Effect of manure application technique on nitrous oxide emission from agricultural soils

Alterra-report 1992
ISSN 1566-7197

G.L. Velthof, J. Mosquera, J. Huis in 't Veld en E. Hummelink

Effect of manure application technique on nitrous oxide emission from agricultural soils

Commissioned by SenterNovem in Utrecht

Effect of manure application technique on nitrous oxide emission from agricultural soils

G.L. Velthof[1]., J. Mosquera[2], J. Huis in ‘t Veld[2], E. Hummelink[1]

1 Alterra, Wageningen UR
2 Wageningen UR, Livestock Research

Alterra-report 1992

Alterra Wageningen UR
Wageningen, 2010

Abstract

Velthof, G.L., J. Mosquera, J. Huis in 't Veld & E. Hummelink, 2010. *Effect of manure application technique on nitrous oxide emission from agricultural soils,* Wageningen, Alterra, Alterra-report 1992, 74 p.; 16 fig.; 8 tables.; 30 refs.

The emission factors for nitrous oxide (N_2O) emission of applied manure are not well quantified. The effect of manure application technique on N_2O emission was quantified in field and laboratory experiments in order to derive N_2O emission factors for (shallow) injected and broadcast cattle and pig slurries in the Netherlands. Fluxes of N_2O were measured using a closed flux chamber technique and a photo-acoustic infra-red gasmonitor. Fluxes of N_2O fluxes were measured 83 times on grassland on sandy soil and 64 times on maize land on sandy soil, in the period 2007-2009. Fluxes of N_2O were measured 64 times on grassland on the clay soil in 2007-2008. In line with the IPCC Guidelines, emission factors were derived after correction for N_2O emission from unfertilized plots. The average emission factor for grassland was 1.7% of the N applied for calcium ammonium nitrate (CAN), 0.4% for shallow injected cattle slurry, and 0.1% for broadcast cattle slurry. The average emission factor for CAN applied to maize land was 0.1% of the N applied. The average emission factor of cattle slurry injected to maize land was 0.9% and that of broadcast cattle slurry 0.4%. The average emission factor of injected pig slurry was 3.6% and that of broadcast pig slurry 0.9%. The high emission factor of injected pig slurry is mainly due to the high emission factor in the wet year 2007 (7.0% of the applied N). The incubation study showed that shallow injection also increased N_2O emission from peat soil, but the total N_2O emission was much higher for the peat soil than for the mineral soils. Concluding, on both grassland and maize land, (shallow) injection of slurry increased the emission factors of N_2O in comparison to broadcast application. The results suggest to use separate N_2O emission factors for grassland and arable land.

Keywords: broadcast application, CAN, cattle slurry, emission factor, grassland, injection, maize land, mineral fertilizer, nitrous oxide, pig slurry

ISSN 1566-7197

Phone +31 317 48 07 00; fax +31 317 41 90 00; e-mail info.alterra@wur.nl

Alterra-report 1992
Wageningen, March 2010

Contents

Summary

Agricultural soils are the main source of nitrous oxide (N_2O) emissions in the Netherlands, and accounted for 56% of national N_2O emissions in 2006. The agricultural N_2O emissions consist of direct emissions through application of animal manures and fertilizers to soils, and indirect emissions from nitrogen leaching, run-off and ammonia (NH_3) emission.

The monitoring protocols used in the Netherlands to calculate the emission of N_2O differentiate between two manure application techniques: broadcast application and incorporation into soil. The N_2O emission factors used in the Netherlands for broadcast application (1% of applied N) are lower than for low ammonia (NH_3) emission manure application techniques (2% of applied N), including shallow injection and injection. In 1990, the reference year for Kyoto, all manure was broadcast to the soil of both grassland and arable land. Because of the Netherlands' policy to reduce NH_3 emissions, only low NH_3 emission manure application techniques are allowed since the early 1990's. According to the monitoring protocol, this change in manure application techniques resulted in higher direct N_2O emissions from agricultural soils. However, the emission factors of applied manure are not well quantified.

The effect of manure application technique on N_2O emission was quantified in field and laboratory experiments. The aim of these experiments was to derived N_2O emission factors for shallow injected cattle slurry (on grassland), injected cattle and pig slurries (on maize land) and broadcast slurries. Shallow injection is the most used NH_3 abatement application method in the Netherlands for grassland and injection for maize land. In the experiments, a treatment with calcium ammonium nitrate (CAN) was included, because it is the most used mineral N fertilizer in the Netherlands.

The effects of cattle and pig slurry application method were quantified in field experiments on grassland (sandy and clay soils) and maize land (sandy soil). The experiments on the sandy soils were carried out for three years (2007, 2008, and 2009), and that on clay soil for two years (2007, and 2008). The grassland experiments consisted of five treatments: 1) no fertilization (control), 2) CAN, broadcast applied, 3) cattle slurry, broadcast applied, 4) cattle slurry, shallow injected (5 cm depth), and 5) object with a combination of CAN and shallow-injected cattle slurry. The maize experiments consisted of six treatments: 1) control, 2) CAN, broadcast applied, 3) cattle slurry, broadcast applied, 4) cattle slurry, injected (15- 20 cm depth), 5) pig slurry, broadcast applied, and 6) pig slurry, injected. In line with the IPCC Guidelines, emission factors were derived after correction for N_2O emission from unfertilized plots.

The application rates of slurry were based on common slurry application rates in the Netherlands. The amount of CAN was adjusted to the amount of applied slurry, so that the total amount of applied plant-available N was similar in the treatments with CAN and (shallow) injected slurry. The CAN and slurry was applied in 4-5 dressings to grassland in the period April to end of August. Manures and fertilizers were applied in one dressing in May/June to maize land. In 2009, the maize experiment was extended with six additional treatments, i.e. two additional application rates for CAN, for injected cattle slurry, and for injected pig slurry. The aim of these additional treatment was to assess the effect of N application rate on the N_2O emission factor.

All treatments were applied in triplicate in a completely randomized block design. Fluxes of N_2O fluxes were measured 83 times on grassland on sandy soil and 64 times on maize land on sandy soil, in the period 2007-2009. Fluxes of N_2O were measured 64 times for grassland on the clay soil in 2007-2008. Fluxes were

measured more intensively in the period just after N application (up to 3 times per week) and less frequently in the winter (at least once per month). Fluxes of N_2O were measured using a closed flux chamber technique and a photo-acoustic infra-red gasmonitor.

The flux of N_2O from maize land increased after N application in May/June for several weeks, decreased thereafter and no significant differences in N_2O flux from fertilized and unfertilized maize land were shown after August. This flux pattern was shown in all years and is most probably related to the N uptake by maize. The pattern of fluxes from the grasslands clearly differed from those from the maize land, i.e. the fluxes were much shorter (i.e. 1-2 weeks) and several peak fluxes during the growing seasons were shown. This pattern is related to the N application in several dressings in combination with the high N uptake capacity of grassland.

On both grassland and maize land, (shallow) injection of slurry increased the emission factor of N_2O in comparison to broadcast application. The average emission factor for grassland (based on both grassland sites and all years) was 1.7% of the N applied for CAN, 0.4% for shallow injected cattle slurry, and 0.1% for broadcast cattle slurry. The average emission factor for CAN applied to maize land was 0.1% of the N applied. The average emission factor of cattle slurry injected to maize land was 0.9% and that of broadcast cattle slurry 0.4%. The average emission factor of injected pig slurry was 3.6% and that of broadcast pig slurry 0.9%. The high emission factor of injected pig slurry was mainly due to the high emission factor in the wet year 2007 (7.0% of the applied N).

Increasing the N application rate on maize land resulted in higher emission factors for CAN, injected cattle slurry, and injected pig slurry in 2009. This shows that a fixed emission factor in % of the applied N, as currently used by IPCC and in the Dutch protocol, does not reflect the effect of N application rate of N_2O emission. These results also suggest that a decrease of the N application rate decreases the N_2O emission by a combination of a smaller N application rate and a lower emission factor. The current protocols only account for the decrease in N application rate. However, more studies are needed to include N rate dependent emission factors in protocols of estimation of N_2O emission.

The field experiments were carried out on sandy and clay soils and can be used to derive N_2O emission factors for mineral soils. However, about 15 percent of the grasslands in the Netherlands are located on peat soils. An incubation study was conducted to quantify the N_2O emission from cattle slurry applied to peat, sand, and clay soils. Two application techniques were tested: surface application and shallow injection. Also the N_2O emission from CAN as reference fertilizer was quantified. Soil cores with intact swards were taken in February 2008 using PVC cylinders (10 cm diameter and 10 depth) that were pushed into the soil. The total N_2O emission in the incubation study increased in the order control < surface applied cattle slurry < shallow injected cattle slurry < CAN, for all soil types. The total N_2O emission increased in the order clay soil < sandy soil < peat soil. The calculated N_2O emission factors in the incubation study are higher than generally found in field experiments. The N_2O emission factor for shallow injected cattle slurry ranged from 0.5% (sandy and clay soil) to 3.5% (peat soil). The N_2O emission factor for broadcast cattle slurry was lower and ranged from -0.1% (sandy soil) to 1.7% (peat soil). The N_2O emission factor for CAN was 4.0% for the sandy soil, 1.4% for the clay soil, and 10.5% for the peat soil.

Calculated indirect N_2O emissions from NH_3 emission from surface spreading (assuming average NH_3 emission factors) were similar to measured direct N_2O emissions for maize, and a factor 2.5 higher for grassland. Total N_2O emissions (measured direct emission + calculated indirect emission from NH_3) for low emission manure application techniques were then 5-10% lower than for surface spreading.

Concluding, on both grassland and maize land, (shallow) injection of slurry increased the emission factor of N_2O in comparison to broadcast application. The results suggest to use separate emission factor for grassland and arable land. For adjustment of the emission factors in the protocol, not only the data of the current study but also those of other studies carried out in the Netherlands and other countries in NW Europe have to be used.

Samenvatting

Nederland rapporteert jaarlijks de emissies van broeikasgassen in het kader van het Kyoto- protocol. De landbouw draagt voor ongeveer 9% bij aan de totale nationale broeikasgasemissie in Nederland (10% in 1990). Het aandeel van lachgas (N_2O) in de totale broeikasgasemissies uit de landbouw was ongeveer 52% in 2006. De N_2O-emissie uit de landbouw bestaat uit directe emissies uit toediening van kunstmest en mest aan bodems en indirecte emissies door ammoniakemissie en nitraatuitspoeling.

In het monitoringsprotocol dat Nederland hanteert om lachgasemissie te schatten (zie www.broeikasgassen.nl) worden twee mesttoedieningsmethoden onderscheiden: bovengrondse toediening en emissie-arme toediening. Voor oppervlakkig mesttoediening wordt een N_2O-emissiefactor van 1% van de toegediende stikstof (N) gebruikt en voor technieken die ammoniakemissie beperken een emissiefactor van 2% van de toegediende N, zoals zodenbemesting bij grasland en injectie bij bouwland. Dit onderscheid is belangrijk omdat in Nederland in het referentiejaar voor het Kyoto-protocol (1990) vrijwel alle mest bovengronds werd uitreden. Sinds begin jaren '90 wordt alle mest in Nederland emissiearm toegediend om ammoniakemissie te beperken. Deze verandering in toedieningstechniek heeft volgens het monitoringsprotocol geleid tot een toename van de lachgasemissie. Er ontbreken echter resultaten van veldmetingen, waarin emissiefactoren bij verschillende mesttoedieningstechnieken zijn afgeleid. Het is onvoldoende duidelijk of de emissiefactor voor bovengronds en emissiearm toedienen verschillend zijn en of de berekende toename in de lachgasemissie in begin jaren '90 juist is.

Voor een consistente berekening van de N_2O-emissie is het van essentieel belang dat Nederland beschikt over wetenschappelijk onderbouwde emissiefactoren, die conform de richtlijnen van The Intergovernmental Panel on Climate Change (IPCC) zijn vastgesteld. Hiervoor is het noodzakelijk de lachgasemissie te meten in vergelijkend veldonderzoek.

Op verzoek van SenterNovem is in het kader van het Reductieplan Overige Broeikasgassen (ROB-landbouw) door Alterra en Wageningen UR Livestock Research onderzoek uitgevoerd met als doel het afleiden van een emissiefactor voor N_2O-emissie bij bovengronds en emissiearm toedienen van mest. In het kader van het BSIK ME1 programma zijn aanvullende metingen naar de ruimtelijke variabiliteit van N_2O-emissie uitgevoerd.

Het effect van mesttoedieningstechniek op N_2O-emissie is gekwantificeerd in veldproeven op zand- en kleigrond in 2007, 2008 en 2009. Het doel van deze proeven was het afleiden van emissiefactoren voor zodebemesting van dunne rundermest op grasland en injectie van dunne rundermest en dunne varkensmest op maïsland. De kunstmest kalkammonsalpeter (KAS) werd als referentiemeststof gebruikt, omdat dit de meest gebruikte kunstmest in Nederland is en de meststof is waarvan de N_2O-emissie het best is bestudeerd.

Er waren vijf objecten op grasland: 1) onbemest (controle), 2) KAS, breedwerpig toegediend, 3) dunne rundermest, breedwerpig toegediend, 4) dunne rundermest, via zodenbemesting toegediend en 5) combinatie van breedwerpig toegediende KAS en dunne rundermest via zodenbemesting toegediend. De maïsproef bestond uit zes objecten: 1) onbemest (controle) 2) KAS, breedwerpig toegediend, 3) dunne rundermest, breedwerpig toegediend, 4) dunne rundermest, via bouwlandinjectie toegediend, 5) dunne varkensmest, breedwerpig toegediend en 6) dunne varkensmest, via bouwlandinjectie toegediend.

De mestgiften waren gebaseerd op de praktijk in Nederland. De hoeveelheid KAS werd afgestemd op de hoeveelheid werkzame N die met geïnjecteerd mest werd toegediend. De KAS en de mest werden in 4 tot 5 giften aan grasland toegediend in de periode april tot eind augustus. De KAS en mest werd in één gift aan maïs gegeven in mei/juni. Het maïsexperiment werd in 2009 uitgebreid met extra kunstmest en mestgiften, zodat het effect van N-gift op de emissiefactor kon worden onderzocht.

De objecten werden in drievoud uitgevoerd in volledig gewarde blokkenproef. Emissie van N_2O werd op 83 tijdstippen gemeten op grasland op zandgrond en op 64 tijdstippen op maïsland op zand in de periode 2007-2009. Op grasland op kleigrond werd de emissie op 64 tijdstippen bepaald in de periode 2007-2008. De emissies werden frequenter gemeten vlak na bemesting (1-3 keer per week) en minder vaak in de winter (1 keer per maand). De emissies werden in het veld gemeten met fluxkamers en een gasmonitor.

De N_2O-emissie uit maïsland nam toe na N-toediening in mei/juni. Deze verhoogde emissie duurde enkele weken, maar in augustus was er geen meetbaar effect meer van N-bemesting op N_2O-emissie. Dit patroon was in alle jaren zichtbaar en is waarschijnlijk gerelateerd aan de N-opname van maïs. Het patroon van N_2O-emissie uit grasland was anders. De emissie nam op grasland gedurende 1 à 2 weken na N-toediening toe, maar aangezien de N op verschillende tijdstippen werd toegediend, waren er dus meerdere pieken in N_2O-emissie zichtbaar voor grasland.

Op zowel grasland en maïsland leidde emissie-arme mesttoediening tot een hogere N_2O -emissiefactor in vergelijking tot breedwerpige mesttoediening.

De gemiddelde emissiefactor voor grasland (beide locaties en alle jaren) was 1,7% van de toegediende N voor KAS, 0,4% voor via zodebemesting toegediende dunne rundermest en 0,1% voor breedwerpig toegediende dunne rundermest.

De gemiddelde emissiefactor voor KAS toegediend aan maïsland was 0,1%, hetgeen veel lager is dan in het protocol dat Nederland gebruikt voor rapportages. De gemiddelde emissiefactor op maïsland voor geïnjecteerde dunne rundermest was 0,9% en die voor breedwerpig toegediende rundermest 0,4%. Dit is ongeveer een factor 2 lager dan het protocol. De gemiddelde emissiefactor voor geïnjecteerd varkensmest op maïsland bedroeg 3,6% en die van breedwerpig toegediende varkensmest 0,9%. De emissiefactor voor breedwerpig toegediende varkensmest is vergelijkbaar met die uit het protocol, maar die van geïnjecteerde varkensmest is duidelijk hoger dan het protocol. Dit wordt voornamelijk veroorzaakt door de zeer hoge N_2O-emissie uit geïnjecteerde varkensmest in 2007 (7,0% van de toegediende N).

Een toenemende N-gift leidde op maïsland tot een hogere N_2O-emissiefactor (in % van de toegediende N) voor KAS en geïnjecteerde varkens- en rundermest. Dit geeft aan dat vaste emissiefactoren, zoals toegepast door IPCC en Nederland, de relatie tussen N-gift en emissiefactor niet juist weergeven. Het verlagen van de bemesting heeft dus een tweeledig effect op N_2O-emissie: zowel de N-gift als de emissiefactor gaan omlaag. De huidige protocollen houden alleen rekening met het effect van N-gift.

De veldexperimenten op zand- en kleigrond kunnen worden gebruikt voor het afleiden van N_2O-emissiefactoren op minerale gronden. In Nederland ligt ongeveer 15% van het grasland op veengrond. In een incubatiestudie werd het effect van toediening van KAS en dunne rundermest aan grasland op zand-, klei- en veengrond gekwantificeerd. De mest werd breedwerpig en emissiearm (simulatie zodenbemesting) toegediend. Het onderzoek werd uitgevoerd met bodemkolommen met graszode (10 cm diameter doorsnede en 10 cm diepte) die in februari 2008 waren gestoken. De N_2O-emissie nam voor alle grondsoorten toe in de volgorde controle < breedwerpig toegediende rundermest < rundermest toegediende via zodebemesting < KAS. De totale N_2O-emissie nam toe in volgorde klei < zand < veen. De emissiefactoren die uit de incubatiestudie waren afgeleid zijn hoger dan die uit de veldexperimenten waren afgeleid. Dit wordt verklaard doordat de omstandigheden voor N_2O-vorming meer optimaal waren in de incubatieproeven. De N_2O-emissie factoren voor zodebemesting varieerde van 0,5% (zand- en kleigronden) tot 3,5% (veengrond). De emissiefactor voor breedwerpig toegediende rundermest was lager en varieerde van -0,1% (zand) tot 1,7% (veen). De emissiefactor voor KAS was het hoogst en bedroeg 4,0% voor de zandgrond, 1,4% voor de kleigrond en 10,5% voor de veengrond.

De berekende indirecte N_2O-emissie uit ammoniakemissie (gebaseerd op gemiddelde ammoniakemissiefactoren) van breedwerpig toegediende rundermest was vergelijkbaar met de directe N_2O-emissies voor maïsland en een factor 2,5 hoger voor grasland. De totale N_2O-emissies (gemeten directe emissie + indirect berekende emissie uit ammoniak) voor emissiearm toegediende mest waren 5-10% lager dan die voor breedwerpige mesttoediening.

Geconcludeerd wordt dat emissiearme mesttoediening (zodebemesting en bouwlandinjectie) de N_2O-emissiefactor verhogen bij zowel grasland en bouwland. De resultaten geven ook aanleiding om aparte emissiefactoren voor grasland en maïsland (en overig bouwland) te gebruiken. De emissiefactoren voor dunne rundermest toegediend aan grasland en maïsland zijn duidelijk lager dan de in het huidige protocol gebruikte emissiefactoren. Die van geïnjecteerde varkensmest is veel hoger dan die uit het protocol. Voor een eventuele aanpassing van emissiefactoren in het protocol moeten ook andere veldexperimenten uitgevoerd in Nederland en andere landen uit Noord-West Europa worden betrokken. Voor bouwland moet worden bepaald of er aparte emissiefactoren voor rundermest en varkensmest worden gehanteerd of één emissiefactor voor alle mesten. De emissiefactoren voor veengrond kunnen worden afgeleid uit resultaten van de hier beschreven incubatie- en veldstudies, alsmede eerdere veldstudies waarin N_2O-emissies uit minerale gronden en veengronden zijn gekwantificeerd.

1 General Introduction

1.1 Nitrous oxide emission trends in the Netherlands

The total greenhouse gas emission from agriculture contributed to about 9% to the total national greenhouse gas emissions in 2006 (10% in 1990). Nitrous oxide (N_2O) was in 2006 responsible for about 52% of total greenhouse gas emissions from agriculture (http://www.greenhousegases.nl/). Fertilized soils are the main source of N_2O emissions from agriculture, and accounted for 56% of national N_2O emissions in 2006 (Figure 1a).

N_2O emissions from agricultural soils include (Figure 1b):

- direct emissions due to the application of animal manure and fertilizer nitrogen and crop residues left in the field, emissions due to manure production in the meadow during grazing,
- and indirect emissions resulting from the leaching and runoff of nitrate to ground water and surface waters, and from deposition of ammonia that had volatilized as a result of agricultural activities.

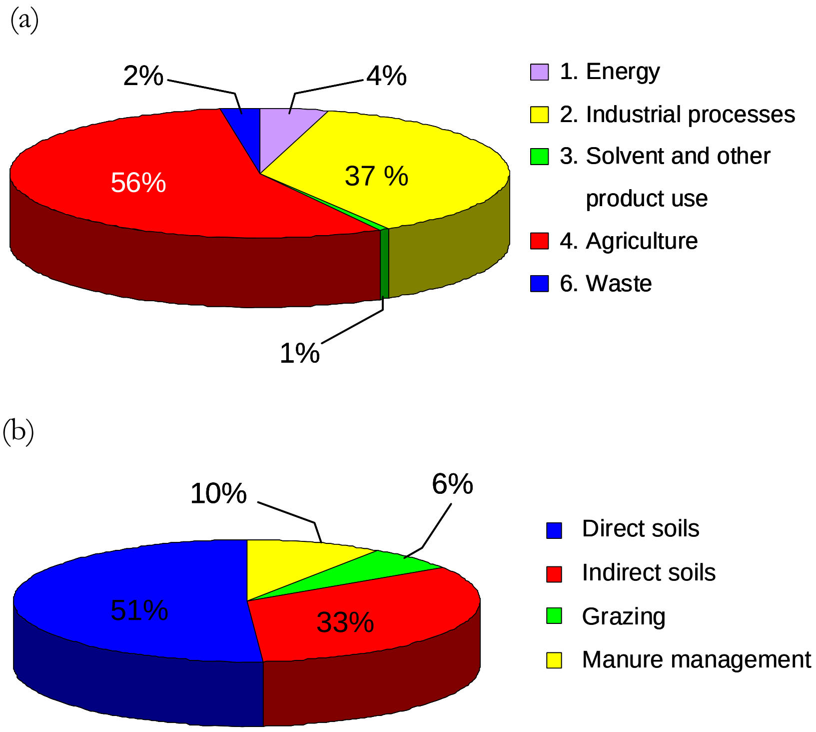


Figure 1.
Sources of N_2O in the Netherlands.

