

The significance of nitrous oxide emission due to cropping of grain for biofuel production: a Swedish perspective

Å. Kasimir Klemedtsson¹ and K. A. Smith^{2,3}

¹Department of Earth Sciences, University of Gothenburg, P.O. Box 460, 405 30 Gothenburg, Sweden

²Woodlands One, Pomeroy Villas, Totnes, Devon, TQ9 5BE, UK

³School of GeoSciences, University of Edinburgh, West Mains Road, Edinburgh EH9 3JN, UK

Received: 17 June 2011 – Published in Biogeosciences Discuss.: 8 July 2011

Revised: 6 November 2011 – Accepted: 16 November 2011 – Published: 8 December 2011

Abstract. The current regulations governing production of biofuels in the European Union require that they have to mitigate climate change, by producing >35 % less greenhouse gases (GHG) than fossil fuels. There is a risk that this may not be achievable, since land use for crop production inevitably emits the potent GHG nitrous oxide (N₂O), due to nitrogen fertilisation and cycling in the environment. We analyse first-generation biofuel production on agricultural land and conclude that efficient agricultural crop production resulting in a good harvest and low N₂O emission can fulfil the EU standard, and is possible under certain conditions for the Swedish agricultural and bioethanol production systems. However, in years having low crop yields, and where cropping is on organic soils, total GHG emissions per unit of fuel produced can be even higher than those released by burning of fossil fuels. In general, the N₂O emission size in Sweden and elsewhere in northern Europe is such that there is a >50 % chance that the 35 % saving requirement will not be met. Thus ecosystem N₂O emissions have to be convincingly assessed. Here we compare Swedish emission data with values estimated by means of statistical models and by a global, top-down, approach; the measurements and the predictions often show higher values that would fail to meet the EU standard and thus prevent biofuel production development.

1 Introduction

In June 2009 the European Union Directive “Promotion of the use of energy from renewable sources” (EC directive 98/70/EG, 2009) came into force, setting goals for 20 % use of renewable energy in 2020. Under the Directive, the transport sector will be required to use at least 10 % renewable fuel. The motives are local energy security and reduced greenhouse gas (GHG) emissions, compared with those emanating from fossil fuels. However, one problem is that cropping of the feedstocks for the first-generation liquid biofuels – mainly cereal grains and oilseeds in the temperate zone, and sugar cane and palm oil in the tropics – inevitably involves emissions of greenhouse gases, nitrous oxide in particular, and some of these fuels may actually cause more emissions than the gasoline and diesel fuels they replace (Crutzen et al., 2008; Mosier et al., 2009). Thus the Directive contains sustainability standards for biofuels; for example, the savings of greenhouse gases expressed in g CO₂-equivalents per MJ when biofuel is used must be at least 35 %, compared to fossil fuel use, and this differential will be increased to 50 % in 2017. Recent modelling suggests that these targets are not being achieved in many circumstances (Ogle et al., 2008; Mosier et al., 2009; Smeets et al., 2009) and this raises the question of how to estimate nitrous oxide emissions caused by biofuel cropping in different regions, to reduce the uncertainties.

Nitrous oxide (N₂O) is a naturally occurring and chemically stable greenhouse gas, with a global warming potential about 300 times greater than that of carbon dioxide, and a lifetime of more than 100 yr in the atmosphere (Forster et al., 2007). It is produced mainly by microbial activity in soils, and expansion of agriculture and increasing



Correspondence to:

Å. Kasimir Klemedtsson
(asa.kasimir@gvc.gu.se)

use of nitrogen (N) in synthetic fertilisers and manures has resulted in agricultural soils becoming globally the main source of N₂O – 65 % of anthropogenic emissions according to IPCC (2006) and as much as 80 % according to Crutzen et al. (2008). In recent years these changes have caused the atmospheric N₂O concentration to increase by 0.25 % yr⁻¹ (Prather et al., 2001). Nitrous oxide emissions from soil have increased by 50 % during the last 150 yr due to increased nitrogen use (Crutzen et al., 2008). The discussion on the importance of N₂O emissions in agricultural production in relation to the achievement of lower emissions from biofuels compared with fossil fuels has also thrown light on GHG emissions in relation to agricultural production in general. Globally, the efficiency with which N fertiliser is used by crops is only of the order of 40 %, as measured by the recovery of N in the harvested crop (Cassman et al., 2002); the figure is slightly higher for crops in northern Europe, e.g. 47 % for Sweden (Oenema et al., 2009). This inefficiency is important in agro-ecosystems with newly added nitrogen amendments and high soil fertility, increasing the likelihood of surplus nitrogen and N₂O production (Wang and Bakken, 1997; Korsaeht et al., 2001).

A key question is: how much N₂O will be emitted by the cropping for biofuel production? Detailed earlier life cycle analyses (LCAs) on three different biofuel production systems showed both higher and lower GHG emissions than those from the use of fossil fuels and the estimated emission of N₂O was a decisive factor for the overall GHG emission level (Mosier et al., 2009). In each EU country, biofuel producers and regulatory authorities need to assess whether or not their products will achieve the threshold set by the EU directive; our purpose here was to examine ways to estimate the size of N₂O emissions from arable crop-based biofuels grown under Swedish conditions.

2 Lifecycle assessment for Swedish conditions

The RES directive [EC directive 98/70/EG] states a need for at least 35 % savings compared to fossil fuels like petrol, emitting 83.8 g CO_{2eq} MJ⁻¹. Thus 54.5 g CO_{2eq} MJ⁻¹ is the maximum allowed emission. We began by asking: how much N₂O emission can be allowed in order to meet this criterion, in production of ethanol from wheat using current farming techniques in Sweden? The calculations were made for two southern regions in Sweden for which standard yields were obtained from the Swedish Agricultural Statistics (Statistics Sweden, 2011) (Fig. 1). We used information showing that only 60.8 % of the harvested energy can be converted into ethanol energy, equal to 7.9 MJ kg⁻¹ grain (Bernesson et al., 2006, cited by Ahlgren et al., 2009); the other part goes into co-products such as distillers' grain. Also, in the ethanol production plant the conversion of the grains into ethanol needs energy, which according to Börjesson (2008) is equal to half the amount

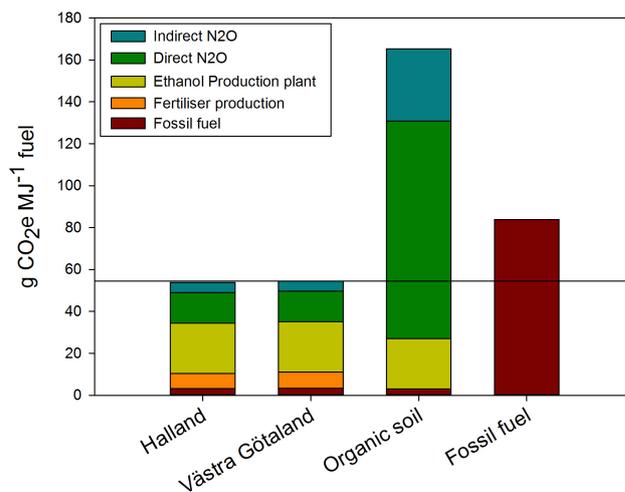


Fig. 1. LCA of greenhouse gas emissions due to production of ethanol from wheat, expressed as carbon dioxide equivalents per MJ ethanol-derived energy. For Halland and Västra Götaland, maximum N₂O-N emissions of 1.5 and 0.5 kg N ha⁻¹ yr⁻¹ for direct and indirect emissions, respectively, are allowed to achieve 35 % savings (horizontal line). Wheat production for bioethanol on unfertilised organic soils with emissions of CO₂ (not included here) and 10 kg N₂O-N ha⁻¹ yr⁻¹ would give higher emissions than fossil fuels and is shown for comparison. Standard yields for winter wheat were 6097 and 5676 kg ha⁻¹ for Halland and Västra Götaland, respectively (14 % water content) (Statistics Sweden). Fertiliser addition: 120 kg N ha⁻¹ yr⁻¹. Emissions connected with industry production of fertiliser production using catalytic conversion of N₂O into N₂, with 90 % efficiency (Yara, 2010), giving 2.9 kg CO_{2eq} kg⁻¹ N.

