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Precise soil management as a tool to reduce CH_4 and N_2O emissions from agricultural soils

January 2007

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Publisher
Animal Sciences Group
P.O. Box 65, 8200 AB Lelystad
Telephon +31 320 - 238238
Fax +31 320 - 238050
E-mail info.po.asg@wur.nl
Internet http://www.asg.wur.nl/po

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Abstract
Soil compaction stimulates the emission of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils. N_2O and CH_4 are potent greenhouse gases, with a global warming potential respectively 296 times and 23 times greater than CO_2. Agricultural soils are an important source of N_2O. Hence there is much interest in a systematic evaluation of management options that are available to minimize agricultural greenhouse gas emissions, in particular N_2O soil emissions. One such option would be to minimize soil compaction due to the use of heavy machinery. Soil compaction in arable land is relatively general. Here we report that emissions of N_2O and CH_4 from an arable field where soil compaction was minimized through application of the so – called '*rijpaden*' (riding track) system was substantially lower than from plots where a traditional system was used. Laboratory experiments were used to underpin these observations. From these observations we developed a simple calculation model that relates N_2O emission to gas filled pore space and soil respiration as input parameters. We suggest to implement the riding track system on clay rather than sand as farmers benefit from lower compaction in terms of lower risk of compaction and better accessibility of fields for work. The potential reduction of the N_2O emission from arable farming in the Netherlands is estimated at ~169 ton N_2O-N per year (~0.1 Mton CO_2-equivalent). This calculation is based on several assumptions and would benefit from testing assumptions and monitoring effects in agricultural day to day practice.

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Report 28

Precise soil management as a tool to reduce CH4 and N2O emissions from agricultural soils

J. Mosquera (ASG)
J.M.G. Hol (ASG)
C. Rappoldt (Alterra)
J. Dolfing (Alterra)

January 2007

Preface

This research was partially supported by the Netherlands' agency for innovation and sustainability (SenterNovem) and the Dutch Ministry of Agriculture, Nature and Food Quality (LNV). This report summarizes the results of a 2-year study dealing with the effects of soil compaction on the emissions of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils. The results presented here are discussed in more detail in the following reports:

- Literature review: Mosquera (2005)
- Field measurements (Mosquera *et al.*, 2005a, 2005b)
- Laboratory experiments (Rappoldt *et al.*, 2006)

Short summary

Soil compaction stimulates the emission of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils. N_2O and CH_4 are potent greenhouse gases, with a global warming potential respectively 296 times and 23 times greater than CO_2. Agricultural soils are an important source of N_2O. Hence there is much interest in a systematic evaluation of management options that are available to minimize agricultural greenhouse gas emissions, in particular N_2O soil emissions. One such option would be to minimize soil compaction due to the use of heavy machinery. Soil compaction in arable land is relatively general. Here we report that emissions of N_2O and CH_4 from an arable field where soil compaction was minimized through application of the so – called '*rijpaden'* (riding track) system was substantially lower than from plots where a traditional system was used. Laboratory experiments were used to underpin these observations. From these observations we developed a simple calculation model that relates N_2O emission to gas filled pore space and soil respiration as input parameters. We suggest implementing the '*rijpaden'* system on clay rather than sand as farmers benefit from lower compaction in terms of lower risk of compaction and better accessibility of fields for work. The potential reduction of the N_2O emission from arable farming in the Netherlands is estimated at ~169 ton N_2O-N (~0.1 Mton CO_2-equivalent) per year. This calculation is based on several assumptions and would benefit from testing assumptions and monitoring effects in agricultural day to day practice.

Keywords: Agricultural soils, Emissions, Greenhouse gases, Nitrous oxide, Methane, Soil compaction, Fertilisation, Soil water content, Land use

Verkorte samenvatting

Landbouwgronden zijn een belangrijke bron van de relatief sterke broeikasgassen lachgas (N_2O) en methaan (CH_4). Bodemverdichting als gevolg van het gebruik van zware machines op het land stimuleert de emissie van N_2O en CH_4. SenterNovem subsidieert onderzoek dat moet vaststellen of door de toepassing van het zogeheten rijpadensysteem bodemverdichting kan worden voorkomen of verminderd. Zo zou de emissie van broeikasgassen uit de akkerbouw kunnen worden verminderd. In dit rapport presenteren we gegevens over emissies uit een akkerbouwgrond waar bodemverdichting gereduceerd werd door het gebruik van het rijpadensysteem. De emissie van N_2O en CH_4 bij rijpaden en minder bodemverdichting was aanzienlijk lager dan de emissie uit controlevelden waar het land op traditionele wijze bewerkt werd. Op grond van veld- en laboratorium waarnemingen hebben we een eenvoudig model opgesteld waarin de emissie van N_2O beschreven wordt als functie van het gasgevulde poriegehalte en de bodemrespiratie. De landbouwers op kleigronden hebben (naar verwachting) het meeste voordeel van toepassing van het rijpadensysteem: ze kunnen zo na een natte periode eerder het land op, kleigrond is gevoeliger voor verdichting dan zand, en de vermeden emissie is op klei het grootst. De invoering van het rijpadensysteem zal kunnen leiden tot een vermindering van de N_2O emissie vanuit de Nederlandse akkerbouw van ~169 ton N_2O-N (~0.1 Mton CO_2-equivalenten) per jaar. Deze schatting is gebaseerd op een aantal aannames, en zal preciezer worden als deze aannames nader getest worden.

Trefwoorden: Landbouwbodems, emissies, broeikasgassen, lachgas, methaan, bodemverdichting, bemesting, watergehalte, gewas

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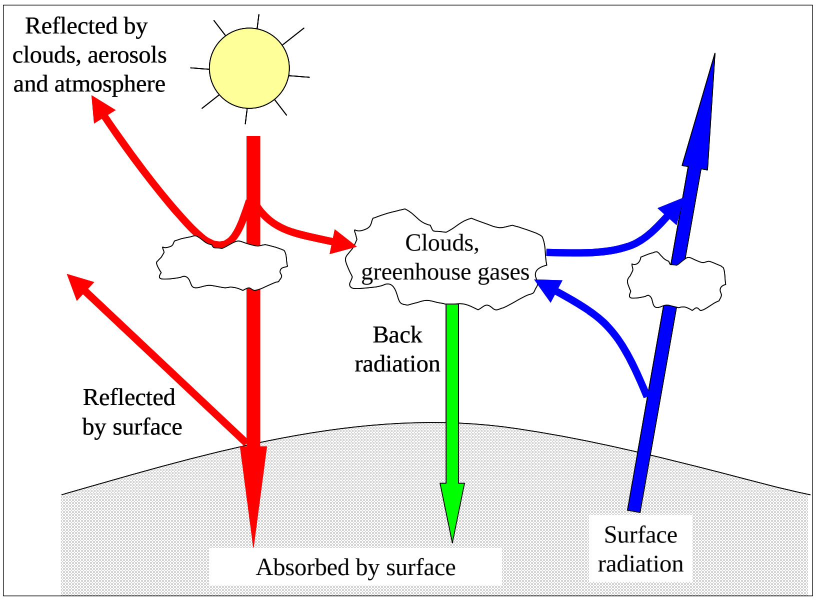
1 Introduction

1.1 Greenhouse gases and climate change

Greenhouse gases are present in the atmosphere as trace gases. They are transparent for incoming short-wave radiation from the sun, but do absorb and re-emit the outgoing infrared radiation from the Earth's surface, thereby warming the atmosphere (figure 1). This warming is referred to as “natural greenhouse effect”.

Figure 1 The greenhouse effect



Greenhouse gases differ in their ability to absorb heat in the atmosphere. In order to be able to compare the emissions of all different greenhouse gases, the concept of Global Warming Potential (GWP) was introduced. The GWP expresses the emission of a gas in terms of carbon dioxide (CO_2) emissions (CO_2 equivalents). Since greenhouse gases have different lifetimes (IPCC, 2001; table 1), the GWP is always coupled to a particular time interval (time horizon). For example, on a molecular basis and over a 100-year time horizon, the GWP of methane (CH_4) is 23 times that of CO_2, and nitrous oxide (N_2O) has a GWP 296 times greater than carbon dioxide (IPCC, 2001; table 1).

Table 1 Some characteristics of the main greenhouse gases (IPCC, 2001)

Greenhouse gases	Pre-industrial concentration	Concentration in 1998	Atmospheric Lifetime [years]	Global warming potential (100 year time horizon)
Carbon dioxide (CO_2)	280 ppmv	365 ppm	5-200	1
Methane (CH_4)	700 ppbv	1745 ppbv	12	23
Nitrous oxide (N_2O)	270 ppbv	314 ppbv	114	296

The concentration of greenhouse gases remained relatively constant for about a thousand years before the industrial revolution. Since then, the concentration of various greenhouse gases has drastically increased. As an example, atmospheric concentrations of carbon dioxide have increased nearly 30%, CH_4 concentrations have more than doubled, and N_2O concentrations have risen by about 15% (IPCC, 2001; table 1). This has resulted in a positive radiative forcing, which tends to warm the surface (“enhanced greenhouse effect”).

Concern about the enhanced greenhouse effect has prompted international action to reduce emissions. A first agreement, intended to stabilise emissions at 1990 levels by 2000, was signed in 1992 at the Earth Summit in Rio de Janeiro. A more binding agreement was reached at Kyoto, Japan, in 1997. Under the Kyoto Protocol (entry into force 16 February 2005), thirty industrialised countries are legally bound to reduce their combined emission of six major greenhouse gases during the five-year period 2008-2012 to below 1990 levels. The European Union, for example, should reduce by 8% its combined emissions. For the Netherlands, a reduction target of 6% has been assigned.

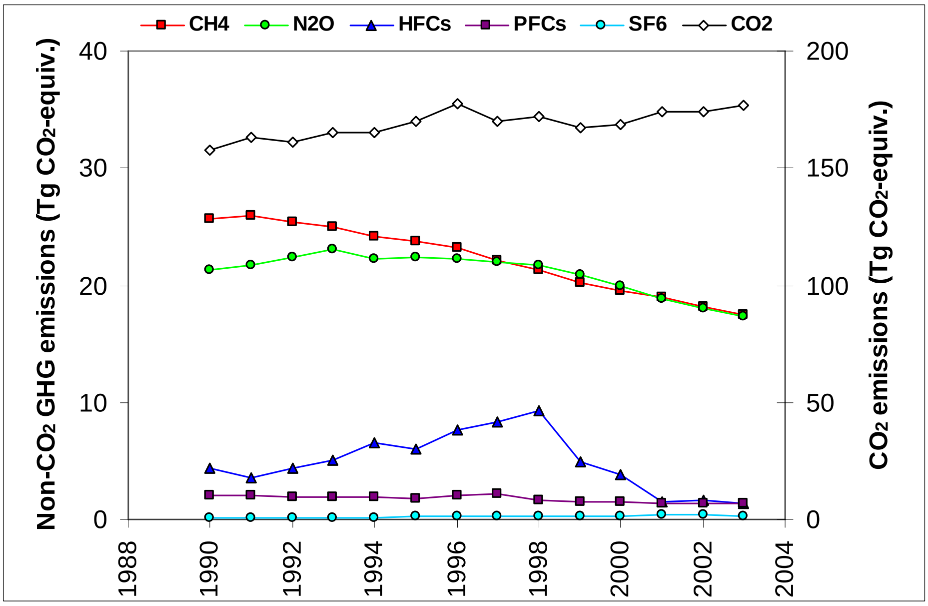
1.2 Greenhouse gas emission trends in the Netherlands

The UNFCCC and the Kyoto protocol specify six main greenhouse gases whose emissions should be reported:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydrofluorocarbons (HFCs)
- Perfluorocarbons (PFCs)
- Sulphur hexafluoride (SF_6)

Emissions of CO_2 increased in 2003 by about 12% relative to 1990 (figure 2), which is considered to be the reference year for the emissions of CO_2, CH_4 and N_2O. In contrast, the emissions of CH_4 and N_2O decreased (in the same period) by about 32% and 19%, respectively. The total emission of the fluorinated gases (HFCs, PFCs, SF_6) decreased by 60% in 2003 relative to 1995, the reference year for these gases. In particular, emissions of HFCs and PFCs decreased by about 75% and 25%, respectively, while SF_6 emissions increased by 11%.

Figure 2 Trend in greenhouse gas emissions in the Netherlands during the period 1990-2003. Source: Klein Goldewijk *et al.* (2005).



The contribution of CO_2 emissions to the total greenhouse gas emission in the Netherlands increased from approximately 75% in 1990, to 82% in 2003 (figure 3). CH_4 and N_2O are the most important non-CO_2 greenhouse gases in the Netherlands. Together they were responsible for about 16% of total greenhouse gas emissions in the Netherlands in 2003. Compared to CO_2, their contribution to the total emissions has been reduced by 6% since 1990.

Agriculture is the most important source of N_2O and CH_4 in the Netherlands (figure 4), and contributes about 8% to the total national greenhouse gas emissions in 2003 (10% in 1990). N_2O emissions are responsible for about 53% of total greenhouse gas emissions from agriculture, whereas CH_4 is responsible for the rest (47%). Emissions of N_2O from agriculture, mainly from agricultural soils (1: direct emissions through application of animal wastes/fertilizer to soils; 2: indirect emissions from nitrogen leaching and run-off), accounted for 54% of national total N_2O emissions. CH_4 emissions from agriculture accounted for 49% of the national total CH_4 emissions in 2003, and were related to enteric fermentation (75% of total agricultural CH_4 emissions) and animal waste management systems (25% of total CH_4 emissions from agriculture).

Figure 3 Shares of greenhouse gases in total emissions in the Netherlands in (A) the reference year (1990 for CO_2, CH_4 and N_2O; 1995 for F-gases), and in (B) the year 2003. Source: Klein Goldewijk *et al.* (2005).

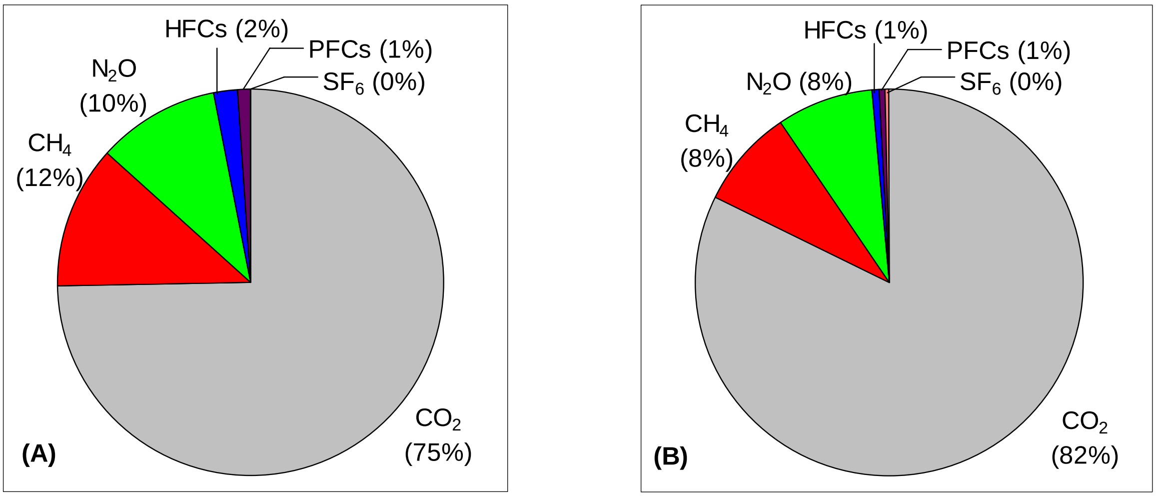
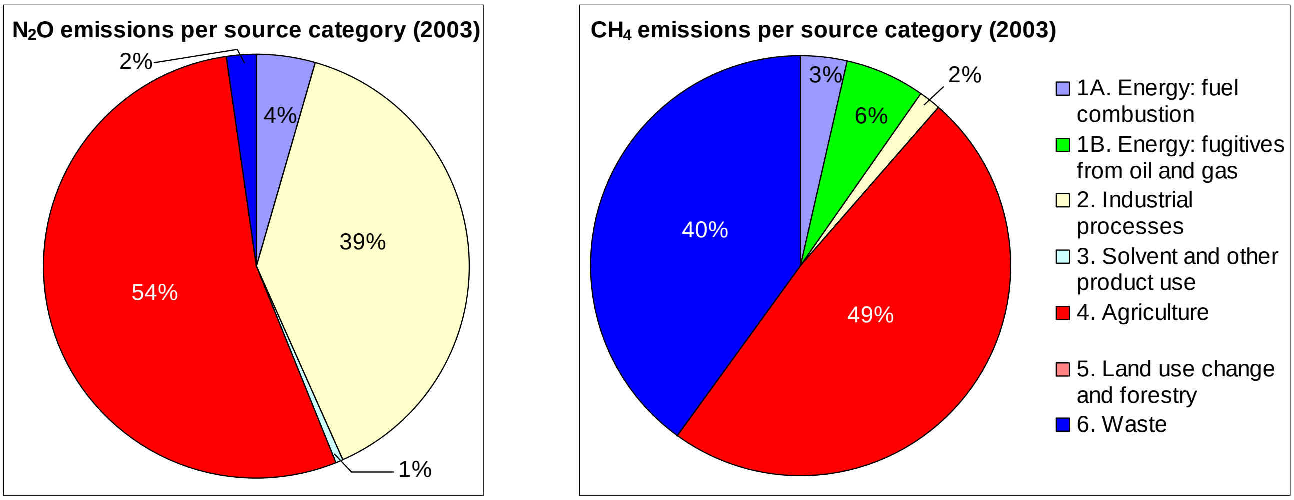
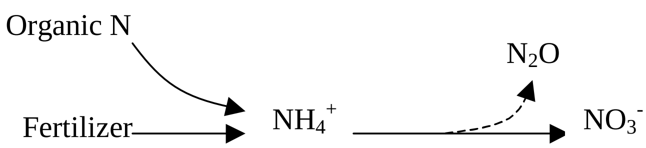


Figure 4 Emissions of N_2O and CH_4 in the Netherlands (2003) per source category. Source: Klein Goldewijk *et al.* (2005).