Direct soil emissions (including animal production in the meadow during grazing) accounted for almost 60% of agricultural N_2O emissions in the Netherlands in 2006 (Figure 1b). Indirect soil emissions contributed to about 30% and manure management (i.e. housing and manure storage) 10% to N_2O emissions from agriculture.

N_2O emissions increased in the early nineties because of the introduction and obligatory use of low ammonia (NH_3) emission techniques for manure application into the field. Use of these techniques resulted in less NH_3 being emitted, and therefore more mineral nitrogen (N) entering the soil and being susceptible for N_2O emission. On the other hand, because of the Dutch manure and fertilizer policy, the total amount of nitrogen applied into the soil as animal manure of mineral fertilizer decreased by approximately 32% between 1990 and 2006. As a result, N_2O emissions decreased from the late nineties on. Since 2003, no further reduction in N_2O emissions has been observed (Figure 2).

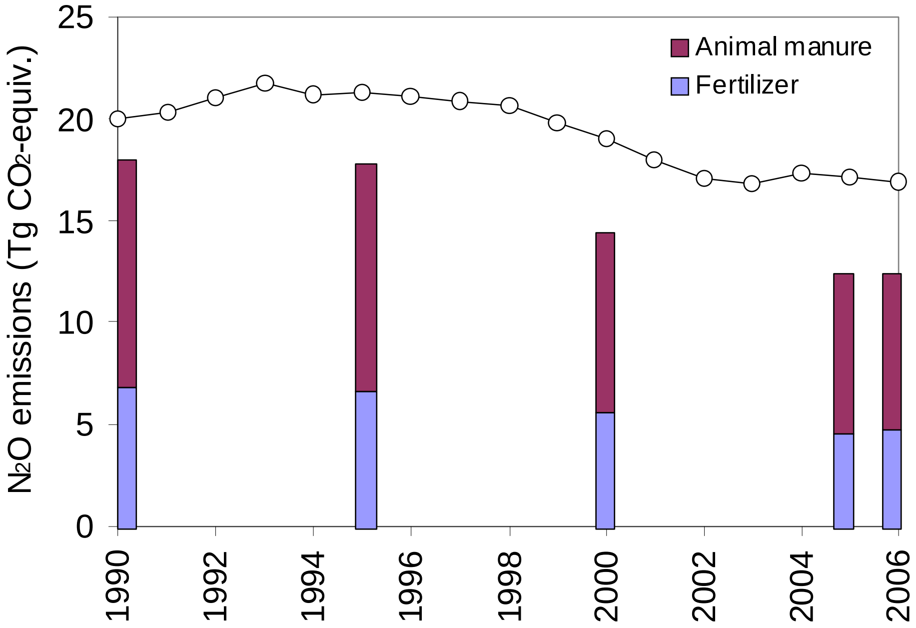


Figure 2.
N_2O emission in the Netherlands and its relation with fertilizer use and animal manure production.

1.2 Key factors controlling N_2O production in soils

N_2O is produced in soils as a by-product during nitrification and denitrification processes (Granli and Bøckman, 1994). Nitrification is an aerobic process which oxidizes ammonium into nitrate. For nitrification to occur are oxygen and ammonium necessary. Denitrification is the microbial transformation of nitrate into molecular nitrogen, and occurs in the absence of oxygen. The concentration of oxygen, nitrate, and easily decomposable organic matter are the key factors in the denitrification process. When the conditions are insufficiently aerobic for nitrification, or insufficiently anaerobic for denitrification, N_2O is likely to be formed (Figure 3).

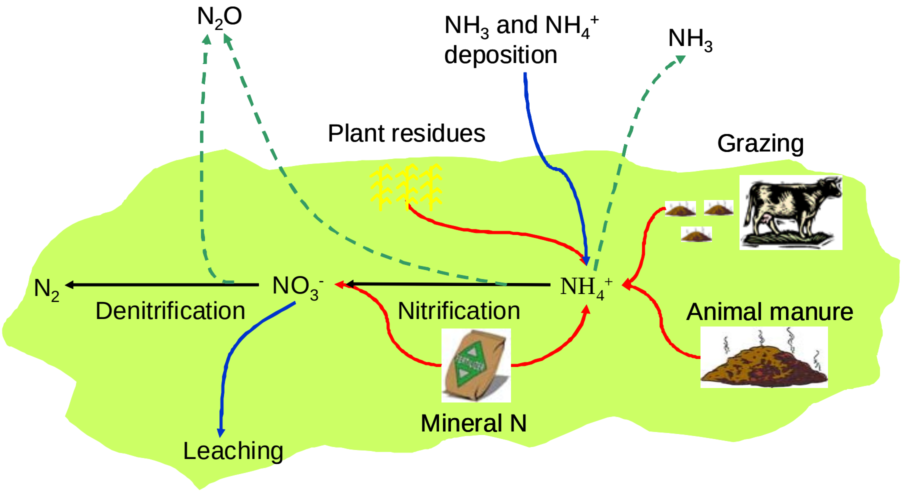


Figure 3.
N$_2$O production in soils.

The amount of organic and in particular mineral N applied into the soil is a key factor affecting the production of N_2O in soils (Mosquera et al., 2007; Stehfest and Bouwman, 2006; Velthof et al., 1996b). This is in turn dependent on management activities such as the type of fertilizer or the application rate. Slurry application technique may also affect N_2O emission, because it affects NH_3 emission and the distribution of N and carbon (C) in the soil (Huijsmans, 2003; Paul and Beauchamp, 1989). The most used nitrogen (N) fertilizers in the Netherlands are mineral fertilizer (calcium ammonium nitrate; CAN), cattle slurry, and pig slurry.

There are several low NH_3 emission application techniques for manure, including surface (broadcast) application directly followed by ploughing or harrowing, narrow band spreading, deep injection (band placed at 15-20 cm depth) and shallow or sod injection (band placed at 5 cm depth) (Huijsmans, 2003). Some studies indicate no clear or no effect of application technique on N_2O emission and denitrification from animal slurries applied to soil (Sommer et al. 1996; Velthof et al. 1997; 2003; Dendooven et al. 1998), but other studies indicate that injection of slurry enhances N_2O emission and denitrification (Flessa and Beese 2000; Thompson et al. 1987).

The presence or absence of crop residues and the nitrogen uptake of crops also has an effect on the production of N_2O from soils after the application of N. This can be influenced by land use management. In the Netherlands, most of the mineral N fertilizer and cattle and pig slurries are applied to grassland and maize land. Grassland is found on sand (46% of grassland area in the Netherlands), clay (39%), and peat soils (15%) and maize land mainly on sandy soils (75%; F. de Vries, Alterra, personal communication).

Production of N_2O is also dependent on water and oxygen supply, because it affects air permeability and gas diffusion, which in turn affects the production of N_2O via nitrification and denitrification. Water management, precipitation levels, and the degree of compaction of the soil are mechanisms which may affect the importance of these parameters (Mosquera et al., 2007). The temperature and pH of the soil may also influence N_2O production by affecting the microbial processes responsible for nitrification and denitrification (Granli and Bøckman, 1994).

1.3 Monitoring protocols

The Intergovernmental Panel on Climate Change (IPCC) has provided a general framework for the calculation of the emission of greenhouse gases (including N_2O) at the national level (IPCC, 2006). These guidelines have been applied to the case of the Netherlands resulting in a number of monitoring protocols, which are published by the Ministry of Housing, Spatial Planning and Environmental Management (VROM) and yearly updated, if needed (www.greenhousegases.nl).

Direct N_2O emissions are calculated by multiplying the available nitrogen, and a specific emission factor per source category, and then adding up the contribution of all different sources:

$$E(direct) = \sum E_{ij} \cdot EF_{ij} \cdot 44/28$$

E(direct) = N_2O emission (in kg N_2O)
E_{ij} = amount of available N for the specific source category (i) and soil type (j) in kg N
EF_{ij} = emission factor for the specific source category (i) and soil type (j) in kg N_2O-N / kg N
44/28 = conversion factor from kg N_2O-N to kg N_2O

The monitoring protocol differentiates between surface (broadcast) spreading and low NH_3 emission manure application techniques. The N_2O emission factor used in the Netherlands for broadcast spreading (1% of applied N) is lower than for low NH_3 emission manure application techniques (2% of applied N). This is important because in 1990, the reference year for Kyoto, all manure was surface applied (broadcast) to the soil of both grassland and arable land. Because of the Netherlands' policy to reduce NH_3 emissions, only low NH_3 emission manure application techniques are allowed since the early 1990's. According to the monitoring protocol, this change in manure application techniques resulted in higher direct N_2O emissions from agricultural soils. This was also the conclusion of the literature study performed by Kuikman et al. (2006), although they could not derive new emission factors for these techniques. Differences in emission factors between broadcast spreading and low emission application techniques were also smaller than those used in the monitoring protocols.

Indirect N_2O emissions from atmospheric deposition of N volatilized from managed soils are estimated using the IPCC default emission factor of 0.01 kg N_2O-N per kg N emitted. Indirect N_2O emissions from N leaching/runoff from managed soils is estimated by using the following equation:

$$E(leaching) = \sum E_i \cdot FRACleach \cdot EF_i \cdot 44/28$$

E(leaching) = indirect N_2O emission (in kg N_2O) from N leaching/runoff
E_i = amount of available N for the specific source category (i) in kg N
FRACleach = fraction of the N that is leaching, 0.30 kg N per kg N that leaches
EF_i = emission factor, 0.025 kg N_2O-N per kg N that is leaching
44/28 = conversion factor from kg N_2O-N to kg N_2O

1.4 Scope of this report

In 2007 a project was started within the framework of the Senter Novem program 'Reduction of Non-CO_2 Greenhouse Gases', with the objective to derive N_2O emission factors for manure application. Chapter 2 summarizes the results of a three-year field measurement campaign performed to quantify the effect of manure type (calcium ammonium nitrate; cattle slurry; pig slurry) and application technique (broadcast spreading; shallow injection on grassland; injection on maize) on the emission of N_2O from fertilized soils (grassland and maize on sandy soils, grassland on clay). Chapter 3 presents the results of an incubation study performed to determine the effect of soil type on fertilizer and manure derived N_2O emissions, as no field measurements were carried on peat soil. The effects of moisture content and compaction on N_2O emission were quantified in a laboratory study, as these factors may largely control spatial variability of N_2O emission in the field. The spatial variability of N_2O fluxes was determined for both fertilized grasslands and maize land. Special attention was paid to the effect of low NH_3 emission manure application techniques (shallow injection on grassland and slurry injection on maize land) on the spatial variability of N_2O fluxes. In the project additional studies were carried out to i) quantify N_2O emission from combinations of CAN and cattle slurry (Chapter 2), to quantify the effect op application rate on N_2O emission from maize land (Chapter 2), and iii) to assess the spatial variability of N_2O fluxes in grassland and maize land (Appendix 2). These additional measurements and treatments were funded by BSIK ME1 program. The results presented in Appendix 2 provide insight in the spatial variability of N_2O emission and factors controlling N_2O emission in the field experiments. The results of Appendix 2 are not presented in the Chapters of the report. The paper Appendix 1 present the results of the field experiments which were available in June 2009, and includes a calculation of the indirect N_2O emission caused by ammonia emission. The main conclusions of this study are presented and discussed in chapter 4.

2 Field experiments

2.1 Introduction

The effect of manure application technique was quantified in field experiments. The aim of these experiments was to derive N_2O emission factors for shallow injected cattle slurry (on grassland), injected cattle and pig slurries (on maize land) and broadcast slurries. Shallow injection is the most used NH_3 abatement application method in the Netherlands for grassland and injection for maize land. Grassland and maize land are the most important crops in the Netherlands and large part of the cattle and pig slurries are applied to grassland and maize land.

In the experiments, a treatment with calcium ammonium nitrate (CAN) was included, because it is the most used mineral N fertilizer in the Netherlands. Moreover, CAN was used in most N_2O studies in the Netherlands (Kuikman et al., 2006), by which results of experiments can be compared.

The BSIK ME1 program funded additional studies, i.e. an additional treatment with combination of CAN and cattle slurry in the grassland studies (which is the most common nutrient management strategy in dairy farming systems) and detailed measurements of effects op N application method on spatial variability of N_2O fluxes (see Appendix 2 for the results of the studies on spatial variability).

2.2 Materials and methods

The effects of slurry application method were quantified in field experiments on grassland and maize land. There were two grassland locations, i.e. a sandy soil and clay soil, and one maize location, i.e. a sandy soil. The grassland was dominated by Lolium perenne L.. All field experiments were located in Wageningen, The Netherlands (51° 58'' N, 5° 40'' E). The soil properties are presented in Table 1. The experiments on the sandy soils were carried out for three years (2007, 2008 and 2009), and that on clay soil for two years (2007 and 2008).

Table 1.
Soil properties, determined in spring 2007.

Location	N_{total}	pH	NH_4	NO_3	DON[*]	DOC[**]	C_{totaal}	< 16 µm
	g/kg		mg N/kg			mg C/kg	g/kg	%
Grassland; sandy soil	1.39	4.9	5.2	1.9	23	133	22.8	5.7
Grassland; clay soil	1.61	7.1	1.3	1.5	12	130	23.7	64.5
Maize land; sandy soil	1.28	4.8	3.3	9.7	6.0	68	18.2	5.9

[*] Soluble organic N

[**] Soluble organic C

The grassland experiments consisted of five treatments:

- No fertilization (control);
- Mineral fertilizer (CAN), broadcast application;
- Cattle slurry, broadcast application;
- Cattle slurry, shallow injection;
- CAN and shallow-injected cattle slurry.

The maize experiments consisted of six treatments:

- No fertilization (control);
- Mineral fertilizer (CAN), broadcast application;
- Cattle slurry, broadcast application;
- Cattle slurry, injection;
- Pig slurry, broadcast application;
- Pig slurry, injection.

In 2009, the maize experiment was extended with six additional treatments, i.e. two additional application rates for CAN, for injected cattle slurry, and for injected pig slurry. The aim of these additional treatment was to assess the effect of N application rate on the N_2O emission factor.

The slurry was applied with equipment designed for field experiments. Shallow injection is a technique in which discs makes slots of 5 cm depth into grassland. The manure was injected to 5 cm depth and the slots remain open. The distance between the slots is 20 cm. In arable land, slurry was injected to a depth of 15 to 20 cm, after which the injected slurry was covered by soil. Figure 4 shows some pictures of the used slurry application techniques.

The N application rates of the different treatments are presented in Appendix 3 and summarized in Table 2. The application rates of slurry were based on common slurry application rates in the Netherlands. The amount of CAN was adjusted to the amount of applied slurry, so that the total amount of applied plant-available N was similar in the treatments with CAN and (shallow) injected slurry. On basis of N fertilizer recommendations in the Netherlands, it was assumed that 60 percent of the (shallow) injected slurry N was plant-available. The total amount of broadcast slurry was equal to that of (shallow) injected slurry. The real N application rates of slurry were calculated from the N contents of slurry samples taken just for application. These samples were analyzed for total N and ammonium (NH4). The average total N content of cattle slurry (n = 17 samples in three years) was 5.0 ± 0.2 g N per kg slurry and that of NH4 2.6 ± 0.2 g N per kg slurry. For pig slurry the average total N content (n = 3 samples in three years) was 10.4 ± 0.4 g N per kg slurry and that of NH4 7.1 ± 0.2 g N per kg slurry (see Appendix 4 for all results of slurry composition). The N content and the percentage of NH4 in total N of the pig slurry were much higher than the average content for pig slurry in the Netherlands. The application rate in 2007 was based on an estimated composition (thus lower N contents), by which the N application rate of pig slurry was higher in 2007 than in 2008, and 2009 and was also high than that of cattle slurry in 2007.

The CAN and slurry was applied in 5 dressings to grassland in the period April to end of August of 2007, and 2008. The dry conditions in August 2009 hampered growth of grass, by which the planned 5th N dressing was skipped. The treatment of CAN in combination of shallow injected cattle slurry on grassland, may be considered as practice in the Netherlands. In this treatment, cattle slurry was applied for the first, third, and fifth grass cut, and CAN for the second, and fourth growing period.

The N was applied in one dressing in May/June to maize land, after which maize was sown.

Table 2.
Total N application rates, kg N per ha.

Land use	Treatment	2007	2008	2009
Grassland	Control	0	0	0
	CAN	175	175	160
	Cattle slurry; shallow injection	322	330	274
	Cattle slurry; broadcast	322	330	274
	CAN + shallow injected cattle slurry	460	400	336
Maize land	Control	0	0	0
	CAN 1			50
	CAN 2	102	102	125
	CAN 3			200
	Cattle slurry; broadcast	166	182	175
	Cattle slurry; injection 1			100
	Cattle slurry; injection 2	166	182	175
	Cattle slurry; injection 3			251
	Pig slurry: broadcast	249	188	181
	Pig slurry; injection 1			106
	Pig slurry; injection 2	249	188	181
	Pig slurry; injection 3			266

All treatments were applied in triplicate in a completely randomized block design. At the grassland site, all plots were 20 m long and 2.5 m wide. The plots at the maize field were 20 m long and 5 m wide. Grass was harvested four to five times per year by mowing to a height of 5 cm using a Haldrup plot harvester. The time of mowing was dependent on the estimated dry matter yields, according to common practice in the Netherlands. The fresh yield of each grass plot was determined in the field, using the Haldrup harvester. The maize yield was quantified by manually harvesting and weighing an area of 30 m^2 per plot. Notice that this method of harvesting may not give an accurate estimate of the yield. The yields of maize must be carefully considered. Dry matter yields were determined from the fresh yields and the dry matter contents (after drying at 105 °C) of samples of grass and maize. After harvesting the maize in October, a winter crop (winter rye) was cultivated. This winter crop was ploughed into the soil in April.

Fluxes of N_2O fluxes were measured 83 times for grassland on sandy soil and 64 times for maize land on sandy soil, in the period 2007-2009. Fluxes of N_2O were measured 64 times for grassland on the clay soil in 2007-2008. Fluxes were measured more intensively in the period just after N application (up to 3 times per week) and less frequently in the winter (at least once per month). Fluxes of N_2O were measured using a closed flux chamber technique, as described by Schils et al. (2008). The chambers (PVC cylinders) had a diameter of 18.6 cm and height of 15 cm (after inserting 3 cm into the soil). The concentration of N_2O in the headspace was measured just after closing and after 30 minutes, using a photo-acoustic infra-red gasmonitor of Innova (Innova 1312; see Figure 4). The analyzer was directly attached to the chambers with polytetrafluorethylene tubes with an internal diameter of 0.3 cm and a length of 400 cm. A trap of soda lime was attached in the air stream to the gas analyzer to reduce the CO_2 concentration and to minimize possible interference of CO_2 on the N_2O measurement. The measured N_2O concentrations of the headspace were corrected for the internal volume of analyzer and tubes, which was about 2.5% of the headspace volume. The flux was calculated assuming linear changes of the N_2O concentration in the headspace over time, as shown by Velthof and Oenema (1995). These concentrations were used to calculate individual fluxes in µg N_2O-N m^{-2} hr^{-1}. Mean fluxes per treatment were based on six flux measurements (two chambers per plot, three plots per treatment). These fluxes were then averaged to obtain an average flux per treatment per measurement time. By interpolation of the fluxes between measurement days, a total emission per treatment was calculated. The total N_2O emission was expressed in kg N ha^{-1}.

Figure 4.
Pictures of the field experiments, showing shallow injection and surface application of slurry on grassland, injection of slurry in maize land, ploughing of winter crop, and the position of flux chambers in grasslands and maize land.

The soil temperature and volumetric moisture contents at 15 cm depth were continuously monitored at two sites on each location, using an ECT Temperature sensor and an EC-10 Soil Moisture Sensor (Decagon Devices, Inc. Pullman, USA), respectively. At each N_2O measurement day, the groundwater level and the amount of rainfall since the previous measurement were recorded.

The N_2O emission factor in % of the total N applied was calculated for each year as:

[(N_2O-N emission of the treatment) – (N_2O-N emission of the control)]/(total N applied),

where N_2O-N emission of the treatment is the emission of the fertilized plot in kg N per ha, N_2O-N emission of the control is the emission of the unfertilized plot in kg N per ha, and total N applied is the total amount of N applied in kg N per ha. The emission factors were based on the periods April 2007 – March 2008, March 2008 – March 2009, and March 2009 – November 2009.

The overall effect of the treatments on N_2O emission was assessed by Analysis of Variance (ANOVA) and Least Significant Difference (LSD) at $p< 0.05$. The average annual N_2O emission was calculated for the whole measurement period, i.e. three years on the sandy soils and two years on the clay soil. The annual N_2O emissions were log-transformed to stabilize variance. The statistical analyses were carried out with with SPSS 15.0 for Windows (release 15.0.1).

2.3 Results and discussion

2.3.1 Weather data and groundwater level

The first measurement year (2007) was dry in spring (till June), but wet in summer (July-August), as shown both by the soil moisture contents and groundwater level. This is illustrated for grassland on sandy soil in Figures 5 and 6. The spring of 2008 was wet, but the summer relatively dry, by which soil moisture content and groundwater were low in the summer of 2008. The growing season of 2009 (April – October) was very dry, resulting in a strong decrease in soil moisture content and groundwater level during the season (Figures 5 and 6). The soil temperature at 15 cm depth ranged from -3°C in the winter 2008-2009 to about 20 °C in the summers of 2007 and 2008 (Figure 6).

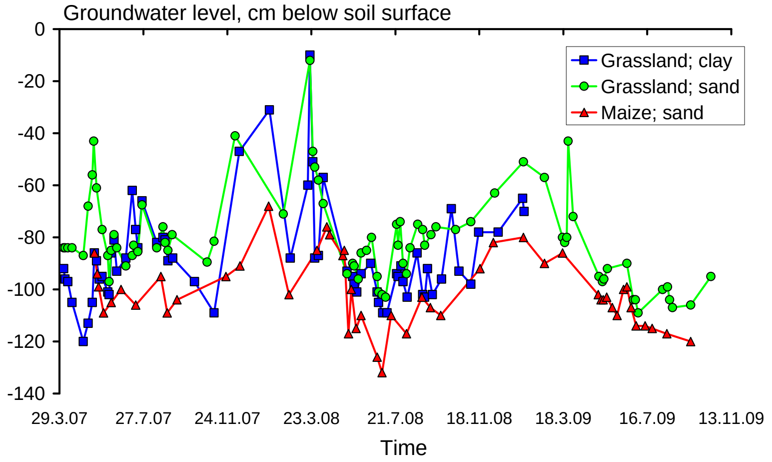


Figure 5.
Groundwater levels on the three sites.

