied during 14 months after harvest. According to Steiner et al. (1998) irrigation treatments during decomposition created a wide range of environmental conditions in this semi-arid location. Climate indices based on air temperature and precipitation plus irrigation were used to normalize the time scale for analysis of decomposition rates. This strategy to relate field environments to conditions producing maximum decomposition rates accounted for irrigation effects. However, use of only climatic parameters was inadequate to account for the different environments found with different amounts of residue. Under the same climatic conditions, relative decomposition rates decreased as initial biomass increased. Climate–soil–residue interactions need further elucidation to understand the impact of residue density on decomposition and on other processes in the agroecosystem. In England, the highest emissions of N_2O occurred after incorporation of grass/clover and were positively correlated with a rise in air temperature (Baggs et al., 1994). This result is not surprising since it is well known that chemical and biochemical reaction rates are dependent on temperature. Rainfall has also been found to influence N_2O emission (Baggs et al., 2000b). Observed N_2O losses were correlated with climatic data; 47% of the annual N_2O emissions occurred during winter (October–February), resulting from both physical release of subsurface-produced N_2O during soil freezing and microbial N_2O production during daily thawing and freezing cycles (Kaiser et al.,

1998b; Smith et al., 1998b). Fertilizer application stimulated emissions in spring whereas crop residues stimulated emissions in autumn and winter (Ball et al., 1999).

The effect of the season of the year was very clear in a field experiment in Eastern England. Treatments without residues and beets, ploughed down in October, showed cumulative emissions of 713 and 268 g N₂O-N ha⁻¹ as compared to 218 and 234 g N₂O-N ha⁻¹ when ploughed down in January. Emissions of NO measured immediately after harvest were stronger in August (0.99–1.55 g N₂O-N ha⁻¹ day⁻¹) than in October (0.09–0.58 g N₂O-N ha⁻¹ day⁻¹) and January (0.1–0.22 g N₂O-N ha⁻¹ day⁻¹) (Harrison et al., 2002). Nitrous oxide fluxes measured from wheat and canola crops varied greatly during the year, with the highest fluxes occurring in association with freeze-thaw events during March and April. Emissions were greater when N fertilizer (100 kg N ha⁻¹) was applied in the fall compared to spring application. Straw removal at harvest in the fall increased the N₂O emissions when N fertilizer was applied in the fall, but it decreased the emissions when no fertilizer was applied. Fall plowing also increased N₂O emissions compared to spring plowing or direct seeding. The study showed that N₂O emissions may be minimized by applying N fertilizer in spring, retaining straw, and incorporating it in spring (Hao et al., 2001).

Soil type

It is known that the type and amount of clay, pH, salt content, hydraulics and other soil properties influence the decomposition rate of plant residues. N₂O losses have been found to correlate with physical and chemical soil properties. A linear reduction of N-fertilization did not result in a linear decrease in N₂O losses, reflecting the high N-mineralization potential of the soil investigated (Kaiser et al., 1998b). Nevertheless, the magnitude and pattern of emissions was found to be influenced by soil mineral N (Baggs et al., 2000b). When N₂O emissions were compared between four different crop-fluvo-aquic soil systems (soybean, peanuts, corn and cotton) the results indicate that the nitrification potential was relatively lower and the denitrification potential was higher in Sajong black soil than in the other four soils: a fluvo-aquic

soil, a cinnamon soil, an aeolian sandy soil, and a salt-affected soil in North China. The potential of nitrification and denitrification was related to soil texture and/or soil pH (Hong et al., 2002).

Soil moisture

The influence of soil water content on N₂O and NO_x emissions has been illustrated in several instances: water logging increases N₂O-N losses to approximately 1% of the N added with sugar beet residues (Flessa and Beese, 1995); a very strong relationship between N₂O emission and soil nitrate content was found for grassland, provided the water-filled pore space was higher than 70% (Smith et al., 1998b); nitrous oxide emission increases exponentially with increasing water-filled pore space in the soil (Smith et al., 1998a); nitrous oxide fluxes are substantial only when the soil water content is high (> 27 g per 100 g) (Ball et al., 1999); under rain fed rice, large N₂O fluxes are observed shortly after rainfall events due to denitrification of accumulated NO₃⁻ (Abao et al., 2000); under flooded soil conditions, nitrate resulting from nitrification quickly disappears due to denitrification, resulting in a very high loss of fertilizer N, up to 70% of N applied (Aulakh and Singh, 2001).