1.3 N_2O and CH_4 emission/consumption processes in agricultural soils

Nitrification and denitrification (figure 5) are generally accepted as the main mechanisms responsible for the production of N_2O in agricultural soils (Sahrawat and Keeney, 1986; Davidson, 1991; Skiba *et al.*, 1993; Mosier *et al.*, 1998). Nitrification refers to the biological oxidation of soil ammonium (NH_4^+) to soil nitrite (NO_2^-) and nitrate (NO_3^-) under aerobic conditions, producing N_2O as a by-product:



When oxygen supply is limited, some bacteria use NO_3^- instead, thereby releasing N_2. This process is referred to as (biological) denitrification. As for nitrification, N_2O may also be released as a by-product during this process:

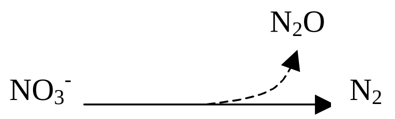
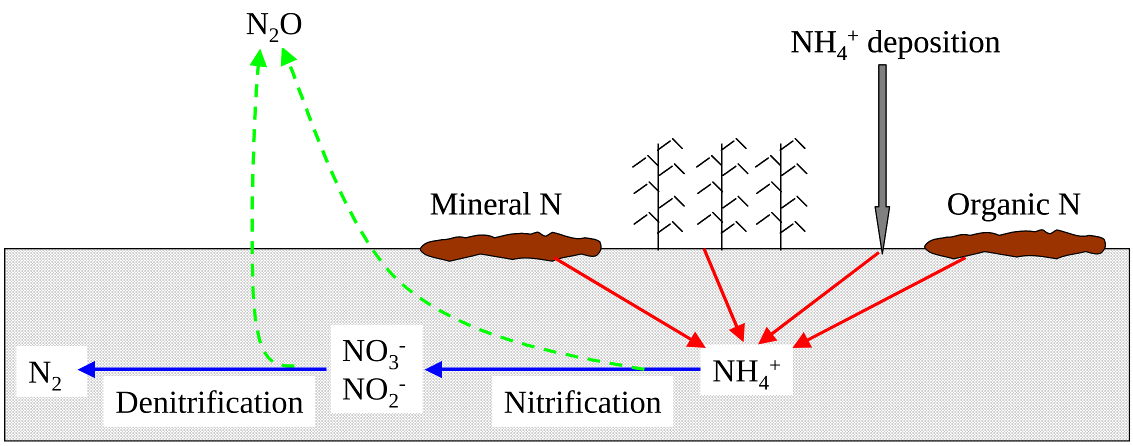
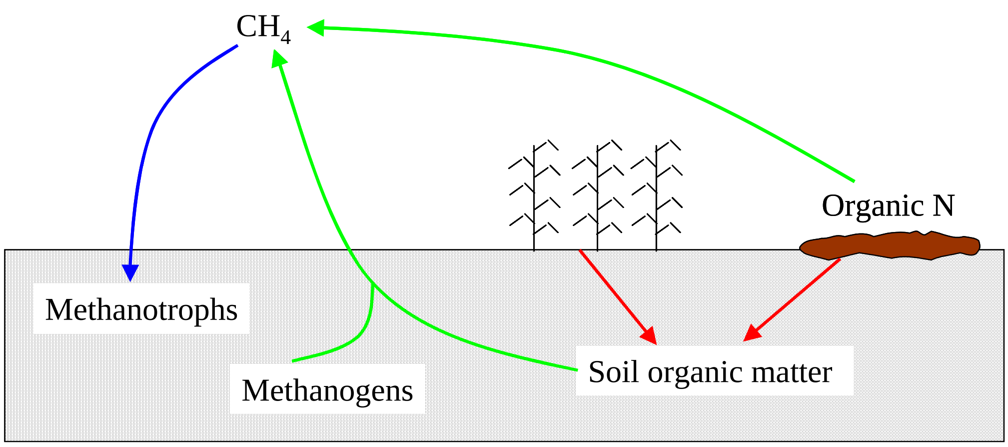


Figure 5 Schematic representation of the N_2O cycle in agricultural soils



CH_4 is produced in soils when organic matter is decomposed under anaerobic conditions, in the absence of electron acceptors other than CO_2 (NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}). Normally, when oxygen supply is adequate, most of the C in decomposing organic matter converts to CO_2. But, in the absence of oxygen, decomposition is incomplete and C is released as CH_4 instead. Once produced, CH_4 can be transported to the atmosphere via diffusion, ebullition, and via the vascular system of plants. However, under aerobic conditions both CH_4 that has been produced in anaerobic parts of the soil and atmospheric CH_4 can be oxidized, resulting in soils “absorbing” CH_4 (Crutzen, 1981; Steudler *et al.*, 1989; Yavitt *et al.*, 1990; Mosier *et al.*, 1991; Castro *et al.*, 1992; Nesbit and Breitenbeck, 1992; Adamsen and King, 1993; Lessard *et al.*, 1994; Prahter *et al.*, 1995; Ambus and Christensen, 1995; Mosier *et al.*, 1997a,b; Priemé and Christensen, 1997). Figure 6 summarizes the different processes involving CH_4 production, transport and consumption in soils.

Figure 6 Schematic representation of the CH_4 cycle in agricultural soils



Both N_2O and CH_4 are produced (or consumed) in agricultural soils as a result of microbial processes, but the size of the fluxes between the soil and the atmosphere strongly depends on different factors affecting the growth of microorganisms, such as soil oxygen content (soil water content), soil temperature, mineral N content/organic matter and pH. Soil management practices (land use, nutrient application via manure and N-fertiliser, incorporation of either crops or crop residues, tillage, reduction of soil compaction), through their effect on these factors, can indirectly influence the fluxes of N_2O and CH_4 from soils.

1.4 Scope of this report

In 2004, a project was started within the program "Reduction of Non-CO_2 Greenhouse Gases", with the objective of studying the potential of using reduction of soil compaction (precise soil management) as a mitigation strategy to reduce the emissions of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils in the Netherlands. As part of this project, the existing literature was first reviewed to determine the main (soil) parameters controlling the emission of N_2O and CH_4 from soils, and quantify their effect (Mosquera, 2005). Secondly, N_2O and CH_4 fluxes were measured from different arable fields during a 2-year period, particularly during the growing season and after (heavy) rainfall events (Mosquera *et al.*, 2005a). Three different levels of soil compaction were studied: 1) compaction due to traditional soil management; 2) precise soil management, by using the riding track system to reduce soil compaction; 3) heavy compaction, by increasing tractor traffic. An extra experiment was performed at a grassland soil to investigate the feasibility of using the riding track system to reduce N_2O and CH_4 emissions from grassland (Mosquera *et al.*, 2005b). Finally, core samples were taken from the (arable) soils (different levels of compaction) and incubated in the laboratory under different fertilisation and soil water content levels, to study the effect of compaction, fertilisation and soil oxygen content on the emission of N_2O and CH_4 from soils (Rappoldt *et al.*, 2006). In this report, the main results of the whole project are summarised. Chapter 2 gives an overview of the effects of soil compaction, fertilisation, drainage/irrigation, and land use change, on the fluxes of N_2O and CH_4 from agricultural soils. Chapters 3 and 4 present the main results of the field experiments performed at, respectively, arable and grassland soils in the Netherlands, whereas chapter 5 summarises the main findings of the laboratory incubation measurements. In chapter 6, the results of this study are used to estimate the potential emission reduction that could be achieved in the Netherlands by applying precise soil management into arable soils. Finally, the main conclusions of this study are presented in chapter 7.

2 Factors controlling N_2O and CH_4 fluxes from soils: literature review

The production and consumption of both N_2O and CH_4 from soils occurs as a result of different microbial processes, which in turn are controlled by factors that influence the growth of microorganisms (soil oxygen content, soil temperature, mineral N content/organic matter and pH). Soil management practices (land use, nutrient application via manure and N-fertiliser, incorporation of either crops or crop residues, tillage, reduction of soil compaction), through their effect on these factors, can indirectly influence these fluxes. This chapter summarises the existing knowledge on the effects of soil compaction, fertilisation, drainage/irrigation and land use change on the fluxes of N_2O and CH_4 from soils.

2.1 Soil compaction

Soil compaction due to tractor traffic or animals is considered to be an environmental problem, due to its potential to reduce the ability of soils to consume atmospheric CH_4 and to increase the emission rate of N_2O. Soil compaction reduces air permeability and gas diffusion (Ball *et al.*, 1997a,b; Ball *et al.*, 1999a) and decreases the proportion of coarse pores (O'Sullivan and Ball, 1993; Breland and Hansen, 1996). This, in turn, potentially increases the abundance of anaerobic microsites, which may favour the emissions of both CH_4 and N_2O (via denitrification).

Soil compaction has been reported to reduce the ability of soils to consume atmospheric CH_4 by 60% on average (table 2, range: 30-90%; based on results reported in Hansen *et al.* (1993), Sitaula *et al.* (2000a), Flessa *et al.* (2002a), Yamulki and Jarvis (2002) and Teepe *et al.* (2004)). The effect of soil compaction on CH_4 fluxes is such that, in some cases, net CH_4 sinks are transformed into net emission sources (Ruser *et al.*, 1998; Teepe *et al.*, 2004). From the reduced number of studies presented here (appendix A), no significant influence of soil texture on the effect of soil compaction on CH_4 uptake rates was found (table 3).

Table 2 Effect of soil compaction on CH_4 fluxes from soils (land use)

Land use	Locations	CH_4 fluxes Compacted/Uncompacted (Average [range])
Arable	18	0.5 [0.2 : 0.7] (1)
Grassland	1	4.4 (2)
Forest	3	0.2 [0.1 : 0.3] (1)
TOTAL	22	0.4 [0.1 : 0.7] (1)

(1) Ratio based on CH_4 consumption rates
(2) Ratio based on CH_4 emission rates

Table 3 Effect of soil compaction on CH_4 fluxes from grassland and arable soils (soil texture)

Soil texture	Locations	Relative CH_4 fluxes Compacted/Uncompacted (Average [range])
Clay	1	4.4 (1)
Silt	2	0.4 [0.3 : 0.4] (2)
Sand	16	0.5 [0.2 : 0.7] (2)

(1) Ratio based on CH_4 emission rates
(2) Ratio based on CH_4 consumption rates

A large number of literature studies (Douglas and Crawford, 1993; Hansen *et al.*, 1993; McTaggart and Smith, 1996; Oenema *et al.*, 1997; Ruser *et al.*, 1998; Smith *et al.*, 1998a; Ball *et al.*, 1999a, 1999b, 2000; Sitaula *et al.*, 2000b; Yamulki and Jarvis, 2002; Flessa *et al.*, 2002a; Thomas *et al.*, 2004; Teepe *et al.*, 2004) have already reported higher N_2O emissions after soil compaction. In general, light soil compaction has been shown to reduce N_2O emissions by 20% (table 4; see also appendix A), whereas heavy compaction resulted in increased N_2O emissions (on average, by a factor of 2). When soil is loosened after heavy compaction, the effect of compaction is reduced, and increased N_2O emissions, by 20% on average, are measured (table 4). The effect of soil compaction on N_2O emissions is generally higher in clay soils, and lower in sandy soils (table 5).

Table 4 Effect of soil compaction on N_2O fluxes from soils as a function of land use

Land use	Treatment	Locations	Relative N_2O emission Compacted/Uncompacted (Average [range])
Arable	Light compaction	9	0.8 [0.5 : 1.0]
	Heavy compaction	21	1.5 [0.8 : 2.9]
	Heavy compaction + loosening to 10 cm	10	1.2 [0.5 : 1.7]
Grassland	Light compaction	–	–
	Heavy compaction	1	3.5
	Heavy compaction + loosening to 10 cm	–	–
Forest	Light compaction	–	–
	Heavy compaction	3	8.0 [1.7 : 20.0]
	Heavy compaction + loosening to 10 cm	–	–
	Light compaction	9	0.8 [0.5 : 1.0]
TOTAL	Heavy compaction	25	2.3 [0.8 : 20.0]
	Heavy compaction + loosening to 10 cm	10	1.2 [0.5 : 1.7]

Table 5 Effect of soil compaction on N_2O fluxes from soils as a function of soil type

Soil type	Treatment	Locations	Relative N_2O emission Compacted/Uncompacted (Average [range])
Clay	Light compaction	–	–
	Heavy compaction	1	3.5
	Heavy compaction + loosening to 10 cm	–	–
Silt	Light compaction	–	–
	Heavy compaction	2	1.5 [1.3 : 1.7]
	Heavy compaction + loosening to 10 cm	–	–
Sand	Light compaction	10	1.2 [0.8 : 2.3]
	Heavy compaction	6	1.3 [0.9 : 1.7]
	Heavy compaction + loosening to 10 cm	6	0.9 [0.7 : 1.0]

Soil compaction has also been observed to negatively influence crop growth (Soane *et al.*, 1982; Perdok and Lamers, 1985; Graham *et al.*, 1986; Lamers *et al.*, 1986; Campbell *et al.*, 1986; Håkansson *et al.*, 1988; Dickson and Ritchie, 1990, 1996; Chamen *et al.*, 1990, 1992; Dickson and Campbell, 1990; Dickson *et al.*, 1992; O'Sullivan, 1992; Vermeulen and Klooster, 1992; Douglas *et al.*, 1992; Hansen, 1996). Based on the results reported in these studies, soil compaction (conventional traffic vs. zero traffic) leads to an average 10% reduction in crop yield, although yields reductions of as much as 34% have also been observed (Hansen, 1996). In order to maintain the same crop yield, either larger amounts of fertiliser have to be applied (Soane and Ouwerkerk, 1995; Dickson and Ritchie, 1996) or larger areas have to be cropped. These two situations are also favourable for larger N_2O and CH_4 emissions.