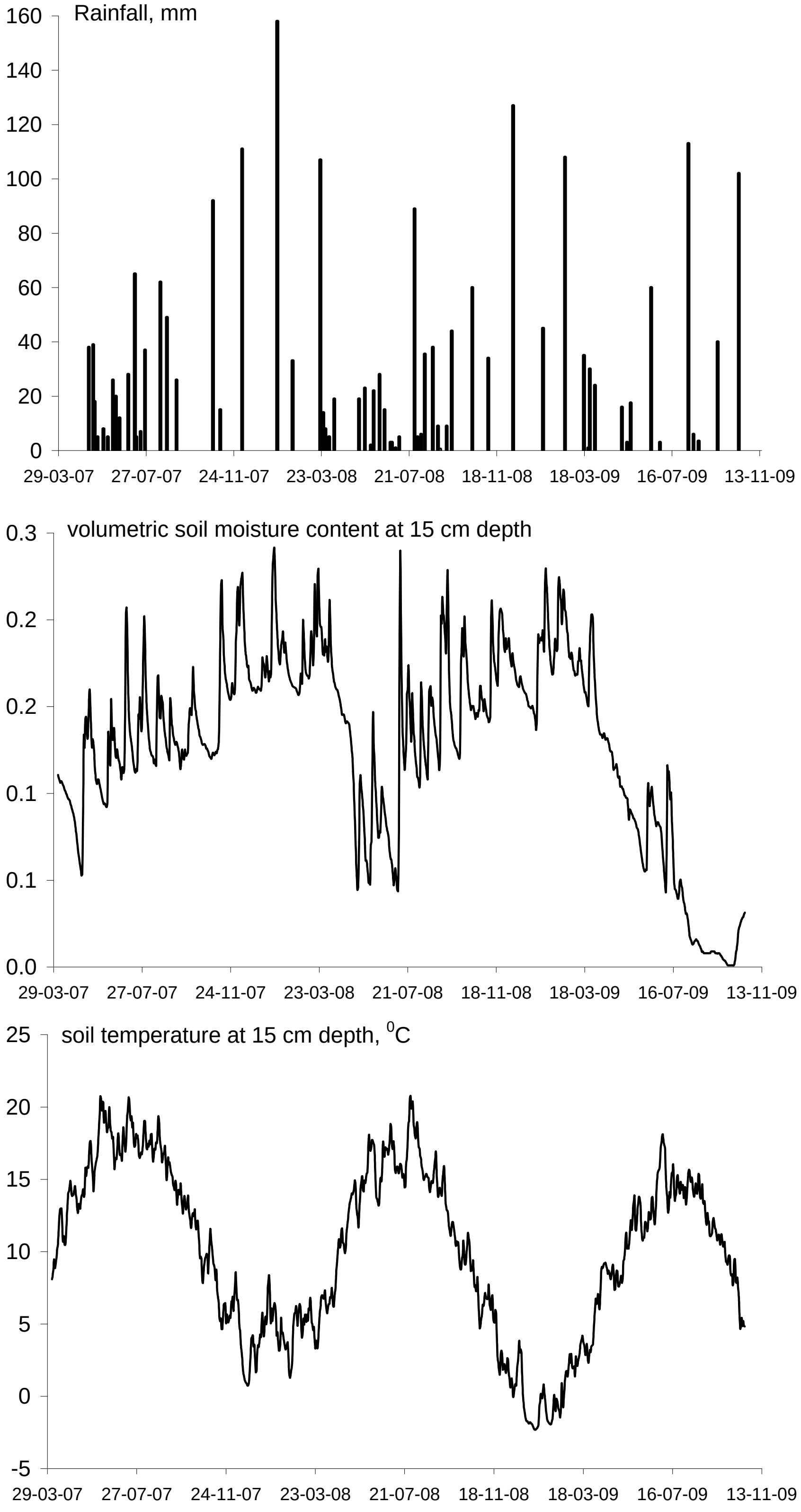


Figure 6.
Rainfall, soil temperature at 15 cm depth, and volumetric moisture contents in the experimental periods. Results for the grassland experiment on sandy soil. Rainfall is the amount of rainfall since previous measurement.

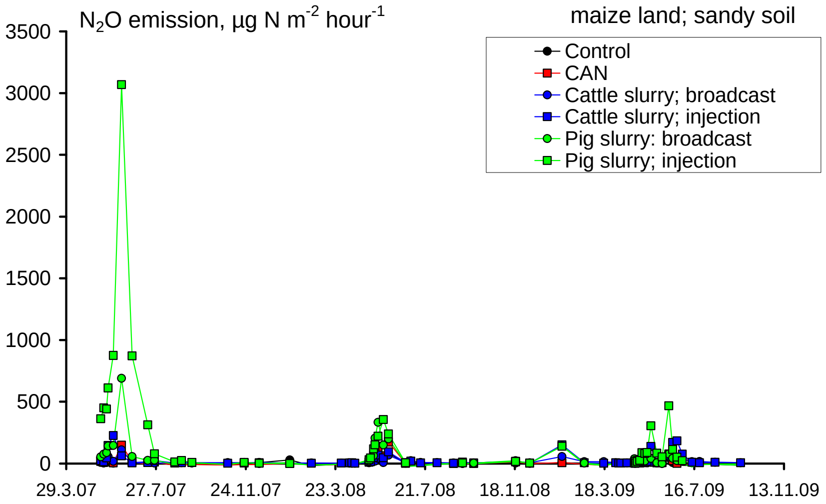
2.3.2 N_2O fluxes and total N_2O emission

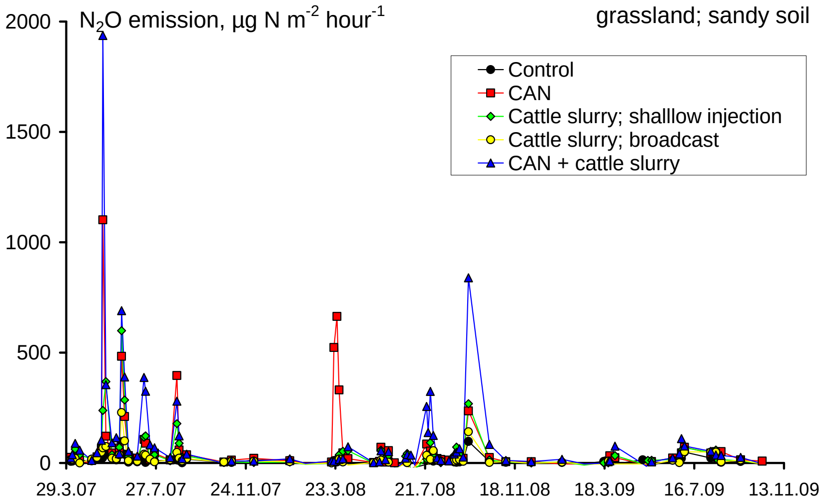
The N_2O flux from maize land increased after N application in May/June for several weeks, decreased thereafter, and there were no significant differences in N_2O flux shown between fertilized and unfertilized maize land after August (Figure 7). This flux pattern was shown in all years and is most probably related to the N uptake by maize. It takes several weeks after sowing, before the N uptake of the maize significantly affects the mineral N contents of the soil. In this period, NH_4 applied with slurry can be nitrified, and denitrification may occur. The higher N_2O fluxes from the maize land plots treated with slurry compared to the plots where CAN was applied, was probably caused by the applied organic carbon in the slurry. Application of organic carbon increases the denitrification potential of the soil. Fluxes from maize land were highest in the wet summer of 2007, especially for pig slurry (Figure 7). The high fluxes from pig slurry in 2007 were probably related to the high N application rate (Table 2) in combination with the wet conditions. Increasing the N application rate of CAN, injected pig slurry, and injected cattle slurry increased fluxes of N_2O from maize land (Figure 10).

Fluxes of N_2O from the maize land (slightly) increased during thawing in January 2009 (Figures 7 and 8), which is often observed in arable land during freeze-thawing cycles. Injection of pig and cattle slurries to maize land resulted in higher N_2O fluxes and total emission than broadcast application of slurries (Figures 8 and 9). Fluxes of pig slurry were much higher than those of cattle slurry, which is probably related to the higher fraction of NH_4 in pig slurry (on average 69 percent of total N) than in cattle slurry (on average 51 percent of total N). Moreover, the organic C in pig slurry is probably more available for denitrifying bacteria than that of cattle slurry. Volatile fatty acids are rapidly degradable C compounds in manures. In soil, volatile fatty acids are metabolized within a few days by soil bacteria, increasing denitrification and/or immobilization of N (Kirchmann and Lundvall 1993; Paul and Beauchamp 1989). Generally, the volatile fatty acids contents are higher in pig slurries than in cattle slurries (Kirchmann and Lundvall 1993; Paul and Beauchamp 1989).

Fluxes of N_2O from grassland were highest in the wet year 2007 and lowest in the dry year 2009 (Figures 7 and 8). The patterns and flux magnitude were similar for the grasslands on the sandy and clay soil. The N_2O fluxes and total N_2O emission from shallow injected cattle slurry were higher than those from broadcast cattle slurry, at both grassland soils (Figures 7, 8, and 9).

The pattern of fluxes from the grasslands clearly differed from those from the maize land, i.e. the fluxes were much shorter (i.e. 1-2 weeks) and several peak fluxes during the growing seasons were shown (Figures 7 and 8). This pattern is related to the N application in several dressings in combination with the high N uptake capacity of grassland. Grass roots can rapidly absorb mineral N, by which soil mineral N contents rapidly decrease after N application. The N_2O fluxes from slurry applied to grassland were much lower than that from CAN applied, which is the opposite to maize land (where emission were higher from the slurries than from CAN). The low emission from animal slurries on grassland is probably related to the high N uptake capacity of grassland, by which part of the NH_4 applied with slurry is already taken up by grassland before it can be nitrified. Moreover, the organic C contents and dissolved organic C (DOC) contents of grasslands are higher than of maize land (table 2), by which the denitrification potential of grassland is higher than that of maize land (Munch and Velthof, 2007). It may be expected that application of organic C via slurry has a larger effect on the denitrification capacity of maize land than that of grassland. Fluxes from grassland did not increase during thawing in January 2009, as shown for maize land (Figure 8).





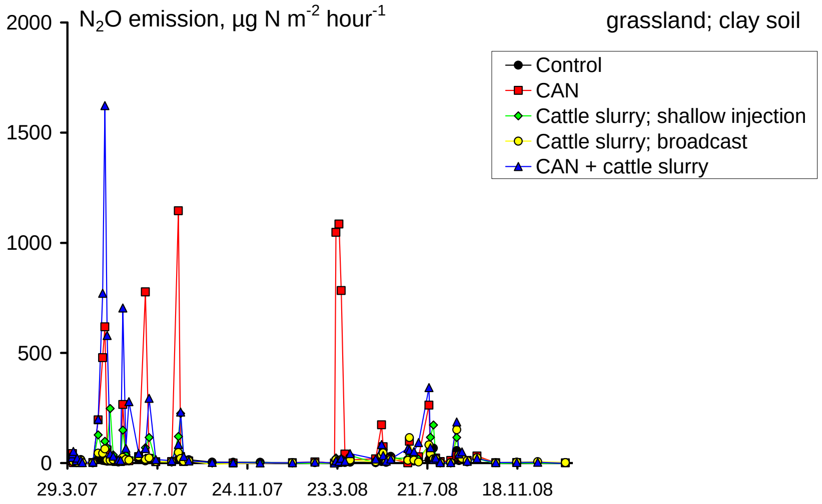


Figure 7.
Fluxes of N$_2$O during the experimental period. The date is presented on the X-axis. Note the differences in scale of Y axes. Measurements were carried out for two years on the clay soil and three years on the sandy soils

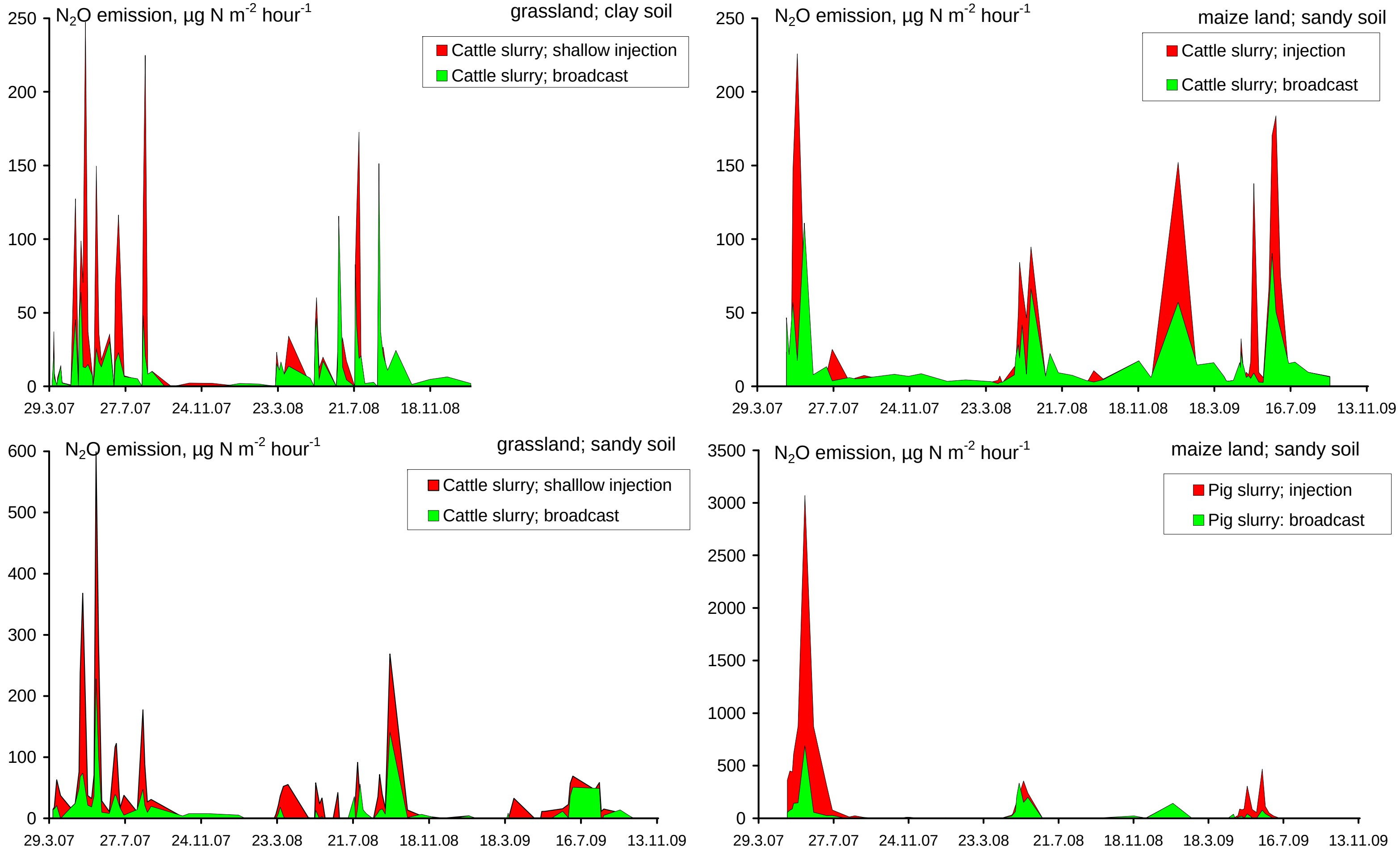


Figure 8.

Fluxes of N2O from broadcast and (shallow) injected slurry at the three sites during the experimental period. The date is presented on the X-axis. Note the differences in scale of Y axes. Measurements were carried out for two years on the clay soil and three years on the sandy soils

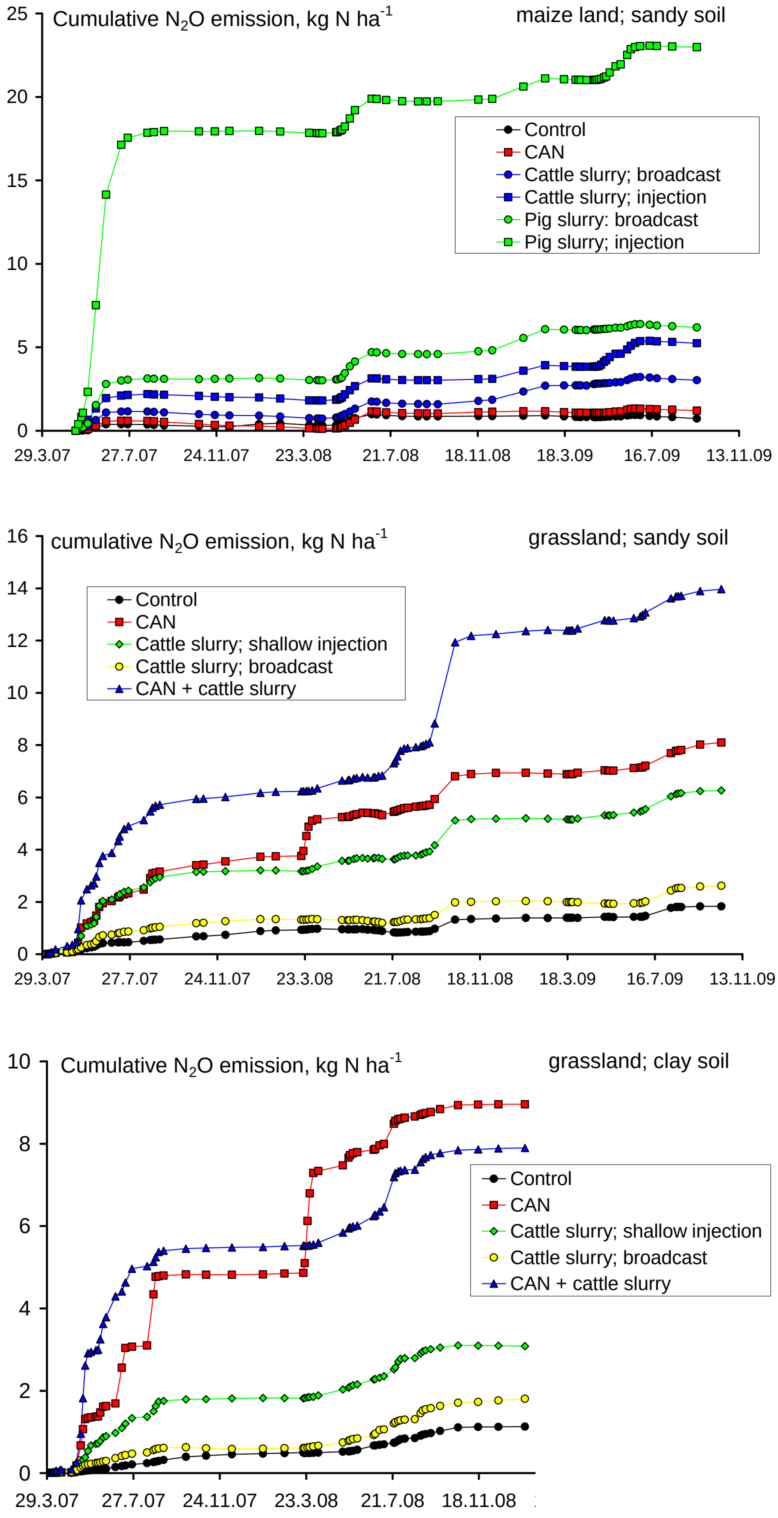


Figure 9.

Cumulative N$_2$O emission during the experimental period. The date is presented on the X-axis. Note the differences in scale of Y axes. Measurements were carried out for two years on the clay soil and three years on the sandy soils.

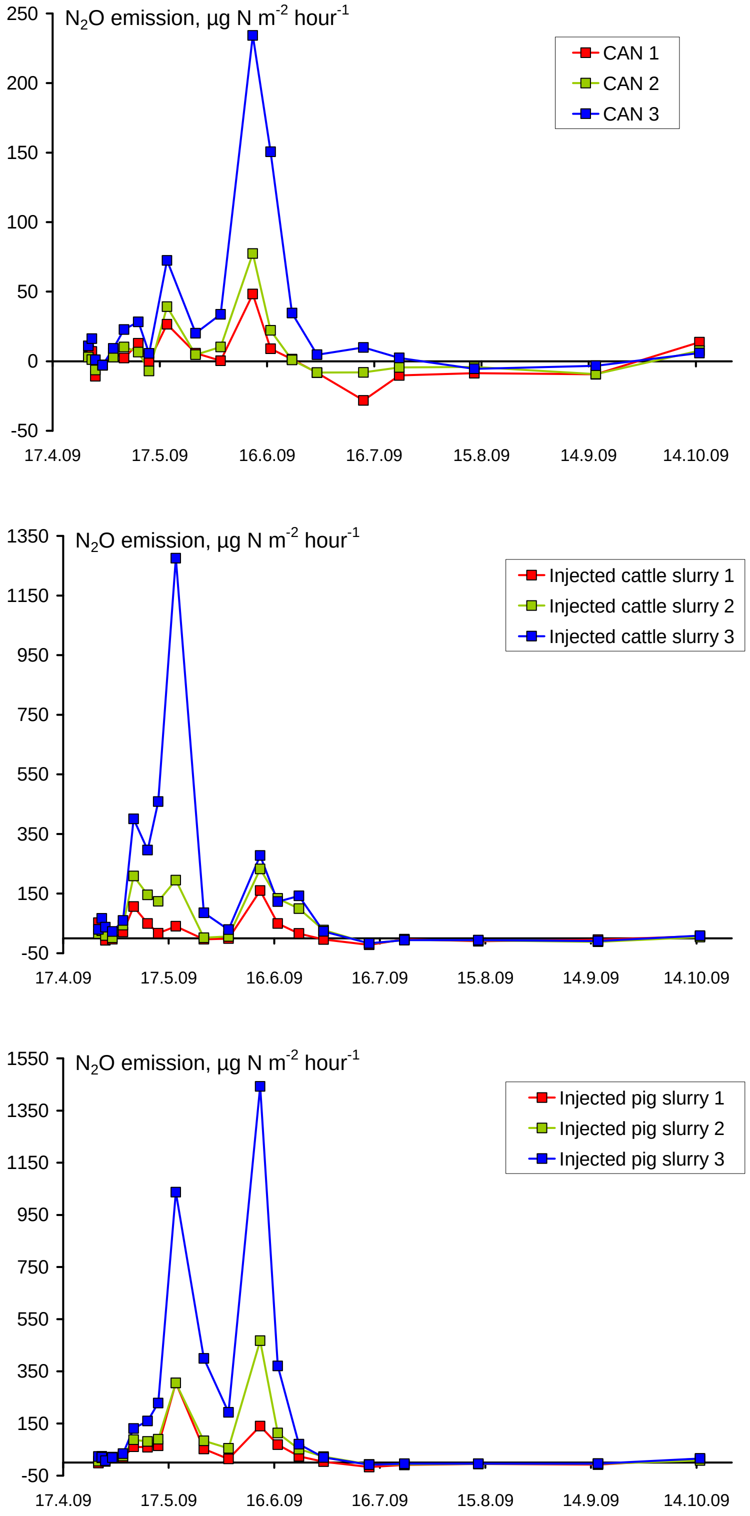


Figure 10.
Fluxes of N_2O from maize land on the sandy soil at different N application rates in 2009 (see Table 2 for the N application rate). The date is presented on the X-axis. Note the differences in scale of Y axes.

