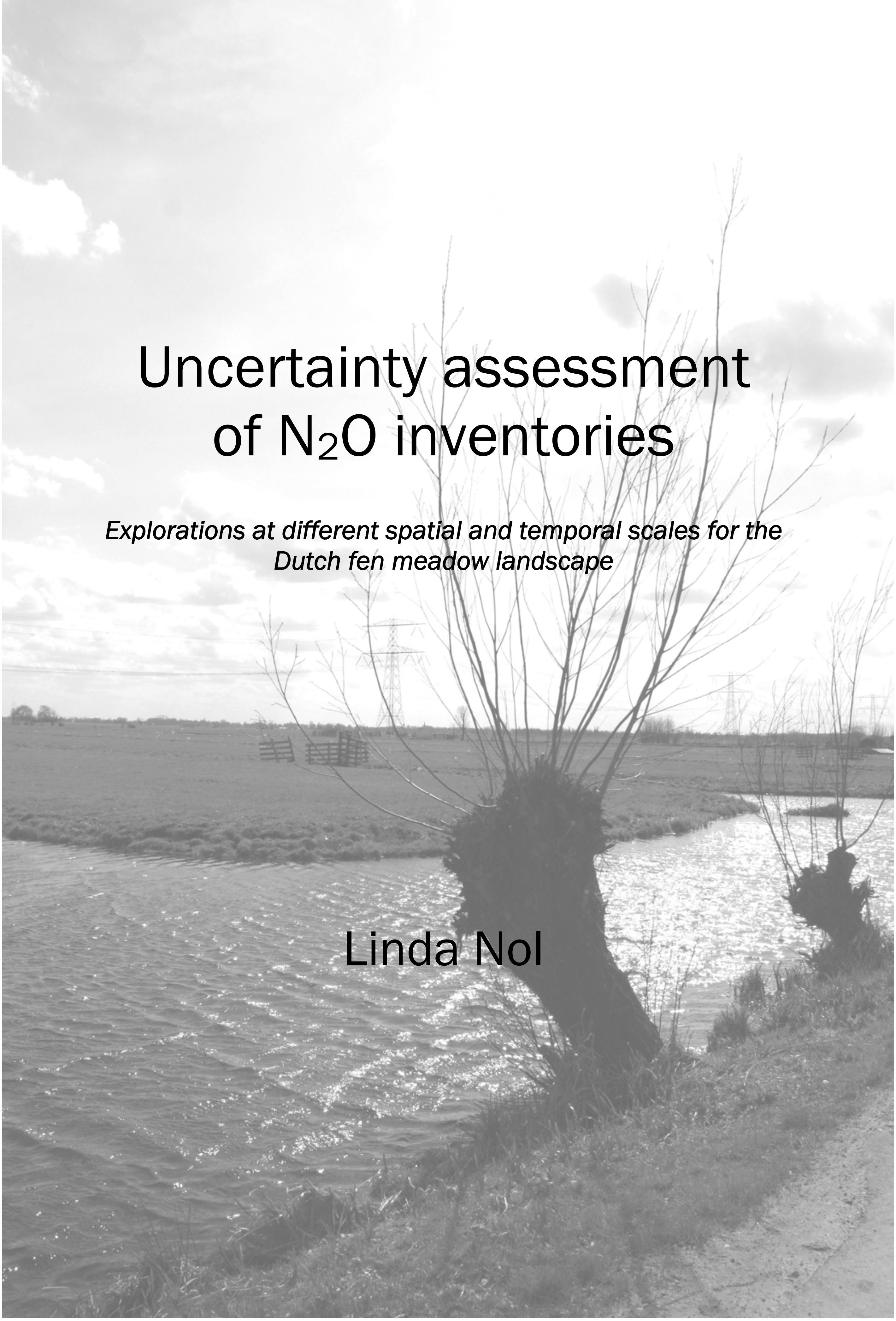

Uncertainty assessment of N_2O inventories

Explorations at different spatial and temporal scales for the Dutch fen meadow landscape

Linda Nol

Thesis Committee

Thesis Supervisors
Prof. Dr. Ir. A. Veldkamp
Professor of Land Dynamics
Wageningen University

Prof. Dr. Ir. P.H. Verburg
Professor of Environmental Spatial Analysis
Institute for Environmental Studies
VU University Amsterdam

Thesis co-supervisor
Dr. Ir. G.B.M. Heuvelink
Associate professor at Land Dynamics
Wageningen University

Other members

Prof. Dr. E. J. Pebesma	University of Münster, Germany
Dr. M. Wattenbach	Freie Universität Berlin, Germany
Prof. Dr. A. J. Dolman	VU University, Amsterdam
Prof. Dr. A. K. Bregt	Wageningen University

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Uncertainty Assessment of N_2O Inventories

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Linda Nol

THESIS
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De sporthal stroomt vol publiek, de scheidsrechters en de lijnrechters zijn er klaar voor, het volleybalnet lijkt er beter bij te hangen dan anders en de spanning is te snijden. Deze streekderby is één van de belangrijkste wedstrijden van het seizoen. Ons team, VV Zaanstad, staat tegenover onze grote concurrent VCC uit Wormer. Iedereen staat op scherp als de scheidsrechter het startsein geeft. Er volgt een zenuwachtige service van VCC, wij verwerken de bal goed en ik krijg de set-up. Ik voel de adrenaline door mijn aderen spuiten en ik raak de bal…. goed! Het eerste punt is binnen… Na de eerste en tweede set gewonnen te hebben, worden we echter zenuwachtig. Het dringt tot ons door dat we de derby kunnen winnen! Dit is geheel tegen de verwachting van de verslaggevers in en bij een serve op mij verkramp ik en schiet de pass weg. "Rustig, rustig" maan ik mezelf tot kalmte toe. Een volgende goede pass kan het verschil helaas niet maken, we verliezen de derde set. Voor de vierde set spreken we af onze angst opzij te zetten en met flair te spelen. Terwijl ik de hele wedstrijd voorzichtig heb geserveerd, denk ik nu: "Geen angst, knallen". De service gaat hard naar rechtsachter en VCC ketst 'm weg, punt voor ons! Ons team speelt geweldig; verwoestende services en snoeiharde aanvallen, maar vooral spelplezier en teamspirit zorgen ervoor dat we de vierde set winnen en daarmee ook de wedstrijd!

Het winnen van een volleybalwedstrijd is een ultieme teamprestatie. Raar toch, zult u misschien denken, dat ik deze sport beoefen terwijl een promotie echt een soloprestatie lijkt. Lijkt, want, dit proefschrift is geen soloprestatie. In veel opzichten lijkt een promotie op een volleybalwedstrijd; het schrijven van de artikelen is te vergelijken met het verliezen (als een manuscript wordt afgewezen) of het winnen (als een manuscript wordt geaccepteerd) van een set. Een volleybalwedstrijd kent, net als een promotie, zijn pieken en dalen en je hebt je teamgenoten zijn nodig om uit deze dalen te komen, voor steun, om te juichen als het goed gaat en voor de gezelligheid. Net als bij mijn volleybalteamgenoten, zijn er tijdens mijn promotietraject ook veel mensen die van belang zijn geweest en op (wetenschappelijke, sociale of mentale) manier hebben bijgedragen en die wil ik graag bedanken.

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Symbols and Abbreviations

BME	Bayesian Maximum Entropy
BP	Before present
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
c.v.	Coefficient of variation
DNDC	Denitrification-decomposition model
GHG	Greenhouse gas
GIS	Geographical Information System
ha	Hectare (100 x 100 m)
INITIATOR	Integrated NITrogen Impact Assessment Tool On a Regional Scale
IPCC	Intergovernmental Panel on Climate Change
kt	Kilotonne = 1 Gigagram = 10^9 gram
MC	Monte Carlo
MHW	Mean highest groundwater level
MLW	Mean lowest groundwater level
N	Nitrogen
N_2O	Nitrous oxide
N	Nitrogen
NIR	National Inventory Report
PDF	Probability Distribution Function
s.d.	Standard deviation
t	Tonne = 1 Megagram =10^6 gram (= 1000 kilogram)
WFPS	Water-filled pore space

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1

General Introduction

1.1 Role of N_2O in the greenhouse gas balance

1.1.1 The greenhouse effect

Climate is changing. Global average surface temperatures have raised 0.13ºC±0.03ºC over the past 50 years (IPCC, 2007a). The projections of climate change are alarming; a global mean temperature increase of 1.8ºC to 3.1ºC is projected for the last decade of the 21st century. The International Panel of Climate Change, IPCC (2007a), stated that most of the global warming since the mid-20th century is very likely caused by humans, or specifically, by the increase in anthropogenic greenhouse gas (GHG) concentrations. This is also known as the greenhouse effect. The best-known GHG is carbon dioxide (CO_2), which contributes approximately 77% (IPCC, 2007a) to the global GHG balance. It is also the largest source of global warming. However, also methane (CH_4) with a share of 14% and nitrous oxide (N_2O) with a share of 8% are significant components of the total GHG balance (IPCC, 2007a).

Nitrous oxide (N_2O) is a natural gas in the Earth's atmosphere. However, the atmospheric concentration has increased by 18% since pre-industrial times (IPCC, 2007a; Fig. 1.1). This increase is subject of concern, because N_2O is a long-lived GHG with a large global warming potential (310 times that of CO_2; IPCC, 2007b). N_2O is not

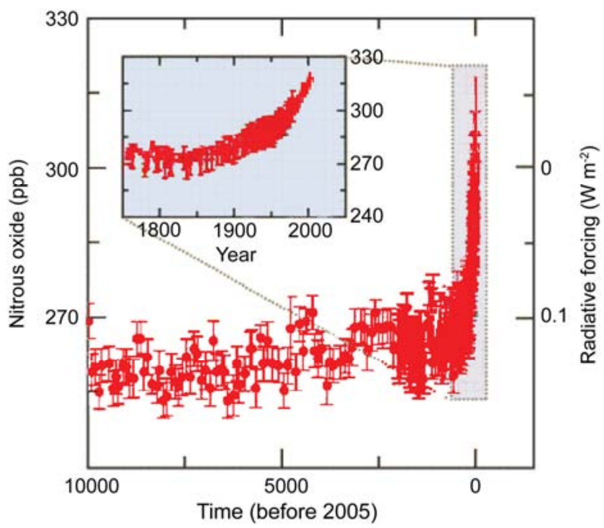

Fig. 1.1 Atmospheric concentrations of N_2O over the past 10,000 years (large panel) and since 1750 (inset panel). Measurements are derived from ice cores and atmospheric samples. The corresponding radiative forcing relative to 1750 is shown on the right hand axis of the large panel (IPCC, 2007a).

only a GHG, but it is also a destructor of stratospheric ozone (Crutzen, 1970) causing an increase in the amount of harmful solar radiation. N_2O is emitted by natural, anthropogenic, and interrelated sources. To get more insight into the processes of N_2O emission, it is necessary to look at the nitrogen cycle.

1.1.2 N_2O in the nitrogen cycle

A graphical sketch of the nitrogen (N) cycle is shown in Fig. 1.2. The main sources of human-related N_2O emissions are energy industries, transport, chemical industries, and waste handling. Notwithstanding the importance of these sources, agriculture is by far the largest source. The IPCC (2007b) indicated enhanced microbial production in expanding and fertilized agricultural areas as the primary driver for the increase of N_2O in the industrial era. In agriculture, N_2O is not solely produced by anthropogenic processes, but is a product of the interplay between nitrogen input and soil microbial processes.

About 78% of the Earth's atmosphere consists of inert N_2. Because this molecule has a strong triple bond, it is unavailable to most organisms (Galloway *et al.*, 2004).

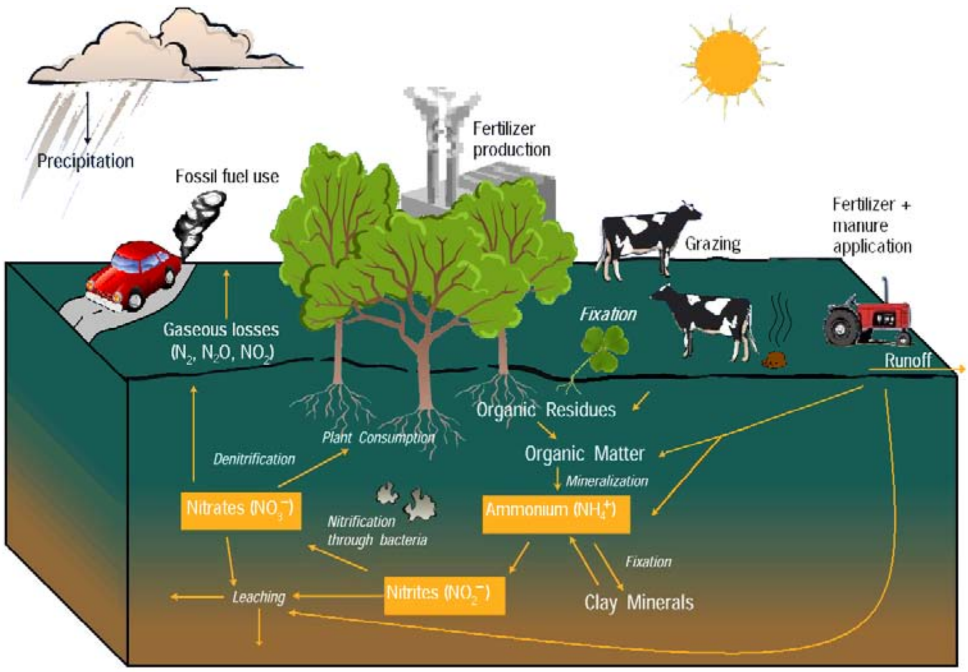

Fig. 1.2 The nitrogen cycle. Some of the most important sources and flows of N are shown (derived from NCAR)

Therefore, nitrogen is often most limiting in many ecosystems. Only few bacteria and archaea can fix nitrogen. Plants from the legume family (*Fabaceae* or *Leguminosae*), like clover, host N-fixing bacteria in their roots as suppliers of reactive forms of nitrogen (NO_3^- and NH_4^+).