2.2 Fertilization

The reported effects of fertilization on CH_4 emission are complex and sometimes contradictory, and they usually depend on the type and amount of applied fertilizers (see appendix A). Inhibition of CH_4 uptake rates by various forms of N has been reported both in field measurements in forest (Steudler *et al.*, 1989; Adamsen and King, 1993; Sitaula *et al.*, 1995a; MacDonald *et al.*, 1997), grassland (Mosier *et al.*, 1991; Willison *et al.*, 1995a, b; Mosier *et al.*, 1996) and arable (Mosier *et al.*, 1991; Hansen *et al.*, 1993; Sitaula *et al.*, 2000a) ecosystems, and in laboratory studies (Nesbit and Breitenbeck, 1992; Bosse *et al.*, 1993; Crill *et al.*, 1994; Hütsch *et al.*, 1994; King and Schnell, 1994; Willison *et al.*, 1995a, b; Hütsch, 1996; Priemé and Christensen, 1997; Powlson *et al.*, 1997). However, some examples can also be found of studies where no significant effect or even a small increase in CH_4 uptake after application of N-fertiliser was reported (Whalen *et al.*, 1991; Hütsch *et al.*, 1993; Goulding *et al.*, 1995; Cochran *et al.*, 1995; Dobbie and Smith, 1996; Gulledge *et al.*, 1997; Mosier and Delgado, 1997; Mosier *et al.*, 1997b; Van den Pol-Van Dasselaar, 1997, 1998, 1999c; Flessa *et al.*, 1998; Smith *et al.*, 2000; Glatzel and Stahr, 2001; Flessa *et al.*, 2002b).

Based on the selected literature (see appendix A), with studies comparing different types of fertilizer, it can be concluded that application of N fertiliser usually results in a reduction of CH_4 uptake rates both for grassland (15% on average) and arable (40% on average) soils (table 6). In general, higher reductions are obtained after application of cattle slurry or ammonium nitrate than after application of urea. Application of ammonium sulphate resulted in contradictory effects, ranging from a 30% reduction to a 50% increase in CH_4 sink strength of soils.

Table 6 Effect of fertiliser type on CH_4 fluxes from soils

Land use	Fertilizer type	Locations	Relative CH_4 uptake Fertilized/Unfertilized (Average [range])
Arable	Ammonium nitrate	4	0.6 [0.6 : 0.7]
	Cattle slurry	8	0.6 [0.4 : 0.9]
Grassland	Ammonium nitrate	3	0.7 [0.6 : 1.0]
	Ammonium sulphate	6	1.1 [0.7 : 1.5]
	Cattle slurry	1	0.7
	Urea	3	0.9 [0.7 : 1.1]
TOTAL	Ammonium nitrate	7	0.7 [0.6 : 1.0]
	Ammonium sulphate	6	1.1 [0.7 : 1.5]
	Cattle slurry	9	0.6 [0.4 : 0.9]
	Urea	3	0.9 [0.7 : 1.1]

Several studies (Mosier *et al.*, 1991, 1997b; Sitaula and Bakken, 1993; Skiba *et al.*, 1994; Sitaula *et al.*, 1995b, 2000b; Clayton *et al.*, 1997; Mosier and Delgado, 1997; MacDonald *et al.*, 1997; Anger *et al.*, 2003) have reported higher N_2O emissions after the application of N fertiliser into soils. Fertiliser application can have an immediate effect on N_2O emissions (Sitaula *et al.*, 1995b; Yamulki *et al.*, 1995; Velthof *et al.*, 1996, 1997; Jamber *et al.*, 1997; Freney, 1997; Yoh *et al.*, 1997; Yamulki and Jarvis, 2002; Dobbie and Smith, 2003a), but increased emissions 1-4 weeks after fertiliser application have also been observed (Christensen, 1983; Brumme and Beese, 1992; Hansen *et al.*, 1993; Skiba *et al.*, 1996; Clayton *et al.*, 1997; Jørgensen *et al.*, 1997; Freney, 1997; Yoh *et al.*, 1997; Mogge *et al.*, 1999; Goossens *et al.*, 2001; Anger *et al.*, 2003).

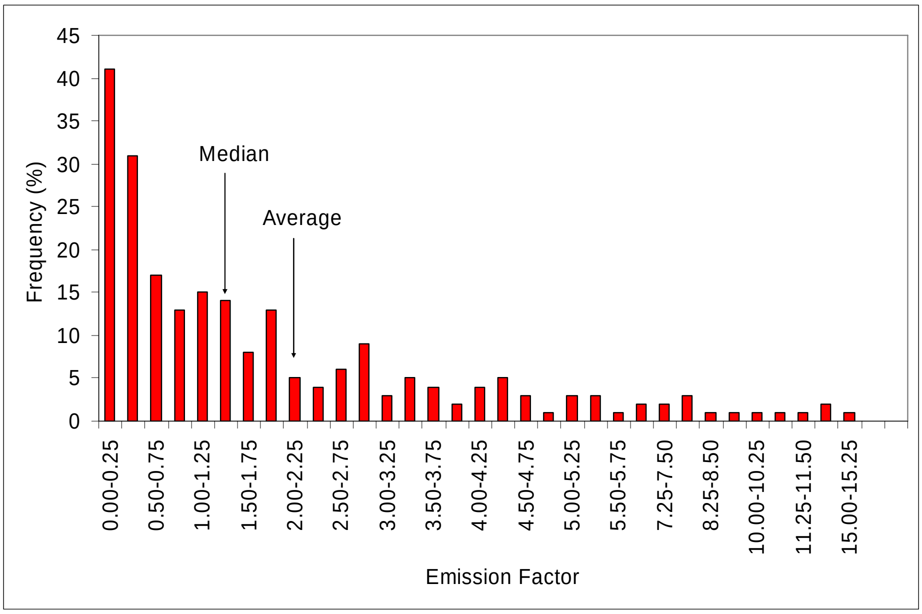
From the studies where data was available (see appendix A for a complete overview of the studies used in this analysis) it can be concluded that, on average, N_2O emissions are enhanced by a factor of 5 after applying N fertiliser into the soil (table 7), although increased emissions by as high as a factor 80 have also been measured (Clayton *et al.*, 1997).

Table 7 Effect of fertiliser type on N_2O fluxes from soils and emission factors

Land use	Fertiliser type	Locations	Relative N_2O emission Fertilised/Unfertilised	Emission factor
Arable	Ammonium nitrate	2	6.8 [5.2 : 8.4]	2.3 [0.7 : 3.9]
	Ammonium nitrate urea	24	1.2 [0.6 : 1.6]	2.7 [0.7 : 8.6]
	Ammonium sulphate	1	5.4	0.8
	Calcium ammonium nitrate	4	1.2 [1.1 : 1.4]	0.3 [0.1 : 0.5]
	Cattle slurry	2	4.8 [4.0 : 5.7]	2.6 [1.9 : 3.2]
	Potassium nitrate	1	4.3	0.6
	Urea	3	2.8 [2.0 : 4.3]	0.5 [0.4 : 0.6]
Grassland	Ammonium nitrate	7	9.4 [1.1 : 41.0]	3.1 [0.4 : 8.2]
	Ammonium sulphate	8	5.6 [1.9 : 19.0]	1.3 [0.2 : 3.6]
	Calcium ammonium nitrate	5	2.4 [1.0 : 4.5]	0.5 [0.3 : 0.8]
	Cattle slurry	2	13.5 [2.0-25.0]	1.0 [0.2 : 1.8]
	Urea	5	22.1 [1.7 : 82.0]	0.6 [0.2 : 1.5]
TOTAL	Ammonium nitrate	11	8.0 [1.1 : 41.0]	2.9 [0.4 : 8.2]
	Ammonium nitrate urea	24	1.2 [0.6 : 1.6]	2.7 [0.7 : 8.6]
	Ammonium sulphate	9	5.6 [1.9 : 19.0]	1.2 [0.2 : 3.6]
	Calcium ammonium nitrate	9	1.9 [1.0 : 4.5]	0.4 [0.1 : 0.8]
	Cattle slurry	4	9.2 [2.0 : 25.0]	1.8 [0.2 : 3.2]
	Potassium nitrate	1	4.3	0.6
	Urea	8	14.8 [1.7 : 82.0]	0.6 [0.2 : 1.5]

The emission factors (EF: amount of N_2O-N emitted expressed as a fraction or a percentage of the N applied) reported in the literature (Bremner and Blackmer, 1978; Galbally, 1985; Eichner, 1990; Vermoesen *et al.*, 1996; Clayton *et al.*, 1997; Jørgensen *et al.*, 1997; Hénault *et al.*, 1998a, 1998b; Kaiser *et al.*, 1998a, 1998b; Mackenzie *et al.*, 1998; Dobbie *et al.*, 1999; Mogge *et al.*, 1999; De Klein *et al.*, 2001; Goossens *et al.*, 2001; Flessa *et al.*, 2002b; Hou and Tsuruta, 2003; Dobbie and Smith, 2003a; Koga *et al.*, 2004) range from values as low as 0.1%, to values as high as 15% of N applied (table 7 and figure 7). By using all the available data (see also appendix A), an average emission factor of 2.1 ± 2.6% has been obtained. When only long-term measurements (> 1 year) are considered, the estimated average emissions factor is 2.4 ± 2.5%. This is almost a factor 2 higher than the relationship found by Bouwman in 1996 (1.25 ± 1% of the N applied). The N_2O-emission factor is usually taken to be independent of crop type and the chemical form of N used. However, table 7 shows that N_2O emissions can be greatly affected by the type of fertiliser applied.

Figure 7 Frequency distribution of N_2O emission factors



2.3 Drainage and irrigation

By controlling the soil oxygen content, both drainage and irrigation have been considered to be important management factors affecting the emission rate of N_2O and CH_4 from soils. Drainage affects the ground water level, which roughly indicates the transition between anaerobic (CH_4 production) and aerobic (CH_4 consumption) layers in the soil. If the ground water table drops, the aerobic top layer of the soil becomes thicker and conditions become less favourable for CH_4 production and more favourable for CH_4 consumption (Barlett and Harriss, 1993; Moore and Roulet, 1993; Bubier *et al.*, 1995; Van den Pol-Van Dasselaar *et al.*, 1997, 1998, 1999a,b,c; Flessa *et al.*, 1998; Smith *et al.*, 2000). Irrigation and precipitation may also be important as they influence the soil moisture content, which also determines the proportion of anaerobic/aerobic sites in the soil (Mosier *et al.*, 1991; Keller *et al.*, 1993). CH_4 consumption rates usually show a negative relationship with soil moisture, often expressed in terms of water-filled pore size (WFPS). This effect has been observed in laboratory studies (Nesbit and Breitenbeck, 1992; Priemé *et al.*, 1997), and in the field at forest (Castro *et al.*, 1992, 1995; Lessard *et al.*, 1994; Sitaula *et al.*, 1995a; Dobbie and Smith, 1996), grassland (Mosier and Delgado, 1997; Mosier *et al.*, 1997b; Wang *et al.*, 2005) and arable ecosystems (Koga *et al.*, 2004). However, MacDonald *et al.* (1997), Priemé and Christensen (1997) and Flessa *et al.* (2002a) could not find any significant correlation between CH_4 fluxes and soil water content in their experiments.

The importance of irrigation/drainage on N_2O emissions has been widely reported in the literature (Goodroad and Keeney, 1984; Linn and Doran, 1984; Davidson, 1991; Mosier *et al.*, 1991; Sitaula and Bakken, 1993; Yamulki *et al.*, 1995; MacKenzie *et al.*, 1997; Clayton *et al.*, 1997; Mosier and Delgado, 1997; Jørgensen *et al.*, 1997; Mogge *et al.*, 1998; Flessa *et al.*, 1998; Kaiser *et al.*, 1998a; Kamp *et al.*, 1998; Hénault *et al.*, 1998b; Smith *et al.*, 1998a; Dobbie *et al.*, 1999; Williams *et al.*, 1999; Simojoki and Jaakkola, 2000; Ruser *et al.*, 2001; Dobbie and Smith, 2001, 2003a, 2003b; Sehy *et al.*, 2003; Regina *et al.*, 2004; Syväsalo *et al.*, 2004; Koga *et al.*, 2004; Thomas *et al.*, 2004; Wang *et al.*, 2005). In contrast, no significant relationship between N_2O emissions and soil moisture content or rainfall was found in a Velthof *et al.* (1996), MacDonald *et al.* (1997), Kaiser *et al.* (1998b), Mahmood *et al.* (1998), Mogge *et al.* (1999), Kusa *et al.* (2002) and Yamulki and Jarvis (2002). High N_2O emissions usually occur only when the water-filled pore space (WFPS) is about 60% and soil N is not limiting. Very large (WFPS>90%) or low (WFPS<40%) values usually result in low N_2O emissions.

2.4 Land use

Several authors (Keller *et al.*, 1990, 1993; Mosier *et al.*, 1991; Dobbie and Smith, 1994, 1996; Hütsch *et al.*, 1994; Willison *et al.*, 1995a, b; Dobbie *et al.*, 1996; Hütsch, 1996, 1998; Flessa *et al.*, 1998; Chan and Parkin, 2001) have already reported the reduction of the potential of soils to consume CH_4 after the conversion of native grasslands and forest to agricultural soil (managed pastures, cultivated crops). Reductions in CH_4 uptake rates can be as high as 50-85% (Mosier *et al.*, 1991; Ojima *et al.*, 1993; Dobbie *et al.*, 1996; Powlson *et al.*, 1997; Smith *et al.*, 2000), and persist for months (Willison *et al.*, 1995b), years (Mosier *et al.*, 1991; Hütsch *et al.*, 1994; Priemé *et al.*, 1997) or even decades (Ojima *et al.*, 1993) after the primary cause of inhibition has ceased.

Table 8 summarises the results found in the literature from a large number of studies (see appendix A) focusing on the effect of land use on CH_4 uptake rate. CH_4 uptake rate at forest sites is on average a factor 3-4 higher than at native grasslands, whereas arable soils show only about 10% of the CH_4 sink of forests. When fertilised, grasslands are, on average, converted to net sources of CH_4.

Table 8 Effect of land use on CH_4 fluxes from soils

Land use	Locations	CH_4 fluxes (mg CH_4 m^{-2} day^{-1})
Forest	24	-1.8 [-5.4 : -0.3]
Native grassland	21	-0.5 [-1.4 : 0.1]
Arable (unfertilised)	4	-0.2 [-0.3 : -0.1]
Arable (fertilised)	14	-0.2 [-0.8 : -0.1]
Grassland (fertilised)	21	0.3 [-0.7 : 7.8]

N_2O emissions from agricultural soils are usually found to be greater and more variable than those from uncultivated land or natural ecosystems (Luizao *et al.*, 1989; Keller *et al.*, 1993; Vermoesen *et al.*, 1996; Velthof *et al.*, 1996; Skiba *et al.*, 1996, 1998; Smith *et al.*, 1998a; Mahmood *et al.*, 1998; Kaiser *et al.*, 1998a,b; Kamp *et al.*, 1998; Dobbie *et al.*, 1999; Mogge *et al.*, 1999; Ruser *et al.*, 2001; Dobbie and Smith, 2001; Goossens *et al.*, 2001; Kim and Kim, 2002; Grant *et al.*, 2004; Regina *et al.*, 2004). However, Mosier *et al.* (1991) measured emissions from wheat and grassland fields that were 58 and 78% of the emission from a fallow site. Flessa *et al.* (1998) found no significant effect of land use on N_2O emissions when measuring during 1 year N_2O emissions on 4 cultivated peat soils (2 meadows, 1 field with rye grass, 1 field with maize) in Germany. And Syväsalo *et al.* (2004) found no statistical differences between the annual fluxes from grass, barley and fallow.

Table 9 summarizes the results reported in all available studies (see also appendix A). In general, fertilised grasslands emitted 2-3 more N_2O than fertilised arable fields. However, when referring to emission factors (N_2O emission as % of N applied), differences in emissions from grassland and arable fields are not significant. Fertilised grasslands emitted, on average, a factor of 5 more N_2O than unfertilised arable fields. Natural grasslands emitted 8-9 times less N_2O than fertilised grasslands, whereas the lowest emission was found by forest, emitting approximately 10 times less N_2O than fertilised grasslands.