According to FAO (2004), soil–water content influences N₂O and NO_x emissions from all types of soil. In general, microbial activity peaks at 30–60% water-filled pore space. Nitrification and associated N₂O and NO_x production also show a maximum activity at 30–60% water-filled pore space, while optimum conditions for denitrification may occur at 50–90 % water-filled pore space.

Descriptive analysis of collected quantitative data

Rates of emission and other data vary greatly between reported results. The average N₂O emission, calculated from 59 measured values, was 1.40 kg ha⁻¹ with a standard deviation (SD) equal to 2.12 kg ha⁻¹. In 50 of the reported studies, the average applied N was 108.4 kg ha⁻¹ with a SD of 167 kg ha⁻¹. The average N content of 27 plant residues was 1.96 % with a SD of 1.12 %. The average sampling period, out of 63 experiments, was 90 days and the SD was 50.3 days. Out of 59

cases analyzed, only the following two method of residues application were found, (a) residue incorporated into the soil; and, (b) residue left on top of the soil (mulch). The average value of the C/N ratio of 46 residues was 29.3 with a SD of 19.6. The average EF of 20 residues, calculated by different authors, was 1.54 % with the SD equal to 0.86 % and range 0.17–2.9 % (Table 1).

Statistical analysis and model building

Definition of variables

The variables included in the analysis, their units of measurement and codes used in the regression models were:

Emitted N ₂ O-N	(kg ha ⁻¹)	EmN
N in plant residues	(kg ha ⁻¹)	NPR
Application Method		ApM=0 Residues incorporated into the soil
		ApM=1 Residues left on top of the soil (mulch)
Rain	(mm)	Rain
Temperature	(°C)	Tem
Temperature ²	(°C ²)	Tem ²
Soil clay	(%)	Clay
Measuring period	(day)	MPer
C/N		C/N

As indicated in a subsequent section, a linear and a quadratic term for temperature were included in the regression models.

The observed values for these variables are in Table 1. Some of the values were directly reported in the publications reviewed while others were derived from complementary sources of information as it was explained elsewhere in this manuscript. The maximum, median and minimum values, as well as the mean and the standard deviation of the variables are in Table 2.

Correlation analysis

A matrix of correlation coefficients was calculated as a first step to evaluate the degree of association between emitted N₂O-N and the variables in the dataset as well as the pair-wise correlation between the variables. Correlation coefficients are in Table 3. The significant high correlation $r=0.776^{**}$ between emitted N₂O-N and the N content in crop residues explains 60 % of the observed variation in the former variable. Table 3 also shows a significant high correlation,

$r=0.81^{**}$, between N content in crop residues and clay content in the soil. This may probably be because high clay content is normally associated with high soil organic matter and soil N. However, high correlation or multicollinearity between pairs of potential explanatory variables may obscure the results of regression analysis and model building as will be seen in subsequent sections (Greene, 1998).

Emitted N₂O-N also have significant correlation coefficients with application method of crop residues and with soil clay, $r=0.35^*$ and $r=0.53^{**}$, respectively. Therefore these variables should also explain part of the variation of emitted N₂O-N. The C/N ratio resulted with very low correlation with N₂O-N emission, only the negative sign being in accordance with accepted knowledge on this subject. However, with no further analysis, a variable having low pair-wise correlation with emitted N₂O-N may not be excluded from the group of potential explanatory variables. These variables could show a significant relation with the dependent variable in a more elaborate statistical analysis (Daniel and Wood, 1980).