2.3.3 Emission factors of N_2O

The total emissions and the emission factors are presented in Tables 3 and 4. The statistical analyses showed that for grassland, the average annual N_2O emission significantly ($P < 0.05$) increased in the order broadcast cattle slurry < shallow injected cattle slurry < CAN (details of statistical analysis are not shown). The average annual N_2O emission of the CAN + injected slurry treatment was not statistically significant different from that of CAN.

The statistical analysis showed for maize land that average annual N_2O emission of CAN was significantly ($P < 0.05$) smaller than that of the slurries and that the N_2O emission of injected pig slurry was significantly higher than that of the other slurry treatments. The differences between the treatments broadcast cattle slurry, injected cattle slurry, and broadcast pig slurry were not statistically significant.

In general, the emission factors were highest in the wet year 2007 and lowest in the dry year 2009. At both grassland sites and all years, the emission factors were highest for CAN, followed by CAN + shallow injected cattle slurry, shallow injected cattle slurry, and broadcast cattle slurry. The average emission factor for grassland (both sites and all years) was 1.7% of the N applied for CAN, 0.4% for shallow injected cattle slurry, and 0.1% for broadcast cattle slurry (Table 4). The emission factor for CAN was somewhat higher than that of the current protocol used in the Netherlands to calculate N_2O emission (http://www.greenhousegases.nl/), but the emission factors for shallow injected and broadcast cattle slurry were much lower. The emission factor for shallow injected cattle slurry was a factor 4 higher than that of broadcast slurry; in the protocol the difference in emission factor between broadcast application and injection is only a factor 2.

The emission factor for pig slurry injected in maize land was very high (7.0% of the N applied) in the wet year 2007. This is attributed to the high N application rate (Table 2). Indeed, an increase in the N application rate increased the emission factors for CAN, injected cattle slurry, and injected pig slurry in 2009 (Figure 11). The year 2009 was a dry year, so that it may be expected that the effect of N application on the N_2O emission factor is higher in a wet year, such as 2007.

In all years, the emission factor for CAN on maize land was smaller than that of injected pig slurry and injected cattle slurry. Injection clearly increased emission factor for pig and cattle slurry on maize land in comparison to broadcast application in 2007 and 2009, but the differences in 2008 were small (the emission factor for broadcast cattle slurry was somewhat higher than that for injected cattle slurry in 2008). On average, the emission factor for CAN applied to maize land was 0.1% of the N applied, which is much smaller than the factor of 1% in the current protocol (Table 4). The average emission factor of injected cattle slurry was 0.9% and that of broadcast cattle slurry 0.4%, which is about a factor 2 smaller than the emission factors in the current protocol.

The average emission factor of pig slurry injected to maize land was 3.6% and that of broadcast pig slurry 0.9% (Table 4). The emission factor for broadcast pig slurry is similar to the protocol. That of injected pig slurry is much higher than the protocol, but the average emission factor is strongly affected by the high emission factor in 2007. The emission factor of injected pig slurry was slightly higher than that of the protocol in 2008 and 2009.

Table 3.

Total N_2O emission and N_2O emission factors (EF) for the different treatments, locations, and years.

Crop and location	Object	2007/2008			2008/2009			2009			average total period		
		N rate, kg N/ha	N_2O-emission, g N/ha	EF, % of N	N rate, kg N/ha	N_2O-emission, g N/ha	EF, % of N	N rate, kg N/ha	N_2O-emission, g N/ha	EF, % of N	N rate, kg N/ha	N_2O-emission, g N/ha	EF, % of N
Grassland; clay soil	Control	0	499		0	631					0	565	
	CAN	174	4863	2.5	175	4094	2.0				175	4479	2.2
	CM; shallow injection	322	1817	0.4	330	1268	0.2				326	1543	0.3
	CM; broadcast	322	612	0.0	330	1193	0.2				326	903	0.1
	CAN + CM	460	5526	1.1	400	2371	0.4				430	3948	0.8
Grassland; sandy soil	Control	0	931		0	463		0	438		0	611	
	CAN	174	3760	1.6	175	3125	1.5	160	1210	0.5	170	2699	1.2
	CM; shallow injection	322	3175	0.7	330	1979	0.5	274	1107	0.2	309	2087	0.5
	CM; broadcast	322	1318	0.1	330	671	0.1	274	630	0.1	309	873	0.1
	CAN + CM	460	6234	1.2	400	6151	1.4	336	1581	0.3	398	4656	1.0
Maize land; sandy soil	Control	0	342		0	478		0	-94		0	242	
	CAN	102	145	-0.2	102	926	0.4	125	133	0.2	110	401	0.1
	CM; injection	166	1821	0.9	182	2019	0.8	175	1407	0.9	174	1749	0.9
	CM; broadcast	166	753	0.2	182	2036	0.9	175	241	0.2	174	1010	0.4
	PM; injection	249	17846	7.0	188	3172	1.4	181	1964	1.1	206	7661	3.6
	PM; broadcast	249	3040	1.1	188	3017	1.3	181	134	0.1	206	2063	0.9

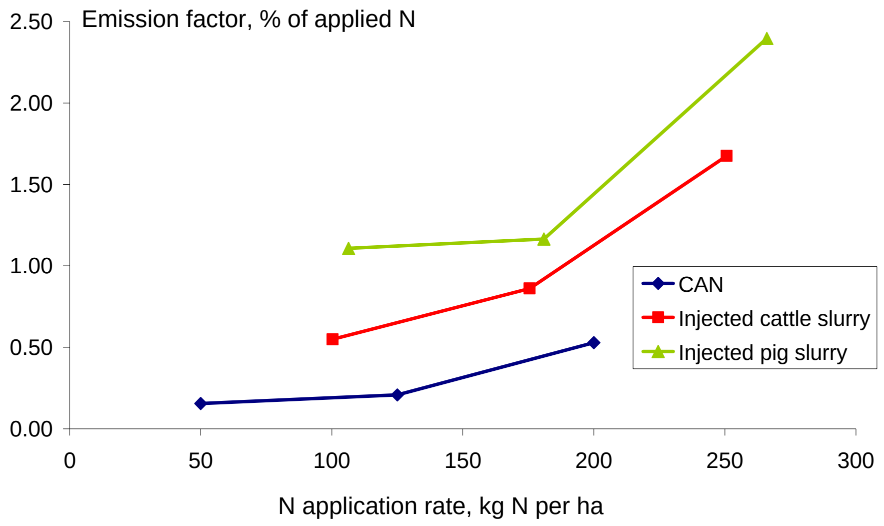


Figure 11.
Relation between N application rate and emission factor for N_2O for maize on the sandy soil. The emission factor in the main experiment are the emission factors derived from the middle application rate (Tables 3 and 4).

Table 4.
Average emission factors (EF) from mineral soils derived from the field experiments (grassland is the average of the sand and clay soil), and the relative emission factor compared to CAN.

		EF derived from experiments, %	Relative EF compared to CAN
grassland	CAN	1.7	1
	CM; shallow injection	0.4	0.22
	CM; broadcast	0.1	0.05
arable land	CAN	0.1	1
	CM; injection	0.9	5.9
	CM; broadcast	0.4	3.0
	PM; injection	3.6	24.7
	PM; broadcast	0.9	6.1

[1] www.greenhousegases.nl

2.3.4 Yields

The results of the dry matter yields of grassland clearly show lower yields of the clay soil than of the sandy soil, which is probably due to the historic management. The grassland in the clay soil was extensively managed and that of the sandy soil was intensively managed. In general, the yield obtained with broadcast cattle slurry was lower than of injected slurry and CAN. This is probably due to NH_3 volatilization from broadcast slurry, by which the amount of applied plant-available N is lower. The yield in 2009 was low, which is caused by the dry conditions in (late) summer, by which grass could only four times be harvested instead of the planned five times. The dry matter yields of maize were high and there was a tendency that yields with CAN were lower than yields with slurry. Notice that the manually harvesting of the plots may not give an accurate estimate of the maize yield. The yields of maize must be carefully considered. There was no clear overall effect of slurry application method on dry matter yield of maize. In some cases injection resulted in higher yields than broadcast application, but in other cases the opposite effect was shown.

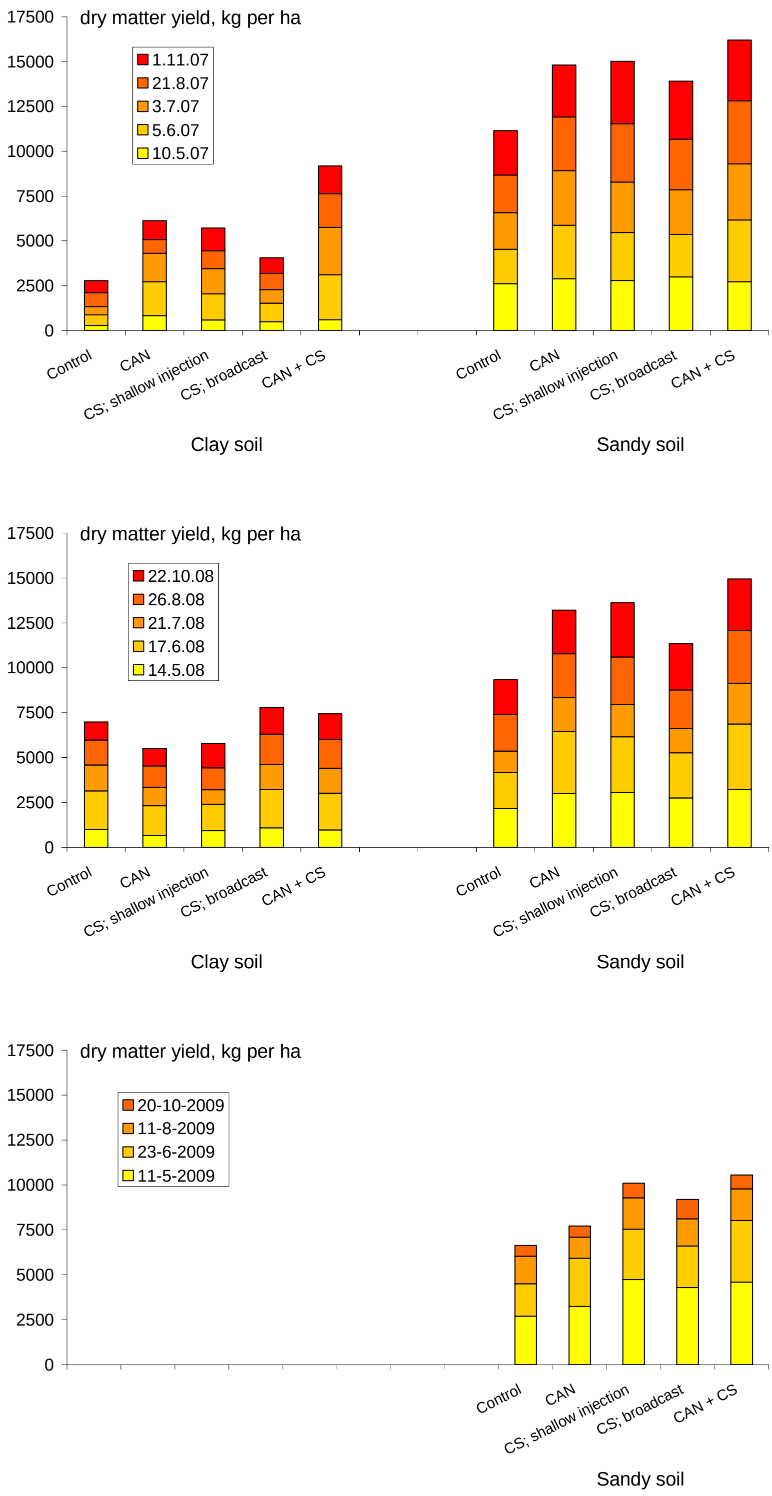


Figure 12.
Dry matter yields of grassland in 2007, 2008, and 2009. CS is cattle slurry.

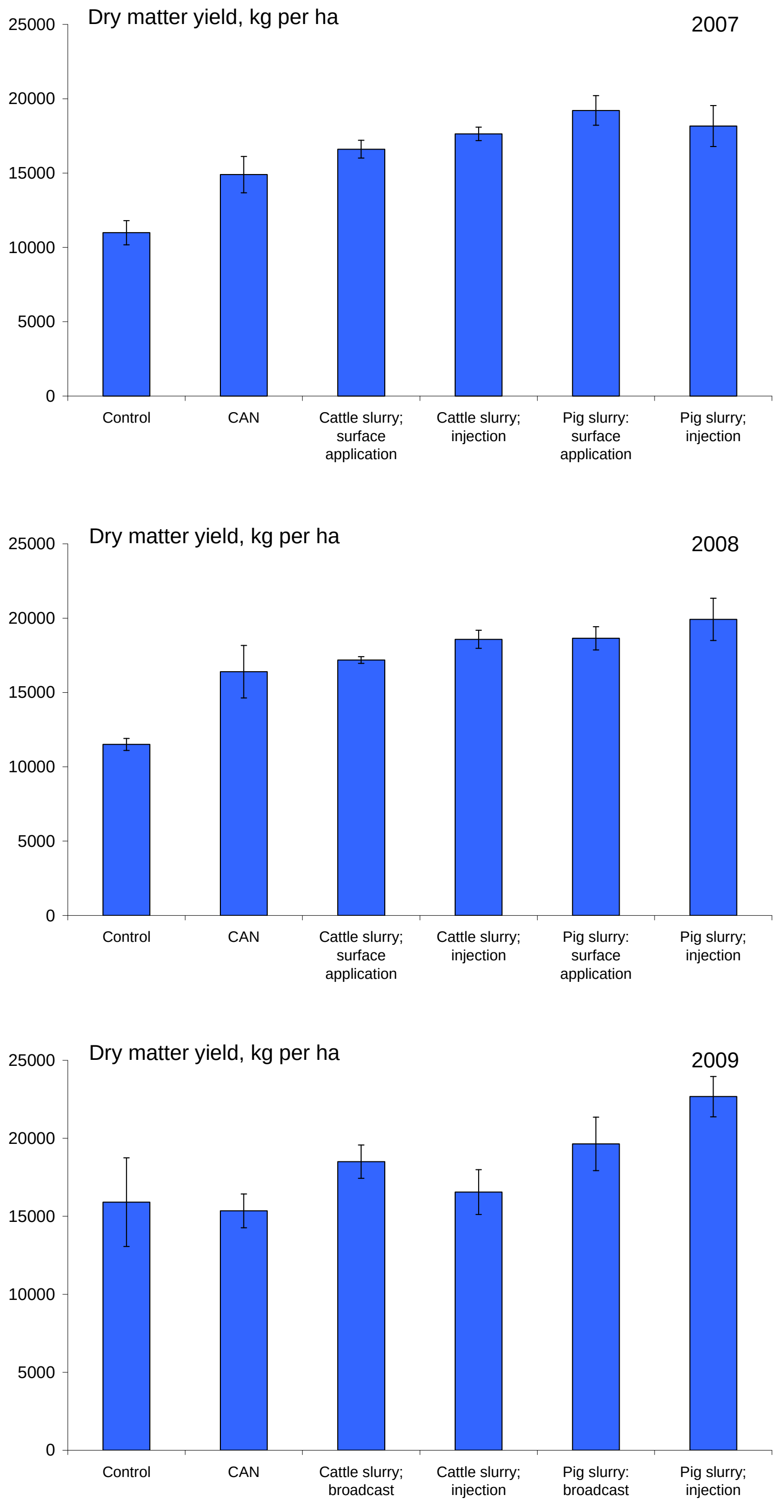


Figure 13.
Dry matter yields of maize in 2007, 2008, and 2009.

2.4 Conclusions

The major conclusions of the field experiments on grassland and maize land are:

- On both grassland and maize land, (shallow) injection of slurry increased the emission factor of N_2O in comparison to broadcast application.
- The major conclusions for grassland are:
  - The average emission factor (both grassland sites and all years) was 1.7% of the N applied for CAN, 0.4% for shallow injected cattle slurry, and 0.1% for broadcast cattle slurry.
  - The emission factor for CAN was somewhat higher than that of the current protocol used in the Netherlands for calculation of greenhouse gas emissions, but the emission factors for shallow injected and broadcast cattle slurry were much lower.
  - The emission factor for shallow injected cattle slurry was a factor 4 higher than that of broadcast slurry; in the protocol this is a factor 2.
- The major conclusions for maize land are:
  - The average emission factor for CAN was 0.1% of the N applied, which is much smaller than the factor of 1% in the current protocol.
  - The average emission factor of injected cattle slurry was 0.9% and that of broadcast cattle slurry 0.4%, which is about a factor 2 smaller than the emission factors in the current protocol.
  - The average emission factor of injected pig slurry was 3.6% and that of broadcast pig slurry 0.9%. The emission factor for broadcast pig slurry is similar to the protocol. That of injected pig slurry is much higher than the protocol, but it is strongly affected by the high emission factor in 2007 (7.0% of the applied N).

3 Incubation experiment

3.1 Introduction

The field experiments (see Chapter 2) were carried out on sandy and clay soils and can be used to derive N_2O emission factors for mineral soils. However, about 15 percent of the grasslands in the Netherlands are located on peat soils. Both cattle slurry and CAN are used as fertilizers on the grasslands.

It is well-known that N_2O emission from peat soils fertilized with CAN are higher than from mineral soils fertilized with CAN (Velthof et al., 1996b). This is due to a combination of the higher organic carbon contents and wet conditions, which promote denitrification. However, it is not known whether the N_2O emission from manure is also higher for peat soils than for mineral soils. Moreover, it is also unknown if the effect of manure application technique on N_2O emission is the same for peat soils as for mineral soils.

An incubation study was conducted to quantify the N_2O emission from cattle slurry applied to peat, sand, and clay soils. Two application techniques were tested: surface application and shallow injection. Also the N_2O emission from CAN as reference fertilizer was quantified. The results of this study can be used in combination with the field studies of chapter 2 and those on peat, clay and sandy soils of Velthof et al. (1996b) to derive N_2O emission factors for cattle slurry on peat soils.

3.2 Materials and methods

The incubation study was carried out using a similar methodology which has been used in earlier studies (Velthof et al., 2002, 2003, 2005; Van Groenigen et al, 2005).

The set-up of the field experiments was as follows:

- 3 soil types, i.e. sandy soil (same site as in Chapter 2), a clay soil (same site as in Chapter 2) and a peat soil (derived from experimental farm Zegveld). The sandy and clay soils were the same as the field experiment in order to translate the results of the incubation study to field conditions. In table 5 some chemical properties of the soils are presented.
- 4 fertilization objects, i.e. control (no N application), CAN, broadcast cattle slurry, and shallow injected cattle slurry.
- 4 replicates.

Table 5.
N and C contents of the soils.

Soil type	Total N g kg^{-1}	NH_4-N g kg^{-1}	NO_3-N G kg^{-1}	Soluble organic N g kg^{-1}	C g kg^{-1}
Sandy soil	1.92	6.8	4.0	12.2	21.0
Clay soil	1.74	2.5	1.3	10.2	25.9
Peat soil	16.3	13.2	19.7	64.1	197

Figure 14.

Photos of sampling of the soil cores in the field (upper pictures), incubation in the laboratory (middle pictures), and during measurement of N_2O emission using flux chamber (lower pictures).

Soil cores with swards were taken in February 2008 using PVC cylinders (10 cm diameter and 10 depth) that were pushed into the soil. The cores were dug out from the soil and transported to the laboratory (Figure 14). It is well-known that N_2O emission from disturbed peat soils may be high in incubation studies, because of a high N mineralization. This high background N_2O emission strongly hampers the quantification of N_2O emission from applied fertilizers. Therefore, the cores were pre-incubated at 15 °C for about one month in a laboratory. During this month, emission of N_2O was measured regularly to test if N_2O emission was low.

Just before N application, grass was cut. The CAN was grinded and homogeneously applied on top of the soil. The surface-applied cattle slurry was homogeneously applied on top of the grass and soil using a pipette. The shallow injected cattle slurry was band-placed into a slot of 5 cm depth in the soil (in the middle of the core), which was created with knife. The target N application was 80 kg N per ha (i.e. 67 g N for each core). The application rate of the slurry was based on the average N content of the cattle slurry in the field experiment (i.e. 5 g N per kg slurry). The slurry was sampled at the time of application. The measured N content of the cattle slurry used in the experiment was lower (3.6 g N per kg slurry), by which the N application rate of the cattle slurry was smaller than of CAN. The N application rates were 0 kg N per ha for the control, 80 kg N per ha for CAN, and 58 kg N per ha for the surface-applied and the shallow injected cattle slurry. The dry matter content of the slurry was 7%, the total N content 3.6 g N per kg, the NH_4 content 1.6 g N per kg, and the C content 30.4 g C per kg.

The soil cores were placed into ditches with water (Figure 14), creating relatively wet conditions, which is favourable for denitrification. Eighteen days after N application, the cores were dried out to simulate a relatively dry period, which is favourable for mineralization and nitrification. After 28 days after N application, 12 mm water was added to simulate rainfall after a relatively dry period. These changes in soil moisture content in time were created to simulate field conditions in which large changes in soil moisture content occur. The drying and wetting of soils may stimulate emission of N_2O (Granli and Bøckman, 1994)

Fluxes of N_2O were assessed from the increase in N_2O concentrations in the headspace following the closure of the bottles with flux chambers (see Figure 14) for 1 hour. Concentration of N_2O was measured using a Innova photo-acoustic gas analyzer. Emission of N_2O was measured 17 times during a period of 47 days. The total N_2O was calculated by linear interpolation of the measured fluxes at different times. Between the measurement times, the bottles were left open.

The differences in N_2O emission between the treatments and soils were statistically assessed using ANOVA analysis and Least Significant Differences (LSD) test with SPSS 15.0.1.

3.3 Results and discussion

Figure 15 shows the fluxes of N_2O measured in the incubation study. The pattern of fluxes are the same for the three soils, i.e. low fluxes during the pre-incubation period of 10 days, a strong increase just after N application followed by a gradual decrease in time (10 – 38 days) and a strong increase after addition of water after 38 days. However, the magnitude of the fluxes differed between the soils with highest fluxes from the peat soil and lowest for the clay soil (Figure 15). The differences between the soils are likely due to a combination of available C, which controls the potential for denitrification, and the aeration status. The results indicate that the conditions for denitrification were most favourable in the peat soil, which is in agreement with the expected differences and the field studies of Velthof et al. (1996b).