Table 9 Effect of land use on N_2O fluxes from soils and emission factors

Cultivation	Locations	N_2O fluxes (mg N_2O m^{-2} day^{-1})	N_2O emission factor (% of N applied)
Arable (unfertilised)	25	0.5 [0.0 : 1.3]	—
Cabbage	1	0.3 [0.3 : 0.3]	—
Oilseed rape	8	0.3 [0.0 : 0.9]	—
Onion	3	0.4 [0.1 : 0.7]	—
Potato	1	0.7 [0.7 : 0.7]	—
Sugar beet	3	0.6 [0.4 : 0.7]	—
Winter barley	5	0.5 [0.3 : 0.8]	—
Winter wheat	4	0.8 [0.3 : 1.3]	—
Arable (fertilised)	105	1.1 [0.0 : 5.9]	2.4 +/- 2.9 [0.1 : 15.2]
Cabbage	4	0.6 [0.2 : 0.8]	0.5 +/- 0.1 [0.4 : 0.6]
Corn	4	0.6 [0.4 : 1.0]	1.5 +/- 0.6 [0.9 : 2.1]
Maize	11	1.4 [0.1 : 2.9]	2.3 +/- 1.9 [0.2 : 5.4]
Oilseed rape	19	0.9 [0.1 : 3.9]	1.3 +/- 1.0 [0.1 : 3.3]
Onion	9	3.2 [0.4 : 5.9]	3.2 +/- 3.0 [1.2 : 10.3]
Potato	11	1.0 [0.0 : 1.9]	2.7 +/- 3.3 [0.2 : 11.5]
Soybean	4	1.6 [0.2 : 4.5]	1.6 +/- 1.7 [0.2 : 3.5]
Spring barley	8	0.7 [0.2 : 1.7]	4.4 +/- 5.9 [0.1 : 15.2]
Sugar beet	8	0.6 [0.1 : 1.0]	3.1 +/- 2.7 [0.2 : 8.6]
Tobacco	2	2.4 [1.2 : 3.6]	2.3 +/- 0.4 [2.0 : 2.6]
Winter barley	11	0.5 [0.2 : 1.0]	1.6 +/- 1.2 [0.1 : 4.3]
Winter wheat	14	0.7 [0.1 : 1.9]	1.9 +/- 1.4 [0.1 : 4.6]
Grassland (unfertilised)	26	0.3 [0.0 : 0.8]	—
Grassland (fertilised)	76	2.6 [0.0 : 30.0]	2.2 +/- 2.7 [0.1 : 12.0]
Forest	28	0.2 [-0.3 : 1.1]	—

2.5 Conclusions

In this chapter, different soil management factors affecting the fluxes of N_2O and CH_4 from soils were reviewed, including fertilisation, drainage/irrigation, compaction and land use. Conversion of natural ecosystems (native grasslands, forest) to cultivated land (managed grasslands, arable land) has been observed to result in higher N_2O emissions and lower CH_4 uptake capacity of soils. On average, CH_4 uptake rate from forest is a factor 3-4 higher than from native grassland, whereas CH_4 consumption rate from arable land is only 10% of the one from forest. Managed grasslands are, on average, a net CH_4 source. For N_2O, higher emissions (a factor 2 on average) are observed from managed grasslands when compared to (fertilised) arable land, although both show a similar emission factor (N_2O emissions as % of N applied). Managed grasslands emit on average 5 times more N_2O than unfertilised arable land, whereas N_2O emission from native grasslands (forest) is a factor 8 (13) lower than from managed grassland. Changes in soil physical properties (including water availability, gas diffusivity, oxygen supply and soil structure) and soil fertility (particularly N input) are suggested to greatly contribute to this effect.

Fertilisation increases soil N and organic matter contents, and generally results in enhanced N_2O emissions (by a factor 5 on average), and reduced CH_4 consumption rates (by 25% on average), although some studies did not found any significant effect. Both a short-term effect (immediate effect of after a few weeks after fertilisation) and a long-term effect (soils that are left unplanted for some time may still emit significant amounts of N_2O or show significant inhibition levels for CH_4 uptake) have been observed. Based on the existing literature, a new relationship was found between N_2O emissions and the amount of N applied as fertiliser (emission factor, EF=2.4±2.5%), which is a factor 2 higher than the relationship reported in Bouwman (1996). The form of fertiliser applied is also an important factor affecting the fluxes of N_2O and CH_4. In general, higher N_2O emissions (as a percentage of N applied) and higher reductions in CH_4 uptake have been measured from ammonium nitrate and cattle slurry than from urea or ammonium sulphate.

Drainage and irrigation influence the ground water level and soil water contents, which in turn affect gas diffusivity and oxygen supply. High N_2O emissions have been observed to occur when the water-filled pore space (WFPS) is about 60% and soil N is not limiting. Very large (WFPS>90%) of low (WFPS<40%) values usually resulted in low N_2O emissions. CH_4 consumption usually shows a negative relationship with WFPS and ground water level. As for

N_2O, this relationship is only expected to occur when other factors (such as organic matter content) are not limiting.

Soil compaction decreases air permeability and gas diffusion, which in turn affect the production and consumption rates of N_2O and CH_4 from soils. On average, N_2O emissions were reduced by 20% after light compaction and enhanced by a factor 2 after heavy compaction. When heavy compacted soils were loosened to a depth of 10 cm, N_2O emissions were 20% higher than in the uncompacted soils. In general, soils with clay (sand) texture showed the highest (lowest) N_2O emissions. For CH_4, heavy compaction reduced CH_4 uptake capacity of soil by 60% on average, and this effect was not significantly influenced by soil texture. When soil compaction was avoided, higher crop yields (10% on average) or reductions in fertilizer application (by 15-30%) maintaining a similar crop yield have been measured.

From these results it can be concluded that precise soil management, aimed to decrease heavy compaction of the soil, could be used as a control or mitigation tool to reduce the emissions of CH_4 and N_2O from agricultural soils.

3 Effect of soil compaction on N_2O and CH_4 fluxes from arable land: Field measurements

In this chapter, field measurements of N_2O and CH_4 fluxes at different agricultural (arable) soils in the Netherlands are reported. First, the measurement location is described according to soil type, management and cultivation. Next, a description is given of the experimental set-up and measurement equipment. Finally, the main results and conclusions are illustrated.

3.1 Materials and methods

3.1.1 Site characteristics and field management

The experimental site was situated in the southwest of the Netherlands (West Brabant), and is managed by a cooperative of farmers practicing organic farming (BEKO bv). The soil is classified as marine clay, and has a sandy clay to light clay soil texture. Measurements were performed at three experimental fields with variable crop rotation. Main soil characteristics and field management treatments are summarized in table 10.

Table 10 Soil characteristics and management treatments (arable). n.a.: not available.

	Field 1		Field 2	Field 3
Crop (year)	Carrot (2004)	Spinach (2005)	Seed onion (2004)	Onion sets (2005)
Soil characteristics				
pH-KCl	7.2	7.2	7.6	7.5
$CaCO_3$ (%)	5.6	5.6	5.9	8.5
Organic matter (%)	3.7	3.7	4.5	3.9
Mineral N (60-90 cm; kg N ha^{-1})	185.8	185.8	92.0	n.a.
Growing period				
Planting	11/06/2004	09/05/2005	18/05/2004	26/03/2005
Harvesting	11/10/2004	22/06/2005	02/09/2004	15/07/2005
Fertilisation				
Day of application	—	27/04/2005	19/04/2004	28/04/2005
Fertiliser type	—	Cattle slurry + vinasse	Cattle slurry	Cattle slurry + vinasse
Fertiliser rate (kg N ha^{-1})	—	182.8 (57.4 + 125.4)	78	124.4 (52.2 + 72.2)
Measurement period	14/07-17/08	28/04-22/06	12/07-17/08	21/04-15/07

Three different compaction treatments were considered:

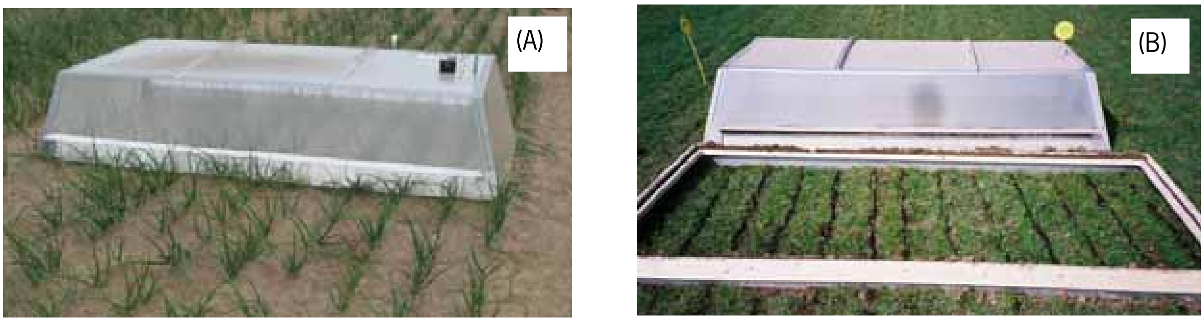
- Compaction due to traditional soil management (TR). Soil traffic is arbitrary, which results in old and new tracks lying on different places.
- Precise soil management (RT, Riding Track system), by using a tractor equipped with an RTK-DGPS system (Geotec). Old and new tracks are superposed (±5 cm), limiting compaction to traffic lines.
- Heavy compaction (HC) by increasing tractor traffic.

At all measurement fields, 4 plots were applied for each of the traditional and riding track treatments, whereas for the heavy compaction treatment one plot was used. This results in a number of 9 plots per measured field. In addition, an extra heavy compaction plot (unfertilised) was added in 2005 at the field cultivated with spinach.

3.1.2 Measurement methods

Gas exchange between the soil surface and the atmosphere was measured using closed flux chambers (3.5 m^2 surface area, 1.5 m^3 volume) that were either placed on top of the soil (figure 8a) or on permanently installed wooden frames (inserted 5-10 cm into the soil; figure 8b). Every chamber was equipped with a small axial flow fan and an external 12-V battery to allow for good mixing of all gases in the chamber. In order to account for possible leakages, a known amount of a tracer gas (SF_6) was injected into the chamber and the decay in concentration of the tracer gas with time monitored. The rate of decay method (Mosquera *et al.*, 2002) was applied to obtain an estimate of the leakage over the measured period. Gas samples were collected in 30 ml syringes 0, 10, and 20 min (0, 20 and 40 min in 2005) after the start of the measurements, which was considered to be short enough to minimise the effect of the chamber on the production and consumption rates (Scott *et al.*, 1999). The samples were analysed the same day *in situ* by using a gas chromatograph equipped with an electron capture detector (ECD) for N_2O and SF_6, and a flame ionisation detector (FID) for CH_4.

Figure 8 Flux chamber on top of the soil (A) and on permanently installed frames (B)



Soil structure was characterised by measuring the soil water content in the field with the ECH_2O Dielectric Aquameter Sensor (Decagon Devices, Inc.). The sensor was introduced into the soil to a depth of approximately 10 cm, in order to measure soil water content at the upper 10-cm soil layer. At every measurement day and for every flux chamber, 1-4 measurements were performed with this sensor.

A paired one-tailed t-test was applied to study the significance of the differences measured between the applied treatments (traditional, riding track, heavy compaction). This test assesses whether the means of two groups are statistically different from each other by comparing the mean of the daily differences of the groups ($\overline{x}_d$) in relation to the variation in the data (σ_d, standard deviation of the mean difference):

$$t = \frac{\overline{x}_d}{\sigma_d} \cdot \sqrt{n}$$

Where *n* indicates the number of measurements performed (measurement days). If the calculated "t-value" exceeds the tabulated value for a particular significance level (Weiss, 2000), the treatments are considered to be significantly different (at that particular significance level). In this study, a significance level of 95% ($p \leq 0.05$) was selected.

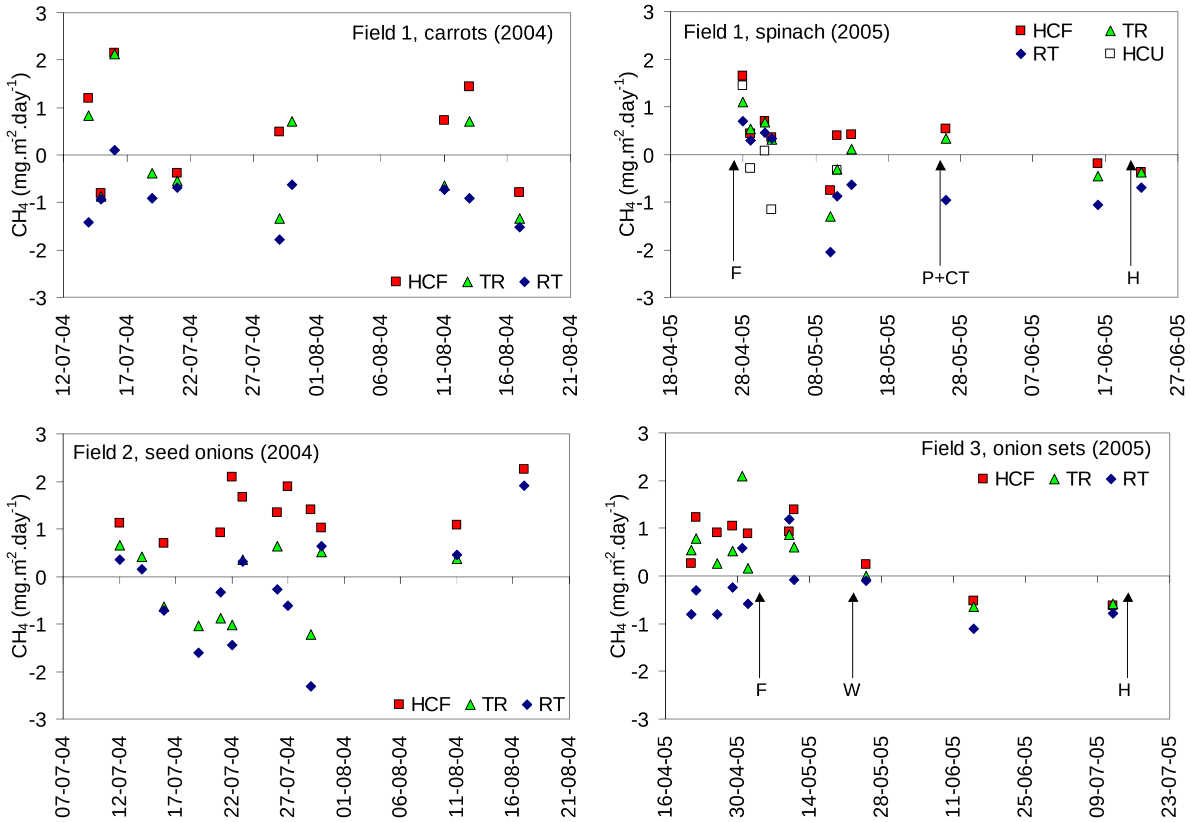
3.2 Results

3.2.1 Methane (CH_4)

CH_4 fluxes at all arable sites varied between –3 and 3 $mg.m^{-2}.day^{-1}$ (figure 9) and showed a large within-site variation. The average coefficient of variation for the spatial variation ranged between 30 and 100%, although values as high as 600% were found for individual measurements. The spatial variation could not be explained by differences in WFPS.

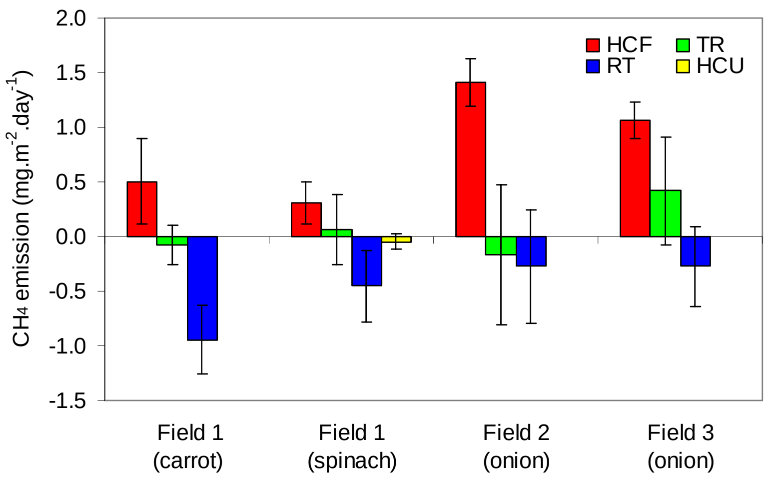
The effect of manure application on CH_4 fluxes was not consistent between different sites. Fertilisation did not significantly affect CH_4 emissions at field site 3, cultivated with onions sets in 2005. At field 1, cultivated with spinach in 2005, fertiliser application increased CH_4 emissions by a factor 2-3 with respect to the control plots, dependent on the degree of compaction of the soil.

Figure 9 Individual CH_4 flux measurements at all fields. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RT: riding track; TR: traditional; F: manure application; CT: soil compaction treatments; P: planting; W: weed; H: harvesting.