Nitrogen application on agricultural soils causes an increase in the decomposition rate of soil organic matter (SOM). Decomposers, like bacteria and fungi, can decompose organic nitrogen into ammonium (NH_4^+). Nitrification, nitrifier denitrification, and denitrification produce most of the N_2O in soils (Firestone & Davidson, 1989; Granli & Bøckman, 1994; Wrage *et al.*, 2001). Nitrification is the process of oxidation of ammonia (NH_3) to nitrite (NO_2^-) and nitrate (NO_3^-; Fig. 1.3). Nitrate is very soluble and is leaches from the soil to surface and groundwater. It is the main cause of eutrophication of ecosystems. Denitrification and nitrifier denitrification are processes in which NO_3^- and NO_2^- are transformed into N_2 and N_2O. Wet soil conditions (a WFPS of about 60% to 70%) are optimal for N_2O emission. However, when the soil water content is continuously large, gasses are not able to escape from the soil. Therefore, N_2O is mainly produced when the soil experiences wet-dry cycles. Besides the WFPS, the availability of mineral N (NH_4^+ and NO_3^-), the availability of degradable organic carbon, the occurrence of frost-thaw cycles, and soil temperature are important controls of N_2O emission from soil. Besides the emission from agricultural soils, N_2O is also emitted by enteric fermentation and manure management in stables. However, these emissions are about ten times smaller (Van der Maas *et al.*, 2009) than the N_2O emission from agricultural soils. In this thesis, the emphasis is on N_2O emission from agricultural soils. Fig. 1.4 shows that the Netherlands has a very large gross N balance of soils compared to other OECD (Organisation for Economic Co-operation and Development) countries (OECD, 2008; OECD & EUROSTAT, 2007). The Netherlands also has the largest N_2O emission per hectare agricultural land in the European Union (Velthof *et al.*, 2009).

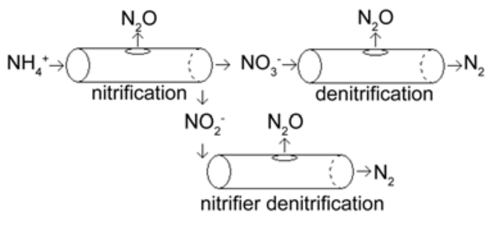

Fig. 1.3 The extended "hole-in-the-pipe" model indicates how N_2O is produced in the microbial processes of nitrification, nitrifier denitrification and denitrification (based on Firestone & Davidson, 1989; Wrage *et al.*, 2001).

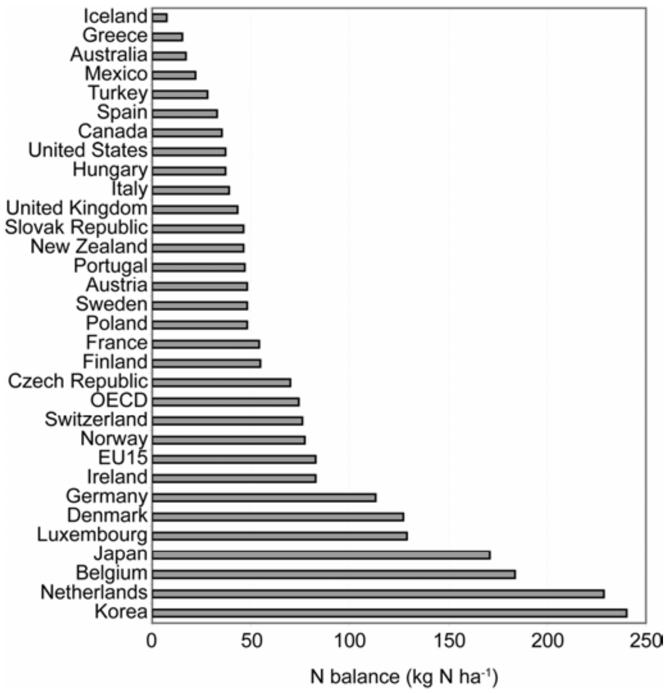

Fig. 1.4 Gross N balances for OECD countries (OECD, 2008).

1.1.3 Kyoto Protocol and Copenhagen

Countries are required to produce an annual national inventory of their GHG emissions under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (UNFCCC, 1997). Thirty-seven industrial countries and the European Community agreed upon reducing their GHG emission for the years 2008–2012 by 5% compared to the emission in 1990. The EU committed to decrease its emission to at least 30% below 1990 levels by 2020 (EU, 2008). At the Climate Conference in Copenhagen in 2009, delegates of 192 countries were not able to agree upon a new binding convention to reduce GHG emissions.

The IPCC produced guidelines (IPCC, 1997; IPCC, 2006) for making annual national GHG inventories. There are three different levels of complexity of the methodology, also called Tier levels. Tier 1 is the most basic level in which simple, linear equations and default data are used. Tier 2 is of intermediate complexity in which country-specific emission factors are used. Tier 3 is the most demanding in terms of complexity and

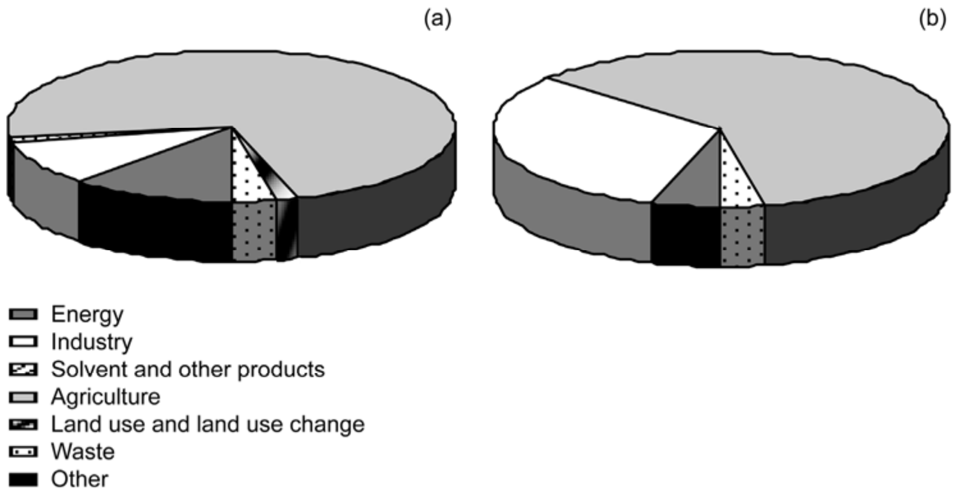

Fig. 1.5 Distribution of (a) global N_2O emission sources (Annex I countries; UNFCCC, 2010) and (b) Dutch N_2O emission sources (Van der Maas *et al*., 2009).

data requirements and comprises the use of process models and spatially explicit data stored in GIS.

In the last Dutch National Inventory Report (NIR; Fig 1.5), 29 of the 43 key sources identified are reported at Tier 2 level while the others are reported at Tier 1 level (Van der Maas *et al.*, 2009) The reported total N_2O emission from the Netherlands in 2007 is 50.3 Gg N_2O-N (or 15.6 Tg CO_2-eq), which is about 8% of the total Dutch GHG balance (207.5 Tg CO_2-eq). The reported GHG emissions in 1990, the base year, were 213.3 Tg CO_2-eq, which means that Dutch emissions in 2020 should be reduced to 170.6 Tg CO_2-eq or less.

To reach such a decrease in emission, the agricultural N_2O emission should be decreased because it is the main source of N_2O emission. Organic soils emit larger amounts of N_2O than mineral soils. The Dutch fen meadow landscape, which has both organic soils and a large agricultural sector, is an important hotspot of agricultural N_2O emission. Therefore, it is worthwhile to focus on N_2O emissions from this landscape.

1.2 The Dutch fen meadow landscape

The Dutch fen meadow landscape (Figs. 1.6, 1.7) is a geologically young area. During the most recent ice age (Weichselien, 116,000-11,500 yr BP), the entire Netherlands was covered by Pleistocene cover sands and the North Sea was almost completely dry. The Weichselien was followed by the warm Holocene era, in which sea level was rising.

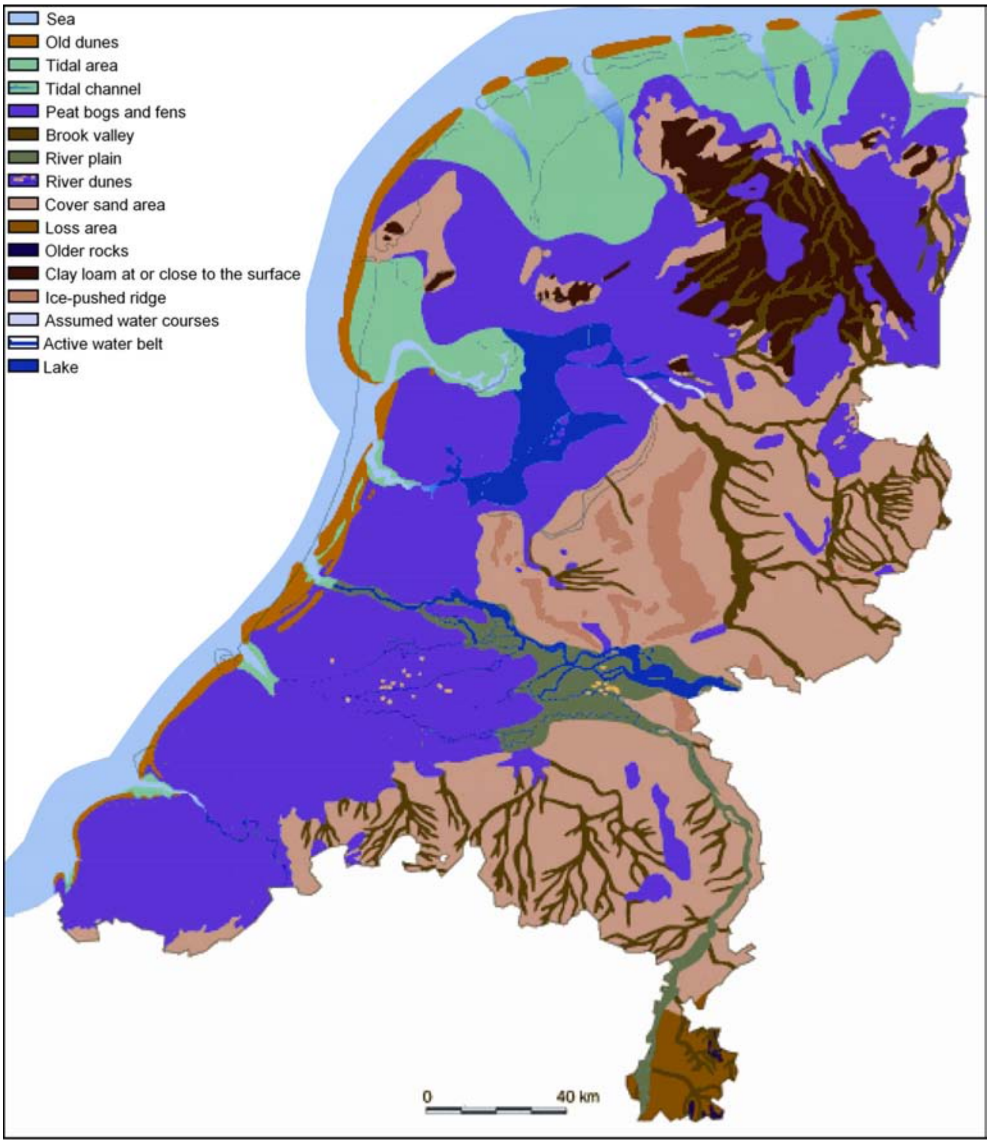

Fig. 1.6 The Netherlands about 3800 yr BP during the Subboreal age (based on TNO-NITG (2010)).

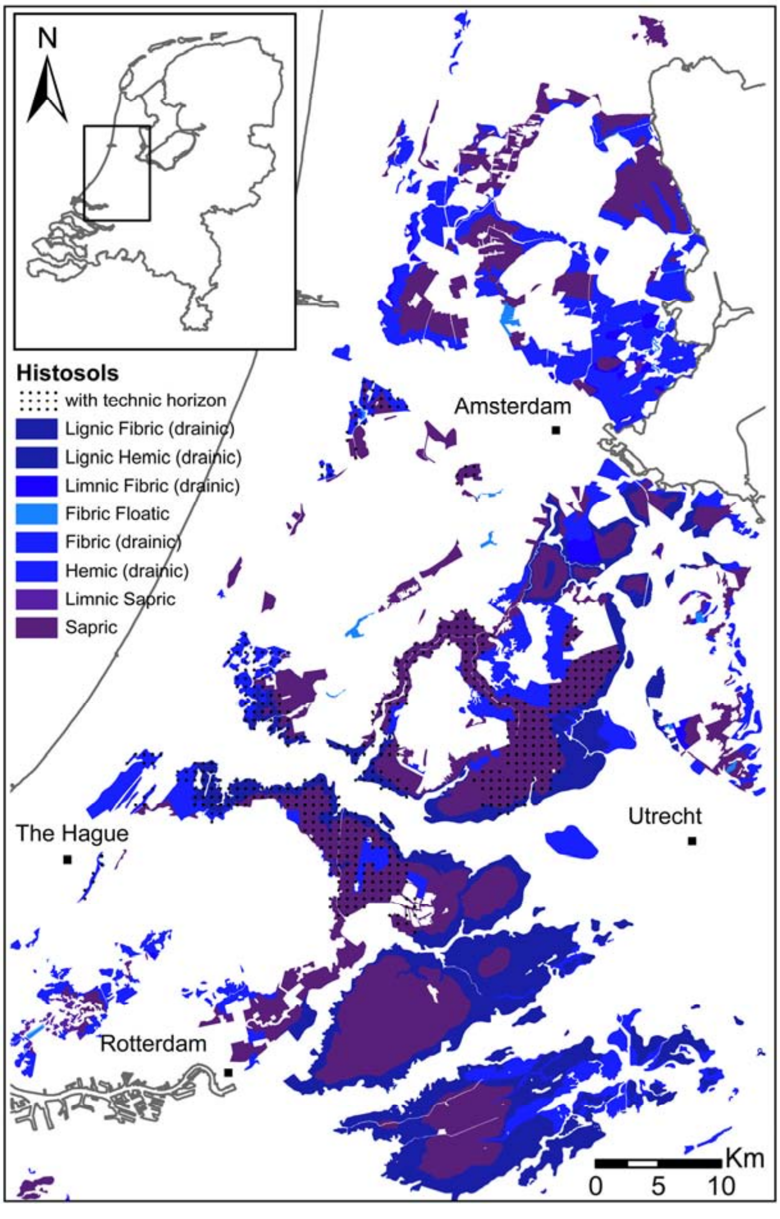

Fig. 1.7 Current location of the fen meadow landscape in the Netherlands (inset) and different peat soils (Histosols) according to the FAO classification.

