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Nitrous oxide emissions from drained organic forest soils—an up-scaling based on C:N ratios

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Abstract Total emissions of N_2O from drained organic forest soils in Sweden were estimated using an equation linking the C:N ratio of the soil to N_2O emissions. Information on soil C:N ratios was derived from a national database. It was estimated that the emissions from Histosols amount to 2,820 tonnes N_2O a^{-1}. This is almost five times the value calculated for the same soils using the method suggested by the Intergovernmental Panel on Climate Change: 580 tonnes N_2O a^{-1}. The higher value in the present study can mainly be explained by improved accuracy of estimates of N_2O emissions from nutrient-rich soils, including former agricultural soils. In Sweden, in addition to 0.94 Mha of drained Histosols, there are 0.55 Mha of other types of drained organic soils. The annual emissions from these soils were estimated to amount to 1,890 tonnes of N_2O. The total emission value calculated for drained organic forest soils was thus 4,700 tonnes N_2O a^{-1}, which, if added, would increase the current estimate of the Swedish anthropogenic N_2O source strength by 18%. Of these emissions, 88% occur from sites with C:N ratios lower than 25. The exponential relationship between C:N ratio and N_2O emissions, in combination with a scarcity of data, resulted in large confidence intervals around the estimates. However, by using the C:N ratio-based method, N_2O emission estimates can be calculated from a variable that is readily available in databases. Also, the recent findings that there are exceptionally large emissions of N_2O from the most nitrogen-rich drained organic forest soils are taken into account.

Keywords C:N ratio · Drained · Emissions · Forest · Nitrous oxide · Organic soils

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Introduction

Nitrous oxide (N_2O) is one of the most important gases associated with global warming. Approximately 60% of annual global N_2O emissions are produced by soils, either naturally or as a result of anthropogenic influences (Houghton et al. 2001). In the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), all anthropogenic N_2O soil emissions were attributed to agricultural practices (Houghton et al. 2001).

However, drained organic forest soils in temperate and boreal areas can emit considerable amounts of N_2O (Maljanen et al. 2003). These emissions are

anthropogenic, since they are induced by the drainage. When the oxygen content of an organic soil increases as a result of drainage, the N stored in the organic matter is mineralized and may become available for nitrification (Kasimir-Klemedtsson et al. 1997). Both mineralization and nitrification rates have been shown to increase as the C:N ratio of soil organic matter is reduced, i.e., with increased fertility (Gundersen et al. 1998; Ollinger et al. 2002; Aber et al. 2003). Mineralization and nitrification, in turn, are known to be closely linked to N_2O emissions (Firestone and Davidson 1989).

Across the world's temperate and boreal regions, a total of around 15 Mha of wetlands have been drained for forestry (Paavilainen and Päivänen 1995). In countries like Sweden, with large areas of drained forest-land, the emissions from these soils can contribute considerably to the total national N_2O budget (von Arnold et al. 2005a). In particular, the most nutrient-rich drained organic forest soils, e.g., soils formerly used for agriculture, have been found to be very large N_2O sources (Brumme et al. 1999; Maljanen et al. 2003; von Arnold et al. 2005b). This has not been taken into account in previous Swedish estimates of total N_2O emissions from forest land (von Arnold et al. 2005a), or in the default emission factors for drained organic soils suggested by the IPCC (Penman et al. 2003).

Scaling up N_2O emissions to regional or national levels is generally associated with large uncertainties (Penman et al. 2003; Schulte-Bisping et al. 2003), since the production of N_2O is a result of several interdependent processes that are affected by a number of factors (Firestone and Davidson 1989). Butterbach-Bahl et al. (2004) and Kesic et al. (2005) applied different versions of the process-based model PnET-N-DNDC to Saxony in Germany and Europe, to obtain better estimates of N_2O emissions and to examine their spatial and temporal distribution. Schulte-Bisping et al. (2003) used a combined stratification and modeling approach for the same purpose for Germany. These studies were focused on forest soils in general and did not specifically address either drained or organic soils. The need to clarify the impact of organic soils on the total N_2O budget was highlighted by Kesic et al. (2005).

Klemedtsson et al. (2005) found a strong exponential relationship between soil C:N ratios and mean annual N_2O emissions from drained organic forest soils. Similar relationships have been reported previously for several nitrogen cycling processes in relation to the C:N ratio of the forest floor litter layer, in ecosystems that vary widely with regard to other properties, such as P status and climate (Adams et al. 2004). Klemedtsson et al. (2005) suggested that the correlation between C:N ratios and N_2O emissions may be suitable for scaling up N_2O fluxes from drained organic forest soils to national levels.

The work presented here focuses on estimates of N_2O emissions from drained organic forest soils, using the C:N ratio scaling approach (Klemedtsson et al. 2005). Sweden was used as an example, since the Swedish National Forest Soil Inventory (NFSI) (The Swedish National Inventory of Forests 2006a; Olsson 1999) provides detailed and reliable data on drained areas and their C:N ratios, covering the whole country. In addition, the present study aimed to test the hypothesis that the net N_2O emissions from Swedish drained organic forest soils, calculated using C:N ratios, would be higher than emissions previously calculated using other methods (von Arnold et al. 2005a), because it accounts for the high emissions from former agricultural soils and other fertile sites.

Materials and methods

N_2O flux estimates

The basis for the calculation of national N_2O emissions was the equation

$$\text{mean annual } N_2O \text{ emission} = a \cdot e^{(-b \cdot C:N ratio)} \quad (1)$$

for which $R^2_{adj} = 0.92$, as presented by Klemedtsson et al. (2005).