contained in the ethanol produced. We then assumed the same energy mix as in the overall Swedish energy system, with 43 % from renewable energy sources (Swedish Energy Agency, 2010), having low CO₂ emissions with only 1 g CO_{2eq} MJ⁻¹ (a number given by the RES directive [directive 98/70/EG]). For fossil fuels the corresponding number is 83.8 g CO_{2eq} MJ⁻¹. The production plant emissions were then estimated to be 24 g CO_{2eq} MJ⁻¹ ethanol-derived energy. Energy used for transportation and crop management, field operations and drying results in 3 g CO_{2eq} MJ⁻¹ ethanol-derived energy (Ahlgren et al., 2009). The manufacture of N fertiliser (and to a lesser extent biocides) needs much energy and also produces N₂O. The fertiliser source category is shown separately in Fig. 1 because of the large total impact, and we use a low emission value for N fertiliser production, since products produced in low-emission factories with catalytic destruction of N₂O dominate the Swedish market. Also we assume a conventional rate of fertiliser addition, 120 kg N ha⁻¹ yr⁻¹. Maximum acceptable direct N₂O emissions (E_{N₂O}), to achieve 35 % savings compared to fossil fuels, i.e. ≤54.5 g CO_{2eq} MJ⁻¹, were estimated by:

$$E_{N_2O} = (E_{CO_2M} - E_{EM}) \cdot Y \cdot (3/4) \cdot (28/44) / 298 \quad (1)$$

where E_{CO_2M} is the maximum allowed emissions for 35 % savings ($54.5 \text{ g CO}_2\text{eq MJ}^{-1}$) and E_{EM} is the sum of emissions caused by energy use and manufacturing (management, transportation, ethanol production plant and N manufacturing), Y is the crop grain yield converted into ethanol (MJ ha^{-1}), direct emissions are 3/4 and indirect emissions are 1/4 of the total N₂O emissions, division by 298 (GWP) converts CO₂ into N₂O and multiplication by 28/44 converts N₂O into N₂O-N.

All emissions in this simple introductory LCA are attributed to the ethanol production. Summing the emissions, we concluded that for the two Swedish regions N₂O emission from agricultural fields cannot exceed in total $2 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ (1.5 kg for direct emission and 0.5 kg for indirect), if the required saving of 35 % (Fig. 1) is to be achieved. Measurements on unfertilised organic soils in Sweden have shown much larger emissions from barley production (a direct emission of $10 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$) (Kasimir Klemedtsson et al., 2009); use of such land would not be possible if the “sustainability goal” were to be achieved. Therefore in the remainder of our investigation we only include mineral soils, and determine the magnitude of the emissions we may expect on the basis of flux measurements and estimation models.

3 Method

To estimate the size of agricultural N₂O emissions as a consequence of cropping of the biofuel feedstock, we need measurements. The simplest and most common measurement method is by use of flux chambers: gas-tight lids placed on frames inserted permanently (apart from having to be removed briefly during seeding and soil management operations) in the soil surface. The rate of accumulation of N₂O in the chambers is measured by gas chromatography. This gives data on direct emissions, i.e. those from the surface of the agricultural field. Chamber measurements, in spite of their limitations, are still the staple method for obtaining emission data, and are the only technique readily available to most researchers. In principle, better measurements can be made by micrometeorological techniques, which make it possible to measure the emission while disturbing neither the soil nor the crop (Wagner-Riddle et al., 2007). The emissions are often characterised by large temporal variations; thus it is important to detect sudden increases that commonly occur after fertiliser N additions or rainfall/irrigation events. This makes field measurements complicated and prolonged – they should run for at least a 12-month cycle – and consequently costly. However, since the 1980s, data have been collected in this way in many different countries and locations.

3.1 Data from Swedish measurements

Emission measurements in Sweden on crops appropriate for producing biofuels such as ethanol or biodiesel include wheat, rye, barley and oilseed rape. Here we report data on emissions from two experimental farms, both on mineral soils: Mellby gård in Halland, south west Sweden, and Logården in Västra Götaland, west Sweden. Both farms have conventional plant production systems with no livestock, and in both cases the crop was spring wheat.

The first farm, Mellby ($56^{\circ}29' \text{ N}$, $13^{\circ}0' \text{ E}$), has a mean annual temperature of 7.5° C and mean annual precipitation of 736 mm . The soil is coarse sand, with 5 % organic matter and 5–10 % clay. The experimental field was arranged as a randomized block design; each plot in the block was $3 \times 36 \text{ m}$. N₂O emissions were measured by use of 24 permanently installed manual stainless steel chambers covering an area of 0.32 m^2 (Klemedtsson et al., 1997). Extension frames (height 0.24 m) were used when the crop was too tall to be enclosed by ordinary chamber lids. When the lids had been closed (sealed by a water lock) for 35 min, the air inside the chamber was sampled by pumping it from the chamber through a gas-tight 22 ml glass vial, and back again (Weslien et al., 1998). Sampling occasions were 72, from May 1995 to June 1997, with interruptions during cold winter periods. Concomitant with the sowing, calcium ammonium nitrate (CAN) was added in April, $120 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, either by broadcasting or drilling, but one treatment was maintained without fertiliser addition.

The second farm, Logården ($58^{\circ}20' \text{ N}$, $12^{\circ}38' \text{ E}$), has a mean annual temperature of 7.9° C and mean annual precipitation of 690 mm . The soil is light clay with 30–40 % clay in the topsoil and more than 50 % in the subsoil, and an organic matter content of $>4 \%$: a soil type identified as one providing a risk of high emissions, due to small soil pores having high water-holding capacity, increasing the risk of lack of oxygen. Logården has a 7-yr crop rotation in which all crops are grown each year; it is conventionally managed, with low additions of fertiliser and minimum pesticide use. Thus to study emissions from spring wheat in successive years we had to move the sampling in the spring to the new wheat plots. The fertiliser nitrogen (NH_4NO_3 , Axan) was added at sowing in April and May and varied between 117 and $128 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. N₂O emissions were measured from April 2005 until December 2006 using six stainless steel chambers of the same type as described above. Sampling of gas was made 56 times (mostly every second week) at 10, 20, 30 and 40 min after lid closure. Occasionally sampling was unfortunately hampered due to frozen equipment during winter.