The rate of sea level rise was not constant. In Western Europe, five periods in the Holocene can be distinguished. In two of these periods (Boreal and Subboreal, Table 1.1) with slow sea level rise, large areas in the Netherlands were covered by swamps. Besides the sea level rise, the northwest part of the Netherlands is also dipping down towards the North Sea due to tectonic subsidence. In the northeast part of the Netherlands nutrient-poor rainwater developed oligotrophic peat bogs; while in the western part of the Netherlands, nutrient-rich groundwater developed eutrophic fens. At some places in the west of the Netherlands peat domes developed on top of the fens. These peat deposits could reach a thickness of about 10 m. In the Early Subboreal age, about half of the Netherlands was covered by peat bogs and fens. During the Atlantic and Subatlantic ages, large tidal basins developed and parts of the peatland were washed away.

Table 1.1 Geological eras and corresponding sea level change

Period	Epoch	Years BP (ka)	Age	Sea level change
Quaternary	Holocene	2.4 – present	Subatlantic	fast rise
		5.7 – 2.4	Subboreal	slow rise
		9.2 – 5.7	Atlantic	fast rise
		10.6 – 9.2	Boreal	slow rise
		11.7 – 10.6	Preboreal	rise and drop
	Pleistocene	116 – 11.7	Weichselien (glacial age)	drop
		128 – 116	Eemien (interglacial age)	rise
		238 – 128	Saalien (glacial age)	drop
		$2.6*10^3$ – 238	Other ages	rise and drop

In medieval times, fens were reclaimed for agricultural use. The fens were drained by ditches, by deepened natural watercourses and by dams. Due to lowering of the groundwater levels, the peat started to oxidize and as a result the soil started to subsidize. First, the agricultural use was arable farming, mainly wheat cultivation. However, when the area became wetter due to soil subsidence, the main land use changed from arable land into grassland for dairy farming. Between the 16^{th} and the 19^{th} century, oligotrophic peat was excavated and used as fuel. The western fen meadow landscape still exists primarily of grassland on peat soils and is intensively managed and owned by dairy farmers. However, more and more grassland is being extensively managed by nature organizations. A recent development in the area is the increase in maize crops from 960 ha to 1940 ha between 2000 and 2009 (CBS, 2010).

The western fen meadow landscape (further called the 'the fen meadow landscape') is delineated by peat soils on the Dutch soil map 1:50,000 (De Vries *et al.*, 2003a) and covers approximately 16,000 ha (Fig. 1.7). Peat soils in the eastern part of the Netherlands are not part of the fen meadow landscape, because they have different characteristics (i.e., they have smaller peat layers, they have different land use, and they are mainly bogs instead of fens). The fen meadow landscape is thus bordered by the 'IJsselmeer' in the northeast and the line dividing land below and above sea level in the southeast. To estimate N_2O emissions for the fen meadow landscape, inventory methods or models are used.

1.3 Inventory methods and models

1.3.1 Tier methods

Three levels of complexity of the inventory methodology; also called Tier levels as distinguished by the IPCC, vary from basic methods with simple equations and default data to complex process models; which requires large amounts of data. The Tier 1 method makes use of activity data (e.g., animal numbers, car numbers) that are multiplied by a default emission factor. Countries that ratified the Kyoto protocol should specify their key emission sources, i.e., which sources have large emissions (level) or large changes in emissions (trend). Non-key sources can be reported at Tier 1 level. For key sources, Tier 2 or Tier 3 level inventories should be used (IPCC, 2000a). At Tier 2 level, country-specific emission factors and nationally derived data are used. Tier 3 methods make use of process models, such as DNDC (Li *et al.*, 1992) and Century (Parton, 1996). The simplified INITIATOR model (De Vries *et al.*, 2003b) is used for analyses in between Tier 2 and Tier 3 level. Because this model has been extensively used in this thesis, it will be described in detail in the next section.

1.3.2 INITIATOR

The INITIATOR model (Integrated Nitrogen Impact Assessment Tool on a Regional scale) is developed to gain insight in all nitrogen flows in the Netherlands and their uncertainties (De Vries *et al.*, 2003b). An advantage of this model is that it is simple, transparent, and does not require detailed input data. Another reason why this model has been frequently used in this thesis is that N flows in the typical Dutch fen meadow landscape are adequately modelled by INITIATOR (De Vries *et al.*, 2001; De Vries *et al.*, 2003b). The Dutch fen meadow landscape is unique, because it has been cultivated for centuries and it has thick mesotrophic and eutrophic peat soils in combination with intensive dairy farming. This requires tailored modelling, which has been incorporated in INITIATOR.

The INITIATOR model includes N inputs and N transformations in terrestrial and aquatic ecosystems. An overview of the main N flows in INITIATOR is shown in Fig. 1.8. Nitrogen is supplied to the soil by deposition, biological fixation, application of animal manure

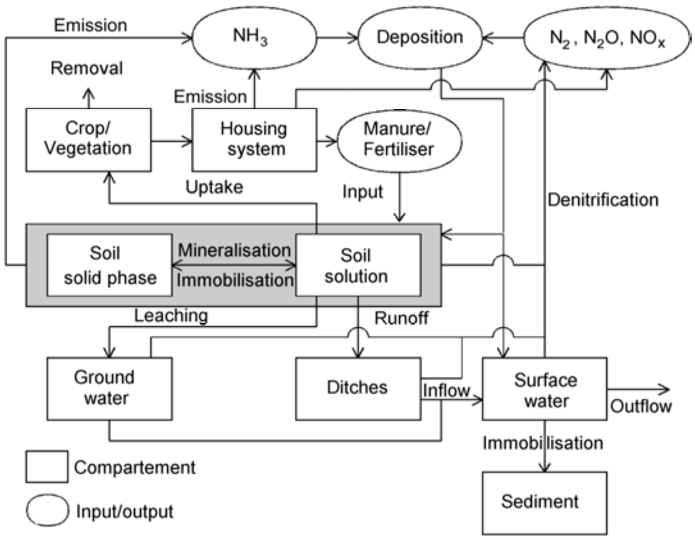

Fig. 1.8 Overview of N inputs and processes in terrestrial and aquatic ecosystems in INITIATOR (de Vries *et al.*, 2001)

and synthetic fertilisers. Ammonia emissions can arise from housing, grazing, application of animal manure, and application of synthetic fertilisers. Nitrogen is taken up by vegetation and removed by mowing, by grazing cattle as meat and milk or recycled as manure. Nitrogen in the soil is transformed from organic to mineral forms by mineralization or vice versa by immobilization. Nitrification and denitrification in soil, groundwater, and ditches cause N_2O emission. INITIATOR uses manure and fertilizer input numbers in kg per ha. Therefore, available data, such as animal numbers and excretion fractions, are used to allocate fertilizers and manure within the Netherlands. Other inputs are landuse and soil type. All inputs and model parameters are described in the Annex. The spatial resolution of the model is 250 m and the temporal resolution one year. The spatial extent of INITIATOR is the Netherlands, however, in this thesis the focus is on the fen meadow landscape.

1.3.3 Other methods and models

Besides the INITIATOR model, many other models are capable of simulating N_2O emission. They vary in scale, complexity, and focus. A widely used model, also used in this thesis, for simulating N_2O emissions is the DeNitrification-DeComposition (DNDC) model (Li *et al.*, 1992). It is a process-based model, which can simulate C and N biogeochemistry in agro-ecosystems. DNDC was extended for certain ecosystems (Forest-DNDC, Wetland-DNDC)f coupled to other models (e.g. CAPRI-DNDC, EFEM-

DNDC). Descriptions of the DNDC model can be found in Chapter 3 and in Li *et al.* (1992).

The DAYCENT model (Del Grosso *et al.*, 2006) is an extended version of the CENTURY model (Parton, 1996) that uses daily time steps. DAYCENT is very comparable to DNDC, because it is also a biogeochemical model including C and N cycles. However, P and S cycles are also included and this model is more complex and requires much data. The model SWAP-ANIMO is even more complex and data requiring. The coupled models SWAP and ANIMO calculate the flow and quantity of water and nutrients from and to soil and surface water (Kroes *et al.*, 2008). Due to the complexity and data requirements, these models are best suited for GHG inventory at field scale. The detailed coupled model is a valuable tool for understanding emission processes at small scales (Stolk *et al.*, subm.). MITERRA-EUROPE (Oenema *et al.*, 2007; Velthof *et al.*, 2009) is a simpler model, which has a deterministic and static N cycle and uses emission factors and leaching fractions. The model can be classified as an IPCC Tier 2 method. The model can be applied to large scales (Europe) and was developed to demonstrate the effects of different policy measures.

1.3.4 Scales of GHG inventories and measurements

Since GHG emissions are measured and modelled at different spatial and temporal scales, it is important to introduce some concepts of scale. The impreciseness of the term 'scale' contributes to the difficulty of developing universal theories of scale effects (Curran *et al.*, 1997). The meaning of 'scale' varies across (and within) disciplines (Evans *et al.*, 2003). Gibson (2000) defined scale as the spatial, temporal, quantitative or analytical dimensions used to measure and study any phenomenon. Bierkens *et al.* (2000) focused on methods for environmental research. They defined scale as the temporal and spatial units at which information is available or required. In this thesis, the term 'scale' is limited to spatial and temporal dimensions. Scale is assumed to consist of the triplet support, extent, and resolution (Western & Blöschl, 1999). The extent is defined as the area or time interval over which model outcomes are simulated or over which observations are made (Bierkens *et al.*, 2000). The resolution is the grain (cell size) or timestep, which a model uses. The support indicates the size, shape, volume, and/or orientation of samples or model entities. An example is used to explain the difference between resolution, extent, and support. When an N_2O measurement is made every hour during 5 minutes for one day (24 hour); the extent of the experiment is one day (24 hour), the resolution is one hour, and the support 5 minutes. The choices about support, extent, and resolution critically affect the type of patterns that will be observed, because patterns that appear at one scale may be lost at smaller or larger scales.

Results of investigations are scale dependent (Gibson, 2000). Observations and theories derived at one scale may not apply at another. Furthermore, the differences observed between locations at different scales may be enormous, with, for instance, large changes in both the strength and direction of relationships noted when the scale of the study changes (Curran *et al.*, 1997). Ecologists call this the 'ecological fallacy' and geographers call it the 'Modifiable Areal Unit Problem (MAUP)' (Openshaw, 1983). The ecological fallacy or MAUP consists of two problems: (1) a scale problem in which variation in results that can often be obtained when data for one set of areal units are progressively aggregated into fewer or larger units and (2) an aggregation problem in which alternative combinations of areal units exist at equal or similar scales. Easterling (1997) showed how Integrated Assessment Models, such as global climate models, suffer from MAUP. Rastetter *et al.* (1992) illustrated that aggregation of CO_2 uptake (by photsynthesis) is overestimated due to the MAUP, even for an idealized canopy in with leaves that are oriented horizontal and homogenously distributed. In this thesis, spatial scale plays an important role and many different spatial scales are used; from point scale to national scale. GHGs are usually measured at small spatial support, with boxes of about a few dm^2 to a few m^2 or with measurement towers that cover a few tens of m^2 to a few km^2. However, for the NIR, GHG emissions should be reported at national scale. Therefore, upscaling is necessary. In §1.3.1, §1.3.2, and §1.3.3 different upscaling methods are presented. Nevertheless, upscaling (and downscaling) introduces errors. The objective of the study determines, ideally, the support of the measurement or model. However, researchers often depend on available data and available models, which are not always at the preferred scale. Therefore, they should be cautious using these data models for their own objectives. Heuvelink (1998b) and Verburg *et al.* (2006) warn for directly applying fine-scale relations and models on larger scales. The problem is that the aggregate does not generally behave the same way as the fine-scale components from which it is constituted, because of feedbacks within the system and non-linear system behaviour. Different processes act on different scales.

Besides spatial scale, temporal scale also plays an important role in this thesis. Considered temporal scales in this thesis differ from seconds and hours to years and decades. Scaling issues along spatial dimensions have much in common with scaling issues along temporal dimensions. For instance, GHG models with an annual resolution describe different processes than GHG models that operate at daily resolution.

1.4 Uncertainty of N_2O emission inventories

1.4.1 Dimensions of uncertainty

Dealing with uncertainty is an important issue in GHG inventory (IPCC, 2007b). However, just as the definition of 'scale', also the definition of 'uncertainty' is subject of debate. Walker *et al.* (2003) defined uncertainty as any deviation from the unachievable ideal of completely deterministic knowledge of the system under consideration. While others assumed that uncertainty is the state of mind that expresses a lack of confidence about reality or an expression of our lack of confidence about what we 'know' (Brown & Heuvelink, 2005). The main difference between these definitions is that Walker *et al.* assumed that uncertainty is a property of the system (or model), while others interpret uncertainty as a perspective of a person. Rypdal *et al.* (2001) investigated the uncertainty of GHG inventories and stated that uncertainty covers all sources of errors due to limited knowledge. Uncertainty can arise from a variety of sources. According to Walker *et al.* (2003) sources of uncertainty are model context (boundaries, completeness), model structure (variables and their relationships), model inputs (drivers), parameters (data, calibration), and model outcome (important for decision makers). Measurements can also be a source of uncertainty, due to limitations in the measurement equipment (Kroon *et al.*, 2008). In this thesis, different sources of uncertainty of N_2O emission inventory will be described and their size of uncertainty will be estimated. Three ways to express the size of uncertainty are used. The first way is the standard deviation (s.d.) of a sample of observations, which is defined as the square root of the mean squared deviations about the mean (Burt & Barber, 1995). The second way is the relative standard error (IPCC, 2000a), which is the standard deviation divided by the mean and typically expressed as a percentage. The third way is the range or confidence interval, which is an interval that contains the majority of the values of an uncertain parameter (e.g. the 95% confidence interval).