The degree of compaction clearly affected the CH_4 fluxes at all sites (figure 10). Heavy compaction increased CH_4 emissions at the arable soils cultivated with spinach (field 1) and onion (field 3) by a factor 2-5 with respect to the control plots. The effect of heavy compaction on CH_4 fluxes at the other two arable sites (carrot, field 1; seed onions, field 2) was such that a net CH_4 sink was transformed into a net emission source. The riding track treatment resulted in an increase in CH_4 uptake by a factor 2-12 at the arable soils cultivated with seed onion (field 2) and carrot (field 1), compared to the control plots. At the other two arable sites, a net CH_4 source was transformed into a net CH_4 sink. A statistical analysis showed that differences between different treatments were significant at the 95% significance level for all arable sites.

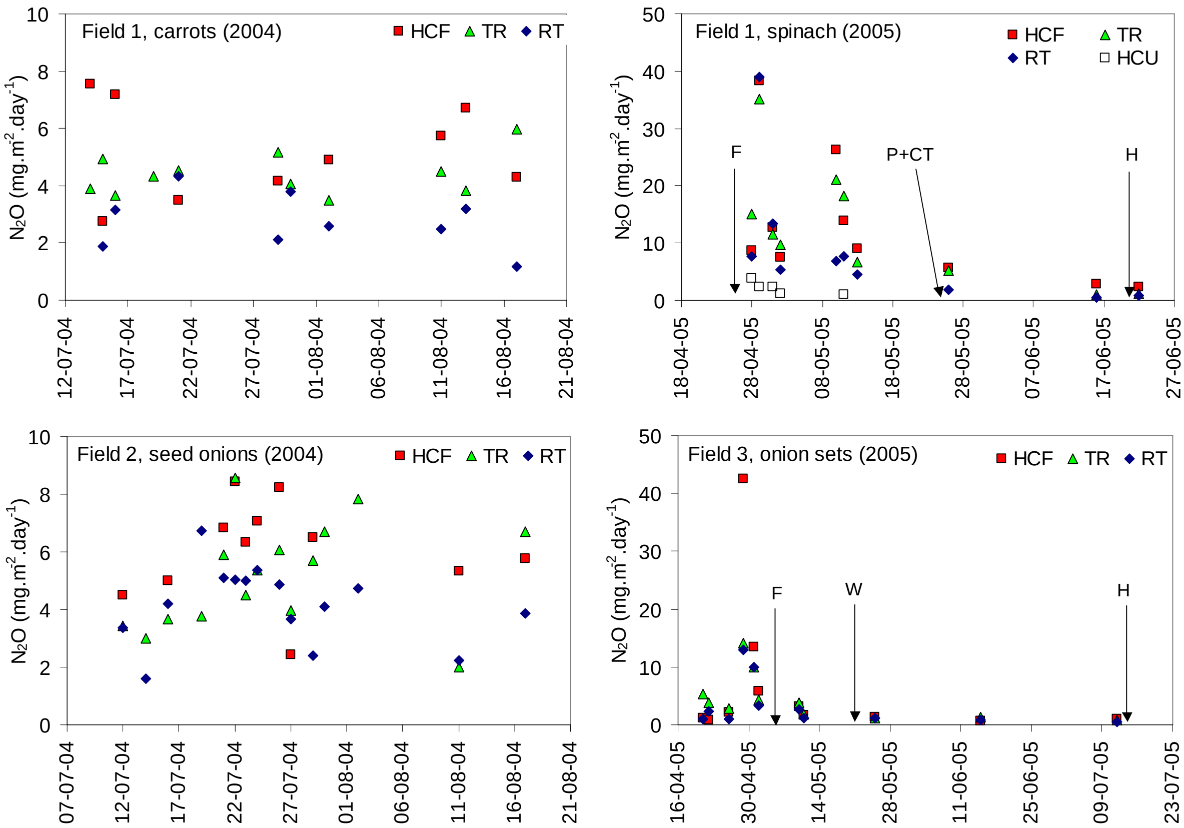
Figure 10 CH_4 fluxes as a function of soil compaction for different crops. HCF: heavy compaction fertilised; RT: Riding track; TR: traditional system; HCU: heavy compaction unfertilised.



3.2.2 Nitrous oxide (N_2O)

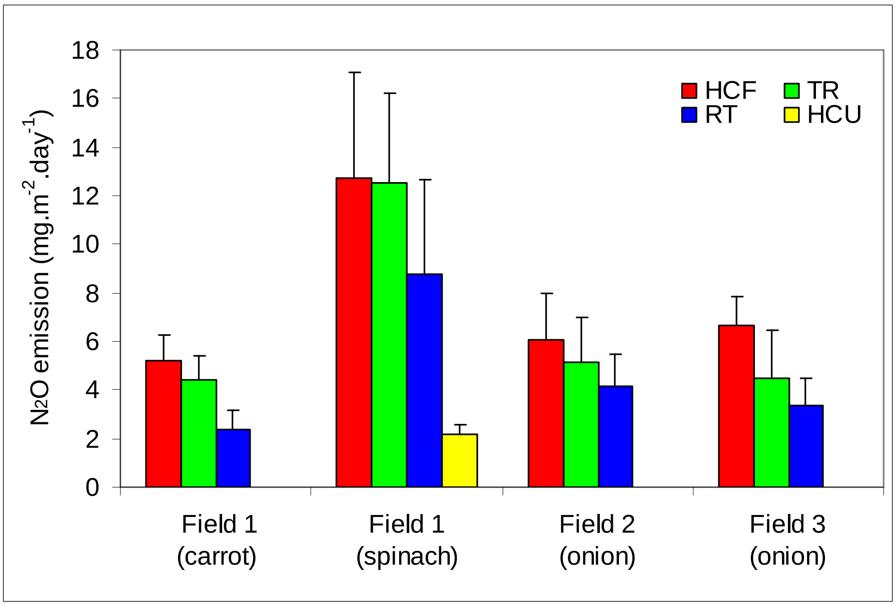
All sites were net sources for N_2O, with values ranging from 0 to 50 $mg.m^{-2}.day^{-1}$ (figure 11). The average coefficient of variation varied between 25 and 35%, with maximum values of up to 80% for individual measurements. Higher N_2O emissions were measured after manure application at all sites (figure 11). This effect was observed one day after fertilisation at the field cultivated with onion sets in 2005 (field 3), and two days after fertiliser was applied at the site cultivated in 2005 with spinach (field 1). Emissions decayed rapidly and lasted for no more than a couple of days. At the spinach site, where a plot was kept unfertilised, the effect of fertilisation could be quantified: N_2O emissions were enhanced by a factor 6 at the fertilised plot with respect to the control (unfertilised).

Figure 11 Individual N_2O flux measurements at all fields. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RT: riding track; TR: traditional; F: manure application; CT: soil compaction treatments; P: planting; W: weed; H: harvesting.



Soil compaction markedly influenced N_2O emissions from all sites (figure 12). Heavy compaction resulted in significantly higher N_2O emissions (by 20-50%) than the traditional treatment at three of the four arable sites. At the field cultivated with spinach in 2005, heavy compaction plots showed similar emissions as the traditional treatment. An statistical analysis showed that differences between the heavy compaction and the traditional systems were only significant (at the 95% significance level) at field 2 (cultivated with seed onions in 2004). The application of the riding track treatment always resulted in a decrease of N_2O emissions by 20-50%. The differences between the emissions measured at the riding track plots and the traditional treatments were significant at the 95% significance level for all sites. Differences in WFPS between treatments had no significant effect on the soil emissions of N_2O.

Figure 12 N_2O emission as a function of soil compaction for different crops. HCF: heavy compaction fertilised; RT: Riding track; TR: traditional system; HCU: heavy compaction unfertilised.



3.3 Conclusions

Soil compaction had a markedly effect on both N_2O and CH_4 fluxes. Heavy compaction increased N_2O emissions by 20-50% and resulted in a factor 2-5 higher CH_4 emissions than the traditional system. The effect on CH_4 was such that some plots that were acting as a sink were transformed into net CH_4 sources. The riding track system resulted in a reduction of N_2O emissions by 20-50%, and reduced CH_4 emissions by a factor 2-12. In two of the sites, the effect was such that the site was transformed from a net CH_4 source into a net sink. Soil water content (WFPS) did not significantly influence the fluxes of N_2O and CH_4. Fertilisation resulted in higher N_2O emissions (by a factor 6), whereas its effect on CH_4 ranged from no significant effect to higher emissions (conversion of a small sink into a net CH_4 source). These results are comparable with those presented in chapter 2, and suggest the possibility of using precise soil management (for example with the riding track system) to control and reduce N_2O and CH_4 emissions from agricultural soils.

4 Effect of soil compaction on N_2O and CH_4 fluxes from grassland soils: Field measurements

In this chapter, results of a preliminary field study performed to investigate the effect of precise soil management on N_2O and CH_4 fluxes from grassland soils are reported. First, the measurement location is described according to soil type, management and cultivation. Next, a description is given of the experimental set-up and measurement equipment. Finally, the main results and conclusions are illustrated.

4.1 Materials and methods

4.1.1 Site characteristics and field management

Measurements were performed at a grassland field (grass clover), where no grazing or fertilisation events occurred in the last few years. Three plots were prepared for this experiment according to the following management treatments (see chapter 4 for more details):
1. Heavy compaction, unfertilised (HCU).
2. Heavy compaction, fertilised (HCF).
3. Riding track system, fertilised (RTF).

Fertilisation occurred manually, by applying a known amount of cattle slurry into (manually) prepared slots in the soil. There were no replicates for the selected management treatments, although the experiment was repeated three times, in order to compare the measured results under different conditions. Table 11 summarises the main characteristics of the different experiments. During the first two experiments, the same plots were used for the measurements, whereas for the third experiment a new plot was prepared for each of the selected treatments.

Table 11 Field management for all three experiments

	Experiment 1	Experiment 2	Experiment 3
Fertilisation			
Day of application	23-03-2005	14-06-2005	27-06-2005
Fertiliser type	Cattle slurry	Cattle slurry	Cattle slurry
NH_4-N (g kg^{-1})	2.32	1.08	1.08
Total N (g kg^{-1})	4.13	2.95	2.95
Application rate (m^3 ha^{-1})	17	18	18
Application rate (kg N ha^{-1})	68.8	53.1	53.1
Measurement period			
Start measurements	23-03-2005	14-06-2005	27-06-2005
End measurements	17-05-2005	05-07-2005	05-07-2005
Measurement days	11	7	5

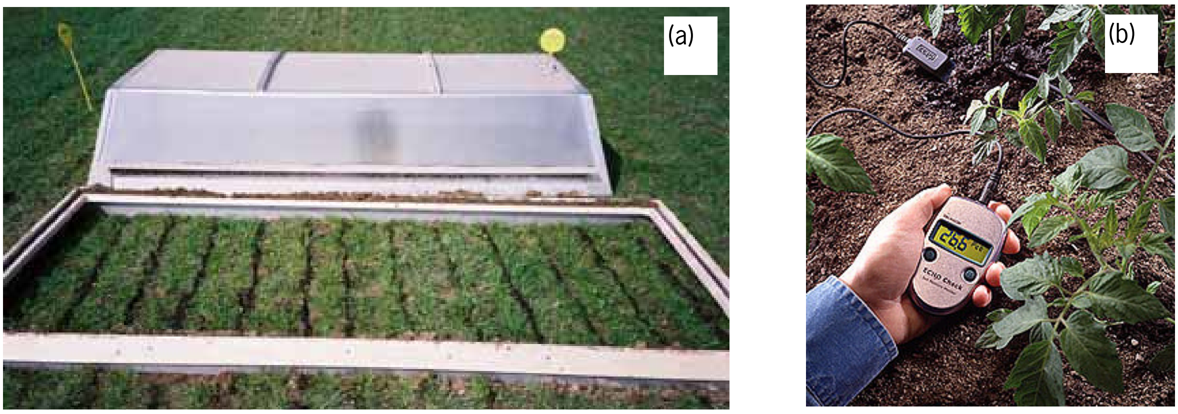
4.1.2 Measurement methods

Gas exchange between the soil surface and the atmosphere was measured using closed flux chambers (figure 13a) as described in chapter 4. The measurement period was always 40 minutes, which was considered to be short enough to minimise the effect of the chamber on the production/consumption rates (Scott *et al.*, 1999). Gas samples were collected in 30 ml syringes 0, 10, and 20 min (0, 20 and 40 min in 2005) after the start of the measurements. The gas samples were analysed the same day *in situ* by using a gas chromatograph equipped with an electron capture detector (ECD) for N_2O and SF_6, and a flame ionisation detector (FID) for CH_4.

Soil structure was characterised by measuring the soil water content in the field with the ECH$_2$O Dielectric Aquameter Sensor (Decagon Devices, Inc.; Figure 13b). The sensor was introduced into the soil to a depth of approximately 10 cm, in order to measure soil water content at the upper 10-cm soil layer. At every measurement day and for every flux chamber, 1-4 measurements were performed with this sensor.

A paired one-tailed t-test was applied to study the significance of the differences measured between the applied treatments (riding track vs. heavy compaction; fertilised vs. unfertilised), as described in chapter 4.

Figure 13 Measurement methods. (a) ECH_2O Dielectric Aquameter Sensor (volumetric water content); (b) Flux chamber and permanent installed wooden frames (CH_4 and N_2O fluxes)

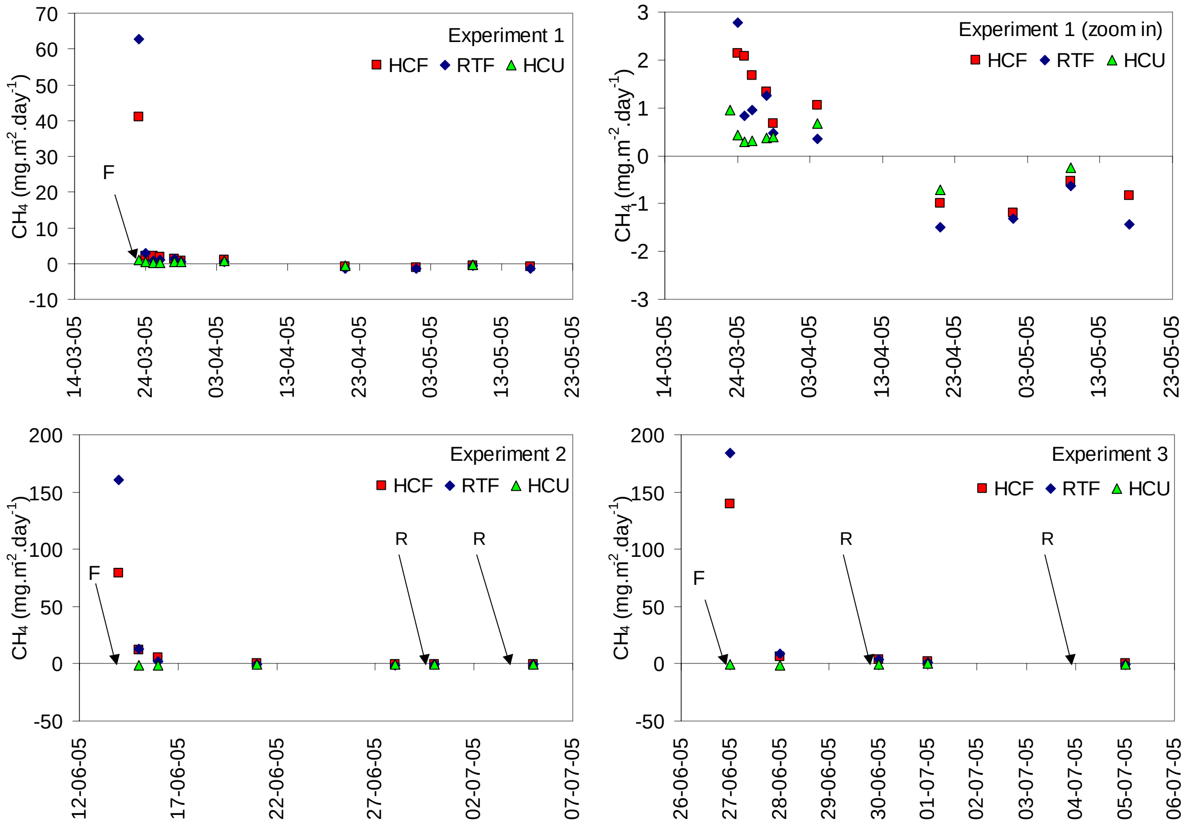


4.2 Results

4.2.1 Methane (CH_4)

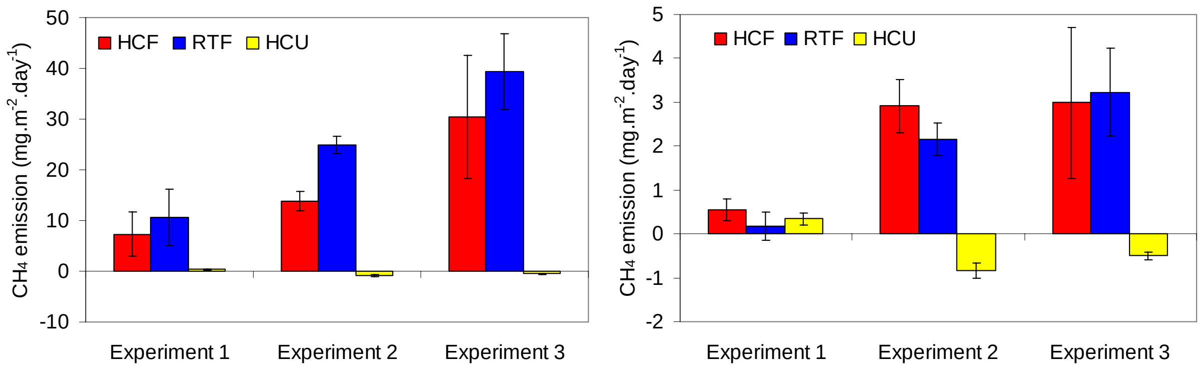
Manure application had a marked effect on the CH_4 fluxes observed at the measurement site for all three experiments (figure 14 and figure 15). In experiment 1, the heavy compacted plot that was fertilised (HCF) emitted, on average, 20 times more CH_4 than the unfertilised plot (HCU). In experiments 2 and 3 the effect was even larger: the HCU plot was, on average, a net sink for CH_4, whereas the HCF plot was a net CH_4 source. Rainfall and/or WFPS did not have any significant effect on the observed CH_4 fluxes for any of the compaction/fertilisation treatments.