Equation 1 was based on annual mean values of N_2O emissions derived from static chamber measurements. Most of the values were averages from measurements collected over a period of 2–3 years. The measurement sites were distributed across southern Sweden, Finland and Germany and represented broad ranges of climate, nutrient status, drainage status, tree species and soil pH. The soils included were all drained organic forest soils, nine of which belonged to category A, one to category B and two to category C. Two of the sites had been under agriculture for some time before afforestation, while

the rest were characterized as afforested wetlands (Klemedtsson et al. 2005).

To enable confidence intervals to be calculated, a model differing slightly from Eq. 1 was fitted to the data points presented by Klemedtsson et al. (2005) (Fig. 1a). A linear fit is needed to determine variability; this was achieved using an ln to ln plot of the data (Fig. 1b), thus allowing the calculation of confidence bands.

The linear model used was:

$$\ln Y = \ln a + b \ln X + \varepsilon \tag{2}$$

where $Y = N_2O$ emission, $X = C : N$ and ε = noise or, in its exponential form:

$$Y = e^{\ln a + b \ln X + \varepsilon}. \tag{3}$$

This is a log-normal model, which can be used on condition that the noise occurs multiplicatively in the data, i.e., the noise must have a N(0, σ^2) distribution. Multiplicative noise is indicated by the residuals ($\ln Y - \ln \hat{Y}$; $\hat{Y}$ = the estimated value of Y) being randomly distributed and fitting closely to a straight line in a normal probability plot. This was the case with the available data points (Fig. 1c, d). It was, therefore, appropriate to use the model and it was possible to determine a confidence band for Eq. 4 using ordinary linear regression (Fig. 1b).

The linear model estimated for the data was

$$\ln Y = 8.69 - 3.26 \ln X \tag{4}$$

where $Y = N_2O$ emission and $X = C : N$

or, in its exponential form:

$$Y = e^{8.69 - 3.26 \ln X} \tag{5}$$

The correlation coefficient, R^2, for the linear regression was 0.87, indicating a reasonably good fit to the data. The 95% confidence band for Eq. 2 is given by the formula

$$\ln \hat{Y} \pm t_{\alpha/2}\, S \sqrt{1/n + (\ln X - \overline{\ln X})^2 / S_{xx}} \tag{6}$$

where α = the significance level, S = the root mean square error and

$S_{xx} = (n\sum(\ln X)^2 - (\sum \ln X)^2)/n$ (Milton and Arnold 2003), which, for Eq. 4, results in:

$$\ln \hat{Y} = 8.69 - 3.26 \ln X \pm 1.58 \sqrt{0.08 + (\ln X - 3.30)^2 / 3.45} \tag{7}$$

(Fig. 1b)

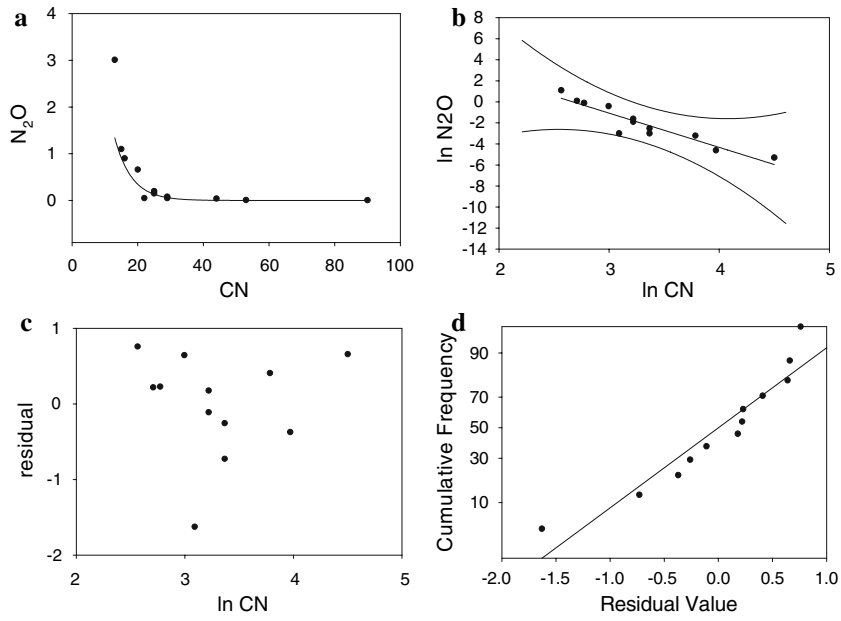

Fig. 1 Correlation between the C:N ratio of soil organic matter, at 0–0.10 m, and N_2O emissions (Eq. 5). Data from Klemedtsson et al. (2005) (**a**). The linear model for the relationship between C:N ratio and N_2O emissions, with confidence band (Eq. 7) (**b**). The residuals were randomly distributed (**c**) and fitted closely to a straight line in a normal probability plot (**d**)

The forest soil database

The C:N scaling of the N_2O emissions was based on data from the Swedish NFSI, which covers all of Sweden outside the mountain range, except arable land and urban areas. In total, about 23,000 permanent plots, each with a 10 m radius, are sampled and/or described with respect to forest status and site conditions during each 10-year sampling period. For each sampling year, the plots visited are distributed across the whole area. In the present study, data from the NFSI 1993–2002 were used, although only data collected up until the end of 2001 were available. The sampling plots in the NFSI are organized in clusters of 4–8 plots, known as *tracts*. These tracts are distributed in a regular triangular grid with random origin (Ranneby et al. 1987). The sampling intensity varies according to climatic region (Fig. 2), with a higher intensity in the south of the country.