Fluxes of N_2O were higher for CAN than for cattle slurry (Figure 15). This is probably due to the relatively wet conditions, by which application of a nitrate containing fertilizer, such as CAN, results in a higher denitrification activity than application of an ammonium or organic N containing fertilizer, such as cattle slurry. Several field studies on grassland have shown that N_2O fluxes during wet conditions are higher for CAN than for cattle slurry (Chadwick et al., 2000; Egginton and Smith, 1986; Velthof et al., 1997).

The N_2O fluxes from shallow injected cattle slurry were mostly somewhat higher than the fluxes from surface applied cattle slurry, but the differences between surface application and shallow injection of cattle slurry were much smaller than the difference in N_2O fluxes between CAN and cattle slurry.

The fluxes of the control of the sandy soil and peat soil also strongly increased after the application of water after 38 days (Figure 15). This is probably related to mineralization and nitrification of soil organic N during the incubation. The fact that this peak in N_2O fluxes from the control was not shown for the clay soil suggest that mineralization was lower in this soil. Moreover, conditions for denitrification were less favourable in the clay soil than in the two other soils, because N_2O emission from CAN and cattle slurry were also relatively small for this soil after water application at day 38.

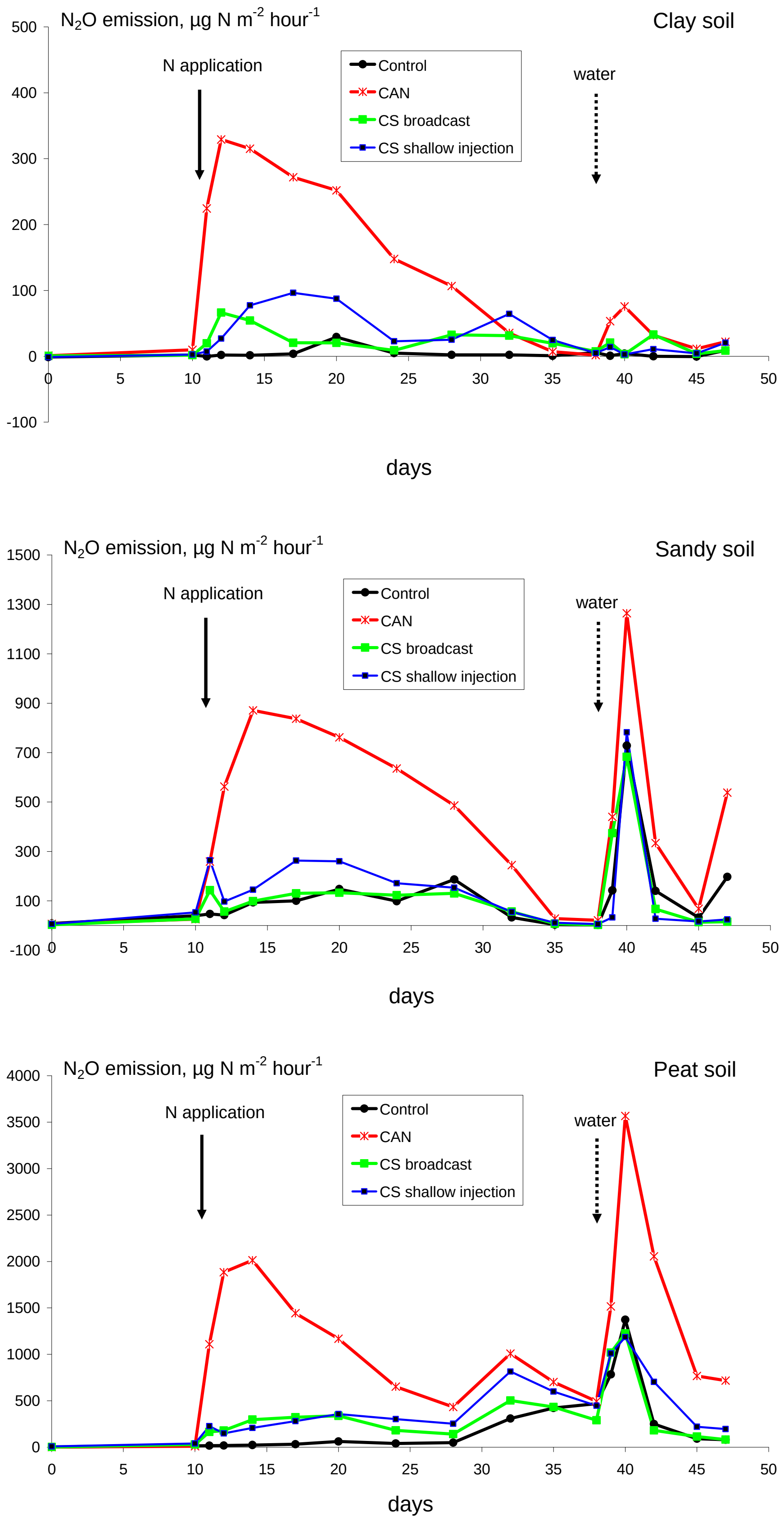


Figure 15.

Fluxes of N_2O from the clay soil (upper figure), sandy soil (middle figure), and peat soil (lower figure). CS is cattle slurry. Note differences in scale of the Y-axis.

In figure 16, the total N_2O emissions are presented. At all soils, the total N_2O emission increased in the order control < surface applied cattle slurry < shallow injected cattle slurry < CAN. The total N_2O emission increased in the order clay soil < sandy soil < peat soil. The variation of the N_2O emission between the replicates was relatively low. The variation coefficient was highest for the clay soil and smallest for the peat soil (Table 6). In field experiments much higher variation coefficients were found (e.g. Appendix 2).

Statistical analysis (LSD test) showed a significant difference ($P<0.05$) in N_2O emission between the three soils. Application of N also significantly increased N_2O emission. The total N_2O emission from CAN was statistically significant ($P<0.05$) higher than that of cattle slurry (both application techniques). However, the difference between surface-applied and narrow-band applied cattle slurry was not significant. This was mainly due to the fact that the difference between the two slurry application techniques were small in comparison to CAN (Figure 16). Therefore and also because the total N application with CAN was higher (80 kg N per ha) than with cattle slurry (58 kg N per ha), a separate statistical test (ANOVA and LSD) was carried out without the results of the CAN treatment. This test showed a statistically significant difference between the two manure application techniques ($P < 0.05$).

Table 6.
Variation coefficients (standard deviation/average) of the total N_2O emission in %.

	Sandy soil	Clay soil	Peat soil
Control	43	65	30
CAN	21	85	13
CS broadcast	39	71	31
CS shallow injection	34	19	19

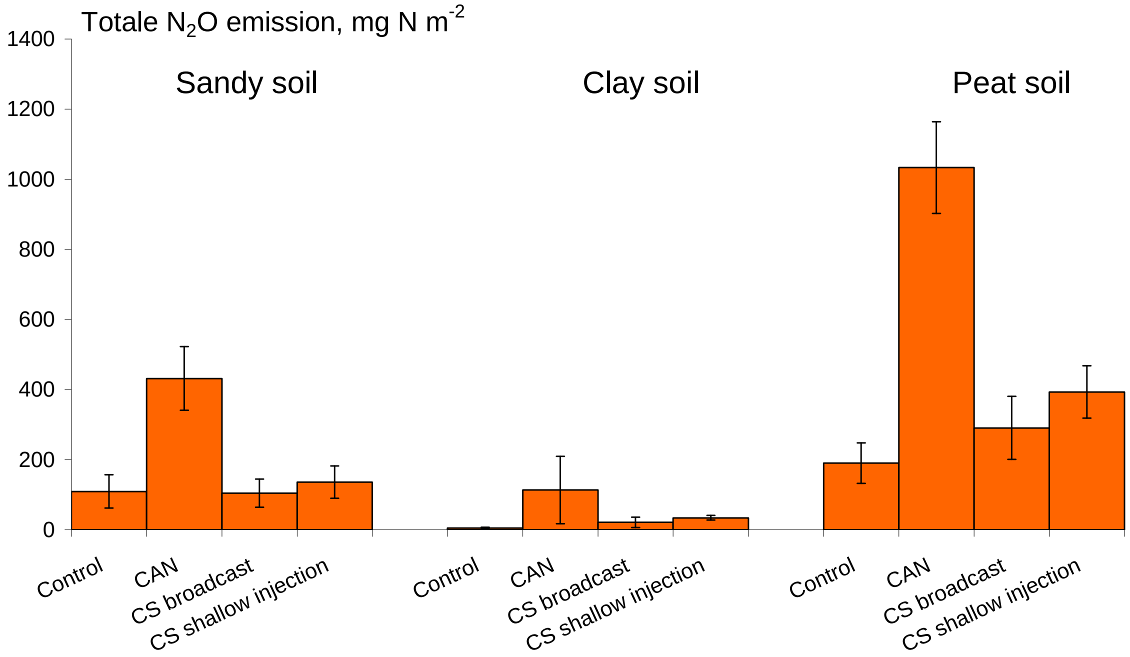


Figure 16.
Total N_2O emission from the treatments and soils (average ± standard deviation). CS: cattle slurry.

Table 7 shows the calculated N_2O emission factors in the incubation study. The N_2O emission for shallow injected cattle slurry ranged from 0.5 percent (sandy and clay soil) to 3.5 percent (peat soil) and that for surface applied cattle slurry from -0.1 (sandy soil) to 1.7 percent (peat soil). The N_2O emission factor for CAN was 4.0 percent for the sandy soil, 1.4 percent for the clay soil, and 10.5 percent for the peat soil. These emission factors are higher than generally found in field experiments (e.g. Chapter 2 and Velthof et al., 1996b). Also in other incubation studies relatively high emission factors for N_2O are found (e.g Velthof et al., 2003). The higher N_2O emissions in incubation studies than in field studies are due to the fact that the created conditions in incubation studies are mostly optimal for N_2O emission (i.e. relatively wet conditions) and N uptake by grass or crop is absent or small. In the current study, there was some growth of the grass in the soil cores during the incubation, but the N uptake was very small and probably not affecting the N_2O emission.

Table 7.
N_2O emission factors, in % of the N applied[1].

Soil type	Treatment	N_2O emission factor, % of the N applied
Sandy soil	CAN	4.0
	Cattle slurry; broadcast	-0.1
	Cattle slurry; shallow injection	0.5
Clay soil	CAN	1.4
	Cattle slurry; broadcast	0.3
	Cattle slurry; shallow injection	0.5
Peat soil	CAN	10.5
	Cattle slurry; broadcast	1.7
	Cattle slurry; shallow injection	3.5

[1] N_2O emission factor = (N_2O emission fertilizer - N_2O emission control)/N applied*100

The absolute emission factors of the incubation studies cannot be used to derive N_2O emission factors, because the conditions do not represent field conditions and, because of this, the emission factors are relatively high. However, the relative differences in N_2O emissions between treatments and soils can be used in combination with results of field experiments (Chapter 2 and Velthof et al., 1996b) to derived N_2O emission factors. The following relative differences between treatments and soils in the incubation study were found:

- The ratio between the N_2O emission from shallow injection of cattle slurry and that from surface application of cattle slurry was 1.3 for the sandy soil, 1.6 for the clay soil and 1.4 for the peat soil. The relative effect of application technique on N_2O emission was therefore similar for all soil types; the average ratio was 1.4.
- The ratio between the N_2O emission from shallow injection of cattle slurry and that from CAN was 0.32 for the sandy soil, 0.30 for the clay soil, and 0.38 for the peat soil. This shows that the relative difference in N_2O emission between shallow injection of cattle slurry and CAN is similar for the three soils; on average the ratio is 0.33.
- The N_2O emission from CAN applied to the peat soil was a factor 2 higher than from CAN applied to the sandy soil and a factor 9 higher than CAN applied to the clay soil.

3.4 Conclusions

The major conclusions of the incubation study are:

- the total N_2O emission increased in the order control < surface applied cattle slurry < shallow injected cattle slurry < CAN for all soils.
- the total N_2O emission increased in the order clay soil < sandy soil < peat soil.
- the calculated N_2O emission factors in the incubation study are higher than generally found in field experiments:
  - The N_2O emission factor for shallow injected cattle slurry ranged from 0.5 percent (sandy and clay soil) to 3.5 percent (peat soil).
  - The N_2O emission factor for surface applied cattle slurry ranged from -0.1 (sandy soil) to 1.7 percent (peat soil).

  - The N_2O emission factor for CAN was 4.0 percent for the sandy soil, 1.4 percent for the clay soil, and 10.5 percent for the peat soil.
- The ratio between the N_2O emission from shallow injection of cattle slurry and that from surface application of cattle slurry was similar for the three soil; the average ratio was 1.4.
- The ratio between the N_2O emission from shallow injection of cattle slurry and that from CAN was similar for the three soils; the average ratio is 0.33.

The N_2O emission from CAN applied to the peat soil was a factor 2 higher than from CAN applied to the sandy soil and a factor 9 higher than CAN applied to the clay soil.

4 General discussion

According to the Tier 1 approach of the IPCC guidelines (IPCC, 2006), about 1% of fertilizer-N added to soils is emitted directly as N_2O, and about another 1% is emitted indirectly after the deposition of volatilized N as NH_3 and NO_x, and after N leaching/runoff. In this approach, direct N_2O emissions are considered to be independent of crop type, chemical form of N used, and application technique.

A recent publication of Crutzen et al. (2008) indicates that the IPCC estimates of N_2O emission factors may be too low by about a factor of two. Davidson (2009) comes to a similar conclusion, by using a multiple linear regression of data for the years 1860-2005: about 2% of manure-N and about 2.5% of fertilizer-N production is emitted as N_2O. Similar results (emission factor: 2.4 ± 2.5% of applied N) were found by Mosquera et al. (2007), using long-term measurements (> 1 year) found in the literature.

In the current research, higher N_2O emissions on grassland and lower N_2O emissions on maize land were measured after the application of mineral fertilizer (CAN) compared to cattle slurry. For the sandy soil, on average, 1.2% of applied fertilizer-N (broadcast spreading) on grassland and 0.1% of applied fertilizer-N (broadcast spreading) on maize land was emitted as N_2O. For grassland on clay soil, 2.2% of applied fertilizer-N (broadcast spreading) was emitted. Regarding to manure-N, 0.1% of applied N (broadcast spreading) as cattle manure on grassland was emitted as N_2O, on both soils. In other studies, also relatively low N_2O emissions (<1% of the N applied) have been found for animal manures applied to grassland (Chadwick et al., 2000; Egginton and Smith 1986; Schils et al., 2008; Velthof et al., 1997).

On maize land (sandy soil), 0.4% of applied N (broadcast spreading) as cattle manure and 0.9% of applied N (broadcast spreading) as pig manure was emitted as N_2O. Fluxes of pig slurry were much higher than those of cattle slurry, which is probably related to the higher fraction of NH_4 in pig slurry (on average 69 percent of total N) than in cattle slurry (on average 51 percent of total N). Moreover, the organic C in pig slurry is probably more available for denitrifying bacteria than that of cattle slurry (Kirchmann and Lundvall, 1993; Paul and Beauchamp, 1989).

The emission factors for broadcast spreading of manure are not corrected for N losses as NH_3 during and after manure application, and therefore overestimate the amount of N available for emission as N_2O. Correction of the applied N for NH_3 losses would therefore result in higher N_2O emission factors. The IPCC has changed its methodology in 2006 and does not correct N inputs for NH_3 emission (which was part of the previous IPCC methodology). This was done because in the field experiments in which emission factors are derived, emission factors are also based on the total N application rate (and not the N application rate corrected for NH_3 emission).

The application of low NH_3 emission manure application techniques (shallow injection on grassland, injection on maize land) resulted in higher N_2O fluxes compared to broadcast spreading. Several other studies (Kroeze, 1994; Kuikman et al, 2006; Van der Hoek et al., 2007) came to the same conclusion. One possible explanation of this effect is that broadcast spreading usually results in higher NH_3 emissions compared to low NH_3 emission manure application techniques (Huijsmans, 2003). This in turn results in less N entering the soil, reducing the amount of N susceptible to be converted to N_2O. An additional effect for injected slurry is the presence of locally high concentrations of ammonium and available carbon in the slots, which may enhance N_2O production during nitrification or nitrification followed by denitrification (Bertora et al., 2008; Paul and Beauchamp, 1989).

Increasing the N application rate on maize land, increased the emission factors for CAN, injected cattle slurry, and injected pig slurry in 2009 (Figure 11). This shows that a fixed emission factor in % of the applied N, as currently used by IPCC and in the Dutch protocol, does not reflect the effect of N application rate of N_2O emission. The results suggest that a decrease of the N application rate decreases the N_2O emission by a combination of a decrease in applied N and a decrease in the emission factor. The current protocols only account for the decrease in N application rate. However, more studies are needed to include N rate dependent emission factors in protocols of estimation of N_2O emission.

Both field and incubation studies showed that shallow injection on grassland, and injection of slurry on maize land, strongly increased spatial variability of N_2O fluxes (Appendix 2). On grassland, the spatial variability of the measured fluxes was higher in the slots with slurry compared to the area between the slots. On maize land, measurements showed no significant effect of the location of maize plants on N_2O emissions, although there was a tendency for chambers between the planting lines to have higher emissions than the ones in the planting lines. Spatial variability of N_2O fluxes should be considered when setting-up measurement strategies to quantify N_2O emission from fields using flux chambers, e.g. the number of chambers, the soil area covered by the chambers, and the position of the chambers in the field.

The incubation study showed a similar effect of fertilizer and slurry application for sand, clay, and peat soils. However, the magnitude of the N_2O emission from peat soil was higher than from mineral soils. Compaction of the soil and increased soil moisture content increased N_2O emission in both the grassland and maize land soils. Avoiding compaction by proper timing of manure and fertilizer application and by precision application techniques (Vermeulen & Mosquera, 2009) is an option to decrease N_2O emission from fertilized soils.

Indirect N_2O emission caused by NH_3 emission from surface spreading (calculated with average NH_3 emission factors for manure application) were similar to direct N_2O emissions for maize, and a factor 2.5 higher for grassland (Appendix 1). Total N_2O emissions (direct + indirect caused by NH_3) for low emission manure application techniques were then 5-10% lower than for surface spreading.

Concluding, on both grassland and maize land, (shallow) injection of slurry increased the emission factor of N2O in comparison to broadcast application. The results suggest to use separate emission factors for grassland and arable land (Table 8). The emission factors for cattle slurry applied to grassland and maize land are smaller than that used in the protocol. That of injected pig slurry is higher than the protocol. For adjustment of the emission factors in the protocol, not only the data of the current study but also those of other studies carried out in the Netherlands (e.g. Kuikman et al., 2006) and other countries in NW Europe have to be used. For arable land, a decision has to be made if separate emission factors for pig and cattle slurries will be used. The emission factors for peat soil, can be derived using the results of the incubation study (Table 7), the results of the field experiments on mineral soils (Chapter 2) and field studies in which emissions from mineral soils and peat soil were compared (Velthof et al., 1996b). The incubation study showed that the ratio between the N2O emission from shallow injection of cattle slurry and that from surface application of cattle slurry was on average 1.4 and was similar for the three grassland soils.

Table 8.
The average emission factors (EF) for mineral soils derived from the field experiments (grassland is the average of the sand and clay soil).

		EF derived from experiments, %
grassland	CAN	1.7
	Cattle slurry; shallow injection	0.4
	Cattle slurry; broadcast	0.1
arable land	CAN	0.1
	Cattle slurry; injection	0.9
	Cattle slurry; broadcast	0.4
	Pig slurry; injection	3.6
	Pig slurry; broadcast	0.9

[1] www.greenhousegases.nl

References

Bertora, C., F. Alluvione, L. Zavattaro, J.W. van Groenigen, G.L. Velthof and C. Grignani, 2008. Pig slurry treatment modifies slurry composition, N_2O, and CO_2 emissions after soil incorporation. *Soil Biology & Biochemistry* 40, 1999-2006.

Chadwick, D.R., B.F. Pain and S.K.E. Brookman, 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. *Journal of Environmental Quality* 29, 277-287.

Crutzen, P.J., A.R. Mosier, K.A. Smith and W. Winiwarter, 2008. N2O release from agro-biofuel production negated global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys*. 8, 389-395.

Davidson, E.A., 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience* 2, 659-662.

Dendooven L., E. Bonhomme, R. Merckx and K. Vlassak, 1998. Injection of pig slurry and its effects on dynamics of nitrogen and carbon in a loamy soil under laboratory conditions. *Biol Fertil Soils* 27:5-8

Egginton, G.M. and K.A. Smith, 1986. Nitrous oxide emission from a grassland soil fertilized with slurry and calcium nitrate. *Journal of Soil Science* 37, 59-67.

Flessa H., and F. Beese, 2000. Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. *J. Environ Qual*. 29:262-268

Granli, T. and O.C. Bøckman, (1994. Nitrous oxide from agriculture. *Norwegian Journal of Agricultural Science*, Supplement 12, 128 pp.

Huijsmans, J.F.M., 2003. *Manure application and ammonia volatilization*. PhD thesis Wageningen University.

IPPC, 2006. *IPPC guidelines for national greenhouse gas inventories*.

Kirchmann, H. and A. Lundvall, 1993. Relationship between N immobilization and volatile fatty acids in soil after application of pig and cattle slurry. *Biol Fertil Soils* 15:161-164.

Kroeze, C., 1994. *Nitrous oxide. Emission inventory and options for control in the Netherlands*. RIVM Report 773001004. Bilthoven, The Netherlands.

Kuikman, P.J., K.W. van der Hoek, A.. Smit and K. Zwart, 2006. *Update of emission factors for direct emissions of nitrous oxide from agricultural soils on the basis of measurements in the Netherlands*. Alterra report 1217, Alterra, Wageningen.

Mosquera, J., J.M.G. Hol, C. Rappoldt and J. Dolfing, 2007. *Precise soil management as a tool to reduce CH_4 and N_2O emissions from agricultural soils*. ASG Report 28.

Munch J.C. and G.L. Velthof, 2007. Chapter 22. Denitrification and agriculture. p. 331- 343. In: Bothe, H., S. Ferguson and V. Newton, (eds.) *Biology of the nitrogen cycle*, Elsevier.

Paul J.W. and E.G. Beauchamp, 1989. Effect of carbon constituents in manure on denitrification in soil. *Can J Soil Sci* 69:49-61.

Schils R.L.M., J.W. Van Groenigen, G.L. Velthof and P.J. Kuikman, 2008. Nitrous oxide emissions from multiple combined applications of fertiliser and cattle slurry to grassland. *Plant Soil* 310: 89 – 101.