Figure 14 Individual CH_4 flux measurements at all fields. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RTF: riding track fertilised; F: manure application; R: rainfall.



It is unclear whether the degree of compaction had a significant effect on the CH_4 fluxes observed at the measurement site. The large CH_4 emission peak occurring just after fertilisation in all experiments seems to override any potential effect of soil compaction. There are a number of factors that could explain this observed effect. First of all, both the preparation of the slots in the soil and fertilisation occurred manually, which could result in a distribution of the amount of manure deposited in the soil different for all different plots. Secondly, we did not apply nitrogen fertiliser but cattle slurry, and if the composition of the slurry was not homogeneous, the available organic matter for decomposition could have also varied between plots. Finally, there were no replicates for any of the plots, which could have reduced the effect of these two factors. Figure 15 shows that, when all data is being considered, the average CH_4 emission from the RTF plot is higher than from the HCF plot, although only in experiment 2 the differences between both treatments were significant (p=0.05). In contrast, when the analysis is performed on data starting the day after fertilisation, the HCF plot emitted (on average) more CH_4 than the RTF plot in experiments 1 and 2, whereas in experiment 3 more CH_4 was emitted from the RTF plot.

Figure 15 CH_4 fluxes as a function of soil compaction for different crops. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RTF: Riding track fertilised. Left: all data used. Right: data starts 1 day after manure application.



4.2.2 Nitrous oxide (N_2O)

All plots were net sources of N_2O, with values ranging between 0 and 7 $mg.m^{-2}.day^{-1}$ (figure 16). Fertilisation resulted in higher N_2O emissions (between 70% and a factor 2.2 on average; figure 16) from the fertilised plot (HCF) compared to the control (HCU). An initial N_2O emission peak (a factor 6 higher than the control plot) was only observed during the first day after fertilisation in experiment 1, whereas in experiments 2 and 3 no emission peak was observed after fertilisation, although the emissions were constantly higher from the fertilised plot. The effect of rainfall on the observed N_2O emissions was significant: after the two rainfall events a new emission peak was measured.

The effect of soil compaction on N_2O emissions is shown in figure 17. In contrast with the results presented for CH_4, the initial N_2O emission peak after fertilisation had no significant effect on the total (average) N_2O emission. Heavy compaction (HCF) resulted in significantly (p=0.05) higher N_2O emissions (by 30-45%) than the riding track system (RTF) in experiments 2 and 3. In experiment 1, emissions from the HCF and the RTF plot were not significant (p=0.05), although emissions from the HCF plot were, on average, 15% higher than from the RTF plot.

4.3 Conclusions

It is unclear whether soil compaction had an important role on the observed CH_4 fluxes. Soil water content did not significantly influence the fluxes of N_2O and CH_4, although higher N_2O emissions were observed after rainfall events. Fertiliser application, which resulted in large emission peaks from the fertilised plots (in contrast with the control (unfertilised) plots, which in most cases were even a sink of CH_4), seems to be the main factor controlling CH_4 emissions during the first day after fertilisation. When this initial CH_4 peak is not considered, the CH_4 emission from the heavy compacted plots was found to be higher than from the riding track system in two of the three experiments, and lower in the other one. Soil compaction did have a significant effect on N_2O emissions from the grassland soil: the emissions from the heavy compacted soils were 15-45% higher than from the riding track system. In order to get more conclusive results, new measurements are needed that should be based on a larger number of replicates per treatment and/or more measurement locations.

Figure 16 Individual N_2O flux measurements at all fields. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RTF: riding track fertilised; F: fertiliser application; R: rainfall.

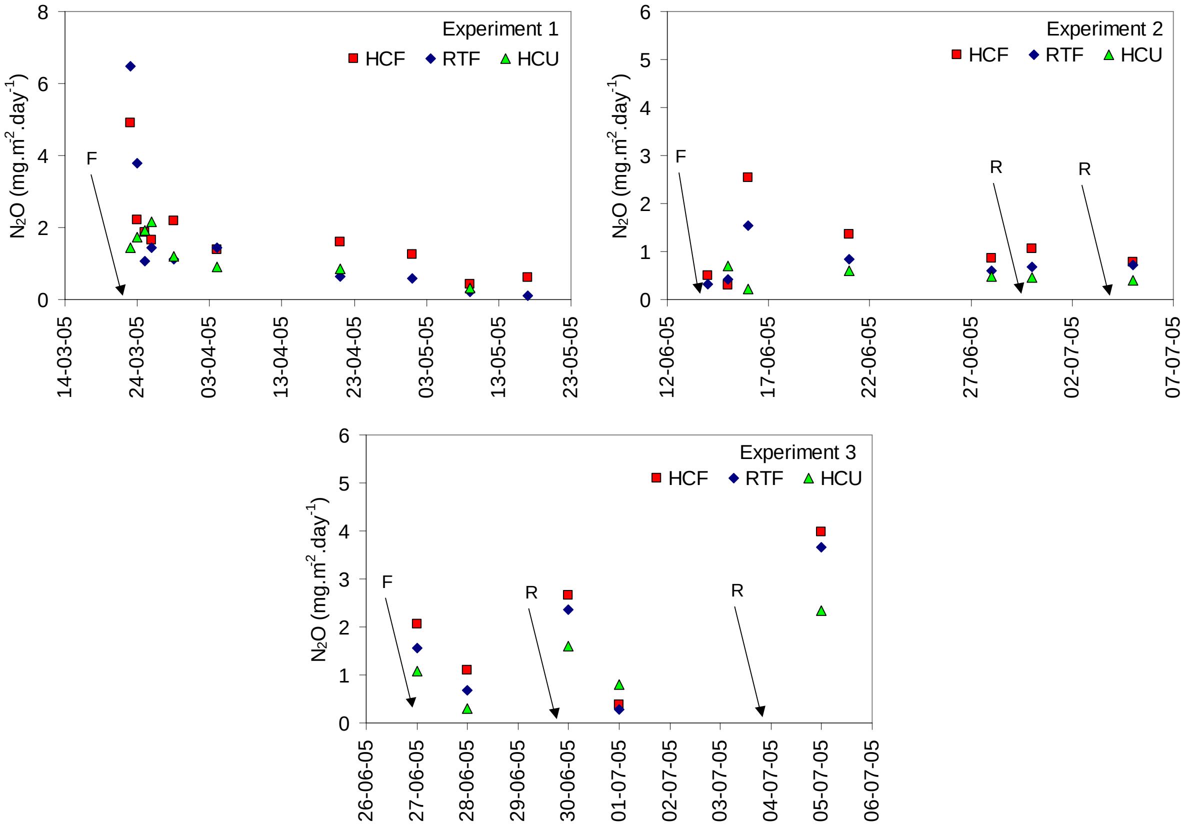
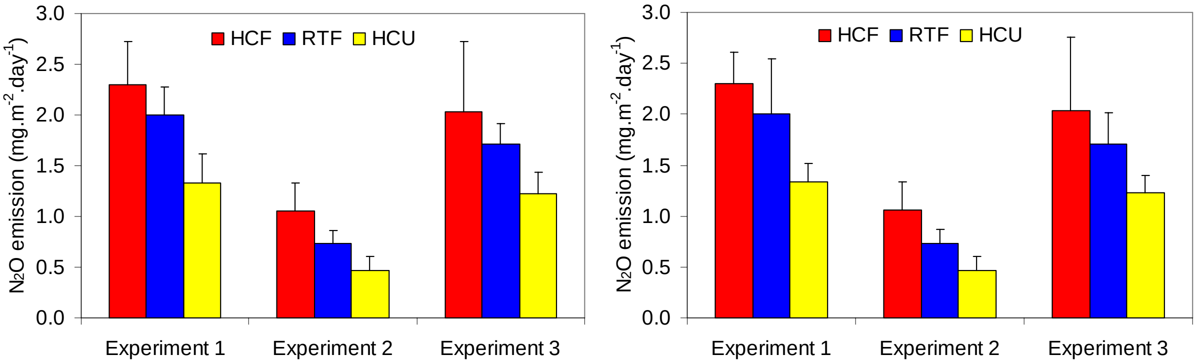


Figure 17 N_2O emission as a function of soil compaction for different crops. HCF: heavy compaction fertilised; HCU: heavy compaction unfertilised; RTF: Riding track fertilised. Left: all data used. Right: data starts 1 day after manure application.



5 Laboratory experiments

In this chapter, results of laboratory experiments performed to obtain more fundamental insight into the effects of soil compaction on the emission of greenhouse gases are reported. First the laboratory set up is described. Next the results are presented and a description is provided that shows that the emission of N_2O is accurately described by a combination of two parameters, viz. soil respiration and gas filled pore space.

5.1 Materials and methods

Soil samples were obtained from an arable field located on a light clay soil in Langeweg (Brabant) in the south west of the Netherlands. On an arable field three different compaction treatments were considered: (i) Precise soil management (riding track system), by using a tractor equipped with an RTK-DGPS system. Old and new tracks are superposed (±5cm), limiting compaction due to traffic lines; (ii) Compaction due to traditional soil management (arbitrary traffic) is simulated by means of additional pressure applied to the beds in between the permanent tracks; (iii) Extra compaction by heavy tractor traffic.

On 27 may 2005 soil cores (100 cc; height 51 mm, diameter 50 mm) were obtained from the above field from each of the three treatments. The samples were taken close to each other and always at two different depths: 3-8 cm and 12 – 17 cm. The porosity was 0.428 ± 0.019 for samples from the riding track system, 0.419 ± 0.009 for the samples from the traditional treatment, and 0.390 ± 0.006 for the samples from the heavy compacted soil.

Nitrate was added to the samples in a quantity resulting in a gift of 50 kg ha^{-1} (in a layer of 5 cm). In subsequent days the emission of greenhouse gases from the samples was measured. Three samples of the same type (soil layer, compaction, water content) were placed in a container. The measurement encompassed that the container (volume 894 cm^3) was closed, and that after 30 minutes accumulated N_2O and CH_4 was measured with two photo-acoustic spectroscopic infra-red gas analyzers (Velthof and Oenema 1995). The first analyzer was used to measure CO_2, the second analyzer, which was equipped with a CO_2 filter, was used to measure N_2O and CH_4.

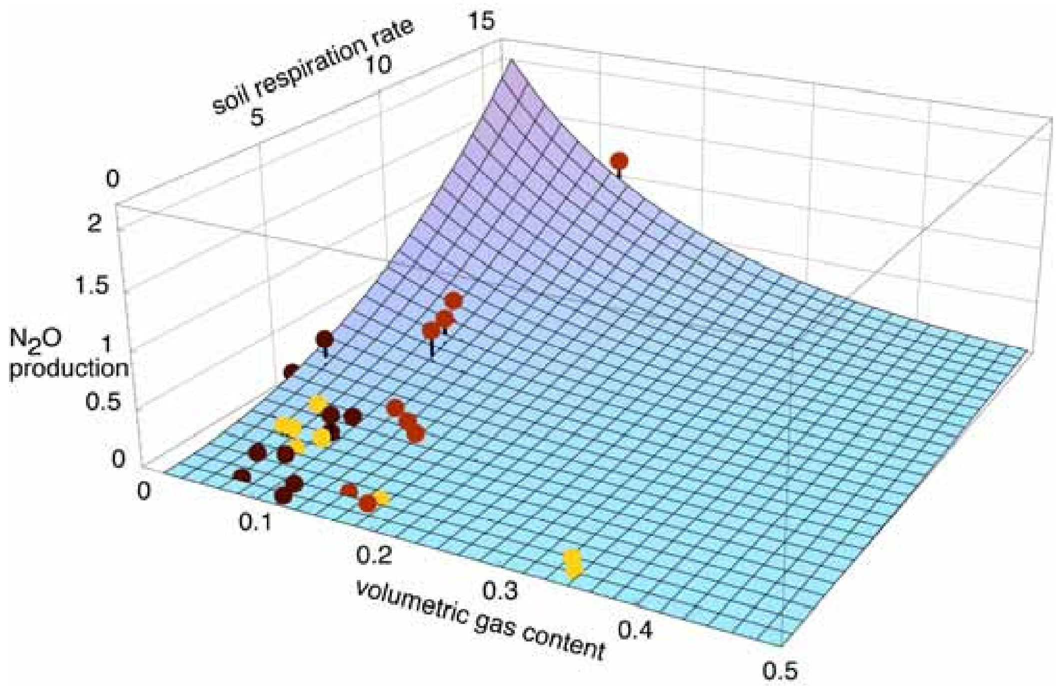
The measurements were carried out in a total of 72 containers, each containing tree soil cores. At two depths (3-8 cm and 12-17 cm) and three compactions (Riding track, traditional compaction and heavy compaction) this implies 12 containers per type. The water content in those 12 containers differed by natural variation and by adding water at the start of the experiment. Over the course of the experiment the water contents were kept constant by weighing the containers each day and subsequently compensating for evaporation losses by a water gift of a few milliliters.

Due to the scale of the measurements (5 cm depth) the emissions are expressed per unit volume and per unit of time. The emission is calculated based on a measured increase in the concentration per unit of time, which is determined relative to the atmospheric background concentration. The sensitivity for small emissions is determined by the variability of the background measurements. For CO_2 the standard deviation in the background measurement was about 5%. Accounting for a closing time of 30 minutes, the volume of the container, and the molecular weight of the compound to be measured this implies a smallest detectable CO_2 production of 0.5 g C m^{-3} day^{-1}. For N_2O the variability was about 10%, which implies a detection limit of 0.002 g N m^{-3} day^{-1} and for CH_4 this was 15% implying a detection limit of 0.03 g C m^{-3} day^{-1}.

5.2 Results and Discussion

Our analysis resulted in a correlation between N_2O emission, soil respiration and gas filled pore space (figure 18).

Figure 18 N_2O emission as a function of soil respiration and gas filled pore space. A fit of equation (1) with a = 0.0074 [0.0040, 0.0109], b = 6.4 [2.5, 10.3] and c = 2.1 [1.9, 2.3] explains 88% of the variation in the data points. The confidence intervals given are for 95%. The results of the samples from the various treatments are indicated with the following symbols: Riding track system (yellow), traditional (light brown) and heavy compacted (dark brown). The unit of respiration is g C m^{-3} day^{-1}, N_2O production is in g N m^{-3} day^{-1}, and the gas filled pore space is dimensionless.