About 18,500 of the NFSI plots are located on forest land, but only those with an estimated annual mean stem production exceeding 1 m^3 ha^{-1}, and those where the total carbon and nitrogen content had been analyzed in the topsoil, were selected for the present study. Thus, 8,543 plots from the database were used.

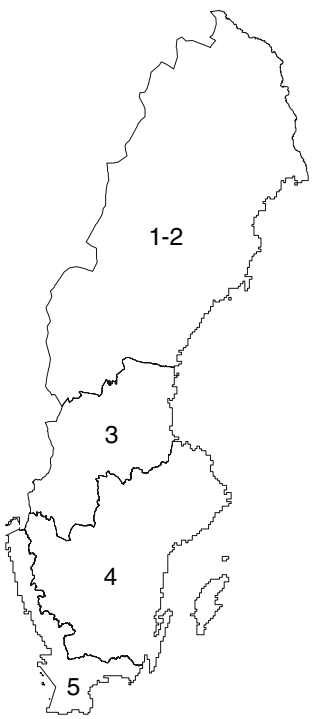

Fig. 2 The Swedish National Forest Soil Inventory (the Swedish National Inventory of Forests 2006a; Olsson 1999) divides Sweden into five regions, based on climatic conditions for forest production. The differences in N_2O emissions between these regions were investigated in the present study

In the NFSI, soil is sampled to a maximum depth of 0.30 m for O horizons and in the top 0.10 m for A horizons. The samples are dried at 35°C and sieved. The total contents of C and N of the soil fine fractions (<2 mm) are determined using a dry combustion element analyzer (LECO CNS-1000).

Definition of drained soil and soil categories

The criterion for defining sites as drained in the NFSI is that a ditch must be located within 25 m of the centre of the plot. By this definition, some undrained sites are included, since ditches (for example, ditches alongside roads) sometimes cut through areas which were initially relatively dry. However, since wet conditions are necessary for the accumulation of carbon, sites that were not previously wet were excluded from the present study: only organic soils were considered.

The drained organic forest soils of Sweden were separated into three distinct categories:

Category A. Histosols

In the Swedish NFSI, Histosols are defined as soils with a peat layer >0.30 m. This definition deviates somewhat from international classifications such as the Good Practice Guidance for Land Use, Land-Use Change and Forestry by the IPCC, where an organic horizon of at least 0.40 m is required (Penman et al. 2003).

Category B. Soils with a 0.15–0.30 m peaty horizon

Soils with a 0.15–0.30 m thick peaty layer are likely to originate from drained Histosols, if there is evidence of ditching. When a Histosol is drained, the soil becomes compacted and substantial amounts of organic material can be lost by decomposition (Berglund 1996). Thus, a large proportion of the category B soils would have been classified as Histosols prior to drainage.

Category C. Organic soils without a peat layer

Soils with an A horizon thicker than 0.10 m and a carbon content of >12% in this upper layer are

categorized as organic soils (Penman et al. 2003). Most of the soils in this category are believed to originate from drained wetlands which have previously been used for agriculture. Decomposition of peat and mixing with mineral soil have resulted in the carbon rich A horizon.

Scaling of the results

Each plot in the NFSI database was assigned a representative area (RA), which was used for scaling up to a regional or national level. This value was calculated on the basis of the sampling intensity of plots for which C and N data were available, the land use class of the plots and the distribution of land use classes at county level (Ranneby et al. 1987). RA values can be summed to give the total area of a certain soil type across regions or the whole country. The standard errors of the calculated areas were determined as follows.

The proportion of the selected class within each tract was:

$$Y_n = \Sigma\ RA_{\text{class}}/\Sigma\ RA_{\text{tract}} \text{ for all tracts, } N. \quad (8)$$

The standard error of the proportions of the class for each region was calculated from the standard deviation, s_y, for the Y_N values:

$$SE_{rg} = s_y/\sqrt{N} \quad (9)$$

The standard error of the estimated area was calculated by multiplying by the total area of the region:

$$SE_{rg(ha)} = SE_{rg} \times \Sigma\ RA_{rg} \quad (10)$$

The standard error for the country as a whole was:

$$SE_{se\ (ha)} = \sqrt{\Sigma\ SE^2_{rg(\text{ha})}} \quad (11)$$

The emissions per unit area at plot level (tonnes N_2O ha^{-1} a^{-1}) were calculated using Eq. 4 and each emission value was multiplied by the corresponding RA value (ha). The values thus obtained were then summed for different climatic regions (Fig. 2), different soil categories and for the whole of Sweden, to provide estimates of the total annual emissions of N_2O (tonnes N_2O a^{-1}).

The uncertainty ranges presented for the different soil categories, NFSI climatic regions and for the whole country are 95% confidence intervals calculated using Eq. 7 and do not account for uncertainties in the area estimates (see *Discussion*). The ranges given for the emission values per unit area are the highest and the lowest site values for each area or category.

Results

Database area estimates and C:N values

The area of drained organic forestland in Sweden amounts to almost 1.5 Mha (Table 1) and is mainly concentrated in the south of the country, with some along the northeastern side (Fig. 3). The area of drained organic forest soil in each of the NFSI climatic regions (Fig. 2) amounts to 0.53 Mha for regions 1 + 2, 0.24 Mha for region 3, 0.60 Mha for region 4 and 0.12 Mha for region 5 (Table 1).