Sommer S.G., Sherlock R.R., and R.Z. Khan, 1996. Nitrous oxide and methane emissions from pig slurry amended soils. *Soil Biol Biochem* 28:1541-1544

Stehfest, E. and L. Bouwman, 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems* 74: 207-228.

Thompson R.B., Ryden J.C., and Lockyer D.R., 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. *J Soil Sci* 38:689–700

Van der Hoek, K.W., M.W. van Schijndel and P.J. Kuikman, 2007. *Direct and indirect nitrous oxide emissions from agricultural soils, 1990-2003, Background document on the calculation method for the Dutch National Inventory Report*. RIVM report 680125003/2007; MNP Report 500080003/2007. Bilthoven, The Netherlands.

Van Groenigen, J.W., P.J. Kuikman, W.K.M. de Groot and G.L. Velthof, 2005. Nitrous oxide emission from urine-treated soil as influenced by urine composition and soil physical conditions. *Soil Biology and Biochemistry* 37, 463-473.

Velthof, G.L., and O. Oenema, 1995. Nitrous oxide fluxes from grasslands in the Netherlands: I. Statistical analysis of flux chamber measurements. *European Journal of Soil Science* 46, 533-540.

Velthof, G.L. S.C. Jarvis, A. Stein, A.G. Allen and O. Oenema,1996a. Spatial variability of nitrous oxide fluxes in mown and grazed grasslands on a poorly drained clay. *Soil Biol and Biochem.* 28:1215-1225.

Velthof GL, A.B. Brader and O. Oenema, 1996b. Seasonal variations in nitrous oxide losses from managed grasslands in the Netherlands. *Plant and Soil* 181: 263-274.

Velthof, G.L., O. Oenema, R. Postma and M.L. van Beusichem, 1997. Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes from intensively managed grassland. *Nutrient Cycling in Agroecosystems* 46, 257-267.

Velthof, G.L., P.J. Kuikman and O. Oenema. 2002. Nitrous oxide emission from soils amended with crop residues. *Nutrient Cycling in Agroecosystems* 62, 249-261.

Velthof, G.L., P.J. Kuikman and O. Oenema, 2003 Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biology and Fertility of Soil* 37, 221-230.

Velthof, G.L., J.A. Nelemans, O. Oenema and P.J. Kuikman, 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. *Journal of Environmental Quality* 34, 698-706.

Vermeulen G.D. and J. Mosquera, 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. *Soil and Tillage Research* 102, 126-134.

Appendix 1 N_2O emission from grassland and arable land (paper NCGG-5)

Differences in N_2O emission from fertilized grassland and arable land in sandy soils

J. Mosquera, J. Huis in 't Veld
Wageningen UR, Animal Sciences Group

G.L. Velthof, E.W.J. Hummelink
Wageningen UR, Alterra

Keywords: nitrous oxide, grassland, maize, cattle slurry, narrow-band spreading, injection

ABSTRACT: A two-year measurement campaign was performed to measure the effect of manure application technique and type on the emission of nitrous oxide (N_2O) from fertilized soils (grassland and maize on sandy soils). Four different treatments were considered: a) mineral fertilizer, surface applied; b) cattle slurry, surface applied; c) cattle slurry, injected (maize) into the soil or applied with a narrow-band spreading technique (grassland); d) no fertilization (reference). All treatments were applied in triplicate in a completely randomized block design. Small flux chambers (20 cm in diameter) were applied in duplicate per plot (n=6 per treatment) to calculate N_2O fluxes. N_2O concentration in the headspace of the chamber were measured with a photoacoustic gas analyzer. Preliminary results show higher N_2O emissions from ammonia emission reduction techniques (injection on maize, narrow-band spreading on grassland) compared to surface spreading. Grassland and maize showed different N_2O emission patterns. This can be ascribed to differences in nitrogen uptake and utilization from both crops. Besides, manure/fertilizer was applied at once on the maize location, whereas on grassland different application rates were used throughout the growing season. On grassland, weather conditions during the first year of the measurements (dry spring, wet summer) resulted in low N_2O fluxes during the first cut, and relatively high N_2O fluxes after manure/fertilizer application during the second and third cut. The emissions during autumn and winter were low. Due to extreme wet conditions during the first manure/fertilizer application in 2008, significantly higher emissions were measured from the mineral fertilizer compared to the cattle slurry.

Introduction

The Netherlands reports every year its emissions on greenhouse gases under the Kyoto protocol: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and the fluorinated gases (HFCs: hydrofluorocarbons; PFCs: perfluorocarbons; SF_6 (sulphur hexafluoride)). Figure 1 shows the emission trend of the different gases in the period 1990-2006 (Maas et al., 2008): CO_2, N_2O and CH_4 contributed respectively with 83%, 8% and 8% to the national greenhouse gas emissions. Emissions of the non-CO_2 gases, N_2O, CH_4 and F-gases, decreased by respectively 36%, 15% and 75% in 2006 compared to the reference year (1990 for N_2O and CH_4; 1995 for F-gases). Agriculture is the most important source of nitrous oxide (N_2O) in the Netherlands, and contributed about 9% to the total national greenhouse gas emissions in 2006 (10% in 1990). Nitrous oxide was in 2006 responsible for about 52% of total greenhouse gas emissions from agriculture. Agricultural soils are the main source of N_2O emissions from agriculture, and accounted for 56% of national N_2O emissions in 2006. The agricultural N_2O emissions consist of direct emissions through application of animal wastes/fertilizer to soils, and indirect emissions from nitrogen leaching, run-off and NH_3 emission.

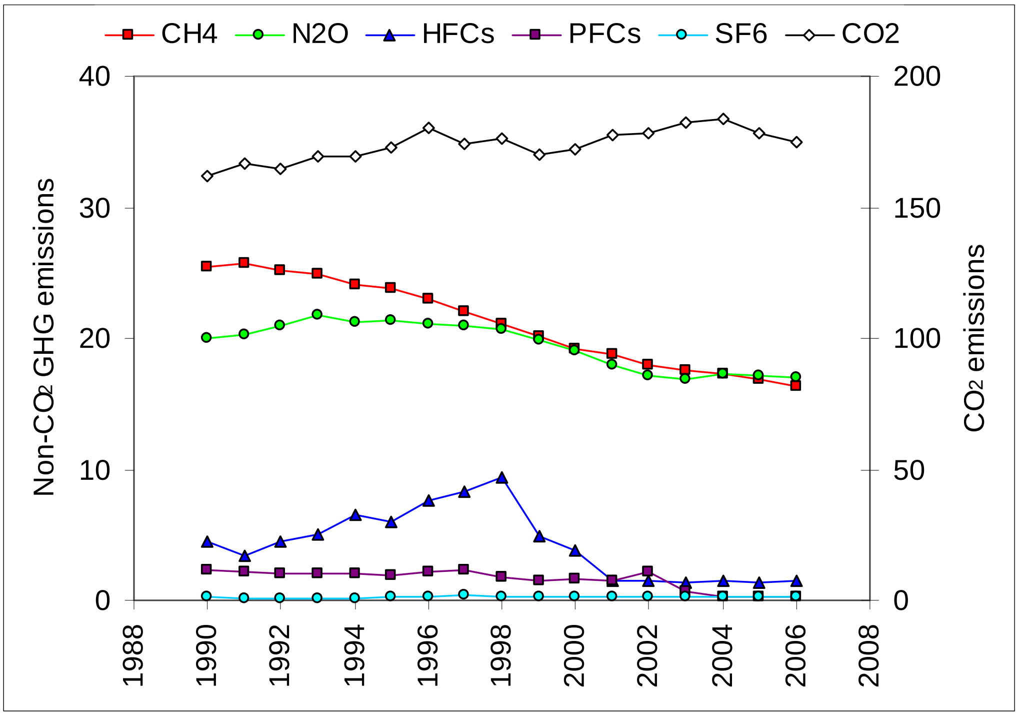


Figure 1. Trend in greenhouse gas emissions (Tg CO_2-equivalents) in the Netherlands during the period 1990-2006. Source: Van der Maas et al. (2008).

The monitoring protocols used in the Netherlands to calculate the emission of N2O (www.greenhousegases.nl) differentiate between two manure application techniques: surface spreading and incorporation into soil. The N2O emission factors used in the Netherlands for surface spreading (1% of applied N) are lower than for low NH3 emission manure application techniques (2% of applied N). This is important because in 1990, the reference year for Kyoto, all manure was surface applied to the soil of both grassland and arable land. Because of the Netherlands' policy to reduce NH3 emissions, only low NH3 emission manure application techniques are allowed since the early 1990's. According to the monitoring protocol, this change in manure application techniques resulted in higher direct N2O emissions from agricultural soils. This was also the conclusion of the literature study performed by Kuikman et al. (2006), although they could not derive new emission factors for these techniques. Differences in emission factors between surface spreading and low emission application techniques were also smaller than those used in the monitoring protocols. Field measurements involving both techniques are needed to verify whether or not this difference in N2O emission between manure application techniques is correct.

This paper summarizes preliminary results of a 2-year measurement campaign performed to measure the effect of manure application technique and type on the emission of nitrous oxide (N2O) from fertilized soils (grassland and maize on sandy soils) in the Netherlands.

Material and methods

This research was performed at a grassland field and a field cultivated with maize, both on sandy soils in the region Wageningen, in the Netherlands. Measurements started in April 2007 and are on-going till November 2009. Four different treatments were applied:

1. No fertilization (reference)
2. Mineral fertilizer (calcium ammonium nitrate), surface applied
3. Cattle slurry, surface applied
4. Cattle slurry, applied with a narrow-band (or sod injection) spreading technique (grassland) or injected into the soil (maize)

All treatments were applied in triplicate in a completely randomized block design. At the grassland site, all plots were 20 m long and 2.5 m wide. The plots with the treatment “mineral fertilizer” received 174 kg N ha^{-1} in 2007, and 175 kg N ha^{-1} in 2008. The plots with the treatment “cattle slurry” received 322 kg N ha^{-1} in 2007 and 330 kg N ha^{-1} in 2008. At the maize field, all plots were 20 m long and 5 m wide. The plots with the treatment “mineral fertilizer” received 102 kg N ha^{-1} in 2007, and 102 kg N ha^{-1} in 2008. The plots with the treatment “cattle slurry” received 166 kg N ha^{-1} in 2007 and 182 kg N ha^{-1} in 2008. After harvesting the maize a winter crop (winter rye) was cultivated, and ploughed into the soil in spring.

Small flux chambers (20 cm in diameter) were used in duplicate per plot (n=6 per treatment) to calculate N_2O fluxes. N_2O concentrations in the headspace of the chamber were measured with a photoacoustic gas analyzer (Innova 1312). These concentrations were used to calculate individual fluxes in μg N_2O-N m^{-2} hr^{-1}. These fluxes were then averaged to obtain an average flux per treatment per measurement day. By interpolation of the fluxes between measurement days, a total flux (per treatment) in kg N ha^{-1} (per year) was calculated.

Results

Figure 2 shows the precipitation pattern (mm rain per month) measured during the period April 2007 – March 2009 at the grassland site. The first year of measurements, with a total precipitation of almost 1000 mm, can be categorized as a wet year (average in the Wageningen area is 798 mm). Of particular importance is the absence of rain in April 2007, and the extreme wet summer of 2007. During the second year of measurements a total precipitation of 821 mm was measured.

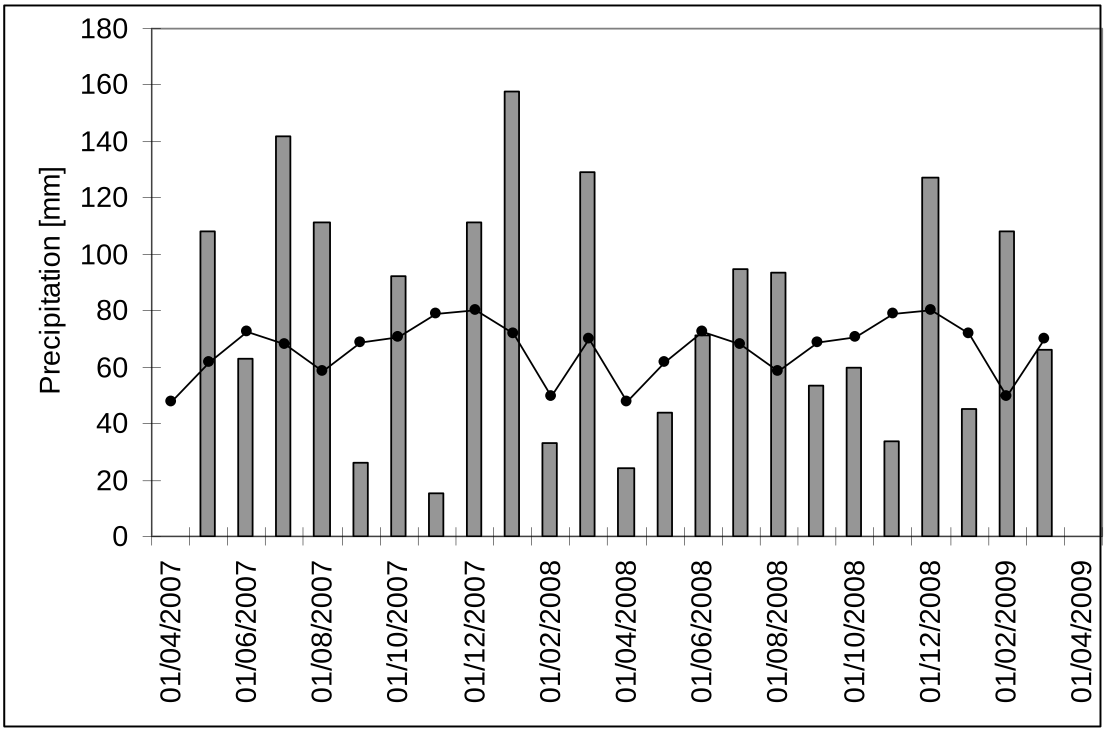


Figure 2. Precipitation pattern as measured at the grassland site (columns), and the monthly average for the period 1971-2000 (Source: www.knmi.nl).

Due to the dry conditions in April 2007, N2O fluxes during the first cut at the grassland site were low for all treatments (figures 3 and 4). The period May-Augustus 2007 was wetter than normal, and resulted in high N2O fluxes after manure/fertilizer application for both grassland as arable land. Due to the low nitrogen concentrations in the soil in autumn and winter (no fertilization), measured N2O fluxes in that period were low. In 2008, the first manure/fertilizer application at the grassland site occurred during a extreme wet period. This resulted in high N2O fluxes after the application of mineral fertilizer, and low N2O fluxes after the application of cattle slurry. N2O fluxes at the maize site increased after the freezing period in January 2009, in particular for the plots were cattle slurry was applied. This effect was not observed at the grassland site.

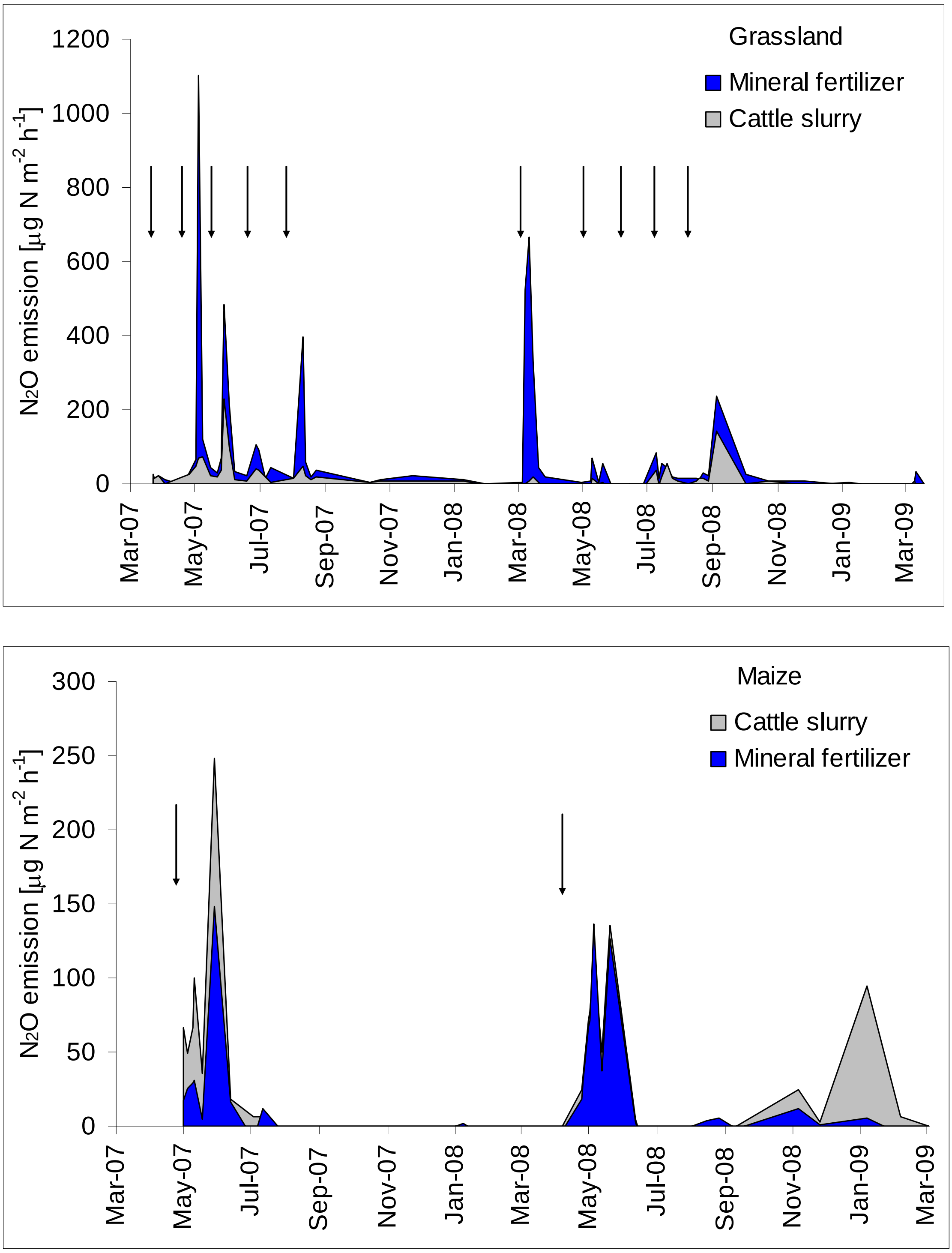
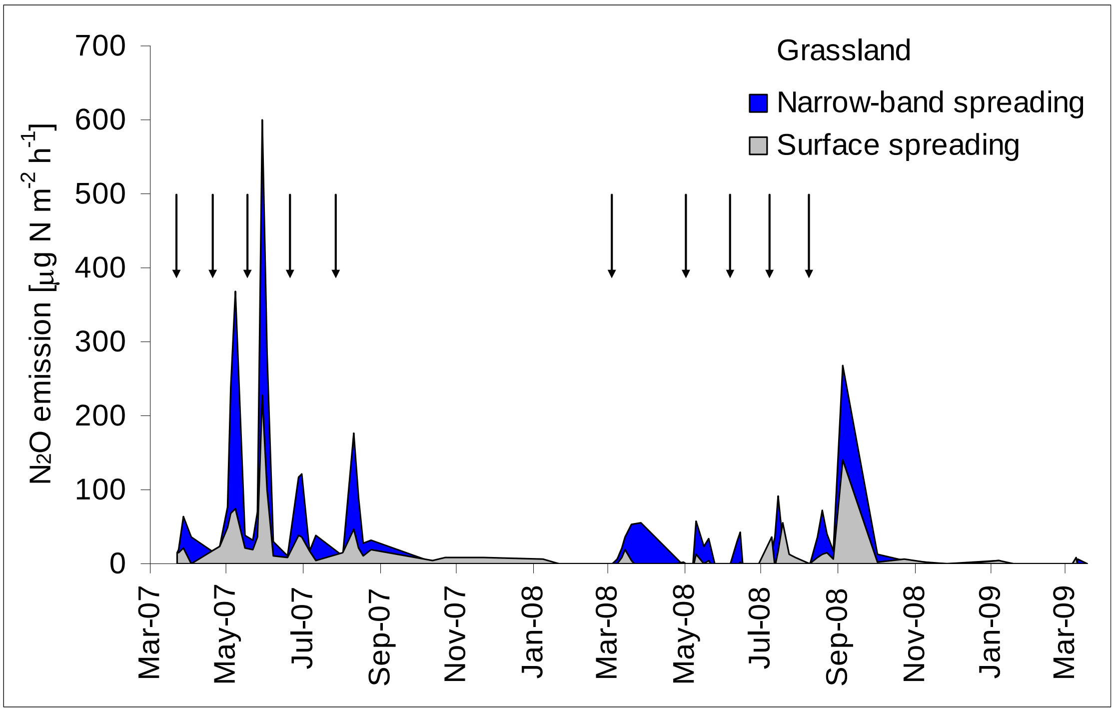


Figure 3. N_2O fluxes at the grassland and maize sites for surface applied cattle slurry and fertilizer. Note the different scale used for the Y-axis (N_2O flux) at both locations. The arrows indicate the timing of manure/fertilizer application.

A different N_2O emission pattern was observed for maize and grassland. One possible explanation for this effect is that the grassland site received (every year) five times manure/fertilizer, maize received all the manure/fertilizer (every year) at once. Besides, grassland and maize also differ in nitrogen uptake, as grassland is a permanent crop (it takes several weeks after N application and seeding, before maize reaches a reasonable nitrogen uptake level).