The gas was analysed by gas chromatography using a Varian 3800 Genesis instrument, equipped with a headspace auto-injector and an electron capture detector for N₂O analysis (Klemedtsson et al., 1997; Weslien et al., 2009). The gas concentration increase in the chambers was checked for

Table 1. Nitrous oxide emissions due to cropping of spring wheat at two Swedish experimental farms.

| Farm | Field/fertilisation method | N ₂ O emission | | Yield kg ha ⁻¹ |
|----------|----------------------------|---|--------|------------------------------|
| | | Average | Median | |
| | | kg N ₂ O-N ha ⁻¹ yr ⁻¹ | | |
| Mellby | Control (no N) | 2.5 | 1.9 | 2400 |
| | Broadcasting | 2.9 | 2.1 | 3300 |
| | Drilling | 1.9 | 1.3 | 3300 |
| Logården | Field C6 ^a | 1.1 | 0.6 | 5800 |
| | Field C2 ^b | 0.5 | 0.2 | 3100 |

^a April 2005–March 2006; ^b April–December 2006

linearity. To obtain an annual emission rate we used the average of the measured daily emission rates.

3.2 Data from northern systems

Published data for similar systems elsewhere were taken from the large data set compiled by Stehfest and Bouwman (2006) (which also is the basis for the new IPCC (2006) direct emission factor – see below), comprising 1008 measurements of N₂O from agricultural systems, of which 223 measurements were made on the crops wheat, rye, barley and rape. We selected only data measured in northern Europe (>46° N) and Canada, with the quality criterion of at least a one-year measurement period. Moreover, data from organic soils were omitted. We have added four data points from Kavdir et al. (2008) and our five values obtained from the measurements at Mellby and Logården. Thus the total number of measurements comes to 46, and the full dataset can be found in the Supplement.

4 Results and discussion

4.1 Swedish measurements

The Mellby farm yearly average emission was between 1.9 and 2.9 kg N₂O-N ha⁻¹; the emission from the control plot with no fertiliser addition was not different from the plots receiving N-addition. A common phenomenon and important for the result was the occurrence of the emission peaks in spring and early summer (June) shown in Fig. 2. These peaks are why there is a difference between the median and the average emission, shown in Table 1. The control plot had a lower yield, which can be important when expressing emission per unit yield, as in this case of ethanol production. For the Logården farm, in spite of the clay soil and fertiliser addition, the emission was low – but had a few peaks, in early spring and after harvest (Fig. 3). This resulted in

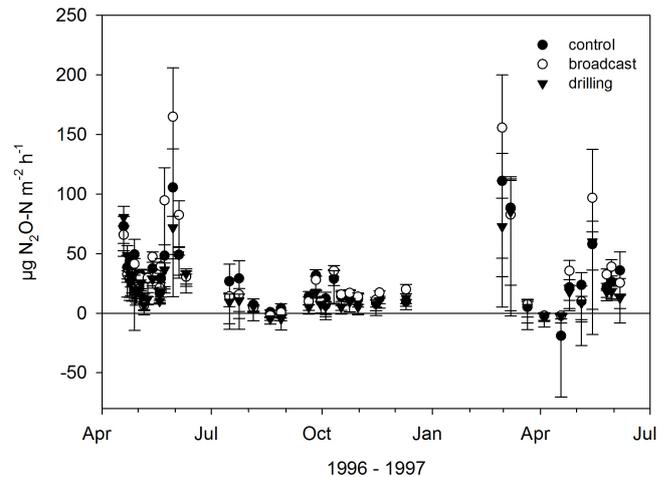


Fig. 2. N₂O emission at Mellby, comparing fertiliser spreading techniques; site had one control plot without N-additions. Average emission and standard error of eight static chambers per treatment.

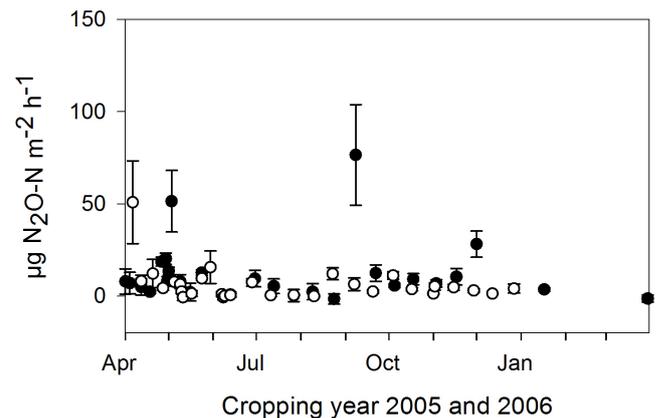


Fig. 3. N₂O emission at Logården, for two different plots with spring wheat in a 7-yr crop rotation (C6 in 2005 (●) and C2 in 2006 (○)); average and standard error of six chambers.

the average emission being two times higher than the median (Table 1). The lower emission in the second year may have been due to lack of measurements during soil thawing in early spring – a time when we frequently have observed higher emissions. The emission from Mellby farm was double that from Logården, in spite of Mellby having a sandy soil, which was unexpected, as was the fact that the fertiliser addition at the Mellby farm did not increase the emission compared with the plot without fertilisation. At the Logården farm the design did not include a zero addition plot but a parallel organic rotation had even lower emissions (half the size) than the conventionally fertilised wheat. Our interpretation is that preceding management actions and crops also have influence on the emissions, which has been pointed out by Liebig et al. (2006). However, our main objective here is not to explain why the emission occurred but to estimate the

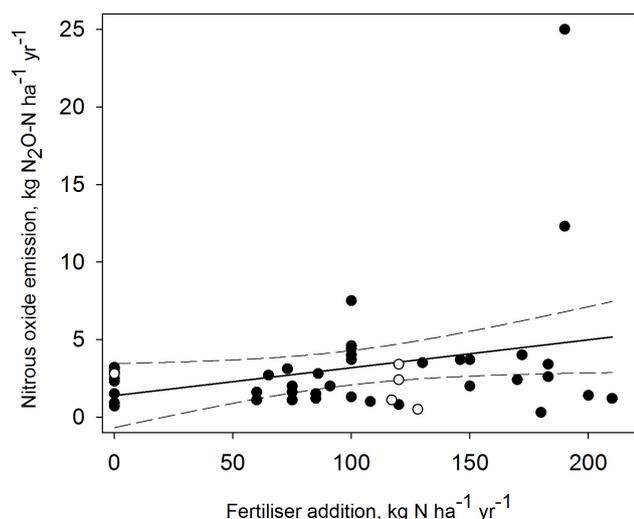


Fig. 4. Compiled measurement data on nitrous oxide emissions from cereal and rape crops in northern Europe and Canada, plotted against N fertiliser addition. White spots denote Swedish data. Linear regression and 95 % confidence interval; emission of N₂O-N = $1.4 + (0.02 \cdot N \text{ in fertiliser})$, $r^2 = 0.08$ and $P = 0.049$.

overall size of the emissions, affecting the sustainability of the conversion of agricultural produce into liquid fuels.