1.4.2 Uncertainty in N_2O emission inventories

Inventories of N_2O emission are notorious for their large uncertainties. Whereas in the Dutch NIR (Van der Maas *et al.*, 2009) the uncertainty in CO_2 emission is about 3% and in CH_4 emission about 25%, the uncertainty in N_2O emission is about 50% at Tier 1 level. Olsthoorn & Pielaat (2002) and Olivier *et al.* (2001) estimated the uncertainty of Dutch agricultural N_2O emissions for the IPCC Tier 1 and Tier 2 methods using Monte Carlo analysis. De Vries *et al.* (2003b) performed a Monte Carlo uncertainty analysis to assess the propagation of errors in input parameters on N_2O and NH_3 emissions and NO_3^- and NH_4^+ leaching and runoff. The 90% confidence interval for N_2O emission in the Netherlands ranged considerably between 18 and 51 Gg N yr^{-1} for the year 1993.

Olsthoorn & Pielaat (2002) and Olivier *et al.* (2001) also found large uncertainty ranges. The 95% confidence interval at Tier 1 level was 20.1 – 48.4 Gg N_2O-N (Olivier *et al.*, 2001) and 25 – 64 Gg N_2O-N (Olsthoorn & Pielaat, 2002) at Tier 2 level for the year 1999. They concluded that most uncertainty arises from lack of knowledge of soil processes that produce N_2O. Further, the spatial variability of factors such as groundwater level is unknown; while both are essential for making accurate N_2O emission estimates. Emission factors used in these studies are based on research that date back to before the nineties; nowadays, emission factors are more up-to-date (Van der Hoek *et al.*, 2007). Especially the emission factors for application of manure and synthetic fertiliser contribute to a large uncertainty in the N_2O emission inventory.

Recent research also pointed out that uncertainties of N_2O emission inventories are large and our ability to predict N_2O fluxes is still limited (Reis *et al.*, 2009; Tonitto *et al.*, 2009). The IPCC (2007b) also report that large uncertainties in the major soil, agricultural, combustion, and oceanic sources of N_2O exists.

Researchers point to the large spatial and temporal variation in N_2O emission as a main source of uncertainty (e.g. Ball *et al.*, 2000; Jones *et al.*, 2005; Kroon *et al.*, 2008; Velthof *et al.*, 1996a; Velthof *et al.*, 1996b). Spatial variation at field scale is mainly caused by spatial variation in denitrification and nitrification processes; which are influenced by soil conditions. In peatlands, especially the soil water content and the groundwater level affect N_2O emission. Wet soils with a soil water content of about 70% are believed to have the largest N_2O emission potential (§1.1.2); however, deep groundwater levels are assumed to enhance mineralization and accordingly large N_2O emissions are expected. At landscape scale, spatial variation is mainly influenced by land use and management. Intensively management agricultural areas have much larger N_2O emissions than other areas; therefore, the exact location and magnitude of agricultural areas are important factors in reducing uncertainties in landscape scale N_2O emission inventories. Variation is also dependent on measurement support; a small support in N_2O measurements will cause a large variation in results when scaling up. The large temporal variation in N_2O emissions is shown by large peak emissions related to N input (by chemical fertilizers or manure application), rain showers, or freeze-thaw cycles.

1.5 Objectives

The main objective of this PhD thesis is to determine and quantify various sources of uncertainty of N_2O emission inventories for the Dutch fen meadow landscape. This objective can be divided into research goals based on different sources of uncertainty:

1. What is the uncertainty as a result of spatial upscaling?
   - Analyse how different land cover representations potentially introduce systematic errors into the results of regional N_2O emission inventories.
   - Compare the effect of different land cover representations on N_2O emission between two different N_2O inventory methods.
2. What is the uncertainty as a result of temporal upscaling?
   - Analyse the effect of temporal resolution by comparing annual N_2O emissions from two models with different temporal resolutions for the period 2001–2006.
   - Estimate emission factors for the simulated years and compare these with emission factors used in the Tier 1 and Dutch Tier 2 methods.
3. What is the uncertainty as a result of uncertainty in model inputs?
   - Quantify the uncertainty of N_2O emission estimates due to uncertain model inputs at point and landscape scale.
   - Identify the main sources of model input uncertainty at both scales.
4. What is the uncertainty originating from variation in land use change?
   - Estimate changes in N_2O emission for the period 2006–2040 under different scenarios.
   - Quantify the share of different emission sources in the scenarios.
   - Compare the uncertainty of N_2O emissions due to the diverging scenario conditions with to other uncertainties in N_2O emission inventories.

The focus of quantifying these different sources of uncertainty is limited to soil-bound N_2O emissions from agriculture and natural sources in the Dutch fen meadow landscape.

1.6 Outline of this thesis

This PhD thesis brings together different types, aspects, and scales of uncertainty in inventorying N_2O emissions. The following four chapters contain the body of this thesis and contain publications (two published and two submitted) to international scientific journals. In each of these chapters, a different type of uncertainty or aspect of uncertainty in N_2O emission from the Dutch fen meadow landscape is discussed. Chapter 2 addresses the effect of land cover data on N_2O emission inventories. In this chapter, the influence of differences in spatial scale between the land cover databases and differences between aims of the databases on N_2O emission inventories will be findings and some recommendations for future research. Chapter 3 focuses on the effect of temporal resolution on N_2O emission inventories. To quantify the uncertainty caused by temporal resolution, two models with different temporal resolution are used. In Chapter 4, the uncertainty due to model inputs is quantified and their propagation through INITIATOR is analysed. This chapter also identifies the largest sources of uncertainty among the uncertain inputs. Chapter 5 describes the uncertainty in future N_2O emissions, due land use change induced by socio-economic developments. Using three diverging scenarios for the Dutch fen meadow landscape, development of N_2O emission until 2040 is assessed. Finally, Chapter 6 contains a general synthesis that reports the main conclusions and puts the results into a broader perspective.

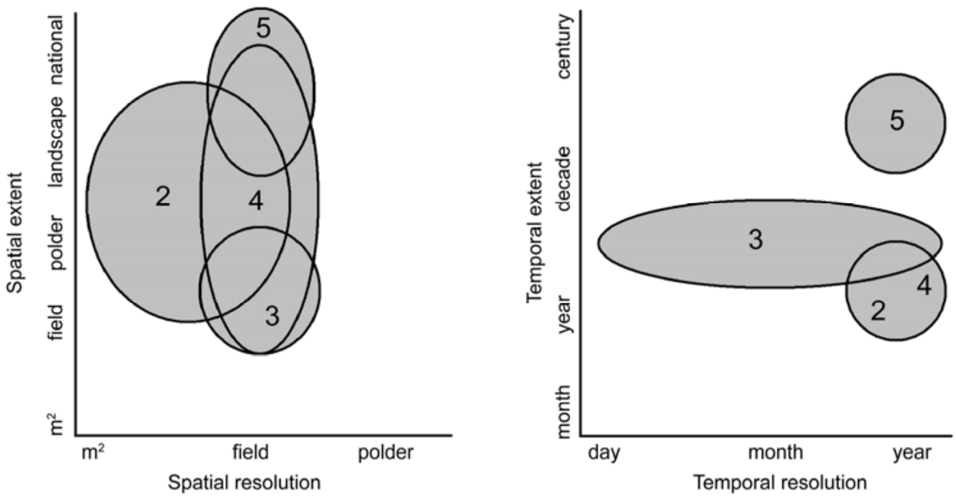

Fig. 1.9 Location of chapters 2 to 5 at spatial and temporal scales.

2

Effect of land cover data on N_2O inventories in the Dutch fen meadow landscape

Abstract

Landscape representations based on land cover databases differ significantly from the real landscape. Using a land cover database with high uncertainty as input for emission inventory analyses can cause propagation of systematic and random errors. The objective of this chapter was to analyse how different land cover representations introduce systematic errors into the results of regional nitrous oxide (N_2O) emission inventories. Surface areas of grassland, ditches, and ditch banks were estimated for two polders in the Dutch fen meadow landscape using five land cover representations: four commonly used databases and a detailed field map, which most closely resembles the real landscape. These estimated surface areas were scaled up to the Dutch fen meadow landscape. Based on the estimated surface areas agricultural N_2O emissions were estimated using different inventory techniques. All four common databases overestimated the grassland area when compared to the field map. This caused a considerable overestimation of agricultural N_2O emissions, ranging from 9% for more detailed databases to 11% for the coarsest database. The effect of poor land cover representation was larger for an inventory method based on a process model than for inventory methods based on simple emission factors. Although the effect of errors in land cover representations may be small compared to the effect of uncertainties in emission factors, these effects are systematic (i.e., cause bias) and do not cancel out by spatial upscaling. Moreover, bias in land cover representations can be quantified or reduced by careful selection of the land cover database.

Based on: Nol, L., Verburg, P.H., Heuvelink, G.B.M. and Molenaar, K. (2008)
Journal of Environmental Quality, 37(3): 1209-1219

2.1 Introduction

Every land cover map or database is a simplification of the complexity of a real landscape (Arbia *et al.*, 1998; Regnauld, 2001; Schmit *et al.*, 2006). However, the scale and mapping technique are a source of variation when comparing different land cover maps (Bach *et al.*, 2006; Ellis, 2004; Schmit *et al.*, 2006; Verburg *et al.*, 2006). Differences between a land cover database and a real landscape are a source of error when the database is utilized (Fang *et al.*, 2006; Fassnacht *et al.*, 2006; Foody, 2002). The large dependence of GHG emissions on land use makes land cover data an essential input in GHG inventories (Denier van der Gon *et al.*, 2000; Kern *et al.*, 1997; Matthews *et al.*, 2000; Plant, 1999). Recently Huffman (2006) acknowledged the need for highly accurate, high-resolution, and nationally consistent land cover data, while others have argued for statistically rigorous and accurate assessment of thematic maps (Heuvelink & Burrough, 2002; Stehman & Czaplewski, 1998). A lot of research has been performed to improve GHG inventories (Denier van der Gon & Bleeker, 2005; Kroeze, 1994; Li *et al.*, 1992; Stacey *et al.*, 2006), but careful analysis of how systematic errors in land cover data affect these inventories has received little attention. Often considerable emphasis is given to the provision of the most exact input data possible for soil and climate while little thought is given to the quality and accuracy of land cover or land use data (Bach *et al.*, 2006; Jansen, 1998a). Bareth *et al.* (2001) noted that the accuracy of spatial data should be regarded with more importance in the estimation of N_2O emissions.

Signatories to the Kyoto Protocol (UNFCCC, 1997) must annually report emissions of their GHGs CO_2, CH_4, and N_2O. The IPCC has established Good Practice Guidelines for reporting and upscaling national GHG emissions. The inventory methods are divided into three levels of increasing complexity and classified as: Tier 1, Tier 2, and Tier 3 (§1.3.1, IPCC, 1997; IPCC, 2000a).

Many countries are still striving to fulfil the Kyoto reporting requirements (Bolan *et al.*, 2004; Brown *et al.*, 2002; Saggar *et al.*, 2004). Especially problematic are methods for N_2O emissions from agricultural soils (Lokupitiya & Paustian, 2006). For the Netherlands, Kuikman *et al.* (2004) stated that current reporting to the Kyoto protocol is incomplete or inaccurate: several sources may not have been identified and others may well be reported incompletely. Accordingly, it is important to focus on decreasing the uncertainty and improving data quality of N_2O emissions from agricultural soils (§1.1). An important source of N_2O emissions from agricultural soils is the emission from 'cultivation of histosols', which differs from estimation of other agricultural N_2O sources because it requires spatial input data. Cultivation of histosols leads to oxidation of organic matter from peat soils due to the lowering of groundwater tables in cultivated areas. Emission of N_2O from cultivated histosols in the Netherlands has been estimated to contribute 10% of the direct N_2O emissions from soils and 5% of the total N_2O emissions from agriculture (Klein Goldewijk *et al.*, 2005). Histosols cover a significant area (approximately 9% of the land surface) in the Netherlands (CBS, 2007; Kuikman *et al.*, 2005) and are predominantly situated in the fen meadow landscape. The main elements of Dutch fen meadow landscape are grassland parcels, ditches, and ditch banks, each with specific emission characteristics (Best & Jacobs, 1997; Van Beek *et al.*, 2004b).

The estimation of land surface area occupied by histosols and the main landscape elements depend on the available spatial input information and associated resolution. The scale of analysis or kind of information an investigator desires also influences the outcomes of the inventory. For example, if an investigator can choose between different land cover databases, each with a different resolution, then the choice for a certain database depends on the element of interest (Woodcock & Strahler, 1987). The optimum scale of analysis is usually the scale at which processes, in this case N_2O emission, occur (Allen *et al.*, 1984). Denitrification and nitrification are the most important processes in converting N into N_2O in soils ({§1.1.2, Firestone & Davidson, 1989). These processes take place at the microbial scale, whereas national inventories require emissions to be reported on a national scale. These inventories are often based on emission factors derived from small-scale chamber measurements (0.03–6 m^2). The chamber measurements in fen meadow landscapes have mainly taken place on grassland parcels, preferably not too close to the ditch (Ambus & Christensen, 1994). Since different landscape elements have different emission characteristics, it is worthwhile estimating the surface area of the different landscape elements using land cover databases and investigating the effect of using these land cover databases on the N_2O emission inventory. The objective of this paper was to analyse how different land cover representations potentially introduce systematic errors into the results of N_2O emission inventories at landscape scale. To this end, five different land cover databases with differences in spatial resolution and accuracy were used in combination with four inventory methods. Understanding the influence of land cover databases on outcomes of emission inventories may help in the further refinement of reporting protocols.

2.2 Materials and methods

N_2O emissions were calculated using different upscaling methods based on alternative land cover databases for two representative landscapes in the Dutch fen meadow landscape. Implications at landscape scale of using alternative land cover databases were analysed by scaling the results up to the fen meadow landscape.

2.2.1 Reclamations in the fen meadow landscape

The formation of the Dutch fen meadow landscape (Figs. 1.7, 2.1) is described in §1.2. From medieval times until the 16th century, this land was reclaimed for agricultural use. A popular way of reclaiming the land was by 'cope agreements'. In these agreements, the length of the parcel was usually prescribed to be about ten times the width of the parcel. This pattern of parcels with the same shape is still recognizable in the fen meadows. However, a common strategy was not applied everywhere resulting in areas with more irregular reclamations. Between the 16th and the 19th century oligotrophic peat was excavated and used as fuel. Today, lakes and grassland intersected by wide ditches are located in these areas. The fen meadow landscape exists primarily of grassland on peat soils and is intensively managed and owned by dairy farmers; however, more and more grassland is being extensively managed by nature organizations.