Table 1 Areas of drained organic forestland in different regions of Sweden and their emissions of N_2O

Region	Number of plots	Area of drained organic soil (ha)	SE area of drained organic soil (ha)	N_2O emissions (tonnes a^{-1})	Uncertainty range N_2O emissions (tonnes a^{-1})[a]	N_2O emissions per unit area (g N_2O m^{-2} a^{-1})	Range N_2O emissions per unit area (g N_2O m^{-2} a^{-1})[b]
1 + 2	125	528,450	51,160	1,680	960–2 980	0.32	0.03–1.50
3	85	242,640	31,760	630	360–1,110	0.26	0.02–1.93
4	324	600,030	36,920	1,980	1,080–3,730	0.33	0.01–4.41
5	140	123,490	10,680	410	220–790	0.33	0.02–3.27
1–5	674	1,494 600	71,440	4,700	2,610–8,600	0.31	0.01–4.41

[a] The uncertainty range for the N_2O emissions is the 95% confidence interval derived from Eq. 7

[b] The ranges for the N_2O emissions per unit area are the highest and the lowest site value for each region

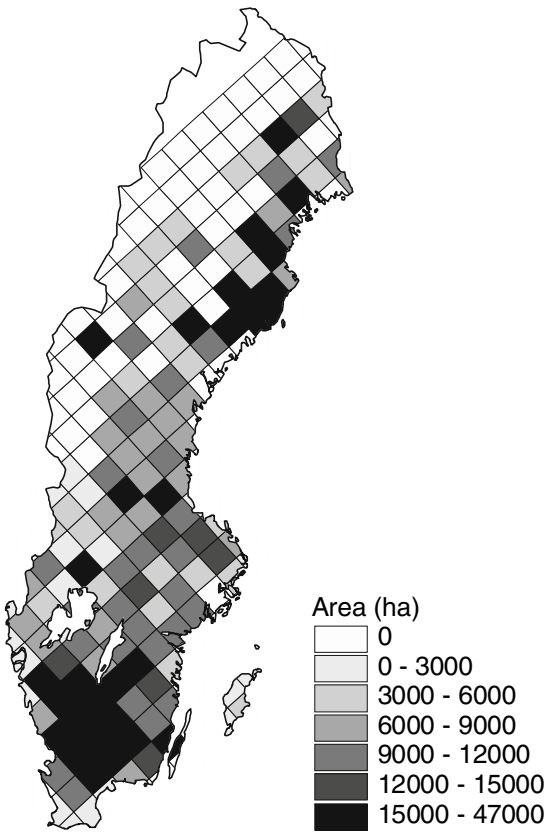

Fig. 3 The distribution of drained organic forest soils in Sweden, based on data from the Swedish National Forest Soil Inventory (the Swedish National Inventory of Forests 2006a; Olsson 1999)

Category A soils (Histosols) accounted for 66% of the total area of drained forest land (Table 2). Category B soils (soils with a 0.15–0.30 m peaty horizon) comprised 26% and category C (organic soils without a peat layer) only 8% of the total area of drained organic forest soils (Table 2). The geographical distribution was similar for categories A and B. Category C was almost entirely confined to the south of Sweden (Fig. 4).

The lower C:N ratio values tended to occur towards the south (Fig. 5). In all three soil categories there were few plots with very high C:N ratios, in accordance with the increased humification rates expected after drainage and observed reductions in C:N ratios with increases in the degree of humification (Berglund 1996). The C:N ratio frequencies were approximately normally distributed (Fig. 6) for the different soil categories. The C:N ratios were very similar for categories A and B, while in category C the C:N ratios were generally lower, and no plots had C:N ratios >35.

Of the total drained organic forest soils in Sweden, 59% had C:N ratios <25 and 88% of the estimated total N_2O emissions was produced by these sites (Table 3). A C:N ratio value of about 25 has been recognized as a cutoff point below which nitrification in organic material begins (Gundersen et al. 2006; Ollinger et al. 2002; Aber et al. 2003). This value also seems to be a cutoff point for significant N_2O production in organic soils (Klemedtsson et al. 2005). Less than 2% of the soils had C:N ratios <13, i.e., lower than the lowest C:N ratio of the data points used to derive Eq. 4 (Table 3).

N_2O emissions

According to the C:N ratio-based calculations, the emissions from the NFSI climatic regions, in tonnes N_2O a^{-1}, were 1,680, 630, 1,980 and 410 for regions 1 + 2, 3, 4 and 5, respectively (Table 1). The average emissions per unit area, in g N_2O m^{-2} a^{-1}, were 0.32,

Table 2 Areas of drained organic forestland of different soil types in Sweden and their emissions of N_2O

Category	Number of plots	Area drained organic soil (ha)	SE area of drained organic soil (ha)	N_2O emissions (tonnes a^{-1})	Uncertainty range N_2O emissions (tonnes a^{-1})[a]	N_2O emissions per unit area (g N_2O m^{-2} a^{-1})	Range N_2O emissions per unit area (g N_2O m^{-2} a^{-1})[b]
A	409	940,100	67,100	2,820	1,590–5,050	0.30	0.01–3.27
B	176	385,560	39,140	1,080	600–1,970	0.28	0.01–2.12
C	89	168,950	30,820	810	420–1,580	0.48	0.06–4.41
A–C	674	1,494,600	71,440	4,700	2,610–8,600	0.31	0.01–4.41