The correlation between N_2O and gas filled pore space only was not significant (figure 19). The rational behind this is that N_2O is a product of anaerobic microbial activity, which occurs at (small) anoxic spots in the soil. Anoxic conditions are likely to occur if (1) there is a large microbial activity in the soil as a whole (observed as a large soil respiration rate) and (2) the gas filled pore space is small which severely hampers the diffusive transport of oxygen through the soil. Hence, it is the combination of a large oxygen demand with a limited oxygen transport which leads N_2O production, *if there is nitrate available*. The following equation expresses the N_2O production P_{N2O} as the product of a term which decreases with the gas filled pore space ε and increases with the soil respiration P_{CO2}:

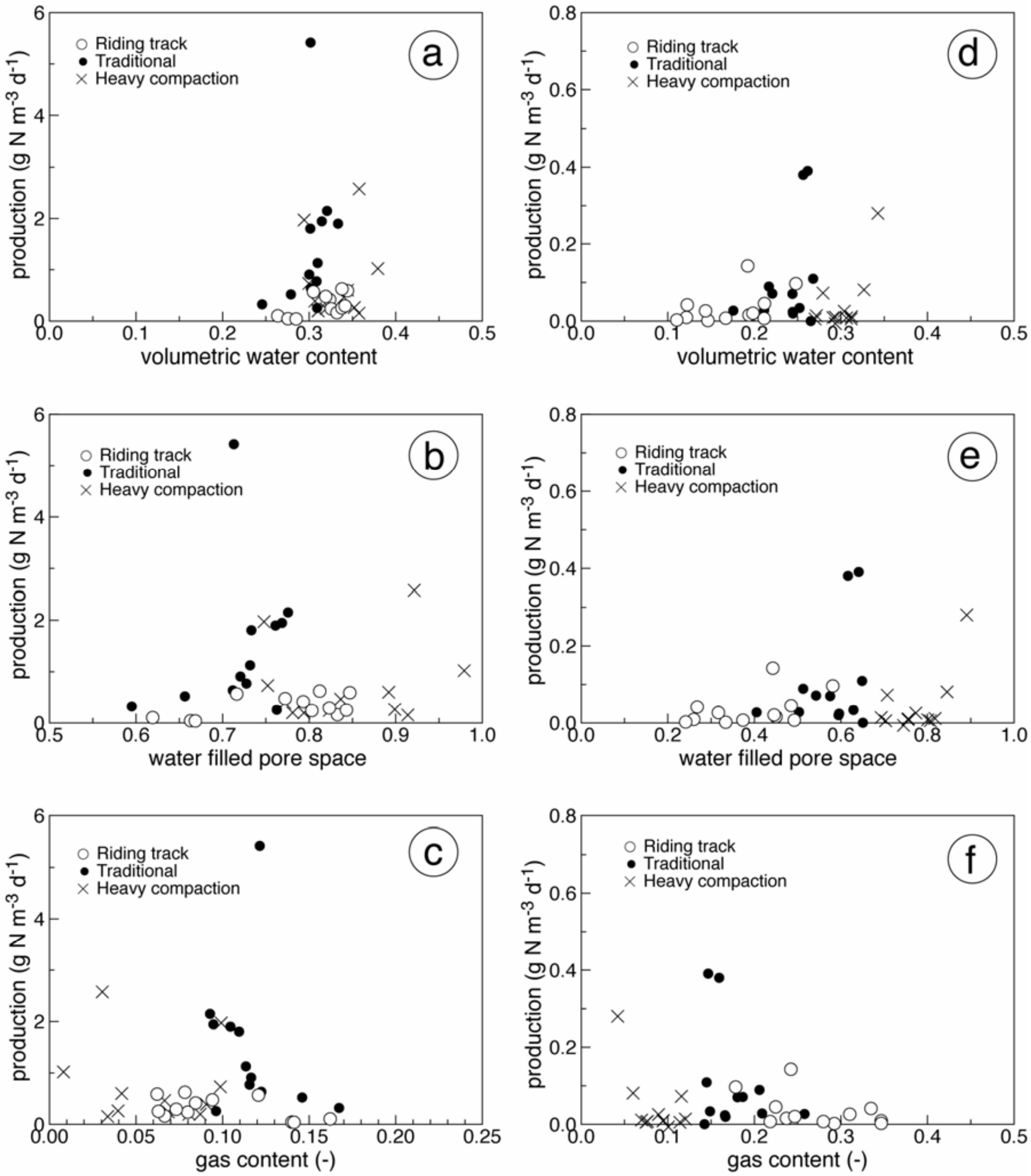
$$P_{N2O} = a \exp(-b.\varepsilon).(P_{CO2})^c \qquad \text{(Equation 1)}$$

where *a* depends on the nitrate content of the soil and *b* and *c* are regression parameters.

Fitting this equation to the data yielded a $r^2 = 0.88$, i.e. the fit explained 88% of the variation in the data. Equation (1) is particularly attractive since it allows an estimate of the effect of soil compaction on the N_2O production. If the main effect of compaction is a decrease of the gas filled pore space ε, this leads to a relative increase of the N_2O production of *b* times the change in ε. Our estimate of *b = 6.4* would imply that a change in ε of 3% yields a change in N_2O production of 6.4 times 3 which is approximately 20%.

We further tested whether this assumption is applicable to field scale calculations and estimated N_2O production during a year with a process model (Fussim2, see Heinen 2001). This exercise yielded estimates of the daily N_2O production per ha for non-compacted sand and silt soils to which we could apply a compaction effect on a day by day basis, using the model described above. Simulated (and observed) soil gas contents are almost always larger than 3% which implies that the application of a compaction effect of that size does not lead to any inconsistencies and yields a 20% emission increase. This 20% is our first estimate of the effect of soil compaction on the emission of N_2O from agricultural arable soils. This estimate needs further validation and testing, e.g. the extent of soil compaction that we have set to a uniform 3% for all soils. Further research is needed to evaluate whether the factor *b* that we have estimated for equation 1 (6.4) is also valid for other soils than the clay soil we have tested.

Figure 19 N_2O production averaged over the first three days after supplementing soils cores with nitrate, as a function of volumetric water content (panels a and d), water filled pore space (panels b and e), and gas filled pore space (panels c and f). Panels a, b, and c are for the 12–17 cm layer, and panels d, e, and f are for the 3-8 cm layer.



6 Emission reduction through precise soil management in the Netherlands

In the previous chapter we have presented and parameterized an equation that allows an estimate of the effect of soil compaction in nitrous oxide (N_2O) production. In the present chapter we will use this calculation rule to evaluate the potential effect of the introduction of the riding track system in the Netherlands on the emission of N_2O from *arable* fields.

Table 12 shows the surface area of Dutch agriculture devoted to the cultivation of specific crops, specified to sandy and clay soils. Also given is the estimated N_2O emission for the specific crops. The estimated emissions are based on the amount of fertilizer and manure applied *conform default fertilizer advice*, and the emission factors for these N sources. Based on this scenario the current emission of N_2O from Dutch arable fields is estimated at 2061 ton N_2O-N per year.

The riding track system is applicable to both sandy and clay soils, but the potential advantages are bigger on clay than on sand, because clay soils tend to be wetter after rainfall. The riding track system makes it possible to work on the field sooner after a rainfall event and hence is more likely to be introduced first on clay soils (Bert Vermeulen, personal communication). We have evaluated a scenario with the following assumptions:

- the riding track system is introduced on 70% of the clay soils and on 10% of the sandy soils
- application of the riding track system reduces soil compaction and results in a 3% higher porosity in soils
- a higher porosity of 3% translates into a 20% reduction in the emission of N_2O

In this scenario N_2O emission from Dutch arable soils is reduced by 169 ton per year (Table 13). This estimate is strongly affected by and depends on the validity of the above assumptions. We feel that the estimate of a 3% increase in porosity due to the use of the riding track system is rather conservative. Reductions in pore space as a result of tractor traffic on a clay soil under barley from 51 to 37% have been reported (Miller and Donahue, 1995). This would imply an even higher potential emission reduction.

Furthermore it is important to stress that the application of the riding track system leads to a more efficient use of the N applied, and hence may result in reduced N gifts and hence in lower N_2O emissions. This potential effect is not included in the above scenario.

We conclude that the potential effect of the application of the riding track system on the emission of N_2O from Dutch arable fields can be substantial, and that an emission reduction of ~169 ton N_2O-N (~0.1 Mton CO_2-equivalent) is realistic. On a national scale the highest gains can be achieved by introducing the system for the cultivation of maize, potatoes, grain and sugar beet, and by focusing on clay soils. For individual farmers the highest gains are to be achieved for crops that receive the highest gifts of fertilizer and manure.

A validation of the above through research directed at underpinning the above assumptions is required to sustain our conclusions. Such research would best be carried out with those crops where introduction of the riding track system promises the highest reductions in N_2O emission.

Table 12 Estimated N_2O production from Dutch agricultural fields[a]

Crop	Area (ha)			N applied (kgN ha^{-1}) Sandy soils		N applied (kgN ha^{-1}) Clay soils		N_2O emission ton N_2O-N per year		
	Total	Sand	Clay	Animal manure	Inorganic fertilizer	Animal manure	Inorganic fertilizer	Sand	Clay	Total
Silage maize	231500	162050	43985	170	15	170	25	575.3	160.5	735.8
Potatoes	179200	66304	96768	120	120	120	130	238.7	358.0	596.7
Grain	137000	31510	90420	100	40	100	55	75.6	230.6	306.2
Sugarbeet	114000	28500	75240	100	50	100	65	71.3	199.4	270.6
Barley	38000	8740	25080	100	40	100	55	21.0	64.0	84.9
Onions	15600	780	14820	0	120	0	130	0.9	19.3	20.2
Other vegetables	10000	1200	7500	100	0	100	10	2.4	15.8	18.2
Maize	7000	1610	4620	120	40	120	60	4.5	13.9	18.4
Rye	5000	1150	3300	100	5	100	15	2.4	7.1	9.5
Total	**737300**	**301844**	**361733**					**992.0**	**1068.5**	**2060.5**

[a] Estimates are for those crops that contribute most to N_2O emission, based on Velthof and Kuikman (2000), Kuikman *et al.* in prep, and expert judgement on the amounts of fertilizer and animal manure applied, assuming an average N content of 4 kgN/m^3 animal manure, and emission factors for fertilizer and animal manure of 10 and 20 gN_2O-N (kg N)$^{-1}$ respectively

Table 13 Estimated effect of the introduction of the riding track system on the emission of N_2O from Dutch agricultural fields[a]

Crop	ton N_2O-N/year N_2O emission			
	Present	Riding track	Reduction	Reduction (%)
Silage maize	735.8	701.8	34.0	**5**
Potatoes	596.7	541.8	54.9	**9**
Grain	306.2	272.4	33.8	**11**
Sugarbeet	270.6	241.3	29.3	**11**
Barley	84.9	75.6	9.4	**11**
Onions	20.2	17.5	2.7	**13**
Other vegetables	18.2	15.9	2.3	**12**
Maize	18.4	16.3	2.0	**11**
Rye	9.5	8.4	1.0	**11**
Total	**2060.5**	**1891.1**	**169.4**	**8**

[a] Estimates are based on Table 1 assuming (i) introduction of the riding track system on 10% of the agricultural fields on sand and on 70% of the fields on clay, and (ii) a 20% lower N_2O production due to the a higher soil porosity as a result of the application of the riding track system

7 Summary, main conclusions and recommendations

Agricultural soils are an important source of N_2O. Soil compaction is known to stimulate the emission of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils. N_2O and CH_4 are potent greenhouse gases, with a global warming potential respectively 296 times and 23 times that of CO_2. Soil compaction in arable land is rather common. Over the last years management options to minimize agricultural greenhouse gas emissions have been evaluated, in particular for N_2O soil emissions. One such option would be to minimize soil compaction due to the use of heavy machinery. Soil compaction in arable land is relatively general. Here we report on the emissions of N_2O and CH_4 from an arable system where soil compaction is minimized through application of the so – called riding track (*rijpaden*) system. The selected arable field was located on a light clay soil in the south west of the Netherlands.

First of all, a literature study was performed to review the effect of compaction and other management factors (fertilization, water management, land use) on the emissions of N_2O and CH_4 from agricultural soils. The results of this study indicated a reduced CH_4 uptake capacity of heavy compacted soils (by 60% on average) compared to least compacted soils. N_2O emissions were, on average, reduced by 20% after reducing compaction and enhanced by a factor 2 after heavy compaction. In general, soils with clay and sand texture showed the highest and lowest N_2O emissions, respectively. These results have been corroborated in both field measurements and laboratory experiments.

In the field, three management methods on soil compaction were applied and compared: (i) a conventional approach in which soil traffic is arbitrary (the effect is that compaction is evenly distributed over the plots); (ii) a heavy compaction approach in which extra heavy equipment was used; and (iii) a precision management approach in which tractors were equipped with a global positioning system (accuracy = ±5 cm) and always were driven over the same track (the effect is that soils are compacted in the tractor tracks only). The emissions of N_2O and CH_4 were measured during a period of two years in the field and in soil cores (laboratory experiments) collected from the measured plots. During the laboratory experiments, the carbon dioxide (CO_2) production was also measured.

Measurements in the field showed a pronounced and clear effect of soil compaction on both N_2O and CH_4 fluxes. On arable soils, heavy compaction increased N_2O emissions by 20-50% and resulted in 2-5 times higher CH_4 emissions than the traditional (less compacted) system. The effect of compaction on CH_4 was such that some plots that were acting as a sink were transformed into net CH_4 sources after increasing compaction. The riding track system resulted in a reduction of N_2O emissions by 20-50%, and reduced CH_4 emissions by a factor 2-12. In two of the sites, the effect was such that the site was transformed from a net CH_4 source into a net sink after reducing compaction. Fertilisation resulted in higher N_2O emissions (by a factor 6), whereas its effect on CH_4 ranged from no significant effect to higher emissions (conversion of a small sink into a net CH_4 source).

On grassland soils, N_2O emissions from compacted soils were, on average, 15-45% higher than from the riding track system. For CH_4, the results were not conclusive. Fertiliser application, which resulted in large emission peaks from the fertilised plots (in comparison with the control (unfertilised) plots, which in most cases were even a sink of CH_4), seemed to be the main factor controlling CH_4 emissions during the first day after fertilisation. When this initial CH_4 peak was not considered, the CH_4 emission from the heavy compacted plots was found to be higher than from the riding track system in two of the three experiments and lower in the other one.

Laboratory experiments showed a correlation between N_2O emission and soil respiration and water or air filled pore space. The correlation between N_2O and air filled pore space alone was not significant. We could explain this by assuming that soil respiration is an indicator for microbial activity and is strongly correlation with consumption of oxygen, thus creating local anaerobic conditions. Including soil respiration, measured as CO_2 production (P_{CO2}), made it possible to describe N_2O emission (P_{N2O}) as a result of air filled pore space (ε) and compaction with a simple calculation rule: $P_{N2O} = a \exp(-b.\varepsilon).(P_{CO2})^c$ (correlation $r^2 = 0.88$). The attractiveness of this equation is that it allows the calculation of the sensitivity of N_2O production for changes in gas filled pore space, which is a good first estimate of the effect of compaction on porosity. Our estimate of b = 6.4 would imply that a reduction in soil porosity of 3% would result in an increase in N_2O by approximately 20 %. We further tested whether this assumption is reasonable and estimated N_2O production during a year with a process model (FUSSIM). This exercise yielded estimates of 26 and 34 kg N_2O-N per ha for non-compacted sand and silt soils and a 20 % higher emission for a soil with 3% more compaction.

Based on these results we conclude:

- Precise soil management that lowers the extent of soil compaction, for example by using the riding track system, will result in lower N_2O emissions and higher CH_4 uptake from soils. Field measurements showed 20-50% lower N_2O emissions and 60% higher CH_4 uptake from soils managed with the riding track system than from soils managed with traditional systems.
- On the basis of laboratory experiments, we developed and parameterized a simple and testable model that relates soil compaction and soil porosity to emission of N_2O. This model predicts an increase in N_2O production in soils by 20% when soil porosity is reduced by 3% (higher compaction).
- The riding track system is in principle applicable to cropping systems on both sand and clay soils, but the potential advantages are more substantial on clay than on sand. First of all, because it would increase the possibilities for soil management in spring and autumn (Vermeulen, personal communication). Secondly, because of the higher risk of compaction and emissions in clay soils than in sandy soils (Van der Akker, personal communication). As a result we conclude that it is likely that this system ('rijpaden') would firstly be promoted and introduced on clay soils. Application of the riding track system could lead to an emission reduction of ~169 ton N_2O-N (~0.1 Mton CO_2-equivalent) per year in the Netherlands.