4.2 Collected data

It is common practice to present emissions in relation to fertiliser addition. Figure 4 shows the compiled literature data together with the Swedish data presented above. Average emission for the whole dataset is $3.1 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$, with a median of $2.4 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$. Sites receiving fertiliser have higher emissions compared to those with no fertiliser addition, averaging 3.4 ± 0.7 compared to $2.2 \pm 0.3 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$. It is also possible to see that the Swedish data are in the same range as other data from the northern European region. It is obviously difficult to explain the variation in emission on the basis of the nitrogen addition, because linear regression statistics of the data in Fig. 4 show a weak correlation, $r^2 = 0.08$ and $P = 0.049$. Thus, other environmental factors have an important influence on the emissions. The seasonal weather has been shown to have a large influence and thus it is important to include measurements during winter periods when soils are frozen, since emission peaks can be found, especially during thawing events (Jungkunst et al., 2006). And like natural ecosystems, fertile arable fields contain several tons of nitrogen per hectare, which has accumulated after many years of N fixation and/or addition in manure or fertiliser. Varying proportions of this organic N can be mineralized, and contribute to the N₂O production, depending on environmental influences and management actions. Effective cropping systems that assimilate most of the available nitrogen may give low nitrous oxide emissions, at moderate fertiliser nitrogen addi-

tions (Snyder et al., 2009). This can be seen in Fig. 4, with a more pronounced tendency for high emissions to follow after high N addition but a less clear connection at low N addition. Since the flux could not exceed $1.5 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ if the goal of a 35 % saving compared to fossil fuels were to be reached, and the median of the emissions shown in Fig. 4 was $2.4 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ and the 25 % percentile is $1.3 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ for studies performed during similar conditions as prevailing in Sweden, the risk of exceeding this limit is of the order of >50 %.

4.3 Comparing measured data with model estimates

The Intergovernmental Panel on Climate Change (IPCC) has agreed on a relatively simple estimation method which can be used by all nations to estimate their national emissions of nitrous oxide. Originally the emission factor of 1.25 % for the direct nitrous oxide emission from soil and fertiliser additions (IPCC, 1996) was based on 20 data points (Bouwman, 1996), measured during one year mainly from mineral soils in USA and UK, which had different crops and types of N additions. A linear increase in nitrous oxide emission with the amount of nitrogen added to the field was obtained. More data have been obtained since then and the correlation has become weaker, especially where $<100 \text{ kg N ha}^{-1}$ has been added to the field (Stehfest and Bouwman, 2006). This is also evident in Fig. 4. In the 2006 updating of the IPCC “Guidelines” the emission factor for nitrous oxide from arable fields has been modified to 1 % (IPCC, 2006) based on Bouwman et al. (2002), Stehfest and Bouwman (2006) and Novoa and Tejada (2006). The IPCC report points out that reporting countries should use the most detailed and appropriate estimation method available, preferably their own equations and emission factors (Tier 2) and, where possible, process modelling (Tier 3). If no such methods are available the reporting country has to use Tier 1, based on the 1996 Guidelines, as the 2006 revised version has not yet come into force. Sweden uses a modified emission factor for agricultural land receiving only inorganic fertilisers, 0.8 % of added N (Kasimir Klemetsson, 2001).

The original purpose of the IPCC emission factors was not to estimate nitrous oxide emission for every field, crop or year, but only to give a method to estimate the possible scale of emissions from a country to include in reports to UNFCCC, and to indicate trends from year to year. Inevitably, in reality there will be countries or regions with greater-than-average emissions, and others with lower-than-average emissions, depending on environmental and local agricultural management factors, but as long as the Tier 1 methodology is employed these differences will not be reported. The IPCC emission factors have led to a general acceptance of a clear connection between N-addition and N₂O emission, despite increasing data collection showing a weak connection to inorganic N-additions up to $400 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Novoa and Tejada, 2006). It is important to recognise that even if

no fertiliser nitrogen is added the nitrous oxide emission will still continue, since agricultural soils may contain much labile nitrogen (Freibauer et al., 2004). Moreover, factors other than nitrogen have an influence on the emission, in particular soil wetness, temperature and carbon availability. This leads into more complex models: the need for estimation models that can match actual emissions is why both IPCC's emission factors and the more complex models were developed. Statistical models trying to include other influencing factors in addition to the nitrogen input have been made by Freibauer (2003), Freibauer and Kaltschmitt (2003) and Stehfest and Bouwman (2006). The first two aimed for a regionalized estimation procedure and compiled data on soil emissions from European measurement and analyzed it by a stepwise multivariate method. The very south of Sweden was included in their region with a "mild westerly climate", but most of Sweden was categorized as being in the sub-boreal region. In the south, determining factors for direct N₂O emission were, besides nitrogen fertiliser addition, the topsoil carbon and sand contents. For the boreal region two important parameters deciding emissions were fertiliser addition and nitrogen content of the topsoil. The procedure gave the following statistical relation for N₂O emission from mineral soils in the south:

$$E_{N_2O} = 0.6(\pm 0.5) + (0.002(\pm 0.002) \cdot N_{\text{fertiliser}}) \\ + (1.27(\pm 0.28) \cdot C_{\text{soil}}) - (0.024(\pm 0.005) \cdot \text{sand});$$

and for the sub-boreal region:

$$E_{N_2O} = -1.3(\pm 2.1) + (0.033(\pm 0.0008) \cdot N_{\text{fertiliser}}) \\ + (28(\pm 13) \cdot N_{\text{soil}})$$

where E_{N_2O} = Nitrous oxide emission in kg N₂O-N ha⁻¹ yr⁻¹, $N_{\text{fertiliser}}$ = Added nitrogen fertiliser in kg N ha⁻¹ yr⁻¹, C_{soil} = Carbon content in the topsoil, % of soil dry weight, N_{soil} = Nitrogen content in the topsoil, % of soil dry weight, Sand = Sand content in topsoil, % of soil dry weight.

The other statistical model was constructed by Stehfest and Bouwman (2006), who applied different parameter values (F) for different conditions to the relation

$$\text{Log}E_{N_2O} = A + \sum F_i$$

where different conditions receive different values of F ; examples of important parameters are given below:

A = constant (-1.5)

$F_1 = 0.0038 \cdot N_{\text{fertiliser}}$,

$F_2 = 0$ if <1 % C and = 0.05 if 1–3 % C,

$F_3 = -0.069$ if pH 5.5–7.3,

$F_4 = 0$ if sandy soil and = 0.43 if clay soil,

$F_5 = 0.02$ if coastal temperate climate,

$F_6 = 0$ if cereal crop and = -0.35 if grass and = 0.44 if other crop as rapeseed,

$F_7 = 1.99$ if data is obtained during year-long measurements.

Top-down estimation based on global-scale calculations by Crutzen et al. (2008) can be used if no local or regional possibilities exist. The method is based on the fact that atmospheric nitrous oxide concentration before industrialization was fairly stable (as evidenced by ice-core data), with the rate of addition to the atmosphere balanced by the rate of loss by stratospheric decomposition (Prather et al., 2001). At present, however, the N₂O concentration in the atmosphere is increasing at about 0.7 ppb yr⁻¹ and the annual addition is 50 % higher than in the pre-industrial period (Crutzen et al., 2008). They argued an overall connection between the N₂O addition to the atmosphere and the global creation of reactive nitrogen by fixation, which also has increased by 50 %. Nitrogen fixation in this context means biological fixation and fixation by the Haber-Bosch process. Thus 3 to 5 % of the newly fixed nitrogen is emitted as nitrous oxide – similar to the proportion of the N that Galloway et al. (2004) estimated to have been emitted from newly fixed N in natural ecosystems in the pre-industrial era. By using the data from measurements on Mellby and Logården where auxiliary data are available we were able to validate the different methods. Table 2 shows the evident inability of the IPCC (2006) method to estimate emission for cases where no N-additions were made. Comparing the use of IPCC emission factors with data from fertilised plots the Swedish results show an underestimation for Mellby and overestimation for Logården. The statistical method by Freibauer and Kaltschmitt estimates an emission 3–14 times as large as what was measured, and also the uncertainty range is above measured emissions. We found that the most important factors in the equations deciding the emission are the soil carbon content (estimated as % of dry soil) for Mellby and the soil nitrogen content for Logården, and the nitrogen addition is of less importance. In contrast we found the Stehfest and Bouwman estimation method to agree, but only for the control plot at Mellby that had no N-addition; however, for all cases receiving fertilisers the emissions were predicted to be 2–8 times higher compared with measured values. In this method, the nitrogen addition and duration of field measurements were the most decisive factors for the estimation. The Stehfest and Bouwman method shows the largest uncertainty and it is somewhat surprising that the length of the measurement period was such an important factor for the result.