Univariate regression analysis

As a first step, the simple linear regression model

$$\text{EmN} = \alpha + \beta \text{NPR} + \varepsilon \quad [1]$$

was fitted to the data. The results are in Tables 4, 5 under column head Model [1.1] (Figure 2). The final regression equation is

$$\text{EmM} = 0.2098 + 0.01055 \text{NPR} \quad [1.1]$$

The significant high correlation coefficient $r=0.776^{**}$ between emitted N₂O-N and N content in plant residues explains 60.2 % of the observed variation in the former variable. The standard error of the regression coefficient is 0.00129.

Although many factors (climate, soil, soil management, length of the measuring period, method of N₂O-N analysis, and others) are known to influence N₂O-N emissions, such a good fit was not expected. Moreover, the Ln transformation of the emission data was found to only worsen the regression results. A test to detect outliers, describer under the Analysis of Residual section, did not provide strong evidence of the existence of such kind of observations. However, the two highest observed emissions values, out of the 46

Table 2. Descriptive statistics of variables included in the analysis and model building of the N₂O emission data.

<i>n</i> = 46	Unit	Maximum	Median	Minimum	Mean	Standard deviation
Emitted N ₂ O-N	[kg ha ⁻¹]	13.0	0.38	-0.07	1.42	2.34
N in plant residues	[kg ha ⁻¹]	1004.6	42.90	5.53	114.60	171.90
Application method	[1]	1.0	0.00	0.00	0.24	0.43
Rain	[mm]	700.0	117.00	47.00	199.70	170.70
Temperature	[° C]	28.0	16.00	7.00	15.90	5.75
Soil clay	[%]	70.0	15.00	5.00	17.07	14.78
Measuring period	[day]	186.0	68.50	19.00	83.00	47.60
C/N		94.0	22.15	9.00	29.9	19.70

[1], indicator variable. 0 = residue incorporated into the soil, 1 = left on top of soil (mulch).

Table 3. Correlation between emitted N₂O from plant residues, N content, C/N ratio, application method of plant residues, measuring period and selected environmental factors.

<i>n</i> = 46	N in plant residues	App. method	Rain	Temp.	Soil clay	Meas. period	C/N
Emitted N ₂ O-N	0.776	0.3514	0.21496	0.0828	0.5315	0.3272	-0.0694
N in plant residues		0.3705	0.1136	0.2591	0.8106	0.1241	-0.2798
App. method			-0.2612	0.354	0.5099	-0.1077	0.0896
Rain				0.2893	-0.0827	0.6118	0.02
Temp.					0.1763	-0.002	0.0168
Soil clay						0.0035	-0.1561
Meas. period							0.3163

Table 4. Regression coefficients, *t* statistics, significance level, *R*² and root mean square for additive models describing N₂O emissions.

Variables	Regression coefficients, <i>t</i> statistics and significance level			
	Model [1.1]	Model [3.1]	Model [3.2]	Model [3.3]
Intercept	0.2098 [0.79] ^a	-2.85 [-1.82]	-2.872 [-1.84]	-3.68 [-2.2]
N in plant residues	0.01055** [8.2]	0.0131** [7.03]	0.0131** [7.10]	0.00905** [7.33]
Application method		1.7321* [3.18]	1.7994** [3.4]	1.2959** [2.38]
Rain		0.0027 ⁺⁺ [1.72]	0.00349** [2.92]	0.00396** [3.10]
Temperature		0.4947* [2.32]	0.5284** [2.55]	0.5465** [2.44]
Temperature ²		-0.0186** [-2.86]	-0.0199** [-3.19]	-0.0201** [-2.98]
Soil clay		-0.0617** [-2.75]	-0.0624** [-2.79]	
Measuring period		0.0037 [0.74]		
<i>R</i> ²	0.602	0.789	0.786	0.743
RMSE	1.49	1.167	1.161	1.255
<i>N</i>	46	46	46	46

^a *t* statistic.**, *P* < 0.01; *, *P* < 0.05; ++, *P* < 0.1.