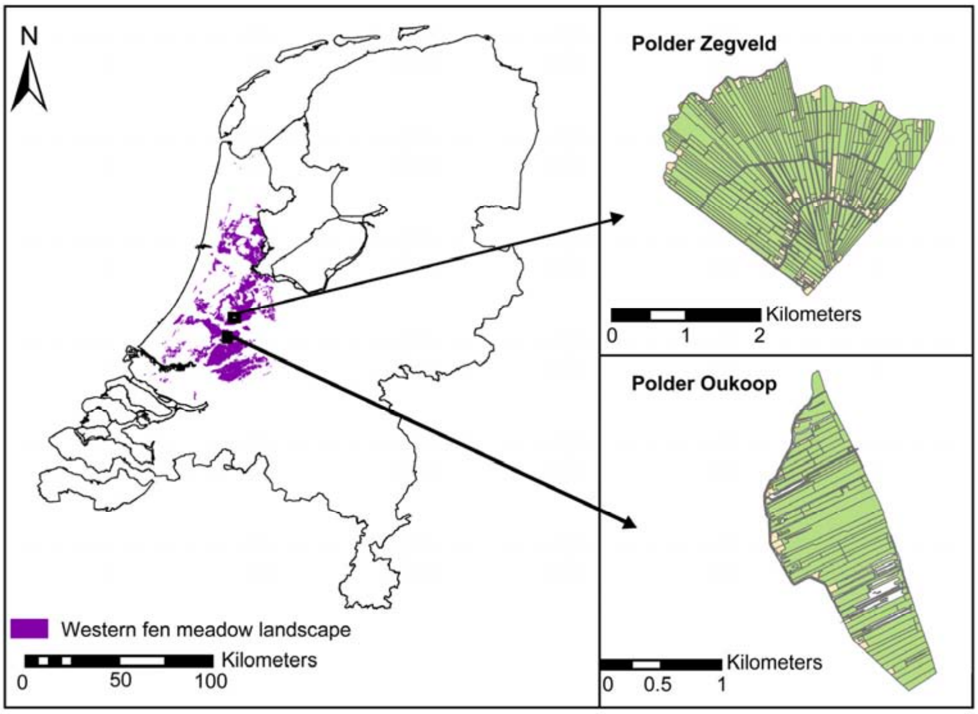

Fig. 2.1 Location of the research polders in the Netherlands.

The Zegveld and Oukoop polders (Fig. 2.1) were chosen as case studies of the two most dominant reclamation types within the Dutch fen meadow landscape: cope (regular) reclamation and reclamation with wide ditches.

The Zegveld polder (52°08"N, 4°48"E) has a surface area of 670 ha (Fig. 2.1) and is representative of the 'cope' reclamation type. The area was reclaimed in the 11th century. The village of Zegveld (Fig. 2.1; south corner) was the reclamation base from where the reclamation of the area started. The parcels stretch from Zegveld to the peat river Meije bordering the north of the polder. Many farms have settled in the centre of the parcels. The polder was one of the latest reclamations in the area, which gave the polder its peculiar shape. At the reclamation base in the south, the parcels are narrow becoming wider toward the north. The polder is predominantly drained 60-cm depth but an area of natural vegetation (25 ha) in the northwest is drained at approximately 30 cm below surface level.

The Oukoop polder (52°03"N, 4°43"E) is smaller than the Zegveld polder and has a surface area of 168 ha (Fig. 2.1). The area was reclaimed in the 11th or 12th century and is representative of the reclamation type with wide ditches. The polder was enclosed by reclamations from the Hollandse IJssel river in the south, the Oude Rijn river in the north, and an old stream (the 'Oude Wetering') in the east. Both peat soils are classified as Terric Histosol and originate from wood and reeds.

2.2.2 Land Cover Databases

Surface areas occupied by grassland parcels, ditches, and ditch banks were estimated for the two research polders and for the entire fen meadow landscape based on five land cover databases. The emissions of N_2O differ with elements in the landscape. Therefore, these landscape elements were separately accounted for in the analysis. The five land cover databases used, more or less ranked in order of decreasing resolution and accuracy, were: a detailed field map unit of the distinguished landscape elements, Top10Vector, LGN4, CBS soil use, and CLC2000.

Fang *et al.* (2006) pinpointed the importance of taking the uncertainty of land cover databases into consideration when using these for landscape studies. The five databases used in this study differ in uncertainty. Uncertainties in vector databases can be subdivided into geometric uncertainty and thematic uncertainty (Heuvelink *et al.*, 2007). Geometric or positional uncertainty is uncertainty about the shape and the location of an object. Thematic uncertainty is uncertainty about the attribute values of an object and occurs in both vector and raster data. It is mainly caused by interpolation errors and wrong classification of pixels or mapping units (Bolstad & Smith, 1992;

Foody, 2002; Steele *et al.*, 1998; Van Oort, 2005). The resolution or minimum mapping unit of the land cover database is a source of geometric uncertainty (Hengl, 2006). This problem, the modifiable areal unit problem (see also §1.3.4), is especially problematic when there are discrete changes within landscapes. Depending on the resolution and shape of data elements, almost any result may be obtained (Openshaw, 1983). In this paper the effect of the differences in geometry and resolution on the estimation of the prevalence of the different landscape elements, important to N_2O emission, was evaluated. Details about the used land cover databases are given in Table 2.1.

The goal of the field map was to accurately delineate ditches and ditch banks (positional uncertainty < 0.2 m in width) and quantifying the surface area of these landscape elements with negligible bias (i.e., much smaller than bias associated with the four commonly used databases). The aim was to measure all ditch widths in the polder, but due to inaccessibility a number of ditch widths had to be estimated. In polder Zegveld 91% of all ditches were measured, 8% were estimated in the field, and 1% was estimated using the Top10Vector and aerial photographs. In polder Oukoop 68% of all ditches were measured, 12% were estimated in the field, and 20% were estimated using the Top10Vector and aerial photographs. The boundary between ditch bank and grassland was defined as the line that separates areas with a clear slope gradient from those without a slope or with minimal relief (slope < 1°). The surface area of ditches and ditch banks were then calculated using the widths from the field map and the lengths from the Top10Vector topographic database. This was acceptable because the bias of the Top10Vector in ditch lengths was small compared to the bias in ditch widths. The Top10Vector was used as the basis for the field map, the ditches were adjusted to the measured ditch widths and ditch banks were added. In the database resulting from the field map, a distinction was made between intensively and extensively managed grassland. The extensively managed grassland was managed by a governmental organization, and was unfertilized and grazed by sheep and beef cattle. The grazing pressure was lower than on the intensively managed grassland, used for dairy cattle.

The Top10Vector database is a detailed topographic database of the Netherlands made by the Dutch National Mapping Agency (TDK). The Top10Vector is a vector file with a closed field structure; built up from coded lines enabling the user to select fields with certain characteristics. The Top10Vector is based on aerial photograph interpretation in combination with field investigation. It consists of several point, line, and polygon layers. The database is partly updated every year and the entire Netherlands is updated each 4 yr. The geometric uncertainty of the Top10Vector database is estimated at 2 m (Van Buren *et al.*, 2003).

Table 2.1 Characteristics of land cover databases.

Type	Year of validity	Minimum mapping unit	Grid cell	Projection	Extent	No. of categories	Source
Field map							
Vector	2006	0.2 m (ditch) 2 m (roads)	–	RD (Dutch)[b]	Research Polders	12	–
Top10Vector							
Vector	2000–2004	3 m (ditch) 2 m (roads)[a]	–	RD (Dutch)[b]	Netherlands	50	TDN (2006)
CBS soil use							
Vector	2000	10,000 m^2 [c]	–	RD (Dutch)[b]	Netherlands	38	CBS (2002)
LGN4							
Raster	1999–2000	5000 m^2	25 m	RD (Dutch)[b]	Netherlands	39	GeoDesk (2006)
CLC2000							
Raster	2000	250,000 m^2	100 m	Lambert Azimuthal	Europe	43	EEA (2000)

[a] Vliegen (2000).
[b] RD = Dutch National Grid.
[c] Except for roads and railroads, which are all included in the database.

The CBS soil use database consists of soil use areas and boundaries. For agricultural land cover the only distinction made is between horticulture under glass and other agricultural use. The Top10Vector was used for the basic geometry (water, railroads, and roads). The geometric uncertainty of the topography is therefore also 2 m (CBS, 2002). The main difference is the larger minimum mapping unit of the CBS soil use database (Table 2.1), which leads to an additional source of geometric uncertainty.

In the analysis of the results, the linkage between the two databases was taken into account. The CBS soil use database provides insight into the distribution of different soil use types in the Netherlands and is used by the Statistics Netherlands (CBS) for deriving surface area and density statistics for regional classifications.

The LGN4 is a land use database for the Netherlands and is based on satellite images from 1999 and 2000 (De Wit, 2001). The LGN4 exists of grid data and vector data of crops. The grid data contain the dominant land cover type per 25 by 25 m grid cell. In total 39 land cover types are distinguished. In this research, only grid data were used, because cropland is marginal in the fen meadow landscape. The main difference between LGN4 and the CBS soil use database is that LGN4 focuses on agricultural land cover whereas CBS soil use focuses more on urban land cover. The category agriculture is split into ten classes and the category nature has seventeen classes where a distinction is made between intensively and extensively managed grassland. Validation of the LGN4 was executed by checking 4000 points using aerial photos and the

Top10Vector. The overall thematic accuracy of the LGN4 was estimated to be 92.2% (GeoDesk, 2006). However, large differences exist between classes. Classes with large abundances are generally more accurate than less abundant classes.

The CLC2000 database is produced by the European Environment Agency (EEA). The database was made as part of the project COoRdinate INformation on the Environment (CORINE). CLC2000 is a raster image, which has a resolution of 100 m. The CLC2000 is based on satellite images, which were interpreted by national teams. In the Netherlands vector databases of land cover (Hazeu, 2003) were developed for 1986 and 2000 where changes in land cover between these years were also mapped. The minimum mapping unit for these vector databases is 25 ha and for changes in land cover between 1986 and 2000 the minimum mapping unit is 5 ha. These national databases were joined together and converted into the raster database CLC2000 using the majority rule (Büttner *et al.*, 2002). This database distinguishes 44 land cover classes. The thematic accuracy of the CLC2000 was estimated to be 87.0±0.5% (EEA, 2006).

2.2.3 N_2O Emission Estimation

For the Zegveld and Oukoop polders, N_2O emissions were estimated using four methods: IPCC Tier 1, Tier 2a, Tier 2b, and INITIATOR (Tier 2.5). The IPCC Tier 1 method estimates emissions by multiplying global activity data by default emission factors (Table 2.2). The emission factor is the fraction of N emitted as N_2O.

Emission factors and activity data from the Good Practice Guidance (IPCC, 2000a) and the IPCC Guidelines (IPCC, 1997) were used. When activity data were not indicated in the Good Practice Guidance, estimates from CBS (2007) were used. In the Tier 1 method, land cover data are used for the estimation of the emission due to the cultivation of histosols. The estimated surface area of grassland on peat soil from each land cover database and the default emission factor were used. In the polder Oukoop, only negligible N_2O emissions from ditches and ditch banks were measured (based on weekly closed chamber measurements in 2005, 2006, and 2007 by Schrier (personal communication; see also Table 2.3). The emissions from ditches and ditch banks in polder Zegveld were also assumed negligible, because the soil, land use, and hydrological conditions in this polder are very similar to those of polder Oukoop.

Table 2.2 Emission factors for N_2O emission from agriculture for different Tier levels.

	Emission factors for direct emissions from managed soils				Emission factors for emissions from animals	Emission factors for indirect emissions	
	1:Synthetic fertilizer applied	1: Animal manure applied	2: Cultivation of histosols	3: Animal grazing	3: Manure management	4: Atmospheric deposition	5: Leaching of N
	kg N_2O-N (kg N from applied fertilizer)$^{-1}$	kg N_2O-N (kg N from applied manure)$^{-1}$	kg N_2O-N ha^{-1} yr^{-1}	kg N_2O-N (kg N excreted in pasture)$^{-1}$	kg N_2O-N (kg N_2O-N in manure system)$^{-1}$	kg N_2O-N (kg NH_3–N+NO_X–N)$^{-1}$	kg N_2O-N (kg N leached)$^{-1}$
Tier 1	0.0125[a]	0.0125[a]	5.0[b]	0.020[a]	0.001 (Liquid) 0.02 (Solid)	0.01[a]	0.025[a]
Tier 2a	0.017[c]	0.020[d]	4.7[e]	0.017[f]	0.001 (Liquid) 0.02 (Solid)	0.01[g]	0.025[g]
Tier 2b	0.020[h]	0.020[d]	5.8[i]	0.017[f]	0.001 (Liquid) 0.02 (Solid)	0.01[g]	0.025[g]
	Denitrification and nitrification kg N_2O-N (kg N input)$^{-1}$						
INITIATOR (Tier 2.5) Netherlands	0.031 ± 0.014[j]				0.001 (Liquid) 0.02 (Solid)	0.031 ± 0.014[jk]	0.033 ± 0.012[jk]
INITIATOR (Tier 2.5) Research Polders	0.049 ± 0.006[j]				0.001 (Liquid) 0.02 (Solid)	0.049 ± 0.006[jk]	0.046 ± 0.005[jk]

[a] Default value (IPCC, 1997; IPCC, 2000a).
[b] Default value for temperate zones (IPCC, 1997).
[c] Emission factor in the Netherlands = Fraction of NH_4^+-fertilizers*0.02 + Fraction of other fertilizers*0.01.
[d] Emission factor in the Netherlands for manure incorporation in organic soils (surface spreading of manure is forbidden in the Netherlands).
[e] Emission factor in the Netherlands (Kuikman *et al.*, 2005).
[f] Emission factor in the Netherlands = (Fraction of urea (65%) * 0.02) + (Fraction of faeces (35%)*0.01).
[g] In the Netherlands there are no country specific emission factors and fractions for indirect sources, therefore the IPCC default values were used (IPCC, 1997; IPCC, 2000a).
[h] All interviewed farmers in the research polders use ammonium fertilizers.
[i] Emission factor for eutrophic peat soils in the Netherlands, measured in Zegveld (Kuikman *et al.*, 2005).
[j] Emission factor depends on local soil and hydrological characteristics.
[k] In INITIATOR N_2O emission due to deposition of NH_3 and NO_X is considered a direct emission (De Vries *et al.*, 2003b).