Both measured and estimated emissions presented in Table 2 are all within the range of emissions measured in northern Europe, but the average emission of compiled measurement data from (inorganically) fertilised arable land in the region, presented in Fig. 4, was found to be 3.4 ± 0.7 kg N₂O-N ha⁻¹ yr⁻¹, which is smaller than that estimated by the Freibauer and Kaltschmitt calculation method but in line with the Stehfest and Bouwman method. However, our Swedish measurements showed a somewhat lower emission. The Crutzen et al. method would, for the fertilised plots, result in a similar high emission to that given by the compiled measurement data, with a total emission around

Table 2. Comparison between measured and calculated direct nitrous oxide emission. Measured data are from Mellby and Logården in Sweden, having mineral soils cropped with spring wheat, with the addition of mineral fertilisers.

| Site and year | Fertiliser addition | Swedish field data ^a | IPCC (1996) ^b | IPCC (2006) ^c | Freibauer and Kaltschmitt (2003) ^d | Stehfest and Bouwman (2006) ^e |
|--|-----------------------|---------------------------------|--------------------------|--------------------------|---|--|
| | kg N ha ⁻¹ | | | | | |
| N ₂ O emission, kg N ₂ O-N ha ⁻¹ yr ⁻¹ | | | | | | |
| Mellby, 1996–1997 | 0 | 2.5 (1.4–3.7) | 1 | 0 (0) | 6.6 (5.9–7.3) | 2.9 (1.4–6.1) |
| Mellby, 1996–1997 | 120 | 2.4 (1.1–3.7) | 2.5 (1.3–3.8) | 1.2 (0.4–3.6) | 6.9 (6.2–7.6) | 4.7 (2.3–9.7) |
| Logården, 2005 | 117 | 1.1 (0.9–1.3) | 2.5 (1.3–3.6) | 1.2 (0.4–3.5) | 6.5 (5.9–7.3) | 3.8 (1.9–7.9) |
| Logården, 2006 | 128 | 0.5 (0.4–0.6) | 2.6 (1.3–3.9) | 1.2 (0.4–3.8) | 6.9 (6.2–7.6) | 4.0 (1.9–8.2) |

^a Measured direct emission, average from measurements all year round is shown together with standard error of the mean.

^b IPCC (1996) emission factor 1.25 % (0.25–2.25 %) of N-addition in fertiliser plus a background emission of 1 kg N₂O-N ha⁻¹ yr⁻¹. Crop residues and indirect emissions are not included.

^c IPCC (2006) emission factor 1 % (0.3–3 %) of N-addition in fertiliser. Crop residues and indirect emissions are not included.

^d For Mellby the function for temperate western climate was used and for Logården the function for alpine/sub-boreal climate.

^e For Mellby, factor values for temperate oceanic climate are used together with a coarse soil texture and a high soil carbon content >3 %. For the Logården case, factor values for temperate continental climate, fine soil texture and soil carbon content between 1 and 3 % were used.

3–6 kg N₂O-N ha⁻¹ yr⁻¹. However, the latter global method does include indirect N₂O emissions following N loss to air and water.

More detailed estimations by use of process-based models has been suggested since the production of nitrous oxide is complex and depends on many soil physical, chemical and biological factors, as interactions with the crop or other plants where the nitrogen uptake efficiency can be important. But yet, to our knowledge, no model has been shown able to mimic the emission patterns over the year, even though the size of the annual N₂O emission can be fairly well estimated (Del Grosso et al., 2008).

4.4 Possibility of achieving required GHG savings in Swedish ethanol production

The production plant producing first generation biofuel in our Swedish LCA releases only 24 g CO₂equiv MJ⁻¹, which is low compared with the Mosier et al. (2009) study where 43–64 g CO₂equiv MJ⁻¹ ethanol-derived energy was reported for such emissions in UK and USA, but this is due to a greater potential for using renewable energy in Sweden, which helps to reduce GHG emissions in this part of the production chain. Despite use of low N₂O-emitting fertiliser production and a high proportion of renewable energy used in the bioethanol production plant, the LCA shows that a biofuel based on the Mellby data does not reach the sustainability goal of 35 % savings (Table 3), since yields are low and field emissions high, and this ethanol production would give more GHG emission than fossil fuels. But the Logården case shows a low emission, <0.5 kg N₂O-N ha⁻¹ yr⁻¹ and despite a low yield it is possible to achieve the 35 % GHG savings (Table 3). With a higher yield and still fairly low emission, 1.1 kg N₂O-N ha⁻¹ yr⁻¹, 40 % savings can be obtained. Even if bioethanol production uses solely renewable energy, the results still show too high an emission for Mellby, with only 25 % GHG savings. But the same test

for Logården shows it may be possible to gain 70 % savings if both a good yield, normal for the region, and fairly low emissions are achieved. The problem is that these low emissions are often not the case since there is more than a 50 % risk of emissions being higher than 1.5 kg N₂O-N ha⁻¹ yr⁻¹ (Fig. 4), when ethanol production will not reach the sustainability threshold.

Three main factors have been shown to be important for the possibility of reaching the threshold of 35 % savings of GHG compared with fossil fuels; these are crop productivity, energy use in the bioethanol production plant, and nitrous oxide emissions (direct and indirect). These indirect emissions are most often calculated by use of the IPCC emission factors. The 2006 IPCC default EFs for these indirect emissions are 1 % (uncertainty range 0.2–5 %) for volatilised N and 0.75 % (0.05–2.5 %) for leached N. At default volatilization fractions of 10 % (mineral fertiliser) or 20 % (animal manure), and the default leaching fraction of 30 %, indirect emissions can be negligibly small, 0.04 % of the added N using the numbers at the lower end of these ranges, but up to more than the direct emission (1.2 %), at the upper end. In most calculations the default EFs are used, resulting in an estimated emission of 0.3–0.4 % of the N applied to the land. More detailed discussion of indirect emissions and the likely EFs can be found in IPCC (2006) and Well and Butterbach-Bahl (2010). Here we have assumed the indirect emissions to be 1/3 of the direct emissions, based on the IPCC emission factors. Experiments for similar systems in Sweden to Logården and Mellby have shown N leaching to be lower from clay soil than from sandy soil, 2–22 and 15–53 kg N ha⁻¹ yr⁻¹, respectively (Aronsson et al., 2011). Leaching at Logården the same years as emission was measured showed values of 18–22 kg N ha⁻¹ yr⁻¹, which confirms a low leaching from clay soil (Wessén et al., 2011). The low leaching from the clay soil compared to the IPCC default may indicate a rather low indirect emission from clay

Table 3. LCA applied to Mellby and Logården data, showing GHG saving possibilities compared to fossil fuels^a.