observations, do play a significant role in the result. If they are not included in the analysis the *R*² value drops to 0.22, although it remains significant (*P* < 0.01). The regression coefficients have quite different values, and the corresponding regression equation is

$$\text{EmN} = 0.492 + 0.006 \text{ NPR} \quad [1.2]$$

Following the Bouwman (1996) reasoning, the emission factor would change from 0.01055 to

0.006. However, since the two highest emission values provide data for high N inputs and no strong evidence could be found to eliminate them, the regression equation (1.1) was retained. Hence, 0.01055 is the estimated average value for the EF for N in crop residues, obtained by fitting a simple linear model to the observations in the dataset (Table 1). It should be noted that the estimated EF value is a little higher than the value of 0.0091 found by Stehfest and Bouwman (2005) for the EF

Table 5. Regression coefficients, *t* statistics, significance level, *R*² and root mean square for interactive models describing N₂O emissions.

Variables	Regression coefficients, <i>t</i> statistics and significance level			
	Model [1.1]	Model [4.1]	Model [4.2]	Model [4.3]
Intercept	0.2098 [0.79] ^a	0.5271 [1.9]	0.49 [1.76]	0.577 [2.3]
N in plant residues	0.01055** [8.2]	-0.0561* [1.9]	-0.0355 ⁺⁺ [-1.53]	-0.0374 ⁺⁺ [-1.63]
N in plant residues × Application method		0.0083 ⁺ [1.5]	0.0089 ⁺⁺ [1.63]	0.00658 ⁺⁺ [1.49]
N in plant residues × Rain		0.000024 [1.18]	0.000042** [3.33]	0.000043** [3.41]
N in plant residues × Temperature		0.0057* [2.13]	0.0055* [2.06]	0.0053* [2.02]
N in plant residues × Temperature ²		-0.00017* [-2.19]	-0.00019** [-2.51]	-0.00019** [-2.46]
N in plant residues × Soil clay		-0.00005 [-0.55]	-0.00007 [-0.73]	
N in plant residues × Measuring period		0.00014 [1.13]		
<i>R</i> ²	0.602	0.767	0.759	0.756
RMSE	1.49	1.227	1.231	1.224
<i>n</i>	46	46	46	46

^a *t* statistic.**, *P* < 0.01; *, *P* < 0.05; ++, *P* < 0.1; +, *P* < 0.2.

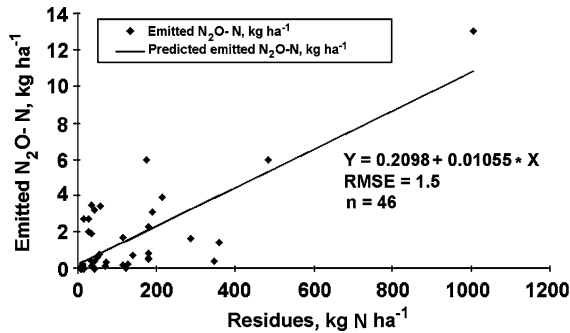


Figure 2. Emitted N₂O-N, kg ha⁻¹ as a response to total crops residue N content, kg ha⁻¹.

for N in nitrogen fertilizers, but lower than the IPCC EF value of 1.25.

The IPCC EF value was deduced from data coming mainly from fertilizers, which are considered to be a faster releasing N source than plant residues. A long term experiment that lasted 27 years, comparing mineral and organic fertilization with an equal total N, P, K content applied to a wheat–bean rotation, showed that yearly rates of 10 ton of manure increased the soil organic matter content during the first years. Later on, all new organic matter was decomposed by soil microorganisms and all N mineralized. Moreover, no significant yields differences were found between long term application of organic matter or mineral fertilizer (Novoa et al., 1991). Hence, it seems that when organic matter is applied for many years to a soil, N coming from organic matter or mineral fertilizer (sodium nitrate, in this case) will have a similar behavior. That could

explain why no important differences were found on the EFs discussed above.