Table 2.3 N_2O emission from grassland parcels, ditches, and ditch banks. Emissions were non-continuously measured using flux chambers.

Treatment	N_2O emission (kg N_2O-N ha^{-1} yr^{-1})
Dry grassland parcel	
Unfertilized	8.6[a]
Fertilized	18.1 [a]
Fertilized and grazed	38.5 [a]
Wet grassland parcel	
Unfertilized	2.0 [a]
Fertilized	8.8 [a]
Fertilized and grazed	14.6 [a]
Ditch bank	negligible[b]
Ditch	negligible[b]

[a] Velthof (1997).
[b] Schrier (personal communication). In polder Oukoop, N_2O emissions from ditches and ditch banks were below the detection limit of the measurement equipment.

Two alternative specifications of the IPCC Tier 2 method are considered in this study hereafter referred to as Tier 2a and Tier 2b. The Tier 2a method uses activity data and emission factors as reported in the most recent Dutch inventory report (Klein Goldewijk *et al.*, 2005) while the Tier 2b method uses polder-specific activity data (i.e., number of animals, amount of fertilizer used) gathered from door-by-door interviews with farmers. Five of the twenty farmers in Zegveld were interviewed; together they own 31% of the area in the polder. In Oukoop, all eleven farmers were interviewed. All farmers could give animal numbers, separated into mature dairy cattle, yearlings, calves, sheep, lambs, goats, and pigs. Based on these interviews, an estimation of the total amount of cattle, applied manure, and applied fertilizer was made. For the Tier 2a method, activity data from the municipality or agricultural region (CBS, 2007) were used. This information was scaled down to the scale of the research polders as follows. Agricultural activity data in the Netherlands, such as the number of cows and the amount of chemical fertilizers used in an area, are correlated to the amount of grassland in that area. Therefore, activity data for the polder were estimated by multiplying the activity data from municipality/agricultural region by the ratio of grassland in the polder to grassland in the municipality/agricultural region.

The process model INITIATOR (De Vries *et al.*, 2003b) was identified as a method between Tier 2 and Tier 3 level and therefore called Tier 2.5 method. The model was developed to represent the crucial processes in the N chain by simple process descriptions, calculated in yearly time steps. Input data were taken from the CBS (CBS, 2007) concerning animal numbers, manure management systems, and fertilizer use. Inputs from the land cover databases were also used. Soil characteristics from the Dutch Soil map (Stiboka, 1969) and hydrological characteristics (Wolf *et al.*, 2003) were added. INITIATOR uses a process model in which N_2O emission is a function of denitrification and nitrification in the soil (De Vries *et al.*, 2003b). Unlike the IPCC methods, the emission factors and denitrification and nitrification fractions vary as a function of soil type and groundwater level in INITIATOR (Table 2.2).

Analysis of variance (ANOVA) was used to analyse whether differences between land cover databases for the polders are significant and whether differences between inventory methods are significant.

2.2.4 Regional Upscaling

In addition to comparing the calculated emissions for the two research polders, an assessment of the regional implications of the use of different databases was made for the entire fen meadow landscape. The field map of the research polders was scaled up (i.e., the extent was increased) to estimate the surface areas of different landscape elements and landscapes: 'cope' reclamations, reclamations with wide ditches, and irregular reclamations. This distinction was made because these three reclamation landscapes differ in the prevalence of landscape elements due to differences in the shape of grassland parcels and open water based on differences in reclamation history. All three reclamation types are common in the fen meadow landscape. The Top10Vector database was used to assign the type of reclamation landscape to each of the 315 polders in the fen meadow landscape. The surface areas of landscape elements found in the two research polders were used to estimate the distribution of these landscape elements in the fen meadows. Polder Zegveld was considered to be representative for 'cope' reclamation patterns with a regular pattern of predominantly rectangular parcels divided by small ditches. The length/width ratio of the parcels is approximately 10:1. The selection procedure for this type of reclamation is therefore based on the length/width ratio of the parcels. Polders, which have more than 70% of the parcels have a length/width ratio equal or greater to 10:1, were considered 'cope' reclamations. Twenty to thirty percent of the parcels in 'cope' reclamations have smaller width/length ratio, because these are situated at the edge of the polder or are dissected by a road. The second reclamation landscape can be described as polders with significant areas of open water. Usually these polders have wide ditches in between the parcels. Polder Oukoop was used as a reference polder for this reclamation landscape. The procedure to distinguish these polders at the regional level was based on the occurrence of open water and ditches wider than 3 m in the polders. Note that the Top10Vector database represents ditches smaller than 3 m as line elements. Polders with surface areas of water equal to or larger than 10% of the grassland surface areas, according to the Top10Vector, were therefore classified as reclamations with wide ditches. This percentage was derived from the standard width of parcels in this area and the average ditch width. The remaining polders were classified as irregular reclamations. A representative for this reclamation landscape is polder Menningweer of which Molenaar (unpublished data) made a detailed field map. After classifying the polders based on the three reclamation landscapes and assignment of the accompanying surface areas of landscape elements, the total surface areas of grassland parcels, ditches, and ditch banks were estimated. These surface areas were used to estimate the total agricultural N_2O emission from the fen meadow landscape. For each land cover database, the amount of grassland on histosols compared to grassland on mineral soil in each agricultural region (CBS, 2007) was calculated to estimate activity data such as amount of cattle and amount of fertilizer use. When emission factors derived from the Dutch situation were available (Klein Goldewijk *et al.*, 2005), these were used. For some N_2O sources, emission factors have not been determined in the Netherlands (i.e., for indirect emissions), and default IPCC emission factors were used. The emission of the fen meadow landscape was also estimated using INITIATOR, based on data on soils, hydrology, and land use data from the STONE database (Wolf *et al.*, 2003).

2.3 Results and discussion

2.3.1 Land Cover Representations

Representations of landscapes based on different land cover databases are shown in Figs. 2.2 and 2.3. The enlargements in Figs. 2.2 and 2.3 clarify the differences between the field map and the Top10Vector database. The Top10Vector database represented ditches smaller than 3 m as lines and did not make a distinction between ditch banks and grassland. The field map represented all ditches as polygons and was the only database that distinguished between ditch banks and grassland. The CBS soil use database ignored farmyards, farms, and small ditches due to the large minimum mapping unit compared to the field map and the Top10Vector. Only the village centre of Zegveld was represented as a residential area. The LGN4 and the field map databases distinguished between intensively managed grassland and extensive managed nature area. For both polders, the LGN4 database recorded a considerable surface area of ‘urban in agricultural area’ compared to the CBS soil use and CLC2000 database. As a result, the LGN4 database recorded a reduced grassland area compared to the other databases. Raster databases have difficulties representing point and line features that are smaller or equal to the pixel size. The farms with farmyard in the polders are features that were represented by the LGN4 database as square and rectangular shapes, which were often different from their real shape (i.e., the field map). The coarse CLC2000 raster database showed the entire polder covered

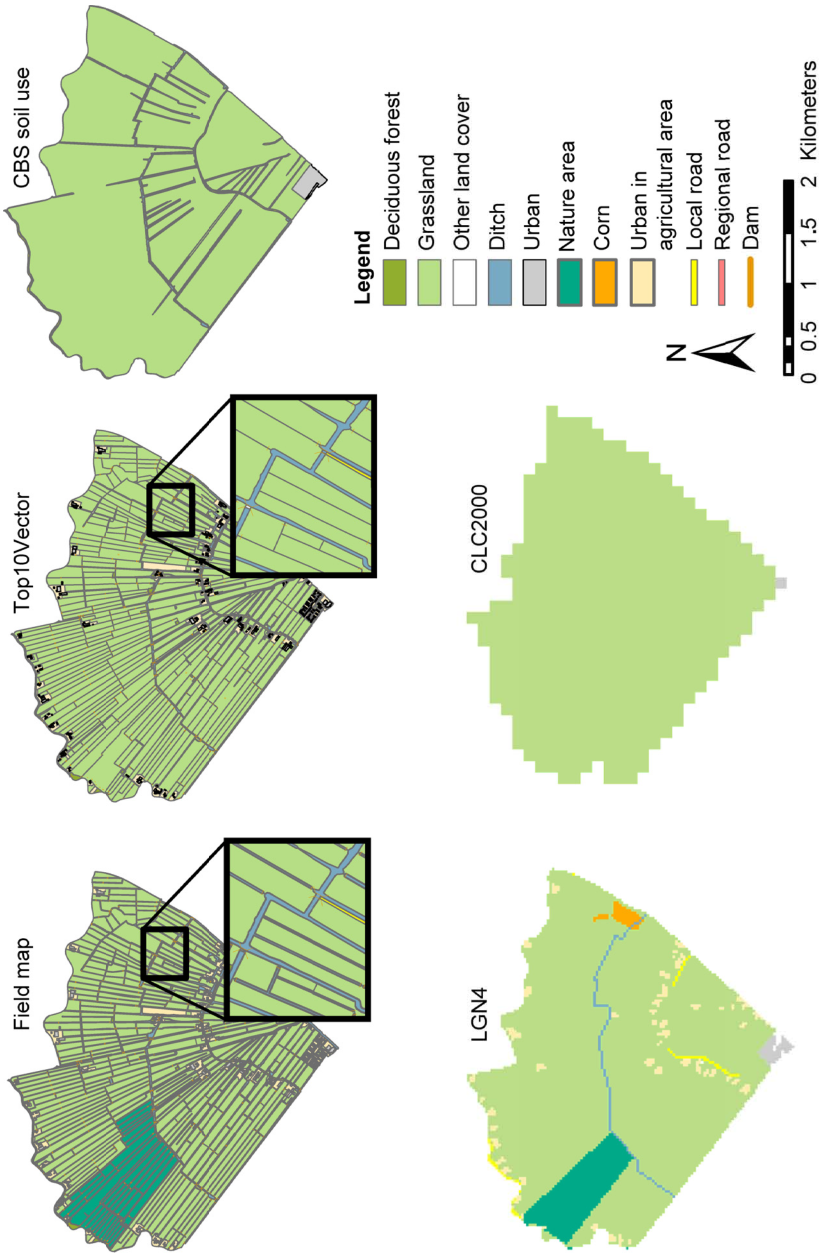

Fig. 2.2 Representations of polder Zegveld using different land cover databases.

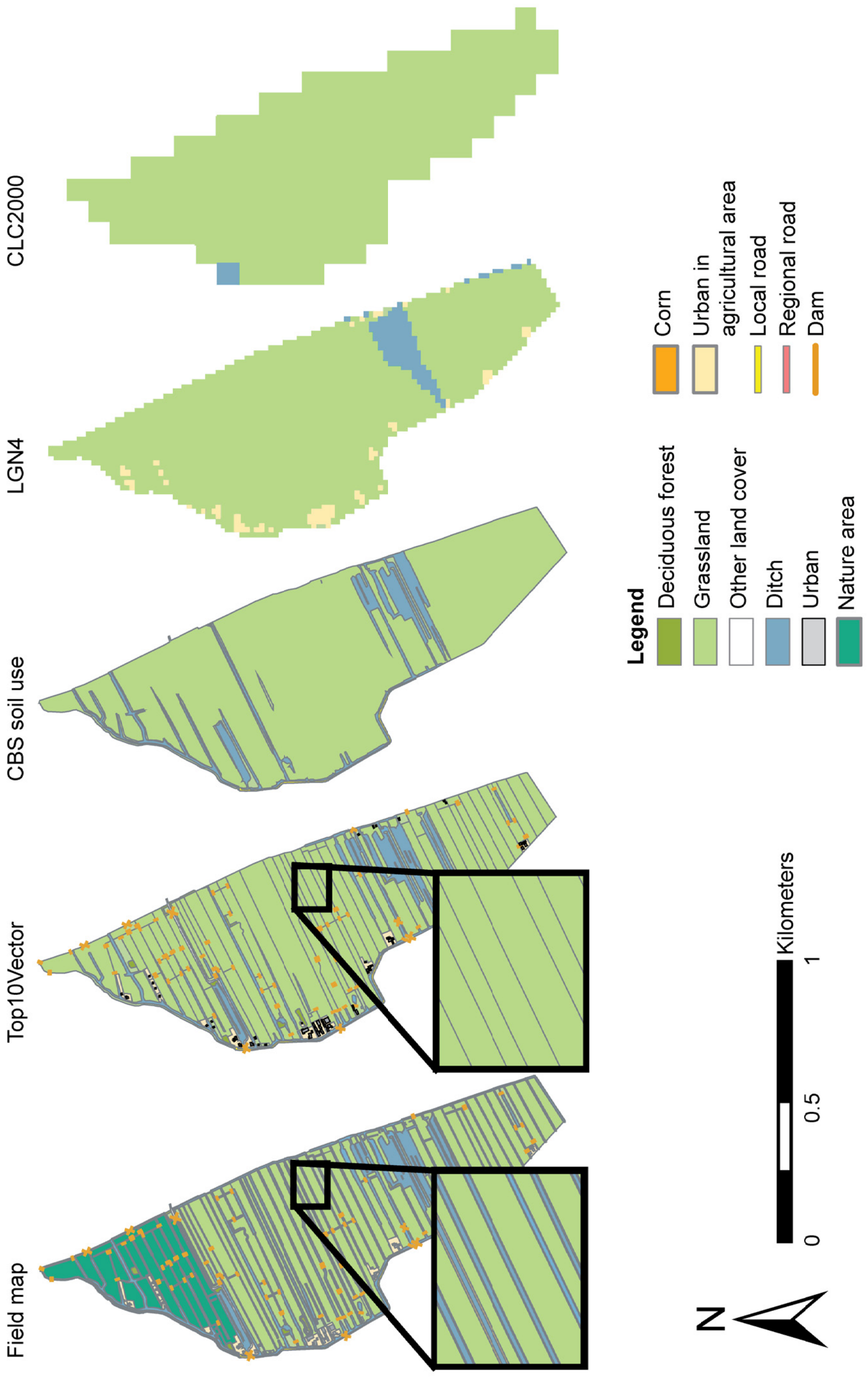

Fig.2.3 Representations of polder Zegveld using different land cover databases.

with grassland, except for one pixel in the Zegveld polder and for one pixel in the Oukoop polder.

Surface areas of (intensively and extensively managed) grassland parcels, ditches, and ditch banks as calculated using the different databases are given in Table 2.4. Except for the field map the land cover data did not have a separate class for ditch banks. These were all classified as grassland. The field map showed the smallest surface area with grassland, except for one pixel in the Zegveld polder and for one pixel in the Oukoop polder.