| Site | Yield | Measured emission | N addition | Energy use ethanol plant | Energy use ^d | Industrial ^c | Direct N ₂ O | Indirect N ₂ O | Total emission | Difference compared to fossil fuels |
|--|--------------------------------------|---|-----------------------|--------------------------|-------------------------|---------------------------------------|-------------------------|---------------------------|----------------|-------------------------------------|
| | kg ha ⁻¹ yr ⁻¹ | kg N ₂ O-N ha ⁻¹ yr ⁻¹ | kg N ha ⁻¹ | | | g CO ₂ eq MJ ⁻¹ | | | | % |
| Bioethanol production plant using average Swedish energy mix | | | | | | | | | | |
| Mellby | 2400 | 2.5 | 0 | 24 ^b | 3 | 0 | 62 | 20 | 109 | +30 |
| Mellby | 3300 | 1.9 | 120 | 24 | 3 | 13 | 34 | 11 | 85 | +3 |
| Logården | 5800 | 1.1 | 117 | 24 | 3 | 7 | 11 | 4 | 50 | -40 |
| Logården | 3100 | 0.5 | 128 | 24 | 3 | 15 | 10 | 3 | 55 | -34 |
| Bioethanol production plant using only renewable energy | | | | | | | | | | |
| Mellby | 3300 | 1.9 | 120 | 0.5 ^c | 3 | 13 | 34 | 11 | 62 | -25 |
| Logården | 5800 | 1.1 | 117 | 0.5 | 3 | 7 | 11 | 4 | 26 | -69 |

^a Fossil fuels emit 83.8 g CO₂eq MJ⁻¹.

^b Assuming the same energy mix in refinery as in the overall Swedish energy system, with 43 % renewable energy sources, having low CO₂ emissions with 1 g CO₂eq MJ⁻¹ and 83.8 g CO₂eq MJ⁻¹ for fossil fuels.

^c Assuming renewable energy used in refinery.

^d Energy use in transport and management.

^e Emissions connected with industry production of fertiliser and biocides. Major part is from fertiliser production using catalytic conversion of N₂O into N₂, with 90 % efficiency (Yara, 2010), giving 2.9 kg CO₂eq kg⁻¹ N.

soils, making the overall picture somewhat better than estimated in Table 3, but the N-leaching from sandy soil may be similar to the default values. We have shown the LCA to be very sensitive to the size of the N₂O emissions, both direct and indirect, where a small change can make it possible or impossible to reach the desired threshold.

An alternative to using annual arable crops as the feedstock for biofuels is to use the cellulosic so-called “second generation” perennial biofuel crops such as willow and *Miscanthus*, which can be expected to have a low N₂O emission due to a need for just a little or no fertiliser N addition (Kavdir et al., 2008). If and when their conversion to liquid biofuel becomes an economic proposition the expected much-reduced contribution to overall emissions from N₂O would make them much more likely candidates to meet the EU emissions reduction threshold.

4.5 N₂O as a consequence of agriculture in general

The expected future global population growth means that agricultural production needs to increase by 70 % to fulfil demands for food over the next 50 yr (FAO, 2009) raising the question: how much more N will be required to meet both increased food needs and biofuel production? And how much N₂O emission will result? Can agriculture management be designed for an overall low N₂O emission? One attempt to answer this was by van Groenigen et al. (2010), who showed that fertiliser addition rates below 200 kg N ha⁻¹ give minimum N₂O emissions per unit of yield (8 g N₂O-N kg⁻¹ crop N). Attempts to increase the yields with higher N additions will decrease the nitrogen use efficiency and inevitably increase N₂O emissions. However, there should be no separ-

ture from attempting to achieve the optimum level of yield and minimum level of N₂O per unit of yield, consequently the option to increase the yields of food and feed crops, thus releasing land for biofuel cropping, is limited. But even the best management options leave reactive nitrogen behind, which can possibly be converted into N₂O over time, providing some explanation for the Crutzen et al. (2008) emission factor of 3–5 % of the new N being converted into N₂O-N.

Due to the transfer of reactive N from agricultural land to surrounding ecosystems, indirect emissions will also take place in the year of application and in following years (IPCC, 2006; Well and Butterbach-Bahl, 2010), as mentioned above. These emissions are included in the estimate produced by the method of Crutzen et al., but on a regional or country scale the overall emissions can be both lower and higher than the global average emission factor of 3–5 % of the newly fixed nitrogen.

Arguments have been raised that the atmospheric N₂O increase depends also on other factors besides the nitrogen fixation, e.g. the roles of an increased livestock production and mineralisation of soil nitrogen as substantial additional sources of liberated N (Davidson, 2009). However, it has been shown very recently that by extending the Crutzen et al. concept to include soil organic N mineralised following land-use change and NO_x deposited from the atmosphere in the estimates of the reactive N entering the agricultural cycle, a 4 % emission factor gives a good match with atmospheric N₂O concentrations over the last 150 yr (Smith et al., 2011). Furthermore, N₂O from livestock production is already implicitly included in the Crutzen et al. concept, because the reactive N has entered the ruminant N cycle either

as fertiliser on grass, or by BNF by fodder legumes and soya beans used in feed supplements.

Use of distiller's grain as a feed is an example of nitrogen circulating back into the agricultural system where it may cause N₂O emissions over many years to come. Suggestions have been made to allocate some of the emissions to the spent grain. This should reduce emissions due to biofuel production in a LCA. Also, the use of this material could avoid some feed production needing nitrogen, but in practice it cannot be ruled out that, instead, the spent grains could be a basis for increased livestock production. Thus it is not straightforward to allocate emissions to spent grains, or to assess their influence on the LCA result. Consequently we have allocated all emissions to the biofuel, as is also done in the EU-regulation where waste and crop residuals are given zero emissions [EC directive 98/70/EG]. In any event, the message that the N₂O emissions from arable crops are an important part of the LCA cannot be ignored.

The large overall emissions calculated by the Crutzen et al. (2008) approach may not always be welcomed by biofuel producers and authorities, who have argued that a lower direct emission factor is more appropriate, since only emissions directly associated with the cropping for bio-ethanol should be included and that background emissions, should be subtracted (Ahlgren et al., 2009). A similar way is to use as a reference case an alternative land use, the hypothetical emissions from which can be subtracted from the actual production emissions [EC directive 98/70/EG]. In Sweden an appropriate reference case could be forest land, the dominant non-agricultural land use. Earlier measurements have shown very low emissions from typical mixed forest dominated by spruce, from 0.02 to 0.2 kg N₂O-N ha⁻¹ yr⁻¹ (Klemetsson et al., 1997), and recent measurements have shown equally small emissions, not significantly separated from zero (Moldan and Klemetsson, 2011). Thus on the basis of these small values we argue that most or all of the agricultural emissions are anthropogenic, resulting from past as well as present agricultural management (IPCC, 2006).

We now turn to the question of whether we can attribute values to the N₂O emission at a regional scale. The most important conclusion is that emission measurements in northern systems on mineral soils cropped with cereals and oilseed rape span a yearly nitrous oxide emission range from nearly zero to >10 kg N₂O-N ha⁻¹ yr⁻¹, with an average of 3.4 kg N₂O-N ha⁻¹ yr⁻¹ for fertilised agricultural mineral soils (Fig. 4). The variability between different investigations could be due to shortcomings in the intermittently performed measurements. But this suggests that the calculated seasonal totals may well be conservative estimates. If a large emission happens, during soil thawing in the spring, this can override small effects of fertiliser additions, making these less important. Such large emissions occur in some years but not in others. An emission below 1.5 kg N₂O-N ha⁻¹ yr⁻¹, needed to fulfil a GHG saving of 35 %, was found for less than 50 % of the data collected. The Logården clay soil had this nec-

essarily low emission, but because of the low yields it was still barely possible to fulfil the 35 % rule, and not possible to achieve the 50 % GHG reduction that will be required in 2017. The Mellby farm LCA estimations resulted in a higher GHG emission compared with fossil fuel, due to both low yields and higher emissions.