Model [1] and corresponding regression equation (1.1) represent a baseline to compare multivariable models. According to the value of the significant (*P* < 0.01) regression coefficient *b* = 0.01055, the emission of N₂O-N is equal to 10.55 g kg⁻¹ of N in crop residues. However, as indicated before, the value of *R*² = 0.602 indicates that regression equation (1.1) explains only 60.2 % of that emission. About 40 % of the variation in N₂O-N emission remains unexplained.

Multivariate regression analysis – linear additive model

To evaluate the effect of environmental and management factors on N₂O-N emission, a multivariate linear regression model was fitted to the data, under the assumption that the effect of the independent variables was additive. The model was

$$\text{EmN} = \alpha + \beta_1 \text{NPR} + \beta_2 \text{ApM} + \beta_3 \text{Rain} + \beta_4 \text{Tem} + \beta_5 \text{Clay} + \beta_6 \text{MPer} + \varepsilon \quad [2]$$

The C/N ratio was not included in the model as a result of the low correlation with N₂O-N emission (Table 3) and considering that a preliminary analysis indicated no improvement in the regression statistics. A graphical analysis indicated that the effect of temperature was quadratic. This is in agreement with the observed fact that temperature has an increasing, optimum and decreasing effect

over biological reactions, in this case, microorganism behavior and enzymes rate of reaction. Hence a quadratic term for temperature Tem^2 was included in model [2] that took the form

$$\begin{aligned} EmN = & \alpha + \beta_1 NPR + \beta_2 ApM + \beta_3 Rain \\ & + \beta_4 Tem + \beta_{44} Tem^2 + \beta_5 Clay \quad [3] \\ & + \beta_6 MPer + \varepsilon \end{aligned}$$

Individual terms should remain in Model [3] if they do not violate accepted biological and agronomic knowledge and satisfy statistical criteria. The Backward Elimination procedure was used to determine what terms should remain in the model. The procedure is based on an F test used to test the significance of the decrease in the sum of squares for regression that results from deleting a variable in the model. If the decrease in the regression sum of squares is non-significant, then the variable in question can be deleted (Draper and Smith, 1981). In the particular case of the last term in the model, the t test of the regression coefficient is equivalent to the F test mentioned above and can be used with the same effect (Freund et al., 2003).

Model [3] was fitted to the data and regression coefficients and related statistics are in column headed Model [3.1] in Table 4. The t statistics for regression coefficients are significant at $P < 0.05$ except that of rain that is significant at the 10 % level and that for the measuring period term that is not significant. However, the sign of the regression coefficient for soil clay is negative and this result is not consistent with accepted agronomic knowledge.

Regression model [3.2] that resulted from deleting the measuring period term (MPer) from regression [3.1] was fitted to the data (Table 4). All regression coefficients in [3.2] are significant at $P < 0.01$.

Regression coefficients for models [3.1] and [3.2] are highly stable, as well as the R^2 and root mean square error. The negative coefficient for soil clay remains unchanged, with a highly significant t statistic, although the sign contradict what is expected from biological and agronomic knowledge. The negative sign is the most probable effect of the high correlation between soil clay and the variable N in crop residues ($r = 0.811$, Table 3). Hence soil clay was deleted from regression model [3.2] and model [3.3] was fitted to the data.

Regression model [3.3] was selected to describe N_2O -N emission as an additive function of N content in crop residues, method of application of residues, rain and linear and quadratic terms for temperature. Regression coefficients resulted with the expected signs and their t statistics are greater than 2, being significant at $P < 0.01$. Model [3.3] explain 74.3 % of the observed variation in N_2O -N emissions and has a root mean square error equal to 1.26.

Multivariate statistical analysis – linear interactive models

The models analyzed in the previous section describe the N_2O -N emission as an additive processes whose end result is the summation of the effect of different factors acting separately. The following alternative model was tested, considering that N_2O emission is the result of a biological transformation of N in plant residues modified by the effect of environmental and management factors. The form of the proposed linear interactive model is

$$\begin{aligned} EmN = & \alpha + \beta_1 NPR + \beta_{12}(NPR)(ApM) \\ & + \beta_{13}(NPR)(Rain) + \beta_{14}(NPR)(Tem) \\ & + \beta_{144}(NPR)(Tem^2) + \beta_{15}(NPR)(Clay) \\ & + \beta_{16}(NPR)(MPer) + \varepsilon \quad [4] \end{aligned}$$

where the N_2O -N emission is proportional to the amount of N in plant residues but the proportionality factor is modified by the interaction effect of related variables.