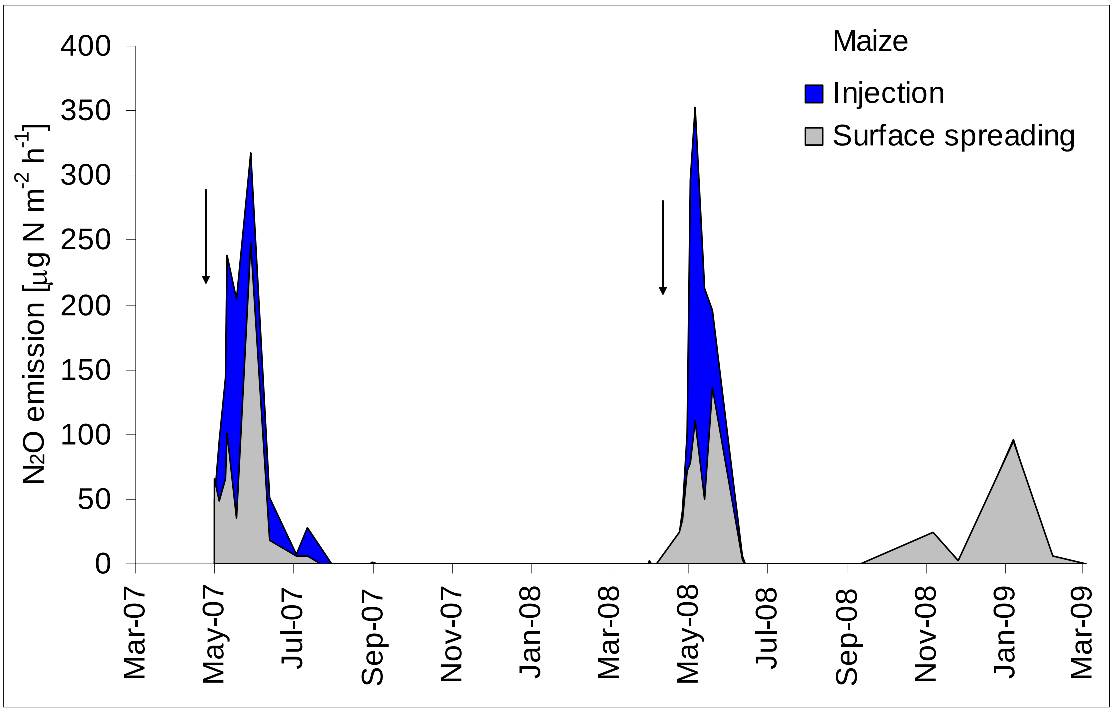


Figure 4. N_2O fluxes for surface spreading and low (ammonia) emission application techniques. Note the different scale used for the Y-axis (N_2O flux) at both locations. Arrows indicate manure/fertilizer application.

The application of mineral fertilizer on grassland resulted in higher N_2O emissions compared to emissions from cattle slurry (figures 3 and 5). On maize the reverse situation was observed, with higher N_2O emissions from cattle slurry. Use of low (ammonia) emission manure application techniques clearly resulted in more N_2O being emitted from the plots fertilized with cattle slurry (figures 4 and 5), both for grassland and maize.

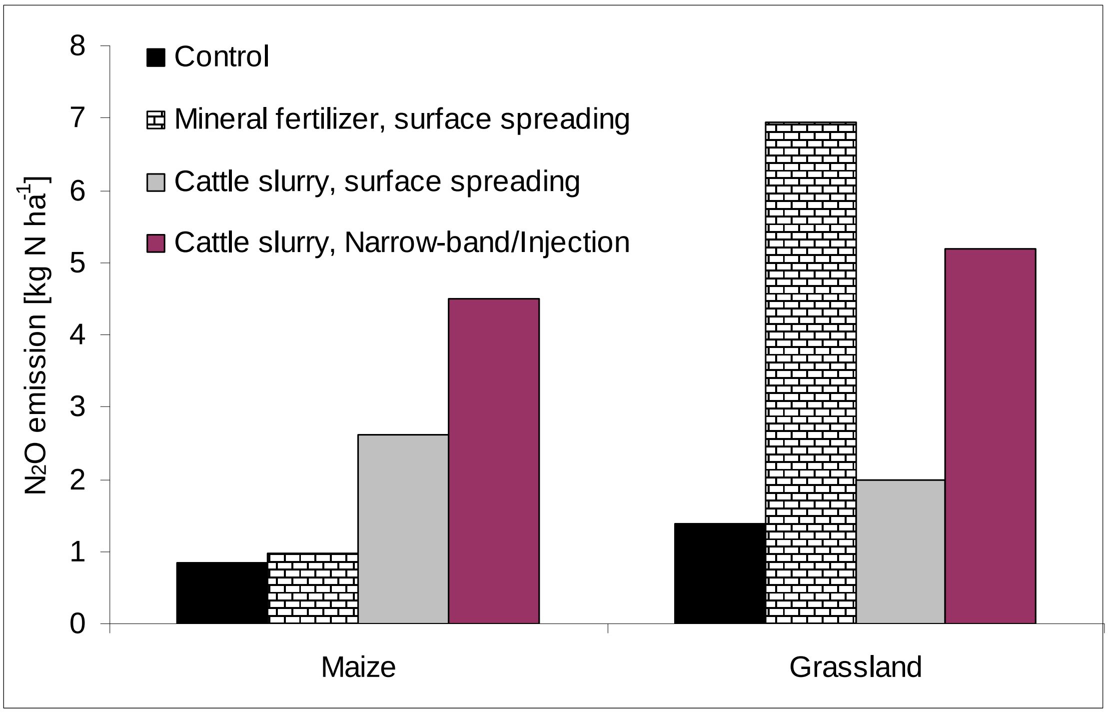


Figure 5. Total N_2O emissions measured in the period April 2007 - March 2009.

Indirect N_2O emissions from N deposition were calculated using the IPPC emission factor of 0.01 kg N_2O-N per kg NH_3 emitted (IPPC, 2006). According to Huijsmans and Vermeulen (2008), the NH_3 emission factors for surface spreading and narrow-band spreading of manure on grassland are respectively 74% and 19% of the applied N. For arable land, the NH_3 emission factors for surface spreading and injection into soil of manure are, respectively, 69% and 2% of the applied N. Indirect N_2O emissions estimated from these emission factors are less than 25% of direct N_2O emissions for low (ammonia) emission manure application techniques, both for maize and grassland. Indirect N_2O emissions from surface spreading are similar to direct N_2O emissions for maize, and a factor 2.5 higher for grassland. Total N_2O emissions (direct + indirect) for low emission manure application techniques are then 5-10% lower than for surface spreading.

Conclusions

This paper shows preliminary results of an on-going monitoring study performed to measure the effect of manure application technique and type on the emission of nitrous oxide (N_2O) from fertilized soils (grassland and maize on sandy soils) in the Netherlands. The application of mineral fertilizer resulted in higher N_2O emissions on grassland and in lower N_2O emissions on maize compared to cattle slurry. Higher N_2O emissions were measured from low (ammonia) emission manure application techniques compared to surface spreading. Indirect N_2O emissions are low (compared to direct N_2O emissions) for low (ammonia) emission manure application techniques. Indirect N_2O emissions are similar or even higher than direct N_2O emissions for surface spreading.

Acknowledgements

This study was supported by the Netherlands' agency for innovation and sustainability (SenterNovem), within the framework of the Non-CO_2 Greenhouse Gases Reduction Programme.

References

Huijsmans J.F.M. and G.D. Vermeulen, 2008. *Ammoniakemissie bij het toedienen van dierlijke mest. Actualisatie emissiefactoren*. PRI rapport 218, Plant Research International, Wageningen (in Dutch).

IPPC, (2006). *IPPC guidelines for national greenhouse gas inventories*.

Kuikman, P.J., K.W. van der Hoek, A. Smit and K. Zwart, 2006. *Update of emission factors for direct emissions of nitrous oxide from agricultural soils on the basis of measurements in the Netherlands*. Alterra report 1217, Alterra, Wageningen.

Van der Maas, C.W.M., P.W.H.G. Coenen, P.G. Ruyssenaars, H.H.J. Vreuls, L.J. Brandes, K. Baas, G. van den Berghe, G.J. van den Born, B. Guis, A. Hoen, R. Te Molder, D.S. Nijdam, J.G.J. Olivier, C.J. Peek and M.W. van Schijndel, 2008. *Greenhouse gas emissions in the Netherlands 1990-2006*. National Inventory Report 2008. MNP Report 500080009.

Appendix 2 Spatial variability of N_2O emission (paper NCGG-5)

Factors controlling spatial variability of N_2O emission from soils

Velthof, G.L., E.W.J. Hummelink, C.L. Van Beek, C. Terrones and J.W. van Groenigen
Wageningen UR, Alterra

J. Mosquera,
Wageningen UR, Animal Sciences Group

Keywords: nitrous oxide, grassland, maize land, spatial variability, manure, fertilizer

ABSTRACT: Fertilized soils are an important source of nitrous oxide (N_2O). Insight in spatial variability of N_2O emissions between fields and within fields is important for setting up measurement strategies using the flux chamber techniques and for mitigation of N_2O fluxes. A study was conducted to quantify the effect of manure application technique on the emission of N_2O from grassland and maize land in the Netherlands. As part of this study, spatial variability of N_2O fluxes was determined in fertilized grasslands and maize land. Furthermore, incubation studies were performed to i) determine the effect of soil type on fertilizer and manure derived N_2O emissions and ii) quantify the effects of moisture content and compaction on N_2O emission. Narrow-band application of slurry strongly increases spatial variability of N_2O fluxes from grassland, with highest fluxes from the slots with manure and lowest fluxes from the soil area between the slots. This spatial variability should be considered in the set-up of measurement campaigns to quantify N_2O emission from fields using flux chambers by the choice of number, diameter, and position of the chambers. In both sand, clay, and peat soils, incorporation of slurry increased N_2O emission, but the magnitude of the emission was highest for the peat soil. Compaction enhanced N_2O emission in the incubation study, showing that avoiding compaction by proper timing of manure and fertilizer application and by precision application techniques is an option to decrease N_2O emission from fertilized soils.

INTRODUCTION

Agricultural soils are the main source of nitrous oxide (N_2O) in the Netherlands (http://www.greenhousegases.nl/). The most used nitrogen (N) fertilizers in the Netherlands are mineral fertilizer (calcium ammonium nitrate), cattle slurry, and pig slurry. The type of applied N and the application method may affect emission of N_2O (Mosquera et al., 2007; Stehfest and Bouwman, 2006). Slurry application technique may also affect N_2O emission, because it affects NH_3 emission and the distribution of N and carbon (C) in the soil (Huijsmans, 2003; Paul and Beauchamp, 1989). If Nh3 emission high, more can be transformed into N_2O. Soil type and crop type also have an effect on the N_2O emission derived from applied N. In the Netherlands, most of the mineral N fertilizer and cattle and pig slurries are applied to grassland and maize land. Grassland is found on sand (46% of grassland area in the Netherlands), clay (39%), and peat soils (15%) and maize land mainly on sand soils (75%; F. de Vries, Alterra, personal communication*).*

A study was conducted to quantify the effect of manure application technique on the emission of nitrous oxide (N2O) from grassland and maize on sandy and clay soils in the Netherlands (Mosquera et al., 2009). The results are used to derive N2O emission factors for manure application. Flux chamber techniques are the most common method to quantify N2O emission and to derive N2O emission factors. This technique is hampered by the high spatial variability of N2O fluxes and a proper choice of the number, dimension, and position in the field are required to obtain an accurate estimate of the average N2O emission from the field. Insight in spatial variability of N2O emissions between fields and within fields is therefore important for setting up measurement strategies using the flux chamber techniques and for mitigation of N2O fluxes.

In this study, the spatial variability of N2O fluxes was determined for both fertilized grasslands and maize land. Special attention was paid to the effect of low ammonia emission manure application techniques (narrow-band slurry application and slurry injection on grassland an maize land, respectively) on the spatial variability of N2O fluxes. An incubation study was performed to determine the effect of soil type on fertilizer and manure derived N2O emissions, as no field measurements were carried on peat soil. The effects of moisture content and compaction on N2O emission were quantified in a laboratory study, as these factors may largely control spatial variability of N2O emission in the field.

MATERIALS AND METHODS

Monitoring study on effect of land use fertilizer type and method

A monitoring study was carried out at a grassland and maize land field on sandy soil, and a grassland field on clay soil, under different fertilizer treatments. The set-up of the experiments on grassland and maize land on the sand soil is described by Mosquera et al. (2009). The set-up of the grassland experiment on the clay soil was identical to that on the sand soil. The study started in April 2007 and is still on-going. All treatments were applied in triplicate in a completely randomized block design. The grassland plots were 20 m long and 2.5 m wide and the maize plots were 20 m long and 5 m wide. The spatial variability of N_2O fluxes of grassland on clay soil and maize land on sandy soil was assessed using flux chambers.

Spatial variability of fertilized grassland

The spatial variability of N_2O fluxes from grassland on the clay soil was determined in the period April to half June 2007, using flux chambers (plastic ring with a diameter of 10.4 cm). On each plot six flux chambers were placed (three rows of two chambers at 2 m distance; the distance between the two chambers was 30 cm). The measurements were carried out on all treatments, i.e. 1) no fertilization, 2) surface applied mineral fertilizer (calcium ammonium nitrate), 3) surface applied cattle slurry, and 4) cattle slurry, applied with a narrow-band spreading technique (or sod injection; tine distance about 20 cm; depth of injection about 5 cm). In the treatment with narrow-band application, three chambers were placed on the slots with slurry and three chambers were place in the unfertilized area between the slots. The measurements were carried out on the three replicates per treatment, so that N_2O fluxes was determined in total at 18 positions per treatment.

Spatial variability was determined 1, 7, and 14 days after N application on 4th April, 4, and 11 days after N application on 14th May, and 5, and 13 days after N application on 6th June. The N_2O concentration in the head space of the flux chamber was measured 30 minutes after closing the chamber, using an photoacoustic gasmonitor (Innova 1312). The N_2O flux was calculated from the change of N_2O concentration in time, the volume of the headspace, and the soil area covered by the chamber. All measurements were carried out within period of 2.5 hours.

Spatial variability of fertilized maize land

Spatial variability of N_2O fluxes from maize land of surface-applied and injected pig slurry was determined on 14th, 23rd and 30th of May, 13th and 19th of June and 19th of July 2007. The first measurement was carried two days after slurry application to the maize land. The experiment was carried out in three replicates and six flux chambers (plastic ring with a diameter of 10.4 cm) were placed in each plot, three in the lines with maize plants and three between the lines with maize plant. In total 18 flux measurements were made per treatment, from which 9 in the planting line and 9 between the planting lines. The method of measuring N_2O emission was the same as described for grassland.

Incubation study on effect of soil type

The field experiments were carried out on sand and clay soils. An incubation study was carried out to quantify the N_2O emission from cattle slurry applied to peat, sand, and clay soils, with surface application and narrow band application. Also the N_2O emission from CAN as reference fertilizer was quantified. These studies provide insight in the variability in N_2O between soil types. The incubation study was carried out in four replicates, using a similar methodology as already used in earlier studies (Van Groenigen et al, 2005; Velthof et al., 2005). The sandy and clay soils were from Wageningen (same as the grassland experiments) and that of peat soil from Zegveld. Intact soil cores with swards were taken in February 2008 using PVC cylinders (10 cm diameter and 10 depth) that were pushed into the soil. The cores were dug out from the soil and transported to the laboratory. Emission of N_2O from disturbed peat soils may be high in incubation studies, because of a high N mineralization. This high background N_2O emission strongly hampers the quantification of N_2O emission from applied fertilizers. Therefore, the cores were pre-incubated at 15 °C for about one month in a laboratory. During this month, emission of N_2O was measured regularly to test if N_2O emission was low.

Just before N application, grass was cut. The CAN was grinded and homogeneously applied on top of the soil. The surface-applied cattle slurry was homogeneously applied on top of the grass and soil. The narrow-band applied cattle slurry was band-placed into a slot of 5 cm depth in the soil (in the middle of the core), which was created with knife. The N application rates were 0 kg N per ha for the control, 80 kg N per ha for CAN, and 58 kg N per ha for the surface-applied and the narrow-band applied cattle slurry. The soil cores were placed into ditches with water, creating relatively wet conditions. Eighteen days after N application, the cores were dried out to simulate a relatively dry period, which is favourable for mineralization and nitrification. After 28 days after N application, 12 mm water was added to simulate rainfall after a relatively dry period.

Fluxes of N_2O were assessed from the increase in N_2O concentrations in the headspace following the closure of the bottles with flux chambers for 1 hour. Concentration of N_2O was measured using a photoacoustic gasmonitor (Innova 1312). Emission of N_2O was measured 17 times during a period of 47 days. The total N_2O was calculated by linear interpolation of the measured fluxes at different times. Between the measurement times, the bottles were left open.

Incubation study on effect of moisture content en compaction

An incubation experiment was carried out to quantify the effects of moisture contents and compaction on N_2O emission. The treatments consisted of two land use treatments (grassland and maize land on sand), two soil moisture treatments (field capacity and saturated), two compaction treatments (no compaction and compaction) and four fertilization treatments (no fertilizer, calcium ammonium nitrate, injected pig slurry, and injected cattle slurry). The measurements were carried out in three replicates. The total experiment consisted of 96 chambers.

The compaction was created by pressing the soil samples until a depression of the soil in the incubation bottle of 2 cm was reached. Water was added on 1st August, one day before the measurements started. The soil was irrigated for a second time on the 13th of August. The N application rate was equivalent to170 kg N per ha. Emission of N_2O was measured 9 times during a period of 22 days, using the same method as described in the paragraph before.

RESULTS AND DISCUSSION

Spatial variability in grassland

Narrow-band application of cattle slurry increased spatial variability of N_2O fluxes from grassland (Figure 1). High fluxes and a high spatial variability was shown in the slots with slurry and low fluxes with a low spatial variability was shown in the area between the slots (Figure 1). This was especially observed during a relatively wet period in May 2007. Fluxes of N_2O were much smaller after surface application of cattle slurry and spatial variability from surface-applied slurry was also relatively small, as indicated by the small standard deviation (Figure 1). The average N_2O emission from surface applied cattle slurry was smaller than from narrow-band applied cattle slurry (Mosquera et al., 2009).

Clearly, slurry application technique has a large effect on both the magnitude and spatial variability of N_2O fluxes from grasslands. Ammonia emission from surface-applied slurry is much higher than from narrow-band applied slurry (Huijsmans, 2003). High NH_3 emission leads to lower N contents in the soil, which may explain the lower N_2O emission observed from surface-applied slurry compared to narrow-band applied slurry. The slots from narrow-band applied cattle slurry have locally high concentrations of ammonium which may have enhanced N_2O production during nitrification or nitrification followed by denitrification. The presence of high contents of available carbon in cattle slurry stimulates denitrification activity and O_2 consumption in the soil, creating hotspots of denitrification (Bertora et al., 2008; Paul and Beauchamp, 1989), which also may have promoted N_2O emission from narrow-band applied slurry.

Spatial variability of N_2O emission should be considered in the set-up of measurement strategies to quantify N_2O emission from fields using flux chambers, e.g. by the choice of number of chambers, the soil area covered by the chambers, and position of the chambers in the field. In this experiment, only the spatial variability in fertilized grassland was determined. Grazing is an important source for spatial variability of N_2O emission in the field, which must be considered when N_2O emission from grazed grassland have to be quantified (Van Groenigen et al., 2005; Velthof et al., 1996a).

Spatial variability in maize land

Fluxes of N_2O were much higher after injection of pig slurry than after surface application of pig slurry (Figure 2). The standard deviation was also higher in the plot with injected slurry. Injection of slurry may enhance N_2O fluxes by a combination of factors, i.e. a lower ammonia emission (causing higher N contents in the soil), placement of N in soil layers with higher moisture contents (promoting N_2O production), and higher local N and C concentrations (promoting N_2O production during nitrification and denitrification). The higher standard deviation points at a higher spatial variability of N_2O fluxes from injected slurry. Injection of pig slurry results in a more heterogeneous distribution of N and carbon than surface-applied slurry, which creates hot spots with favourable conditions for denitrifying bacteria and a high spatial variability of denitrification and N_2O production. This was also clearly shown in the measurement of the narrow-band cattle slurry on grassland (Figure 2).

The measurements showed no significant effect of the location of maize plants on N_2O emissions, although there was a tendency for chambers between the planting lines to have higher emissions than the ones in the planting lines (not shown). Plants may affect N_2O emission by uptake of mineral N, more consumption of water, and exudation of carbon.

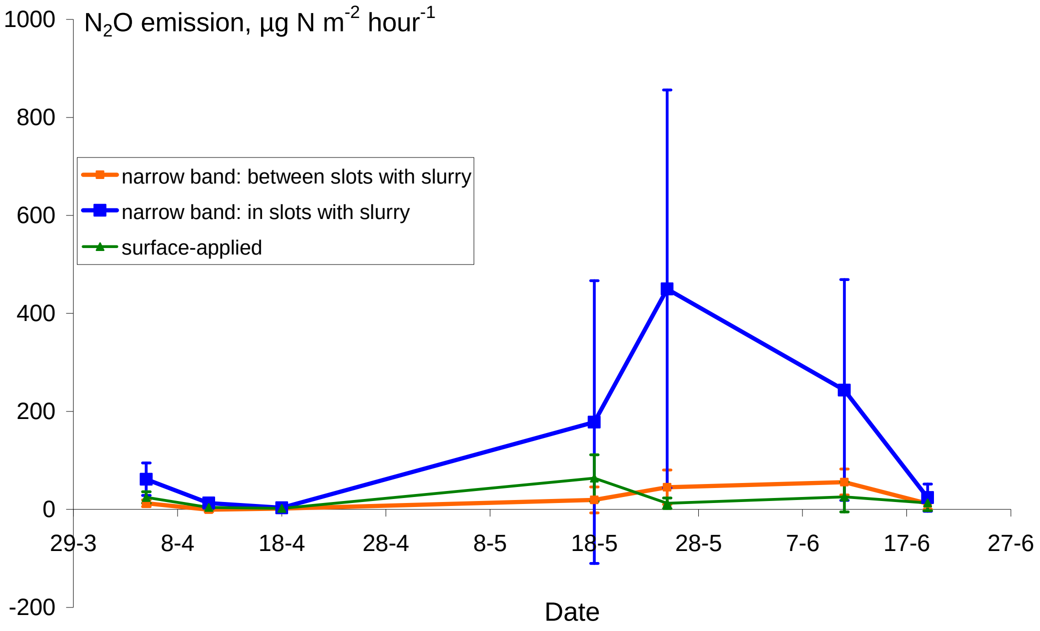


Figure 1. N$_2$O emission from grassland to which cattle slurry was applied with a narrow-band application technique in period spring 2007. Fluxes were measured from the slots with slurry (n=9) and the soil between the slots (n=9). Fluxes from surface-applied cattle slurry (n=18) are also shown.