[a] The uncertainty range for the N_2O emissions is the 95% confidence interval derived from Eq. 7

[b] The ranges for the N_2O emissions per unit area are the highest and the lowest site value for each category

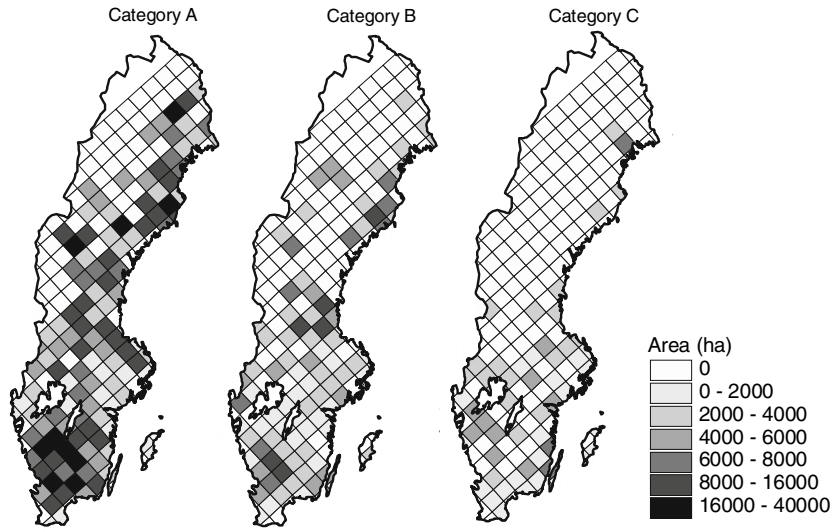

Fig. 4 Distributions of category A, B and C soils in Sweden. The soils in categories A and B show a similar geographical pattern, while the category C soils are concentrated towards the south. Based on data from the Swedish National Forest Soil Inventory (The Swedish National Inventory of Forests 2006a; Olsson 1999)

0.26, 0.33 and 0.33 for regions 1 + 2, 3, 4 and 5, respectively. The total emissions from the three soil categories, A, B and C, were 2,820, 1,080 and 810 tonnes N_2O a^{-1}, while the average emissions per unit area were 0.30, 0.28 and 0.48 g N_2O m^{-2} a^{-1}, respectively (Table 2). The total emissions from drained organic forest soils in Sweden were estimated to be 4,700 tonnes N_2O a^{-1} (uncertainty range 2 610–8 600 tonnes N_2O a^{-1}) (Table 1, 2, Fig. 7).

Discussion

Estimates

The emissions from the Swedish drained organic forest soils, per unit area, calculated on the basis of soil C:N ratios (mean 0.31, range 0.01–4.41 g N_2O m^{-2} a^{-1}) (Table 1, 2) were in the same range as several earlier estimates for German forest soils: Butterbach-Bahl et al. (2004), mean 0.75, range 0.01–6.19 g N_2O m^{-2} a^{-1}; Schulte-Bisping et al. (2003), mean 0.10, range 0.00–3.39 g N_2O m^{-2} a^{-1}; Kesik et al. (2005), mean 0.24 g N_2O m^{-2} a^{-1} (no range specified). Kesik et al (2005) also presented estimates for Sweden (mean 0.19 g N_2O m^{-2} a^{-1}, no range specified) and the whole of Europe (mean 0.18, uncertainty range 0.11–0.22 g N_2O m^{-2} a^{-1}), which are relatively close to the C:N ratio-based mean for Sweden presented here. Maljanen et al. (2004) reported emissions of up to 3.1 g N_2O m^{-2} a^{-1} from drained afforested agricultural soils in Finland, which, as expected, were in the upper part of the range for the C:N ratio-based estimate. Hence, it seems that the N_2O emission values calculated from Eq. 4 are in good agreement with literature data from independent measurements.

Using C:N ratios to scale up N_2O emissions is also consistent with widely accepted mechanisms of N_2O production. In soils, the dominant N_2O production processes are nitrification and denitrification (Firestone and Davidson 1989). Nitrification rates depend on the amount of NH_4^+ available as a result of mineralization, while the amount of NO_3^- available determines the rate of denitrification (Robertson 1989). Consequently, N_2O production from both nitrification and denitrification depends on mineralization rates. In organic soil horizons, mineralization rates, as well as nitrification rates, are closely linked to the C:N ratio (Gundersen et al. 1998; Ollinger et al. 2002).

In its Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF), the IPCC gives different emission factors for nutrient-rich and nutrient-poor sites (Penman et al. 2003). Former fens are regarded as nutrient-rich, while former bogs are regarded as nutrient-poor. The GPG-LULUCF emission factors are intended to be used for peatlands and were applied to category A soils of the present study, for a comparison of emission values. The IPCC gives no detailed instructions on how to separate nutrient-rich and nutrient-poor sites, but assuming that Histosol sites with a C:N ratio <25 were nutrient-