Terms in model [4] can be rearranged by factoring out NPR at the right hand side

$$\begin{aligned} EmN = & \alpha + (\beta_1 + \beta_{12}ApM + \beta_{13}Rain \\ & + \beta_{14}Tem + \beta_{144}Tem^2 + \beta_{15}Clay \quad [5] \\ & + \beta_{16}MPer)(NPR) + \varepsilon \end{aligned}$$

Letting

$$\begin{aligned} B = & (\beta_1 + \beta_{12}ApM + \beta_{13}Rain + \beta_{14}Tem \\ & + \beta_{144}Tem^2 + \beta_{15}Clay + \beta_{16}MPer) \quad [6] \end{aligned}$$

and substituting B in model [5] results

$$EmN = \alpha + B(NPR) + \varepsilon \quad [7]$$

In [7], the coefficient B represents the N_2O emission factor. However emission factor B is not a constant value but, as described in [6], it is a function of a fixed coefficient β_1 and of other factors, each one multiplied by their respective β coefficient, that modify the emission process. The constant term α is the intercept in the regression equation that should be close to zero when N from plant residues is not available. ε is the regression error term.

Model [4] was fitted to the data and regression coefficients and related statistics are under column headed Model 4.1 in Table 5. The regression coefficient for the interaction term (N in plant residues) (Soil clay) is not significant and the value for the t statistics is less than 1.0. The regression coefficient for the interaction term (N in plant residues) (Measuring period) is not significant and the t statistic is greater than 1. The levels of significance for the remaining coefficients are $0.01 < P < 0.25$, and the absolute value of their t statistics are equal or above 1.5. Applying the Backward Elimination procedure, models [4.2] and [4.3] were fitted to the data by successively deleting the terms (N in plant residues) (Measuring period) and (N in plant residues) (Soil clay), respectively. Deleting the last two terms from model [4.1] had no practical effect on the R^2 value or the root mean square error. In model [4.3] the absolute value of the t statistics for all regression coefficients is greater than 1.49. Significance levels for regression coefficients are $P < 0.20$ for term N in plant residues and for interaction (N in plant residues) (Application method), respectively; $P < 0.01$ for interaction (N in plant residues) (Rain); and $P < 0.05$ for interactions (N in plant residues) (Temperature) and (N in plant residues) (Temperature²), respectively.

Model [4.3] provides a closer representation to N_2O - N emission as affected by environmental and management factors, and it also presents a slightly better fit to the data ($R^2 = 0.756$) than model [3.3] ($R^2 = 0.743$).

Analysis of residuals

An analysis of residuals from estimated regressions models [3.3] and [4.3] was conducted. It was found that for observation 35 (Table 1) the value of the standardized residuals were -3.731 and -3.486 in models [3.3] and [4.3], respectively. Standardized residuals with absolute values greater than two

may be suspected to correspond to observations that do not belong to the parent population from the sample being analyzed (outliers). However this evidence is not considered sufficient to declare that the observation is an outlier. The Table for an Approximate Test for Outliers in Linear Models (Lund, 1975) provides a more formal test based on the standardized residual, that can be applied to the case of one suspected outlier. The standardized residuals for observation 35 in models [3.3] and [4.3] are larger than the critical values 3.40 in the Table for $P < 0.01$. However significant, this is an approximate test and the subject deserved further analysis.