The estimated potential emission reduction as a result of the introduction of the riding track system on Dutch agricultural fields of ~169 ton N_2O-N per year in the Netherlands is based on the following assumptions:

1. The riding track system is introduced in arable cropping systems on 70% of the clay soils and on 10% of the sandy soils.
2. The application of the riding track system prevents soil compaction and results in a 3% higher soil porosity as a result of less soil compaction.
3. This higher soil porosity results in an average 20% reduction of N_2O emissions compared to the current (traditional) soil management.

In order to validate whether these assumptions are appropriate further research is needed, both at the field (for better estimates of the emissions and the effect of other management factors) and in the laboratory (e.g. to evaluate whether the b factor is also valid for soils other than the soil type used in this study). This research should focus on those crops where introduction of the riding track system should lead to the highest reductions in N_2O emission. This is a function of fertilizer and manure input and of impact of management for specific cropping systems on avoided soil compaction.

Appendix A Factors affecting CH_4 and N_2O emission: literature review

Table A1 Summary of studies on the effect of land use on CH_4 and N_2O fluxes from soils

Reference	Country	Land use	Cultivation	Measurement days/year	Locations N_2O	Locations CH_4
Anger *et al.* (2003)	Germany	Grassland	Grass	365	4	—
Ball *et al.* (1999a)	UK	Arable	Spring barley	90	1	—
			Winter barley	60-210	2	—
Ball *et al.* (1999b)	UK	Arable	Oilseed rape	90	2	—
			Spring barley	30-61	2	—
			Winter barley	61-210	2	—
Ball *et al.* (2000)	UK	Arable	Oilseed rape	365	1	—
			Winter barley	365	2	—
Chen *et al.* (1997)	China	Arable	Maize	273	1	—
			Soybean	273	1	—
Clayton *et al.* (1997)	UK	Grassland	Grass	365	12	—
Clemens *et al.* (1999)	Germany	Arable	Winter wheat	120	1	—
Dobbie and Smith (1996)	UK	Forest	Forest	365	—	1
Dobbie and Smith (2003a)	UK	Arable	Potato	365	1	—
			Winter barley	365	1	—
			Winter wheat	365	1	—
		Grassland	Grass	365	9	—
Dobbie *et al.* (1996)	UK	Forest	Forest	90-365	—	4
		Grassland	Grass	120	—	1
Flessa *et al.* (1998)	Germany	Arable	Maize	365	1	1
		Grassland	Grass	365	2	2
Flessa *et al.* (2002a)	Germany	Arable	Potato	120	2	—
Glatzel and Stahr (2001)	Germany	Grassland	Grass	365	2	2
Goldman *et al.* (1995)	USA	Forest	Forest	365	—	3
Goodroad and Keeney (1985)	USA	Arable	Tobacco	180	2	—
		Forest	Forest	180	1	—
		Grassland	Grass	180	1	—
Goossens *et al.* (2001)	Belgium	Arable	Maize	365	2	—
			Sugar beet	365	1	—
		Forest	Forest	270-365	2	—
		Grassland	Grass	210-365	5	—
Gulledge *et al.* (1997)	USA	Forest	Forest	365	—	2
Hénault *et al.* (1998a)	France	Arable	Oilseed rape	120	5	—
Hénault *et al.* (1998b)	France	Arable	Oilseed rape	120	9	—
Hou and Tsuruta (2003)	Japan	Arable	Cabbage	180	4	—
Jørgensen *et al.* (1997)	Denmark	Grassland	Grass	210	1	—
Kaiser *et al.* (1998a)	Germany	Arable	Oilseed rape	365	9	—
			Sugar beet	365	9	—
			Winter barley	365	9	—
			Winter wheat	365	9	—
Kaiser *et al.* (1998b)	Germany	Arable	Spring barley	365	3	—
		Grassland	Grass	365	6	—
Kamp *et al.* (1998)	Germany	Arable	Winter wheat	365	1	—
Kasimir-Klemedtsson and Klemedtsson (1997)	Sweden	Forest	Forest	365	—	1
Klemedtsson *et al.* (1997)	Sweden	Forest	Forest	365	1	—
Koga *et al.* (2004)	Japan	Arable	Cabbage	365	1	—
			Potato	365	1	—
			Sugar beet	365	1	—
			Winter wheat	365	1	—

Table A1 Summary of studies on the effect of land use on CH_4 and N_2O fluxes from soils (continued)

Reference	Country	Land use	Cultivation	Measurement days/year	Locations N_2O	Locations CH_4
Kusa *et al.* (2002)	Japan	Arable	Onion	195	6	—
MacDonald *et al.* (1997)	UK	Forest	Forest	365	2	2
Mahmood *et al.* (1998)	Pakistan	Arable	Maize	60	1	—
			Winter wheat	150	1	—
Martikainen *et al.* (1993)	Finland	Forest	Forest	365	2	—
Mogge *et al.* (1998)	Germany	Forest	Forest	365	1	—
Mogge *et al.* (1999)	Germany	Arable	Maize	365	1	—
		Grassland	Grass	365	1	—
Mosier and Delgado (1997)	Puerto Rico	Grassland	Grass	365	6	6
Mosier *et al.* (1991)	USA	Grassland	Grass	180	7	7
Mosier *et al.* (1997b)	USA	Grassland	Grass	120-365	12	12
Pinto *et al.* (2002)	Brazil	Forest	Forest	365	1	—
Priemé and Christensen (1997)	Denmark	Forest	Forest	365	—	1
Ruser *et al.* (2001)	Germany	Arable	Corn	365	2	—
			Potato	365	2	—
			Winter wheat	365	2	—
Sehy *et al.* (2003)	Germany	Arable	Maize	365	4	—
Sitaula *et al.* (1995a)	Norway	Forest	Forest	365	—	3
Sitaula *et al.* (1995b)	Norway	Forest	Forest	365	1	—
Skiba *et al.* (1998)	UK	Arable	Oilseed rape	30	1	—
			Spring barley	240	1	—
		Forest	Forest	30-365	10	—
		Grassland	Grass	60-365	5	—
Smith *et al.* (1998a, b)	UK	Arable	Potato	210-365	3	—
			Spring barley	210	1	—
			Winter wheat	210	1	—
		Grassland	Grass	31-365	6	—
Smith *et al.* (2000)	Denmark	Forest	Forest	365	—	1
		Grassland	Grass	<365	—	1
	Germany	Forest	Forest	365	—	1
	Norway	Forest	Forest	<365	—	1
	Poland	Forest	Forest	<365	—	1
	Sweden	Forest	Forest	365	—	1
	UK	Forest	Forest	365	—	1
		Grassland	Grass	<365	—	1
Steudler *et al.* (1989)	USA	Forest	Forest	180	—	6
Teepe *et al.* (2004)	Germany	Forest	Forest	180	7	7
Thomas *et al.* (2004)	New Zealand	Arable	Potato	120	3	—
Van den Pol-Van Dasselar *et al.* (1998, 1999c)	The Netherlands	Grassland	Grass	30-365	—	14
Van der Weerden *et al.* (2000)	New Zealand	Arable	Onion	240	5	—
Velthof *et al.* (1997)	The Netherlands	Grassland	Grass	25-32	16	—
Vermoesen *et al.* (1996)	Belgium	Arable	Maize	300	1	—
		Grassland	Grass	300-365	2	—
Wang *et al.* (2005)	Mongolia	Grassland	Grass	365	3	3
Williams *et al.* (1999)	UK	Grassland	Grass	365	1	—
Yamulki and Jarvis (2002)	UK	Grassland	Grass	22	1	1
Yamulki *et al.* (1995)	UK	Arable	Winter wheat	365	1	—

Table A2 Summary of studies on the effect of fertiliser type on CH_4 fluxes from soils

Reference	Country	Land use	Measurement days/year	Fertiliser type	Locations
Glatzel and Stahr (2001)	Germany	Grassland	365	Cattle slurry	1
Hansen *et al.* (1993)	Norway	Arable	36	Ammonium nitrate	1
				Cattle slurry	2
Mosier and Delgado (1997)	Puerto Rico	Grassland	365	Ammonium sulphate	3
Mosier *et al.* (1991)	USA	Grassland	180	Ammonium nitrate	2
				Urea	1
Mosier *et al.* (1997b)	USA	Grassland	365	Ammonium nitrate	2
			365	Ammonium sulphate	1
			120	Urea	3
Sitaula *et al.* (2000a)	Norway	Arable	365	Ammonium nitrate	3
				Cattle slurry	6

Table A3 Summary of studies on the effect of fertiliser type on N_2O fluxes from soils

Reference	Country	Land use	Measurement days/year	Fertiliser type	Locations
Anger *et al.* (2003)	Germany	Grassland	365	Calcium ammonium nitrate	3
Clayton *et al.* (1997)	UK	Grassland	365	Ammonium nitrate	2
				Ammonium sulphate	2
				Calcium nitrate	2
				Cattle slurry	1
				Urea	2
Glatzel and Stahr (2001)	Germany	Grassland	365	Cattle slurry	1
Hansen *et al.* (1993)	Norway	Arable	36	Ammonium nitrate	1
				Cattle slurry	2
Hénault *et al.* (1998a)	France	Arable	120	Ammonium nitrate	1
				Ammonium sulphate	1
				Potassium nitrate	1
				Urea	1
Hou and Tsuruta (2003)	Japan	Arable	180	Urea	2
Kaiser *et al.* (1998a)	Germany	Arable	365	Ammonium nitrate urea	24
Kaiser *et al.* (1998b)	Germany	Grassland	365	Ammonium nitrate	2
				Calcium ammonium nitrate	2
Mosier and Delgado (1997)	Puerto Rico	Grassland	365	Ammonium sulphate	3
Mosier *et al.* (1991)	USA	Grassland	180	Ammonium nitrate	2
				Urea	1
Mosier *et al.* (1997b)	USA	Grassland	365	Ammonium nitrate	1
			365	Ammonium sulphate	3
			120	Urea	2
Thomas *et al.* (2004)	New Zealand	Arable	120	Calcium ammonium nitrate	4

Table A4 Summary of studies on the effect of soil compaction on CH_4 fluxes from soils

Reference	Country	Land use	Measurement days/year	Locations
Flessa *et al.* (2002a)	Germany	Arable	120	2
Hansen *et al.* (1993)	Norway	Arable	36	4
Sitaula *et al.* (2000a)	Norway	Arable	365	12
Teepe *et al.* (2004)	Germany	Forest	30	3
Yamulki and Jarvis (2002)	UK	Grassland	22	1

Table A5 Summary of studies on the effect of soil compaction on N_2O fluxes from soils

Reference	Country	Land use	Measurement days/year	Treatment	Datasets
Ball *et al.* (1999a)	UK	Arable	60-180	Heavy compaction	3
				Heavy compaction + loosening to 10 cm	3
				Light compaction	3
Ball *et al.* (1999b)	UK	Arable	30-180	Heavy compaction	6
				Heavy compaction + loosening to 10 cm	6
				Light compaction	6
Ball *et al.* (2000)	UK	Arable	365	Heavy compaction	3
				Heavy compaction + loosening to 10 cm	1
Flessa *et al.* (2002a)	Germany	Arable	120	Heavy compaction	2
Hansen *et al.* (1993)	Norway	Arable	36	Heavy compaction	4
Teepe *et al.* (2004)	Germany	Forest	30	Heavy compaction	3
Thomas *et al.* (2004)	New Zealand	Arable	120	Heavy compaction	3
Yamulki and Jarvis (2002)	UK	Grassland	22	Heavy compaction	1

Table A6 Effects of factors affecting CH_4 and N_2O fluxes from soils. +: positive effect; -: negative effect; +/-: not significant effect; Sign.: significant effect.

Reference	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use
Anger *et al.* (2003)		+	Sign.		+/-, +	+/-								
Ball *et al.* (1999a)	+	+				+								
Ball *et al.* (1999b)	+	+				+								
Ball *et al.* (2000)	+/-	+												
Chen *et al.* (1997)		+					Sign.		+					
Clayton *et al.* (1997)		+	Sign.			+								
Dobbie and Smith (1996)									+/-			-	+/-	Sign.
Dobbie and Smith (2003a)		+				+								
Dobbie *et al.* (1996)														Sign.
Flessa *et al.* (1998)		+/-		+			+/-		+/-		+			Sign.
Flessa *et al.* (2002a)	+	+			+	+		+					+	
Glatzel and Stahr (2001)		+/-							+/-					

Table A6 Effects of factors affecting CH_4 and N_2O fluxes from soils (continued). +: positive effect; -: negative effect; +/-: not significant effect; Sign.: significant effect

Reference	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use
Goldman *et al.* (1995)									-				+/-	
Goodroad and Keeney (1985)		+	Sign.				Sign.							
Goossens *et al.* (2001)		+	Sign.				Sign.							
Gulledge *et al.* (1997)									+, +/-					
Hansen *et al.* (1993)	+	+	Sign.			+		+	+	+/-				
Hénault *et al.* (1998a)		+	Sign			+	+/-							
Hénault *et al.* (1998b)		+												
Hou and Tsuruta (2003)		+												
Jørgensen *et al.* (1997)		+				+								
Kaiser *et al.* (1998a)		+, +/-				+	Sign.							
Kaiser *et al. (1998b)*		+			+/-	+/-	Sign.							
Kamp *et al.* (1998)		+			+	+								
Kasimir-Klemedtsson and Klemedtsson (1997)									+			+	+	
Klemedtsson *et al.* (1997)		+			+/-	+/-								
Kim and Kim (2002)		+/-					Sign.							
Koga *et al.* (2004)		+				+			+/-				+	
Kusa *et al.* (2002)		+/-			+	+/-								
MacDonald *et al.* (1997)		+	Sign.			+/-			+	Sign.		+	+/-	
Mahmood *et al.* (1998)					+/-	+/-								
Martikainen *et al.* (1993)				+, +/-										
Mogge *et al.* (1998)					+	+								
Mogge *et al.* (1999)		+	Sign.		+	+/-	Sign.							

Table A6 Effects of factors affecting CH_4 and N_2O fluxes from soils (continued). +: positive effect; -: negative effect; +/-: not significant effect; Sign.: significant effect

Reference	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use
Mosier and Delgado (1997)		+				+			+, -, +/-				+	
Mosier *et al.* (1991)		+				+	Sign.		+				+	Sign.
Mosier *et al.* (1997b)		+							+/-				+	
Priemé and Christensen (1997)									+			+	+/-	
Ruser *et al.* (2001)	+	+				+	Sign.							
Sehy *et al.* (2003)		+				+								
Sitaula *et al.* (1995a)									+				+	
Sitaula *et al.* (1995b)		+												
Sitaula *et al.* (2000a)								+	+	+/-				
Skiba *et al.* (1998)		+			+	+	Sign.							
Smith *et al.* (1998a, b)		+			+	+	Sign.							
Smith *et al.* (2000)								+	+/-			+/-	+	Sign.
Steudler *et al.* (1989)									+			+/-	+	
Teepe *et al.* (2004)	+					+		+					+	
Thomas *et al.* (2004)	+	+/-				+								
Van den Pol-Van Dasselar *et al.* (1998, 1999c)									+/-	Sign			+	
Van der Weerden *et al.* (2000)		+					Sign.							
Velthof *et al.* (1997)		+	Sign.	+		+								
Vermoesen *et al.* (1996)	+	+			+		Sign.							
Wang *et al.* (2005)		+				+			+				+	
Williams *et al.* (1999)		+			+	+								

Table A6 Effects of factors affecting CH_4 and N_2O fluxes from soils (continued). +: positive effect; -: negative effect; +/-: not significant effect; Sign.: significant effect

Reference	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use	Compaction	N application	Type of fertilizer	Ground water	Soil temperature	Soil moisture	Land use
Yamulki and Jarvis (2002)	+	+						+/-	+					
Yamulki *et al.* (1995)		+				+								

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