Surface areas of (intensively and extensively managed) grassland parcels, ditches, and ditch banks as calculated using the different databases are given in Table 2.4. Except for the field map, the land cover data did not have a separate class for ditch banks. These were all classified as grassland. The field map showed the smallest surface area of grassland and the largest surface area occupied by water and ditch banks. The grassland surface area increased with increased minimum mapping unit for vector data and increased with increased resolution for raster data. This can be explained by the dominance of grassland which, when presented at coarser scales, results in a general overestimation of its prevalence (Moody & Woodcock, 1996; Schmit *et al.*, 2006). In vector data, ditches are ignored when they are < 3 m (Top10Vector) or have a surface area < 1 ha (CBS soil use). In raster data, ditches are ignored when another type of land cover is more abundant within a pixel.

Overestimation of land cover classes with large abundances also occurred in other landscapes (Ellis *et al.*, 2000; Fassnacht *et al.*, 2006; Moody & Woodcock, 1996;

Table 2.4 Surface areas land cover types per land cover database (ha).

Location/ Database	Total grassland	Intensively managed grassland	Extensively managed grassland	Water	Ditch bank
Polder Zegveld					
Field map	513	434	70	70	33
Top10Vector	586	–	–	30	–
CBS soil use	640	–	–	19	–
LGN4	627	579	47	8	–
CLC2000	669	–	–	0	–
Polder Oukoop					
Field map	115	86	29	35	10
Top10Vector	142	–	–	19	–
CBS soil use	152	–	–	15	–
LGN4	155	155	0	8	–
CLC2000	167	–	–	1	–

Schmit *et al.*, 2006; Turner *et al.*, 1989). In the fen meadow landscape, grassland has a large abundance and therefore absorbs the other classes, especially for the databases with small accuracies and coarse resolutions. Other landscapes are less sensitive to aggregation errors (e.g. Turner *et al.*, 1989). Moody and Woodcock (1995) analysed a mountainous forested area in California and found an increasing prevalence of water with increasing resolution due to lakes with a high degree of aggregation situated sparsely across the landscape. The class 'conifers' also increased on average by 20% when aggregating from a resolution of 30 to 100 m. They concluded that the large increase in this class was due to the spatial structure of moderately large patches. The results found by Moody and Woodcock (1995) are large compared with the 7 to 8% difference in grassland in our study areas between the LGN4 (25 m resolution) and CLC2000 (100 m resolution) databases. On the other hand, Bach *et al.* (2006) and Fassnacht *et al.* (2006) found smaller differences between land use classes when aggregating from 25 to 100 m. Van Oort *et al.* (2004) compared the LGN4 database with reference data from randomly chosen areas in the Netherlands. The reference data were based on cadastral information. The grassland surface area was 2.5% larger for the LGN4 database than for the reference data. Larger differences were found between the LGN4 and the field map (20–22%). This is probably due to the fact that Van Oort *et al.* (2004) only estimated areas of grassland and crops, whereas the largest difference was found due to the presence of ditches instead of grassland. In research where thematic errors are small, positional errors can be large (Bach *et al.*, 2006). Fassnacht *et al.* (2006) found the class 'broadleaf', which forms narrow linear features along rivers, to be particularly susceptible to changes in resolution. This is comparable to our findings. Ozdogan and Woodcock (2006) also noted that large landscape elements can support large pixels, but when the landscape elements of interest are small, fine resolution is needed to correctly estimate surface areas.

2.3.2 N_2O Emission Estimates

Using inventory techniques based on the different IPCC Tier levels, the N_2O emissions were calculated with the calculated surface areas (Fig. 2.4). Bias in the estimated area of grassland propagated in the calculated emissions. For all Tier levels and for both polders the most accurate database represented the smallest area of grassland and accordingly the smallest N_2O emission. The N_2O emissions from polder Oukoop are about four times smaller than N_2O emissions from polder Zegveld, which is consistent with the difference in total surface area between the polders. The method with the highest Tier level (INITIATOR) produced the highest N_2O emissions for both polders and for all land covers databases (Figs. 2.4d, 2.4h). Furthermore, INITIATOR showed the largest differences between emission estimates (24% for polder Zegveld and 33% for polder Oukoop) because this method strongly depended on spatial data. Estimated N_2O emission per hectare ranged from 12.7 to 30.0 kg N_2O-N ha^{-1} yr^{-1}, which is comparable to the emissions found by Velthof (1997, Table 2.3).

For polder Zegveld, the emissions of N_2O estimated with the Tier 2b method (Fig. 2.4c), were higher than the emissions estimated with the Tier 1 (Fig. 2.4a) and Tier 2a (Fig. 2.4b) method. From the interviews, it turned out that more cattle were present in the polder than estimated from the municipality data (Tier 1 and Tier 2a). Another reason is that the dairy cattle had spent, according to the local data, more time in the meadow than global and Dutch numbers indicated. For both polders, the smallest N_2O emissions were obtained from the Tier 1 method (Figs. 2.4a, 2.4e). The emission factors in the Tier 2 methods were larger and caused higher emission estimations. In

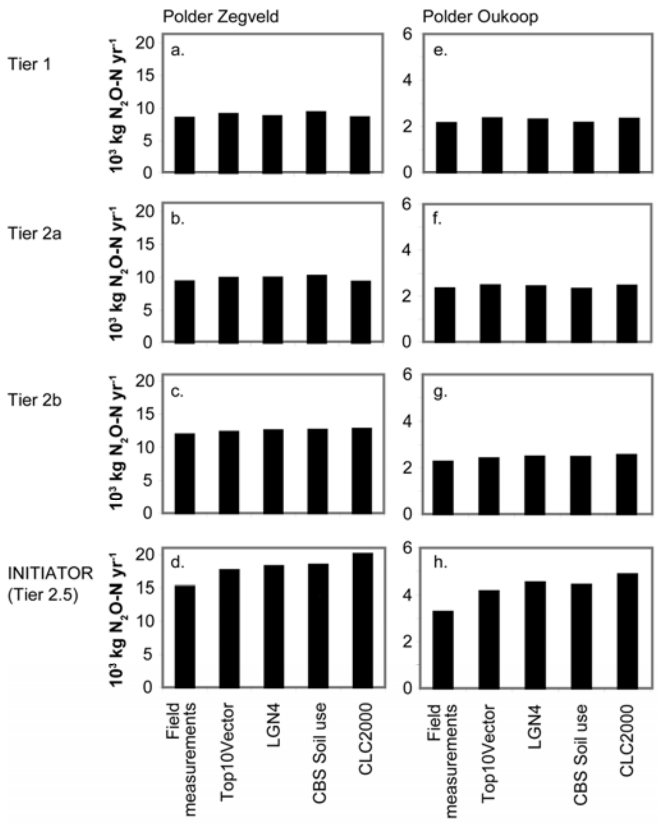

Fig. 2.4 N_2O emission from agriculture using different land cover data.

polder Oukoop the difference between Tier 2a (Fig. 2.4f) and Tier 2b (Fig. 2.4g) was small, indicating that the activity data from the CBS database were close to the activity data estimated from the interviews. Results from the INITIATOR (Figs. 2.4d, 2.4h) were high for both polders compared to the other methods.

The INITIATOR estimates for N_2O emission are based on the amount of denitrification and nitrification. Because the peat soils in the fen meadow landscape have excellent conditions for nitrification and denitrification, the emissions estimated by INITIATOR are much higher than the emissions estimated by other inventory methods. The analysis of variance (ANOVA) showed that differences between inventory methods are larger than differences between land cover databases.

For both polders, the emission estimates differed significantly between all inventory methods, except for polder Oukoop between methods Tier 2a and Tier 2b. Due to the large emissions estimated by INITIATOR, the differences between land cover databases were not significant, except for polder Zegveld between the LGN4 and CBS soil database.

2.3.3 Regional Extrapolation

The surface area distribution of grassland parcels, ditches, and ditch banks from the research polders were used to scale up to the entire fen meadow landscape (Table 2.5). The three polders (Oukoop, Zegveld, and Menningweer) were assumed to be representative for all Dutch fen meadow polders. This is assumed to be correct for the purpose of examining the impact of scale bias in land cover data for estimating N_2O emissions at landscape scale.

The reclamation landscape with wide ditches contained about twice as much open water as the other two landscape types. The irregular reclamation landscape had the smallest share in ditch banks, which can be explained by the large abundance of square parcels compared to more elongated parcels in the other reclamation landscapes. Figure 2.5 shows a map of the fen meadow landscape including a classification of the polders in reclamation landscapes.

Table 2.5 Surface area distribution of landscape elements in research polders used as reference for upscaling.

		Landscape elements		
Research polder	Reclamation landscape	Grassland parcels	Ditches	Ditch banks
Polder Zegveld	‘Cope’ reclamation	87.6 %	10.5 %	4.9 %
Polder Oukoop	Reclamation with wide ditches	84.3 %	20.7 %	6.0 %
Polder Menningweer	Irregular reclamation	87.3 %	12.0 %	2.0 %

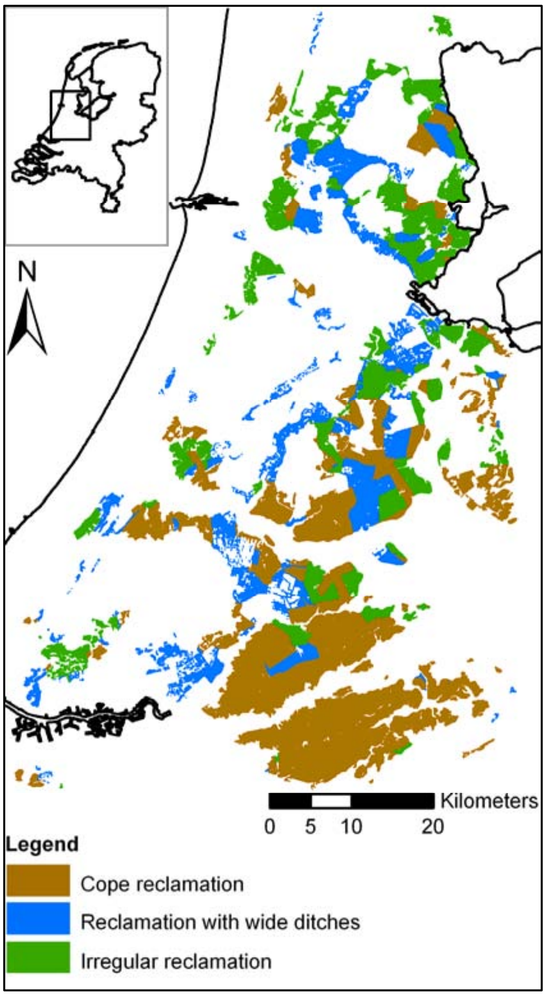

Fig. 2.5 Reclamation types in the fen meadow landscape.

Intersecting rivers and disappearance of peat due to peat excavation caused fragmentation of the fen meadow landscape. In the southern part ‘cope’ reclamations were abundant. The irregular reclamation landscape is common in the northern part of the fen meadow landscape, where there was no common strategy during the reclamation period. The reclamations with wide ditches were most abundant near locations where the peat was excavated for fuel use. The total area of grassland based on the field map was considerably smaller than the other estimated areas of grassland (Table 2.6).

Table 2.6 Surface area of grassland in fen meadow landscape (ha).

Database	Surface area of grassland
Field map	74,049
Top10Vector	86,891
CBS soil use	92,692
LGN4	87,461
CLC2000	96,391

The field map was used to estimate the extent of ditches in the fen meadow landscape, where other databases reported larger areas of grassland. According to the Dutch soil map 1:50,000 (De Vries *et al.*, 2003a) 36% of the Dutch peat soils are situated in the fen meadow landscape. In the current national inventory, the total surface area of grassland on organic soils equals 231,000 ha (Klein Goldewijk *et al.*, 2005). Assuming that there are no meaningful nationwide differences between the proportion of land on peat soils occupied by grassland, this suggests that 83,000 ha of grassland is located in the fen meadow landscape. This estimate is smaller than the estimates from the land cover databases, except for the field map estimate, which is 11% smaller occupied by grassland.

In general, vector data are more suitable for representing distinct boundaries and clear landscape elements; whereas raster data are assumed to better represent natural phenomena with gradual boundaries, such as soils, vegetation types, and slopes (Star & Estes, 1990). The landscape structure of the fen meadow landscape with predominantly sharp boundaries between landscape elements and with long narrow ditches was therefore best represented by vector data. Poor representation of linear elements—especially ditches—in this landscape was a large source of bias by both vector and raster data. Note that the bias would be much smaller for landscapes with fewer line elements and larger patches of the same land use.

The N_2O emission estimates for the fen meadow landscape are shown in Table 2.7. The largest source of agricultural N_2O emissions was the cultivation of histosols, which demonstrates the importance of this source. The highest emissions from this source were obtained with the CLC2000 database because of the larger estimated surface

Table 2.7 Emission of N_2O estimated for the fen meadows using the IPCC Tier 1 and Tier 2a method from different sources (10^3 kg N_2O yr^{-1}).

	Cultivation of histosols		Total emission from agriculture	
Database	Tier 1	Tier 2a	Tier 1	Tier 2a
Field map	370	348	965	1072
Top10Vector	434	408	1097	1215
CBS soil use	463	436	1111	1259
LGN4	437	411	1137	1264
CLC2000	481	453	1210	1339

area grassland (Table 2.6). The total emissions were larger for Tier 2a than for Tier 1 largely due to larger ammonium losses according to the Tier 1 method. For the fen meadow landscape, the maximum difference between the land cover databases was almost twice as large as between the inventory methods. This difference was largely due to two sources of error. The first error was the varying activity data used for the fen meadow landscape. For the research polders, most activity data were relatively constant for all land cover databases. Many Dutch activity data (e.g., number of cows) were reported per agricultural region without information about the distribution (e.g., the amount of cows grazing on mineral soils vs. grazing on organic soils). To estimate these activity data for the fen meadow landscape, estimates about the proportion of organic soils compared to the proportion of mineral soils in the agricultural regions from the land cover databases were used. These activity data, which varied between land cover databases, caused some differences in emission estimates. The second source of error was the bias in representation of landscape elements by the land cover databases.