The final analysis was conducted using a stringent test statistic as described by Janke and Tinsley (2005). The test statistic is based on a particular version of the studentized residual, also called studentized deleted residual or TRESIDUAL (MINITAB, 1996). The residual for observation i th is equal to the difference ($Y_i - \hat{Y}_{(i)}$) between the observed Y_i and the predicted $\hat{Y}_{(i)}$ obtained from a regression calculated after deleting the i th suspicious observation. The test statistic is constructed by dividing ($Y_i - \hat{Y}_{(i)}$) by the standard error of the residual, that uses the variance $s_{(i)}^2$ from the regression that does not include the i th observation. The test statistic has the t distribution with $(n-k-1)$ degrees of freedom, where n is the total number of observations and k is the number of parameters in the model (Janke and Tinsley, 2005).

The calculated t values for the studentized deleted residuals (MINITAB, 1996), corresponding to observation No. 35 in regression models [3.3] and [4.3] were -4.562 and -4.126 , respectively, both being significant at the probability level $P < 0.0005$. According to the test, the probability that observation 35 belongs to the same parent population of the observations in the dataset was considered sufficiently low, providing evidence that the observation can be considered an outlier. The interpretation is that the N_2O - N emission corresponding to observation 35 may have been affected by a particular factor or group of factors whose effects are not present in the remaining observations. It has been suggested that this particular low level of N_2O - N emission may be the result a high C/N ratio (Larson et al., 1998). However, in the same dataset there are other crop residues with higher C/N ratios that do not present comparable low N_2O - N emissions. Hence, obser-

vation 35 was not considered in the final analysis, and the number of observations in the dataset was reduced to $n=45$.

Models selected to describe the effect of environmental and management variables on the N₂O-N emission from plant residues

Regression coefficients and related statistics for regression equations corresponding to models [3.4] and [4.4] estimated with the 45 observations are in Table 6.

The level of significance for all regression coefficients was higher when compared with the significance of coefficients estimated before deleting observation 35 (Tables 4 and 5). R^2 values also improved from 0.743 for model [3.3] to 0.832 for model [3.4] and from 0.756 for model [4.3] to 0.829 for model [4.4] (Tables 4, 5 and 6). Root Mean Square Errors also decreased by 18.2 and 15.5% for models [3.4] and [4.4], respectively.

Considering the calculated statistics and significant levels for regression models [3.4] and [4.4], both models provide a similar result in terms of the degree of statistical fitness to the data. However, as it was stated earlier, a difference results from the algebraic structure of the models. Model [3.4] describes the N₂O-N emission as a linear function of the N content in plant residues, method of residue application, rain, temperature, and temperature². In model [4.4], the N₂O-N emission is a linear function of the N content in plant residues. However the regression coefficient for the variable N in plant residues is itself a linear function of variables method of residue application, rain, temperature and temperature².

Substituting regression coefficients [4.4] from Table 6 in model [5] the regression equation (5.8) results,

$$\begin{aligned} \text{EmN} = & 0.6535 + [-0.0404 + 0.0078 \text{ ApM} \\ & + 0.000044 \text{ Rain} + 0.00567 \text{ Tem} \\ & - 0.000198 \text{ Tem}^2] \text{ NPR}. \end{aligned} \quad (5.8)$$

The resulting emission factor (EF) is the expression in between square brackets at the right hand side of (5.8),

$$\begin{aligned} B = & -0.0404 + 0.0078 \text{ ApM} + 0.000044 \text{ Rain} \\ & + 0.00567 \text{ Tem} - 0.0001975 \text{ Tem}^2. \end{aligned} \quad (5.9)$$

The value B of the EF is not a constant but a function of variables application method, rain, temperature and temperature², derived from regression model [4.4]. Proper values of the variables do adjust the EF value B to particular conditions represented in the sample dataset.

The domain of definition of regression models [3.4] and [4.4] in Table 6 is given by the range of the explanatory variables defined in Table 2, not considering observation 35. However, the regression models may be validated for values of the explanatory variables that are outside their domain of definition, to provide valid estimates of N₂O-N emission under different conditions. Also other explanatory variables might be tested to be included in the regression models provided that sufficient new observations including the new variables become available.

Table 6. Regression coefficients, t statistics, significance level, R^2 and root mean square for models describing N₂O emissions.