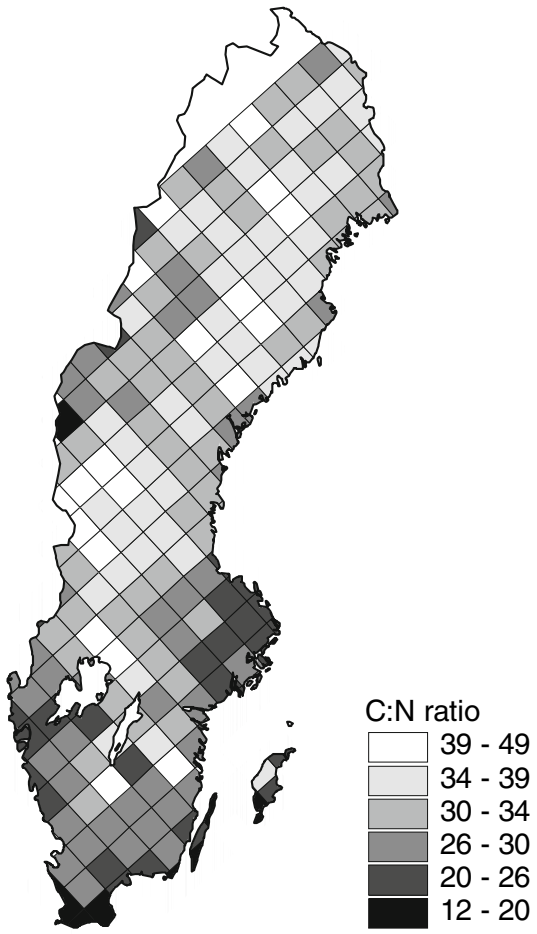

Fig. 5 The distribution of mean measured C:N ratio values of drained organic forest soils in Sweden. Data from the Swedish National Forest Soil Inventory (the Swedish National Inventory of Forests 2006a; Olsson 1999)

rich, the total emissions from drained forested Histosols were estimated to be 580 tonnes N_2O a^{-1} (range 150–2,300 tonnes N_2O a^{-1}). The N_2O emissions calculated for the same soils using Eq. 4 were 2,820 tonnes N_2O a^{-1} (range 1,590–1,595 050 tonnes N_2O a^{-1}). Since the recent evidence of large emissions from very nutrient-rich soils (e.g., Maljanen et al. 2003; von Arnold et al. 2005b) was not included in the GPG-LULUCF calculations, it is reasonable to believe that the lower emission values are due to an underestimation by the GPG-LULUCF method.

In a literature survey conducted by von Arnold et al. (2005a) it was shown that the differences in N_2O emissions between sites within Sweden were better explained by tree species (coniferous or deciduous) than by site fertility. However, in this case, site fertility was defined as potential forest productivity, determined on the basis of tree heights and forest floor vegetation. This measure includes subjective judgments and can be influenced by drainage status, which means that it is a less precise estimate of nutrient status than direct C:N ratio measurements. Based on tree species, von Arnold et al. (2005a) estimated the total N_2O emissions from Swedish drained organic forest soils to be 2,030 tonnes N_2O a^{-1} (range 1,010–3,380 tonnes N_2O a^{-1}). A second calculation for the same areas, using the GPG-LULUCF emission factors and with potential forest productivity to distinguish between nutrient-rich and nutrient-poor sites, resulted in an emission estimate of 680 tonnes N_2O a^{-1} (range 0–2,360 tonnes N_2O a^{-1}) (von Arnold et al. 2005a).

The differences between the total emission values presented by von Arnold et al. (2005a) and the value calculated in the present study (4,700 tonnes N_2O a^{-1}) are partly due to differences in the estimates of the total area of drained organic forest soils: 1.0 Mha in von Arnold et al. (2005a) and 1.5 Mha in the present study. While the C:N ratio scaling presented here was based on data from the Swedish NFSI, von Arnold et al. (2005a) used the Swedish National Forest Inventory (NFI) (the Swedish National Inventory of Forests 2006b). In the NFSI, peat depth is measured at all sites, whereas in the NFI, the proportion of the plot covered by >0.30 m of peat is estimated, and peat depth is measured only in plots where there is no mineral soil in the upper 0.30 m. A cross-analysis between the two methods revealed that the NFI method underestimates the area of Histosols by approximately 14%. In the present study, the Histosol area amounted to 0.94 Mha, compared to the 0.71 Mha estimated by von Arnold et al. (2005a). A second reason for the discrepancy in area between the two studies is that some forested organic agricultural soils (category C), with a total area of 0.17 Mha (Table 2), were included in the present study, but not in the earlier one. The area of drained mineral soils, 0.34 Mha, in von Arnold et al. (2005a) is similar to the area of category B soils, 0.38 Mha, in the present study.

Apart from the smaller area used, the lower emission values in von Arnold et al. (2005a), whether using the GPG-LULUCF method or the alternative tree species method, can probably be partly attributed to the fact