We here included only mineral soils, since these are the typical soils used for arable cropping across Sweden, but unless adequate account is taken of the contribution of organic soils, the average emissions will be underestimated. Of the arable land in Sweden, 9 % is classified as having organic soils, where stored carbon and nitrogen is released by mineralisation, causing high emissions: 10 kg N₂O-N ha⁻¹ yr⁻¹ when cultivated for cereal crops (Kasimir Klemetsson et al., 2009); 28 % of the organic soils in Sweden are used in this way (Berglund and Berglund, 2008). If there is no regulation controlling the soil type that can be used for biofuel production, these emissions should be included in the typical soil emission values for the region, resulting in an average increase of almost 1 kg N₂O-N ha⁻¹ yr⁻¹, which we can conclude would make biofuel production from arable crops impossible under the rules of 35 % (and 50 %) GHG savings.

4.6 Prediction of N₂O emission

To predict the size of the N₂O emission from an area of land, it is necessary to know which environmental factors have the most impact. The IPCC revised Tier 1 method, basing emissions solely on N inputs, is a convenient way to estimate the emissions, as it is easy to obtain the data, but as Fig. 4 shows, the influence of the fertiliser on the emission can be quite small. However, this concept has been used in many life cycle analyses (Smeets et al., 2009), even though it does not work well in some circumstances. Problematic cases are where soil organic matter contributes to the emission, from the release of nitrogen accumulated into the ecosystem long ago. Thus in principle we need attempts like those of Freibauer and Kaltschmitt (2003) and Stehfest and Bouwman (2006), where other influencing factors besides nitrogen addition were also included. However, as it turned out, these methods resulted in estimates that were much higher than the Swedish measurements. Important factors in the Freibauer and Kaltschmitt method were the C and N content of the soil; this could be an indication of turnover of organic matter and release of N, but the contents themselves do not predict the rates of N turnover processes such as mineralisation, nitrification, denitrification and assimilation, that have a major influence on the actual N₂O emissions. There is a need for continued method development for nitrous oxide estimations at a local level, including different soils and crops in the whole agricultural system, and where indirect emissions are also included. This would make emission estimates more reliable and make it easier to adjust towards lower-emission systems.

5 Conclusions

It can be concluded that it is possible to produce first-generation grain-based biofuels having lower GHG emissions than fossil fuels, but only for systems where the N-surpluses in the soil are small but the yields are still good. However, soils having ordinary levels of emissions (>1.5 kg N₂O-N ha⁻¹ yr⁻¹) and high-emitting organic soils cannot be used for biofuel crop production, without failing the 35 % GHG savings threshold. Also important is energy efficiency and low GHG emissions in the production of fertilisers and in ethanol production plants. Overall, the probability of not reaching the 35 % GHG savings threshold with the present agricultural system in Sweden is larger than 50 %. To be able to avoid the high-emission systems in an explicit and reliable way will need better methods than those available today; the available prediction methods discussed here are not adequate to steer reliably towards sites and systems with low emissions. Thus, there is a need for more field data in combination with process-based models where possible controlling factors can be tested and evaluated.

Supplementary material related to this article is available online at:

<http://www.biogeosciences.net/8/3581/2011/bg-8-3581-2011-supplement.pdf>

Acknowledgements. This research was supported by the Swedish Energy Agency, for the project “Estimation of nitrous oxide from cultivation of agricultural crops for liquid fuels” and by the Strategic Research Environment BECC – Biodiversity and Ecosystem Services in a changing Climate, at Lund University and University of Gothenburg.

Edited by: A. R. Mosier

References

- Ahlgren, S., Hansson, P.-A., Kimming, M., Aronsson, P., and Lundkvist, H.: Utsläpp av växthusgaser vid odling av grödor för biodrivmedel samt produktion av biogas från gödsel – tillämpning av Europaparlamentets och rådets direktiv om främjandet av användningen av energi från förnybara energikällor (Emission of greenhouse gases during cropping for biofuels and production of biogas from manure – application of European parliament and council directive of promoting use of energy from renewable sources), Swedish University of Agricultural Sciences Dnr SLU ua 12-4067/08, 2009.
- Aronsson, H., Stenberg, M., and Ulén, B.: Leaching of N, P, and glyphosate from two soils after herbicide treatment and incorporation of a ryegrass catch crop, *Soil Use Manage.*, 27, 54–68, 2011.
- Berglund, Ö. and Berglund, K.: Odlad organogen jord i Sverige 2003 (Farmed organic soil in Sweden 2003), Swedish University of Agricultural Sciences, Div. Hydrotechnics, Uppsala, ISSN 1653-6797, 2008.
- Bernesson, S., Nilsson, D., and Hansson, P.-A.: A limited LCA comparing large- and small-scale production of ethanol for heavy engines under Swedish conditions, *Biomass Bioenerg.*, 30, 46–57, 2006.
- Bouwman, A. F.: Direct emissions of nitrous oxide from agricultural soils, *Nutr. Cycl. Agroecosyst.*, 46, 53–70, 1996.
- Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Emissions of N₂O and NO from fertilized fields: summary of available measurement data, *Global Biogeochem. Cy.*, 16, 1058, doi:10.1029/2001GB001811, 2002.
- Börjesson, P.: Fin- eller fuletanol – vad avgör? (Clean or bad ethanol – what decides?), Lunds Tekniska Högskola Rapport nr 65, ISBN 91-88360-90-5, 2008.
- Cassman, K., Dobermann, A., and Walters, D. T.: Agroecosystems, nitrogen-use efficiency and nitrogen management, *Ambio*, 31, 132–140, 2002.
- Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W.: N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels, *Atmos. Chem. Phys.*, 8, 389–395, doi:10.5194/acp-8-389-2008, 2008.
- Davidson, E. A.: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860, *Nat. Geosci.*, 2, 659–662, 2009.
- Del Grosso, S., Wirth, T., Ogle, S. M., and Parton, W. J.: Estimating agricultural nitrous oxide emissions, *Eos, Trans. Am. Geophys. Union*, 89, 529–530, 2008.
- EC directive 98/70/EG: European Commission DIRECTIVE 2009/30/EC Amendment to Directive 98/70/EC on environmental quality standards for fuel (Fuel Quality Directive), <http://eur-lex.europa.eu>, last access: 4 July 2011, 2009.
- FAO: Feeding the world in 2050, <ftp://ftp.fao.org/docrep/fao/meeting/018/k6021e.pdf>, last access: 4 July 2011, 2009.
- Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R.: Changes in Atmospheric Constituents and in Radiative Forcing, in: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
- Freibauer, A.: Regionalised inventory of biogenic greenhouse gas emissions from European agriculture, *Eur. J. Agron.*, 19, 135–160, 2003.
- Freibauer, A. and Kaltschmitt, M.: Controls and models for estimating direct nitrous oxide emissions from temperate and sub-boreal agricultural mineral soils in Europe, *Biogeochemistry*, 63, 93–115, 2003.
- Freibauer, A., Rounsevell, M. D. A., Smith, P., and Verhagen, J.: Carbon sequestration in the agricultural soils of Europe, *Geoderma*, 122, 1–23, 2004.
- Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., and Vörösmarty, C. J.: Nitrogen cycles: past, present, and future, *Biogeochemistry*, 70, 153–226, 2004.