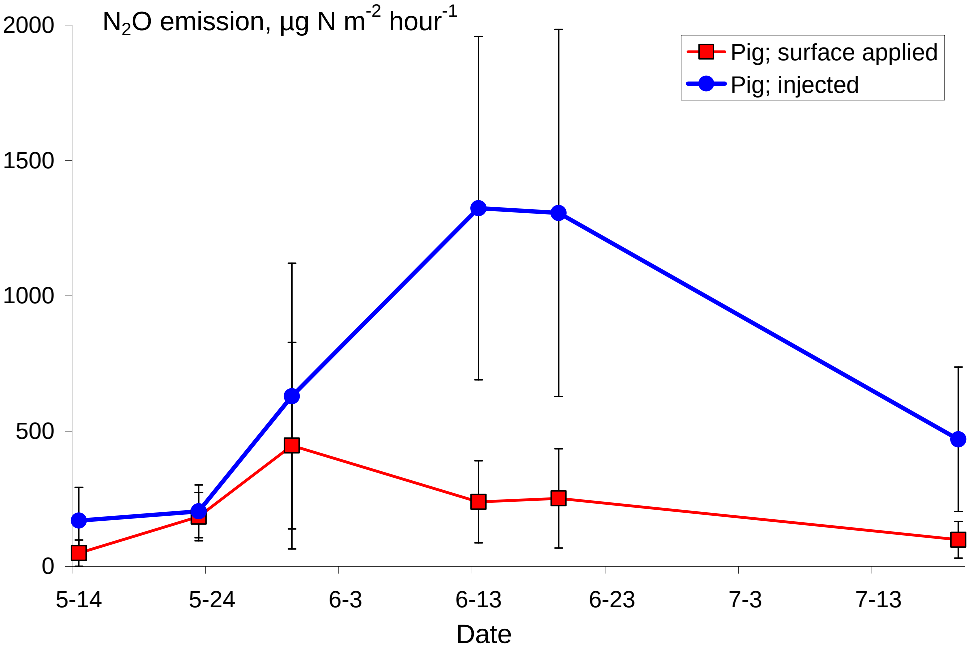


Figure 2. N$_2$O emission from maize land fertilized with pig slurry (average ± standard deviation; n = 18 per treatment).

Effect of soil type

The pattern of N_2O fluxes in the incubation study with grassland soils were similar for the clay, sand, and peat soil; fluxes increased after fertilizer and water application (not shown). However, N_2O flux magnitude increased in the order clay soil < sandy soil < peat soil, which is also shown in the total N_2O emission during the incubation period of 47 days (Figure 3). The much higher N_2O emission from peat soil than from sandy and clay soils is in agreement with field measurements (Velthof et al., 1996b) and is due to the higher organic carbon contents in peat soils, which stimulates denitrification. The total N_2O emission increased in the order control < surface applied cattle slurry < narrow-band applied cattle slurry < CAN, which is agreement with results of field measurements on grassland (Mosquera et al., 2009).

The study was carried out with intact soil cores taken from the field. The variation of the N_2O emission between the replicates was relatively low. The variation coefficient was highest for the clay soil (19-85%) and smallest for the peat soil (10-31%). In field experiments much higher variation coefficients are found (up to more than 150%). Apparently, the adjustment of moisture content and application of N under controlled conditions decreased variability of N_2O fluxes compared to field conditions.

Effect of moisture content en compaction

Compaction of the soil and increased soil moisture content increased N_2O emission in both the grassland and maize land soils (Figure 4). The results pointed at interactions, because the increase in N_2O emission by compaction was higher for soils at field capacity than for saturated soil (Figure 4). Compaction decreases oxygen concentration in the soil, which results in a higher N_2O emission. The effect of compaction of soil at field capacity was larger than increasing moisture content from field capacity to saturation.

Application of manure and fertilizer may result in local compaction of the soil, especially under wet soil conditions. This may enhance N_2O emission. Avoiding compaction by proper timing of manure and fertilizer application and by precision application techniques (Vermeulen and Mosquera, 2009) is an option to decrease N_2O emission from fertilized soils.

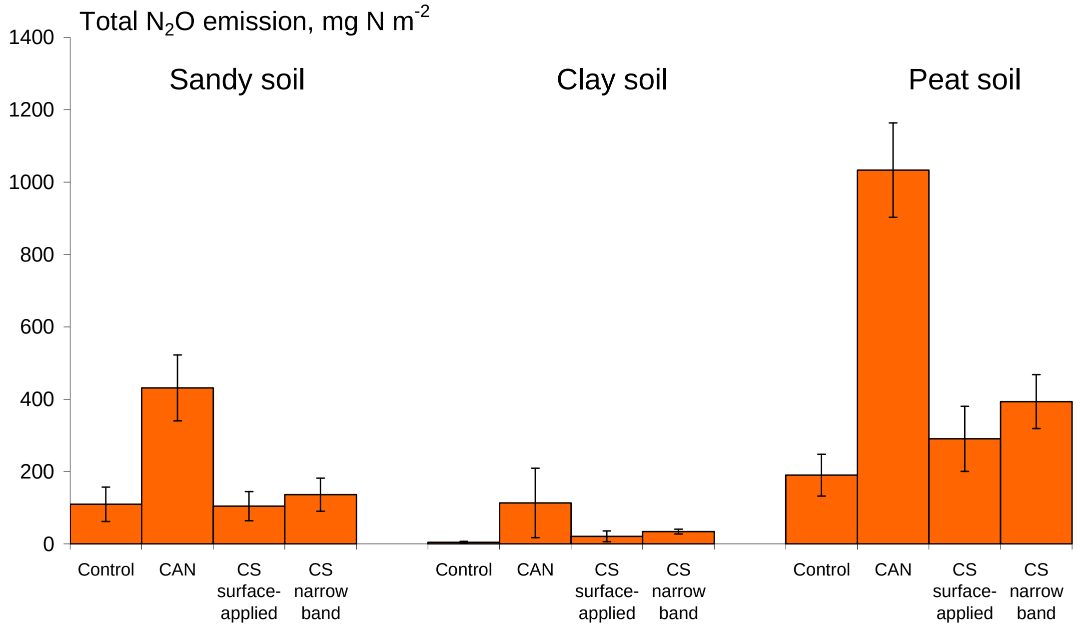


Figure 3. Total N_2O emission from the N treatments and soils in the incubation study of 47 days (average ± standard deviation; n = 4). The N treatments were calcium ammonium nitrate (CAN) and surface-applied and narrow band applied cattle slurry (CS).

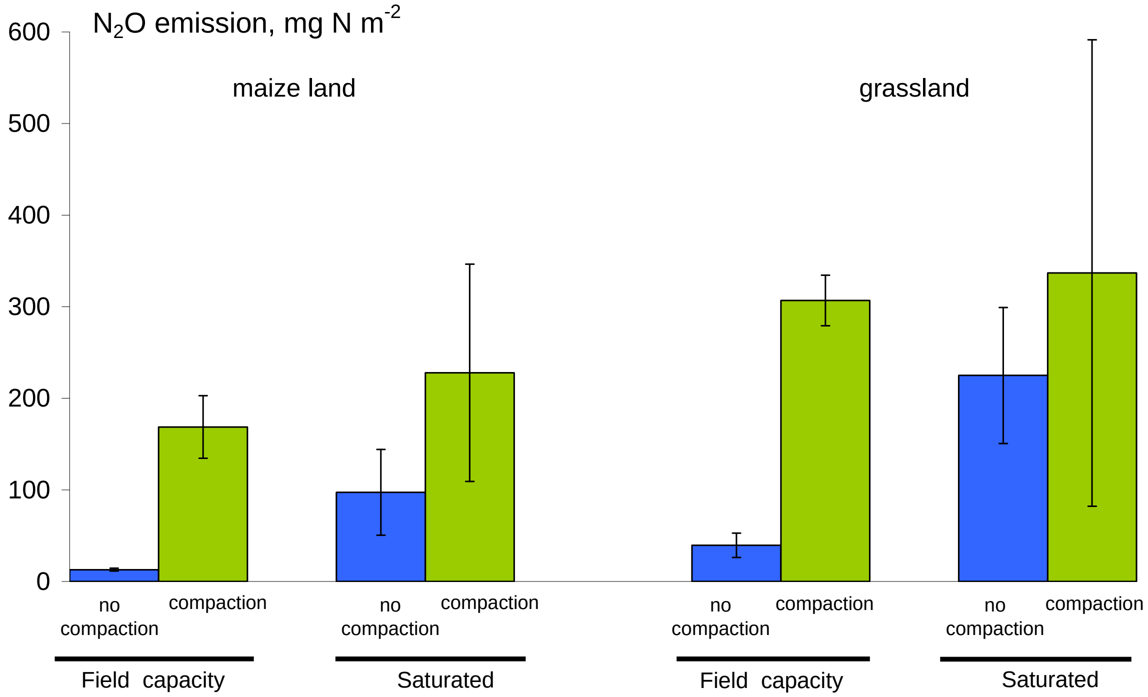


Figure 4. Total N_2O emission from maize land and grassland fertilized with cattle slurry, with different moisture content and with and without compaction in the incubation study of 22 days (average ± standard deviation; n = 3).

CONCLUSIONS

The field and incubation studies showed that narrow-band application and injection of slurry strongly increases spatial variability of N_2O fluxes. This spatial variability should be considered in the set-up of measurement campaigns to quantify N_2O emission from fields using flux chambers. The effect of fertilizer and slurry application was similar for sand, clay, and peat soils, but the magnitude of the N_2O emission of N_2O from peat soil was higher than from mineral soils. Compaction enhanced N_2O emission in the incubation study, showing that avoiding compaction by proper timing of manure and fertilizer application and by precision application techniques is an option to decrease N_2O emission from fertilized soils.
The measurements are still going on and results of the field and incubation experiments of Mosquera et al. (2009) and the present study will be synthesized and published in order to obtain quantitative insight in the effects of manure application technique on N_2O emission from agricultural soils in the Netherlands.

ACKNOWLEDGEMENTS

The study was financed by the Non-CO_2 Greenhouse Gases Reduction Programme under contract of SENTER NOVEM and BSIK ME1.

REFERENCES

Bertora, C., F. Alluvione, L. Zavattaro, J.W. van Groenigen, G.L. Velthof, C. Grignani, 2008. Pig slurry treatment modifies slurry composition, N_2O, and CO_2 emissions after soil incorporation. *Soil Biology and Biochemistry* 40, 1999-2006.

Groenigen, J.W. van, P.J. Kuikman, W.K.M. de Groot and G.L. Velthof, 2005. Nitrous oxide emission from urine-treated soil as influenced by urine composition and soil physical conditions. *Soil Biology and Biochemistry* 37, 463-473.

Huijsmans, J.F.M., 2003. *Manure application and ammonia volatilization*. PhD thesis Wageningen University.

Mosquera, J., J.M.G. Hol, C. Rappoldt and J. Dolfing, 2007. *Precise soil management as a tool to reduce CH4 and N2O emissions from agricultural soils*. Animal Sicences Group, Report 28, 42 p.

Mosquera, J., J. Huis in 't Veld, G.L Velthof and E.W.J. Hummelink, 2009. *Differences in* N_2O *emission from fertilized grassland and arable land in sandy soils*. Proceedings NCGG5 2009.

Paul J.W. and E.G. Beauchamp, 1989. Effect of carbon constituents in manure on denitrification in soil. Can *J Soil Sci* 69:49-61.

Stehfest, E. and L. Bouwman, 2006. N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems* 74: 207-228

Velthof, G.L., J.A. Nelemans, O. Oenema and P.J. Kuikman, 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. *Journal of Environmental Quality* 34, 698-706.

Velthof, G.L. S.C. Jarvis, A. Stein, A.G. Allen and O. Oenema, 1996a.. Spatial variability of nitrous oxide fluxes in mown and grazed grasslands on a poorly drained clay. *Soil Biol and Biochem*. 28:1215-1225.

Velthof GL, A.B. Brader and O. Oenema, 1996b. Seasonal variations in nitrous oxide losses from managed grasslands in the Netherlands. *Plant and Soil* 181: 263-274.

Vermeulen G.D. and J. Mosquera, 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. *Soil and Tillage Research* Volume 102, 126-134.

Appendix 3 Application rates of manure and fertilizers

Application rates of cattle slurry to grassland in 2007(m^3/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	0	0	0	0	0	0
Cattle slurry; sod injection	20	15	10	10	10	65
Cattle slurry; surface application	20	15	10	10	10	65
CAN + cattle slurry, sod injection	35	0	0	17	10	62

Application rates of calcium ammonium nitrate to grassland in 2007 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	57	43	29	20	25	174
Cattle slurry; sod injection	0	0	0	0	0	0
Cattle slurry; surface application	0	0	0	0	0	0
CAN + cattle slurry, sod injection	0	90	60	0	0	150

Total application rates of cattle slurry to grassland in 2007 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	0	0	0	0	0	0
Cattle slurry; sod injection	103	72	50	48	49	322
Cattle slurry; surface application	103	72	50	48	49	322
CAN + cattle slurry, sod injection	180	0	0	81	49	310

Total application rates to grassland in 2007 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	57	43	29	20	25	174
Cattle slurry; sod injection	103	72	50	48	49	322
Cattle slurry; surface application	103	72	50	48	49	322
CAN + cattle slurry, sod injection	180	90	60	81	49	460

Application rates of cattle slurry to grassland in 2008 (m^3/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	0	0	0	0	0	0
Cattle slurry; sod injection	20	15	10	10	10	65
Cattle slurry; surface application	20	15	10	10	10	65
CAN + cattle slurry, sod injection	30	0	25	0	10	65

Application rates of calcium ammonium nitrate to grassland in 2008 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	60	50	30	20	15	175
Cattle slurry; sod injection	0	0	0	0	0	0
Cattle slurry; surface application	0	0	0	0	0	0
CAN + cattle slurry, sod injection	0	50	0	20	0	70

Total application rates of cattle slurry to grassland in 2008 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	0	0	0	0	0	0
Cattle slurry; sod injection	95	76	55	54	50	330
Cattle slurry; surface application	95	76	55	54	50	330
CAN + cattle slurry, sod injection	142	0	138	0	50	330

Total application rates to grassland in 2008 (kg N/ha)

Object	Cut					
	1	2	3	4	5	Total
Control	0	0	0	0	0	0
CAN	60	50	30	20	15	175
Cattle slurry; sod injection	95	76	55	54	50	330
Cattle slurry; surface application	95	76	55	54	50	330
CAN + cattle slurry, sod injection	142	50	138	20	50	400

Application rates of cattle slurry to grassland in 2009 (m^3/ha)

Object	Cut				
	1	2	3	4	Total
Control	0	0	0	0	0
CAN	0	0	0	0	0
Cattle slurry; sod injection	20	15	10	10	55
Cattle slurry; surface application	20	15	10	10	55
CAN + cattle slurry, sod injection	30	0	25	0	55

Application rates of calcium ammonium nitrate to grassland in 2009 (kg N/ha)

Object	Cut				
	1	2	3	4	Total
Control	0	0	0	0	0
CAN	60	50	30	20	160
Cattle slurry; sod injection	0	0	0	0	0
Cattle slurry; surface application	0	0	0	0	0
CAN + cattle slurry, sod injection	0	50	0	20	70

Total application rates of cattle slurry to grassland in 2009 (kg N/ha)

Object	Cut				
	1	2	3	4	Total
Control	0	0	0	0	0
CAN	0	0	0	0	0
Cattle slurry; sod injection	98	81	48	47	274
Cattle slurry; surface application	98	81	48	47	274
CAN + cattle slurry, sod injection	147	0	119	0	266

Total application rates to grassland in 2009 (kg N/ha)

Object	Cut				
	1	2	3	4	Total
Control	0	0	0	0	0
CAN	60	50	30	20	160
Cattle slurry; sod injection	98	81	48	47	274
Cattle slurry; surface application	98	81	48	47	274
CAN + cattle slurry, sod injection	147	50	119	20	336

Application rates on maize land in 2007.

Object	Application rate			
	Cattle slurry m^3/ha	Pig slurry m^3/ha	Total N kg N/ha	Calcium ammonium nitrate kg N/ha
Control	0	0	0	0
CAN	0	0	102	102
Cattle slurry; injection	35	0	166	0
Cattle slurry; surface application	35	0	166	0
Pig slurry; injection	0	24	249	0
Pig slurry; surface application	0	24	249	0

Application rates on maize land in 2008.

Object	Application rate			
	Cattle slurry m^3/ha	Pig slurry m^3/ha	Total N kg N/ha	Calcium ammonium nitrate kg N/ha
Control	0	0	0	0
CAN	0	0	102	102
Cattle slurry; injection	35	0	182	0
Cattle slurry; surface application	35	0	182	0
Pig slurry; injection	0	19	188	0
Pig slurry; surface application	0	19	188	0

Application rates on maize land in 2009.

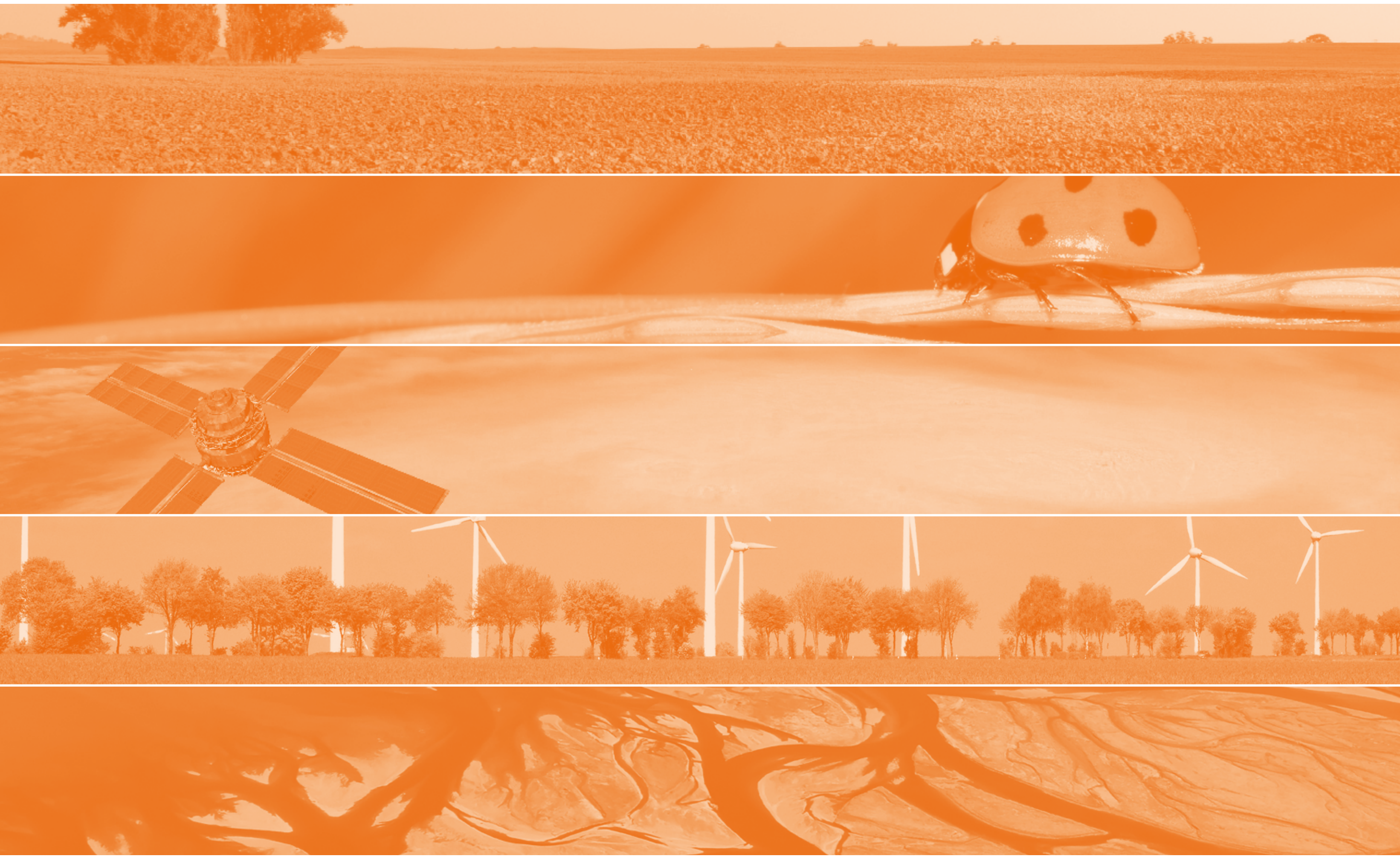
Object	Application rate		
	Cattle slurry m^3/ha	Pig slurry m^3/ha	Total N kg N/ha
Control	0	0	0
CAN	0	0	50
CAN	0	0	125
CAN	0	0	200
Cattle slurry; injection	20	0	100
Cattle slurry; injection	35	0	175
Cattle slurry; injection	50	0	251
Cattle slurry; surface application	35	0	175
Pig slurry; injection	0	10	106
Pig slurry; injection	0	17	181
Pig slurry; injection	0	25	266
Pig slurry; surface application	0	17	181

Appendix 4 Slurry composition

Date of application	Crop	Slurry type	Total N g/kg	Ammonium-N g/kg	Dry matter g/kg	Ash g/kg
10-5-2007	Maize	Cattle	4.8	2.6	85.1	20.1
10-5-2007	Maize	Pig	10.5	7.4	132.0	33.7
2-4-2007	Grassland	Cattle	5.2	2.4	99.8	20.9
14-5-2007	Grassland	Cattle	4.8	2.5	85.6	21.0
6-6-2007	Grassland	Cattle	5.0	2.7	82.5	20.9
9-7-2007	Grassland	Cattle	4.8	2.5	81.3	19.8
22-8-2007	Grassland	Cattle	4.9	2.5	74.7	19.2
5-5-2008	Maize	Cattle	5.2	2.5	94.8	21.3
5-5-2008	Maize	Pig	9.9	6.9	112.4	32.4
21-3-2008	Grassland	Cattle	4.7	2.0	112.0	20.9
19-5-2008	Grassland	Cattle	5.1	2.5	89.4	23.4
23-6-2008	Grassland	Cattle	5.5	3.1	90.3	21.9
22-7-2008	Grassland	Cattle	5.4	3.1	86.6	21.0
27-8-2008	Grassland	Cattle	5.0	2.6	81.9	19.7
27-4-2009	Maize	Cattle	5.0	2.5	87.3	19.6
27-4-2009	Maize	Pig	10.6	7.1	114.0	31.3
18-3-2009	Grassland	Cattle	4.9	2.5	78.0	20.6
11-5-2009	Grassland	Cattle	5.4	2.5	84.3	19.3
24-6-2009	Grassland	Cattle	4.8	2.5	81.8	21.1
12-8-2009	Grassland	Cattle	4.7	2.4	76.5	19.1

Average composition

		Total N g/kg	NH_4-N g/kg	Dry matter g/kg	Ash g/kg
Cattle (n=17)	Average	5.0	2.6	86.6	20.6
	sd	0.2	0.2	9.1	1.1
Pig (n=3)	Average	10.4	7.1	119.5	32.5
	sd	0.4	0.2	10.9	1.2



Alterra is part of the international expertise organisation Wageningen UR (University & Research centre). Our mission is ‘To explore the potential of nature to improve the quality of life’. Within Wageningen UR, nine research institutes – both specialised and applied – have joined forces with Wageningen University and Van Hall Larenstein University of Applied Sciences to help answer the most important questions in the domain of healthy food and living environment. With approximately 40 locations (in the Netherlands, Brazil and China), 6,500 members of staff and 10,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the exact sciences and the technological and social disciplines are at the heart of the Wageningen Approach.

Alterra is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

More information: www.alterra.wur.nl/uk