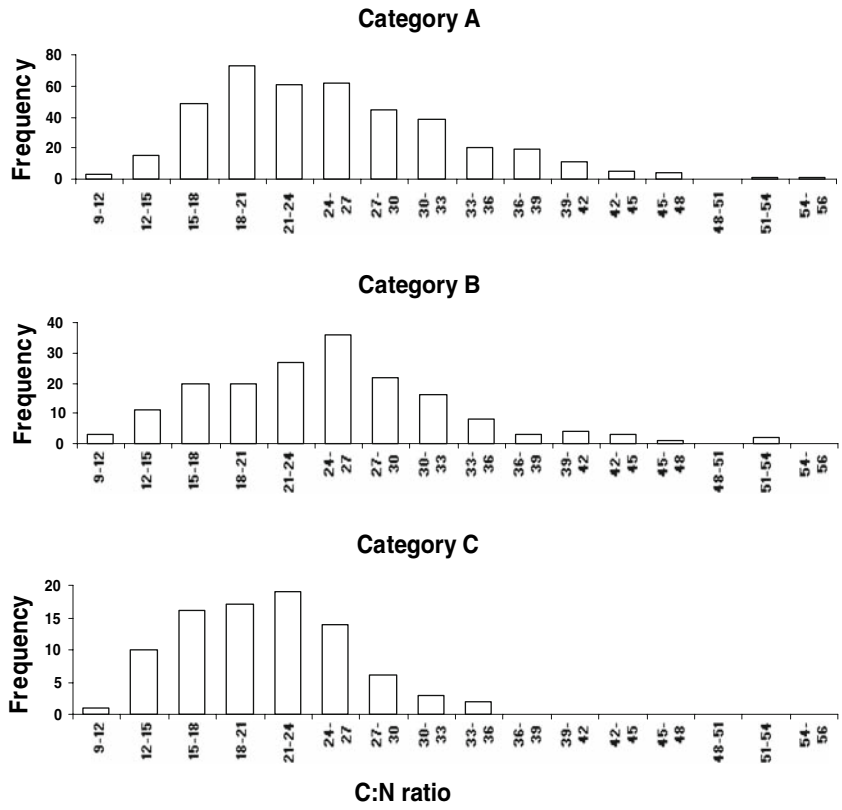

Fig. 6 Frequency distributions of the C:N ratio values used in the present study. The values were derived from the Swedish National Forest Soil Inventory (the Swedish National Inventory of Forests 2006a; Olsson 1999) and represent the drained organic forest soils in Sweden, divided into three categories: A, B and C. None of the category C soils had high C:N ratios. These soils also had a lower mean C:N ratio than the other categories. For all three categories, the C:N ratios were approximately normally distributed

Table 3 Areas of drained organic forestland with C:N ratios <25 and 13

	Area (ha)	Area (%)	N_2O emissions (tonnes a^{-1})	N_2O emissions (%)
C:N < 25	880,480	59	4,130	88
C:N < 13	26,310	2	520	11

that the high-emitting category C soils were not included and that the exponential response of the emissions to nutrient status was not recognized. Both the GPG-LULUCF method and up-scaling according to tree species are very crude approaches, since they only allow two different emission factors. Upscaling using Eq. 4 models the real situation more closely, since the level of emissions from sites are described along a curve, rather than by simple categorization.

Soil categories

In the present study, soil categories B and C have been included, along with the Histosols, when calculating total national N_2O fluxes. These additional categories were added in order to account for the impact of historical land use and management on N_2O emissions.

Soil category B

Category B is believed to consist of both soils at the edges of drained Histosols and soils which once had a thicker peat layer that has decreased in depth due to compaction and decomposition following drainage. The latter type of soil, which is in a transitional stage between a Histosol and a mineral forest soil, is created by drainage. An extensive survey of peatlands drained for forestry in Finland showed a mean subsidence of 0.22 m about 60 years after drainage (Minkkinen and Laine 1998). Berglund (1989) recorded almost 0.5 m subsidence over 14 years in a peat soil drained for agriculture, and estimated that about 80% of this was attributable to primary subsidence, i.e., physical compaction of the peat as a direct result of the removal of water.

All soils in category A that continue to be drained should eventually fall below the minimum of 30 cm

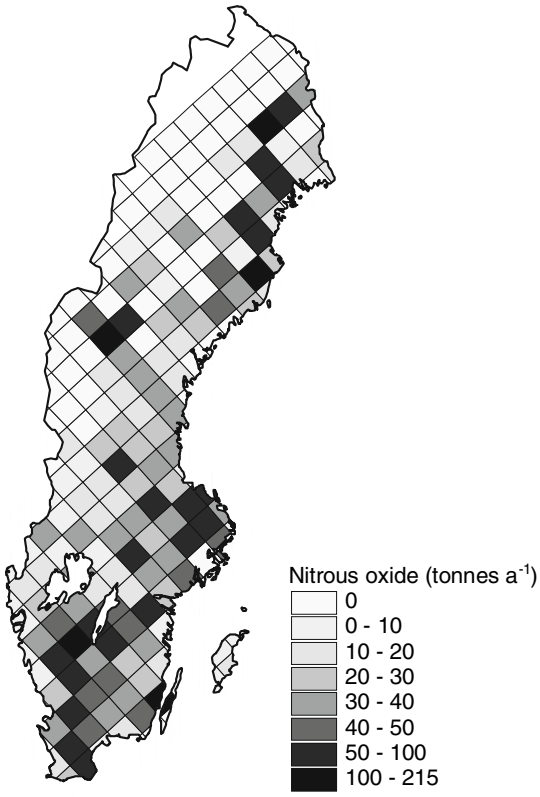

Fig. 7 The distribution of N_2O emissions from Swedish drained organic forest soils, calculated on the basis of the C:N ratio of the soil

of the Histosol definition and be transferred to category B. The regional distribution of category B, as well as its spatial C:N ratio pattern, is similar to that of category A, which is to be expected since these subgroups are, to a large extent, assumed to have a common history. The category B soils should theoretically have a similar potential for N_2O emissions to Histosols, since they are still losing soil organic matter as a result of drainage (see for example the drained alder site in von Arnold et al. 2005b).