- IPCC: Greenhouse Gas Inventory Reference Manual, Vol. 3, Section 4.5, Agriculture, edited by: Houghton, J. T., Meira Filho, L. G., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D. J., and Callander, B. A., IPCC/OECD/IEA, UK Meteorological Office, Bracknell, UK, 1996.
- IPCC: N₂O emission from managed soils, in: Guidelines for National Greenhouse Gas Inventories, Vol. 4: Agriculture, Forestry and Other Land Use, Chapter 11, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Hayama, Japan, 2006.
- Jungkunst, H. F., Freibauer, A., Neufeldt, H., and Bareth, G.: Nitrous oxide emissions from agricultural land use in Germany – a synthesis of available annual field data, *J. Plant Nutr. Soil Sc.*, 169, 341–351, 2006.
- Kasimir Klemedtsson, Å.: Metodik för skattning av jordbrukets emissioner av lustgas. Underlag för Sveriges nationalrapport till Klimatkonventionen, NV-report 5170, (Methodology for assessing agricultural nitrous oxide emissions; a base for Swedish national reporting to the UNFCCC, Swedish EPA report 5170), 2001.
- Kasimir Klemedtsson, Å., Weslien, P., and Klemedtsson, L.: Methane and nitrous oxide fluxes from a farmed Swedish Histosol, *Eur. J. Soil Sci.*, 60, 321–331, 2009.
- Kavdir, Y., Hellebrand, H. J., and Kern, J.: Seasonal variations of nitrous oxide emission in relation to nitrogen fertilization and energy crop types in sandy soil, *Soil Till. Res.*, 98, 175–186, 2008.
- Klemedtsson, L., Kasimir Klemedtsson, Å., and Moldan, F.: Nitrous oxide emission from Swedish forest soils in relation to liming and simulated increased N-deposition, *Biol. Fert. Soils*, 25, 290–295, 1997.
- Korsaeth, A., Molstad, L., and Bakken, L. R.: Modelling the competition for nitrogen between plants and microflora as a function of soil heterogeneity, *Soil Biol. Biochem.*, 33, 215–226, 2001.
- Liebig, M. A., Gross, J. R., Kronberg, S. L., Hanson, J. D., Frank, A. B., and Phillips, R. L.: Soil response to long-term grazing in the northern Great Plains of North America, *Agr. Ecosyst. Environ.*, 115, 270–276, 2006.
- Moldan, F. and Klemedtsson, L.: Nitrous oxide and methane emissions from boreal forest floor subjected to 16 years of increased N deposition, Conference presentation at “Nitrogen and Global Change” in Edinburgh 11–15 April 2011.
- Mosier, A. R., Crutzen, P. J., Smith, K. A., and Winiwarer, W.: Nitrous oxide’s impact on net greenhouse gas savings from biofuels: life-cycle analysis comparison, *Int. J. Biotechnology*, 11, 60–74, 2009.
- Novoa, R. S. A. and Tejada, H. R.: Evaluation of the N₂O emissions from N in plant residues as affected by environmental and management factors, *Nutr. Cycl. Agroecosyst.*, 75, 29–46, 2006.
- Oenema, O., Witzke, H. P., Klimont, Z., Lesschen, J. P., and Velthof, G. L.: Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27, *Agr. Ecosyst. Environ.* 133, 280–288, 2009.
- Ogle, S. M., Del Grosso, S. J., Adler, P. R., and Parton, W. J.: Soil nitrous oxide emissions with crop production for biofuels: implications for greenhouse gas mitigation, www.farmfoundation.org/news/articlefiles/371-2-Ogle.pdf, 2008.
- Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P., and Wang, M.: Atmospheric chemistry and greenhouse gases, in: *Climate Change 2001: The Scientific Basis*, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, and C. A., Cambridge University Press, Cambridge, 239–287, 2001.
- Smeets, E. M. W., Bouwman, L. F., Stehfest, E., van Vuuren, D. P., and Posthuma, A.: Contribution of N₂O to the greenhouse gas balance of first-generation biofuels, *Glob. Change Biol.*, 15, 1–23, 2009.
- Smith, K. A., Mosier, A. R., Crutzen, P. J., and Winiwarer, W.: The role of N₂O derived from crop-based biofuels, and from agriculture in general, in Earth’s climate, *Phil. T. Roy. Soc. B*, in press, 2011.
- Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E.: Review of greenhouse gas emissions from crop production systems and fertilizer management effects, *Agr. Ecosyst. Environ.*, 133, 247–266, 2009.
- Statistics Sweden: Standard Yields 2011, <http://www.scb.se/Pages/PublishingCalendarViewInfo.....259924.aspx?PublObjId=15772>, 10 June 2011.
- Stehfest, E. and Bouwman, L.: N₂O and NO emission from agricultural fields and soils under natural vegetation: summarized available measurement data and modelling of global emissions, *Nutr. Cycl. Agroecosyst.*, 74, 207–228, available at: <http://www.mnp.nl/en/publications/2006>, 2006.
- Swedish Energy Agency: <http://www.energimyndigheten.se/en/>, 14 October 2010.
- van Groenigen, J. W., Velthof, G. L., Oenema, O., van Groenigen, K. J., and van Kessel, C.: Towards an agronomic assessment of N₂O emissions: a case study for arable crops, *Eur. J. Soil Sci.*, 61, 903–913, doi:10.1111/j.1365-2389.2009.01217.x, 2010.
- Wagner-Riddle, C., Furon, A., McLaughlin, N. L., Lee, I., Barbeau, J., Jayasundara, S., Parkin, G., von Bertoldi, P., and Warland, J.: Intensive measurement of nitrous oxide emissions from a corn-soybean-wheat rotation under two contrasting management systems over 5 years, *Glob. Change Biol.*, 13, 1722–1736, 2007.
- Wang, J. and Bakken, L. R.: Competition for nitrogen during decomposition of plant residues in soil: effect of spatial placement of N-rich and N-poor plant residues, *Soil Biol. Biochem.*, 29, 153–162, 1997.
- Well, R. and Butterbach-Bahl, K.: Indirect emissions of N₂O from N deposition and leaching of agricultural N, in: *Nitrous oxide and Climate Change*, edited by: Smith, K. A., Earthscan, London, 162–189, 2010.
- Weslien, P., Klemedtsson, L., Svensson, L., Kasimir Klemedtsson, Å., and Gustafsson, A.: Nitrogen losses following application of pig slurry to arable land, *Soil Use Manage.*, 14, 200–208, 1998.
- Weslien, P., Kasimir Klemedtsson, Å., Börjesson, G., and Klemedtsson, L.: Strong pH influence on N₂O and CH₄ fluxes from forested soils, *Eur. J. Soil Sci.*, 60, 311–320, 2009.
- Wessén, E., Söderström, M., Stenberg, M., Bru, D., Hellman, M., Welsh, A., Thomsen, F., Klemedtsson, L., Philippot, L., and Hallin, S.: Spatial distribution of ammonia-oxidizing bacteria and archaea across a 44-hectare farm related to ecosystem functioning, *ISME J.*, 5, 1213–1225, 2011.
- Yara: Brochure: Climate impact and mitigation potential of plant nutrition, <http://www.yara.com/sustainability/climate/index.aspx>, last access: 9 November 2010.