Variables	Regression coefficients, t statistics and significance level		
	Model [3.4] t statistic	Variables	Model [4.4] t statistic
Intercept	-4.1544 [-3.05] ^a	Intercept	0.6535 [3.07]
N in plant residues	0.00955** [9.40]	N in plant residues	-0.0404* [2.08]
Application method	1.7278** [3.8]	N in plant residues × Application method	0.0078* [2.08]
Rain	0.003996** [3.82]	N in plant residues × Rain	0.000044** [2.08]
Temperature	0.6242** [3.39]	N in plant residues × Temperature	0.00567** [2.54]
Temperature ²	-0.0230** [-4.14]	N in plant residues × Temperature ²	-0.0001975** [-3.07]
R^2	0.832		0.829
RMSE	1.026		1.034
n	45		45

^a t statistic. **, $P < 0.01$; *, $P < 0.05$.

Summary and conclusions

Limited, variable and often contradictory information concerning N₂O emissions from crop residues was found in a review of information published during the last decade. Differences in factors such as (a) type of crop (fixing N, non fixing plants), (b) biochemical composition of crop (C/N ratio, polyphenols, suberin and polymers content), (c) management practices (tillage system, use of nitrification inhibitors), (d) climate and season of the year (T°, rain, spring–summer, autumn–winter), (e) soil properties (clay content as well as pH, salt content, hydraulics and other properties), and, (f) soil moisture (higher nitrification when water filled space is between 30 and 60 % and denitrification increases over 50 %), may have an effect on N₂O emissions and can explain those results.

According to regression equation (1) – calculated following present IPCC indications and with R² equal to 0.6 – a global EF of 1.055 % could be suitable as a general working approximation to estimate N₂O-N emissions from crop residues.

However the EF of crop residues is in fact dependent on environmental and management factors as it has been found in this research. Based on regression analysis applied to a dataset built on information found in the reviewed publications, the following two regression equations were found to provide almost the same high degree of fit to data. They represent statistical models relating measured N₂O emissions with associated management and environmental variables.

$$\begin{aligned} \text{EmN} = & - 4.1544 + 0.00955 \text{ NPR} \\ & + 1.7278 \text{ ApM} + 0.003996 \text{ Rain} \\ & + 0.6242 \text{ Tem} - 0.0230 \text{ Tem}^2. \\ R^2 = & 0.832 \end{aligned} \quad (3.4)$$

$$\begin{aligned} \text{EmN} = & 0.6535 + [-0.0404 + 0.0078 \text{ ApM} \\ & + 0.000044 \text{ Rain} + 0.00567 \text{ Tem} \\ & - 0.000198 \text{ Tem}^2] \text{ NPR}. \\ R^2 = & 0.829 \end{aligned} \quad (4.4)$$

Most regression coefficients are significant at $P < 0.01$, except coefficients for variables NPR and ApM in (3.4) that are significant at $P < 0.05$. Both models explain 83% of the observed variation

associated to N₂O-N emission values reported in the reviewed literature. These represent a 23 % increase in explained variation over the 60% variation explained by the simple linear model and regression equation.

The quantity in square brackets at the right hand side of (4.4) is the coefficient for the variable NPR, and as such, it represents the emission factor (EF) for N in plant residues. This expression indicates that the EF is no longer a constant but a variable coefficient. Given the dataset used in the statistical analysis, EF is a statistical linear function of the variables application method, rain, temperature and temperature². Proper values of the predictor variables adjust the value of the EF to particular situations.

Residual N coming from fertilizers applied to a previous crop should be accounted for when two crops are sown in the same year, not to double count N₂O emissions. The influence of factors such as soil tillage, soil water content, type of crop and biochemical quality of crop residues, and others ranging from a few to an important percentage need more attention and research. Cover crops and green manure emissions can be estimated from the amount of fertilizer used on them and their residues.

Standardization of research methodologies and data gathering and reporting, including type of crop, N content and C/N ratio of applied residues, agricultural management, climate, soil properties, soil temperature and water content, length of measuring period, and others would facilitate further advances in studies oriented to increase the precision of N₂O emission estimates.

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