Soil category C

The category C soils should, to a large extent, represent afforested arable land. A carbon rich A horizon is formed when peat is mixed with mineral soil by plowing. In Sweden, the area of farmed organic soils decreased from about 0.60 Mha in the 1920s (Hallgren and Berglund 1962) to about 0.25 Mha in the 1990s (Berglund 1996). It is likely that a large proportion of these soils have been afforested. The C:N ratios of the category C soils were low, probably because: (1) N-rich soils may have been those selected for cultivation; (2) agricultural soils are fertilized regularly; and (3) the rapid decomposition of organic material in farmed soil lowers its C:N ratio (Berglund 1996). The likelihood of these soils having low C:N ratios implies that the category C soils are potential hotspots for N_2O emissions. It is, therefore, important to include them in national inventories of N_2O emissions.

Statistics and uncertainties

Since Eq. 4 was based on extensive measurements covering soils in categories B and C, as well as the true Histosols of category A, the correlation can be assumed to be valid across the range. However, about 11% of the total national emissions occurred from sites with C:N ratios <13, for which no data on the relationship between C:N ratios and N_2O emissions were available (Table 3). Consequently, this 11% is the result of an extrapolation and may be an overestimate. In order to obtain an estimate of uncertainty for the up-scaling, the original Eq. 1, from Klemedtsson et al. (2005), had to be replaced by Eq. 4. Both equations describe the relationship between flux data and C:N ratios very well (R^2adj = 0.92 for Eq. 1 and R^2 = 0.87 for Eq. 4). Using Eq. 1 would have given a slightly higher total emission value (4,920 tonnes N_2O a^{-1}), but also an even further shift of the estimated emissions towards the soils with low C:N values. The emissions from soils with C:N ratios below 13 would then have been 27% of the total emissions. Equation 4 gives less emphasis to the data point with the highest emissions, which leads to more conservative N_2O emission values for the soils with C:N ratios below 13. To further clarify the uncertainty regarding the low C:N ratio part of the curve, if the data point with the highest emissions were removed, the total emissions would have been estimated to 5,740 tonnes N_2O a^{-1}, of which 10% would have been emissions from soils with C:N ratios below 13.

The method used to generate the confidence interval (Eq. 7) was appropriate, since the criteria for the technique were fulfilled (see methods section and Fig. 1). Nevertheless, the calculated 95%

confidence band was wide, which was also illustrated by the large 95% confidence interval for the total Swedish emissions of 2,610–8,600 tonnes N_2O a^{-1} (Table 2). Parkin et al. (1990) showed that taking a small sample from a highly skewed lognormal population can result in an extremely large confidence interval around a calculated mean value. In the present study, the 12 data points given in Klemedtsson et al. (2005) were too few to generate a reasonable confidence band. To decrease the confidence band, more data points need to be included, especially from sites with C:N ratios <20.

The confidence intervals for the emission values were initially calculated for each site, although uncertainties in the area estimates could not be calculated for an area smaller than a county. Therefore, these uncertainties could not be combined satisfactorily. However, with standard errors of 5% for the total area of Swedish organic forest soils and 6–18% for the different regional or soil category areas (Table 1), the uncertainties in the area estimates were negligible compared to the wide confidence band calculated for the emission values (Eq. 7). The priority, to decrease the overall uncertainty of the estimates, should be to narrow the confidence band for the emission values, through the addition of more data points.

Consequences

The total anthropogenic N_2O emissions reported for Sweden for 2003 were 26,480 tonnes (Swedish Environmental Protection Agency 2005). This value did not include any emissions from forest soils. If the estimate from the present study was added, the total value of anthropogenic N_2O emissions would increase by 18% to 31,190 tonnes N_2O a^{-1}.

If an annual emission of 4,700 tonnes N_2O (i.e., 1.50 Mtonnes CO_2 equivalents) from drained organic forest soils, as was calculated in the present study, was added to the total value of all Swedish greenhouse gas emissions for 2003 (70.6 Mtonnes CO_2 equivalents) (Swedish Environmental Protection Agency 2005), the estimate would increase by approximately 2%. This is a significant amount, especially considering the goal for Sweden being to reduce total greenhouse gas emissions by 4% between 1990 and the period 2008–2012.

The areas in Sweden with category C soils should be regarded as current emission hotspots, but could also become even more significant sources of N_2O in the future. The C:N ratios of these soils are likely to decrease with time, thus promoting higher N_2O emission rates, for two reasons. First, the C:N ratio of peat decreases as decomposition continues (Berglund 1996). Second, these soils are concentrated in the south of Sweden, where the annual N-deposition continues to be high (6–20 kg N ha^{-1} a^{-1} (Persson et al. 2004)). Correlations between N deposition rates and C:N ratios of the forest floor (Aber 2003; Kristensen et al. 2004) indicate that N-deposition can lead to decreased C:N ratios in organic soil layers. N_2O emissions have also been shown to correlate directly with N deposition (Brumme and Beese 1992; Butterbach-Bahl et al. 1998).

Conclusions

1. Drained organic forest soils would make a significant contribution if included in the total Swedish greenhouse gas budget.
2. A substantial proportion of the N_2O emissions from Swedish drained organic forest soils seems to originate from soils previously used for agriculture.
3. If a soil inventory database, including C:N ratios, is available for a region, N_2O emissions for drained organic forest soils can be calculated in a convenient and efficient way using the method presented herein. The method constitutes a valuable intermediate between local measurement schemes and more advanced modeling.
4. As hypothesized, methods of up-scaling used previously, including the default emission factors provided by the IPCC, underestimate regional emissions of N_2O in relation to the C:N ratio based up-scaling presented here. The main difference is that the C:N ratio based method takes into account the high N_2O emission values recorded from very nutrient-rich drained organic forest soils.

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