The N_2O emission was also calculated using INITIATOR and input from the STONE database. The estimated emissions were about twice the emissions estimated with the Tier 1 and 2a method (data not shown). This was partly due to the high denitrification and nitrification estimated by INITIATOR, which was also identified at polder scale, and partly due to the use of STONE, which is a very coarse database (with a resolution of 250 m) compared to the other databases used for the Tier 1 and 2a methods.

2.4 Conclusions

In this research, the surface area of grassland was overestimated when using the land cover databases. When moving to a coarser resolution for raster data or to a larger minimum mapping unit for vector data, classes with large abundances 'absorbed' classes with small abundances. The choice of a certain land cover database can have drastic effects on N_2O inventories, because differences between estimated surface areas sometimes exceed 20% and different surfaces have different emissions. Such differences do not only apply to our study sites; at the regional level the amount of difference is similar.

For the Zegveld and Oukoop polders, the differences in estimated N_2O emissions were larger between the inventory techniques than between land cover databases. For the fen meadow landscape as a whole, the reverse applied because errors in land cover data were mainly systematic errors (bias) and errors from the inventory techniques were mainly random. Bias is consistently in the same direction and does not cancel out when estimates are scaled up to larger regions; therefore, these systematic errors became more distinct for larger areas compared to random errors in emission factors. The effect of using a more detailed land cover database had the opposite effect of using a more detailed inventory method. Largest emissions were estimated using the coarsest land cover database and the most detailed inventory method and vice versa. Although focusing on the reduction of uncertainty by improving emission inventory methods may be efficient at the local scale, this study has shown that for large-scale inventories the careful selection, inventory, and use of land cover data may be as important in reducing inventory uncertainties. While significant effort has gone into improving emission factors and improving inventory techniques, in this chapter was demonstrated that with relatively little effort emission inventories can be improved by improving land cover data input.

3

Effect of temporal resolution on N_2O emission inventories in the Dutch fen meadow landscape

Abstract

Most countries use a one-year-resolution emission factor approach to estimate terrestrial N_2O emissions as part of their national GHG inventory, either by applying default values (Tier 1 method) or nationally derived values (Tier 2 methods). This approach employs an annual temporal resolution and uses yearly averaged inputs to predict emission. Little attention has so far been paid to the effect of the temporal resolution of the approach (e.g. day, season, year) on N_2O emission estimates. The effect of lumping temporal variation can be very large due to daily or seasonal variations of processes causing N_2O emissions. Therefore, annual N_2O emissions from a model (DNDC) with daily time steps were compared with those of a model (INITIATOR) with annual time steps. N_2O emissions were simulated for two intensively managed grassland plots in the Dutch fen meadow landscape in the period 2001–2006. The years with the largest differences in model results were used to estimate the effect of the within-year temporal distribution of rainfall, fertilization, and manure application on the annual N_2O emission. Emission factors based on N_2O results from DNDC and INITIATOR for the six simulation years were estimated using the available management and climate data. Annual N_2O emissions from the investigated grasslands were sensitive to rainfall distribution within the year, especially to summer rainfall. An adjustment for relative summer rainfall is recommended for Tier 2 N_2O emission estimates for intensively managed grasslands on peat soils.

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3.1 Introduction

Terrestrial N_2O emission is an important component of the Dutch anthropogenic GHG balance. Brandes *et al.* (2007) estimated the contribution of N_2O to the total Dutch GHG emission for the year 2005 as 8%, from which more than half originates from agricultural soils. These estimates were obtained in compliance with the Kyoto protocol and the UNFCCC guidelines, which imply the use of region-specific emission factors based on total emissions per year (Brandes *et al.*, 2007; IPCC, 2006).

It is widely known that N_2O emissions from soils have a large spatial and temporal variability, particularly at the small space-time measurement scales that are often applied (Flechard *et al.*, 2007; Skiba *et al.*, 1996; Velthof *et al.*, 1996b). Some ecosystems, e.g. needle-leaved forest, have an almost constant emission throughout the year (Schulte-Bisping *et al.*, 2003). Other ecosystems have seasonal or event-based emission patterns. In fertilized grasslands, the largest part of the annual N_2O emission occurs as 'peak' emissions (e.g. Calanca *et al.*, 2007; Jones *et al.*, 2007; Velthof *et al.*, 1996a). These peak emissions are caused by events such as fertilizer or manure application (Bouwman, 1996), rainfall events (Ryden, 1983) or freeze-thaw cycles (Christensen & Tiedje, 1990). A soil water filled pore-space (WFPS) between 50% and 70% is believed to be optimal for N_2O peaks (§1.1.2; Davidson *et al.*, 1991). At dryer conditions (smaller WFPS), N_2O is a by-product of nitrification and N_2O emission is relatively small. At wetter conditions (larger WFPS), denitrification is the main process and formation of N_2 is favoured over N_2O formation (Granli & Bøckman, 1994). Other major controls on N_2O emission are soil mineral N availability, temperature, and labile organic compounds availability (Skiba & Smith, 2000). Cultivated organic soils are large emitters of N_2O due to large C and N availability.

Besides the well-known issues concerning the choice of spatial scale for measurement (Chapter 2), modelling, and reporting N_2O emissions (Velthof *et al.*, 1996b); also different temporal scales can be distinguished. The IPCC Tier system (§1.3.1) distinguishes different temporal scales (IPCC, 2006). In the IPCC Tier 1 and Tier 2 methods that most countries use to estimate and report emissions, the annual N_2O soil emission induced by N inputs is calculated as a fraction of the N input. The N_2O emission factor (in %) depends on the type of N input (e.g. N input from grazing animals, animal manure, fertilizers, crop residues, fixation, or deposition). The temporal resolution of both the Tier 1 and 2 method is typically a year (annual emission factor), because many activity data are not available at finer temporal resolution. Tier 3 methods make use of process-based models that incorporate relevant factors and processes that affect N_2O emission. The temporal resolution is usually small because daily or hourly soil processes are simulated. Process models which are widely used to simulate N_2O emissions are DNDC (Li *et al.*, 1992), DayCent (Parton *et al.*, 1998), and PaSim (Riedo *et al.*, 1998; Schmid *et al.*, 2001). N_2O emission factors for Tier 1 and Tier 2 methods are annual averages generally obtained from experimental research, lasting between one and three years and lumping all small-scale temporal variation. Little attention has so far been paid to the effect of lumping small-scale temporal variability on annual N_2O emission estimates. However, the effect of small-scale temporal variations can be very large due to the strong dynamic nature of causal factors behind N_2O emission and strong non-linearities in the emission processes. With more information about the temporal variation of the causal factors, one could possibly adjust the emission factor for a specific year and improve the emission estimate of a Tier 2 method, without the need to use data-demanding Tier 3 methods.

The main objective of this paper is to analyse the effect of temporal resolution by comparing annual N_2O emissions from two models with a different temporal resolution. Accordingly, simulated N_2O emission of a Tier 2 model with a coarse (annual) temporal resolution were compared to results of a Tier 3 model with a fine (daily) temporal resolution. The differences between the models and the effects of these differences on the estimated annual N_2O emissions were studied. For years with large differences in simulated annual N_2O emissions, small-scale processes that could cause these differences were identified. Emission factors were also estimated for the simulated years and compared with emission factors used in the Tier 1 and Dutch Tier 2 methods, to analyse whether the factors appropriately average the annual variations in N_2O emissions. As such, the results of this work can contribute to improved identification of emission factors used in Tier 2 based inventories. Identification of the effect of temporal variation on annual N_2O emission may be used to adjust the Tier 2 emission factors for a given year to the specific temporal variation patterns of that year.

3.2 Materials and methods

3.2.1 Research plots

The N_2O emission was modelled for the years 2001–2006 for two intensively managed grassland plots on peat soils in the Dutch fen meadow landscape. The research plots are located in polder Zegveld (Figs. 2.1, 2.2), which is in the centre of the fen meadow landscape. Two plots were studied; a ‘dry’ plot (52°8‘19”N 4°50’10”E) and a ‘wet’ plot (52°8‘12”N 4°50’18”E).

The plots are rectangular parcels (approximately 300 m by 50 m in size) bordered by ditches and owned by a dairy farmer. The plots are surrounded by other dairy farms. The soil consists of peat originating from wood. The dry plot is representative for most intensively managed grasslands in the fen meadow landscape. It has a summer groundwater level of about 51 cm below soil surface, whereas the wet plot has a summer groundwater level of about 28 cm below soil surface. For the year 2001 through 2006, the average annual precipitation in the area was 889 mm (Fig. 3.1) and the average annual temperature was 10.9ºC (KNMI, 2007).

3.2.2 Data collection

Management, soil, and hydrological parameters were measured on the plots for the years 2001 through 2006 (Table 3.1). Overall, the management for both research plots is comparable. Both plots were grazed by cattle. A time series of N_2O measurements was also available for model verification (Jacobs *et al.*, 2003). On 27 dates between 15 May 2001 and 28 June 2002, N_2O emissions were measured at ten randomly selected locations in each plot. The measurement frequency was between once a month during winter and twice a week during the growing season. Ten static flux chambers were used to carry out the measurements.

3.2.3 Models for N_2O estimations

Emissions of N_2O were simulated for both plots for the years 2001 through 2006 with the models INITIATOR and DNDC. INITIATOR (De Vries *et al.*, 2003b) has a yearly temporal resolution and DNDC (Li, 2007) has a daily temporal resolution.

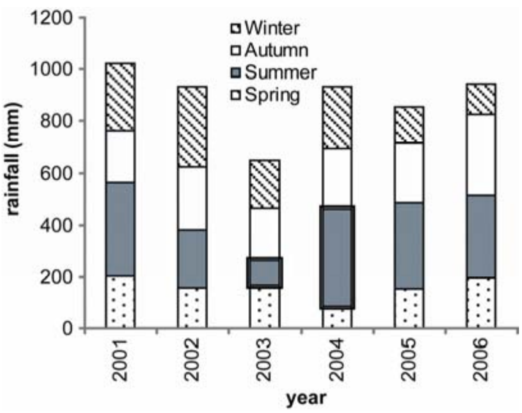

Fig. 3.1 Rainfall distribution (mm) for the simulation years 2001 through 2006. In the black boxes the years 2003 and 2004 with a large difference in summer rainfall. The black boxes represent the years with the smallest and largest amount of summer rainfall

Table 3.1 Management data from both research plots from 2001 through 2006.

Year and plot	Manure Application[a]	Removal by Mowing[a]	Excretion during grazing[ab]	Manure Application[a]	Removal by mowing[c]	Fertilizer Use[a]	Excretion during grazing[d]	Grazing days[a]	
	C (kg C ha^{-1} yr^{-1})		kg DM ha^{-1} yr^{-1}	N (kg N ha^{-1} yr^{-1})				Sheep (heads/ha)	Cows
2001									
Dry plot	129	2822	1539	46	176	133	45	272	61
Wet plot	185	2454	3760	68	153	132	129	0	251
2002									
Dry plot	905	1421	6605	46	89	129	226	1024	338
Wet plot	168	2495	5856	77	156	137	200	0	391
2003									
Dry plot	157	2112	6080	85	132	120	194	657	268
Wet plot	155	1659	6175	85	104	122	232	450	417
2004									
Dry plot	0	6388	1500	0	399	71	15	300	0
Wet plot	0	5496	0	0	344	68	0	0	0
2005									
Dry plot	167	2517	12250	89	157	149	148	0	289
Wet plot	158	3946	7500	85	247	149	82	0	159
2006									
Dry plot	824	3207	8001	38	200	140	197	300	298
Wet plot	128	2434	7750	60	152	122	103	30	190
Average									
Dry plot	104	3078	5996	51	192	124	138	426	209
Wet plot	132	3081	5714	63	193	122	124	80	235

[a] Information from the farmer (K. Van Houwelingen, personal communication, 2008)

[b] The C content is about 35% of the dry matter content (Martinez, 2002); the models use the dry matter content as input.

[c] Estimated using information from the farmer (K. Van Houwelingen, personal communication, 2008) and C/N ratio grass yield (Lantinga, 1985).

[d] Estimated using information from the farmer (K. Van Houwelingen, personal communication, 2008), animal numbers, grazing days, C excretion, and N excretion numbers (Bussink, 1994)

An extensive description of the model INITIATOR can be found in §1.3.2 and in De Vries *et al.* (2003b). Table 3.2 gives a summary of the characteristics of INITIATOR that are relevant for comparison with DNDC. The denitrification-decomposition process-model (DNDC) was selected because it has been calibrated and validated for many sites around the world (Brown *et al.*, 2002; Butterbach-Bahl *et al.*, 2001; Cai *et al.*, 2003; Grant *et al.*, 2004; Jagadeesh Babu *et al.*, 2006; Kesik *et al.*, 2005; Kiese *et al.*, 2005; Pathak *et al.*, 2005; Saggar *et al.*, 2004; Xu-Ri *et al.*, 2003; Zhang *et al.*, 2006) and can simulate drained organic soils. Version 9.1 of DNDC was used. DNDC is based on biogeochemical concepts (Li, 2007). The core of the model is a combination of the

Table 3.2 Overview of model characteristics of INITIATOR and DNDC relevant for comparison

Aspect	INITIATOR (De Vries *et al.*, 2003b)	DNDC (Li, 2007)
General characteristics		
Domain	Agricultural and natural soils	Agricultural and natural soils
Compounds	N, C (Organic matter)	N, C (Organic matter)
Inputs to the soil	Animal manure application, fertilizer application, grazing, deposition, and biological N fixation	Animal manure application, fertilizer application, grazing, deposition, and biological N fixation
Outputs	NH_3, NOx and N_2O emissions from soil	NH_3, NOx and N_2O emissions from soil
Soil layers	Two layers: rooting zone and saturated zone	One soil layer, typically 50 cm, divided into sub layers of 5 cm
Dynamics and time step	Steady state; yearly balance	Dynamic; with a time step of 1 hour to 1 day
Hydrology	Yearly water balance based on a separate hydrological model	One-dimensional soil heat flux and moisture flow model to calculate daily soil temperature and soil moisture. Driven by daily precipitation and temperature
Processes		
N-fixation	Model input	Dependent on N demand by crops
NH_3 emission	Emission fractions for: manure application, dependent on application technique fertilizer application grazing	Emission fractions for: manure application fertilizer application grazing
N uptake by vegetation	Growth function dependent on crop type, soil type, soil moisture and N availability	Growth function dependent on light, N availability, moisture and temperature
N Mineralization	Fraction of the field N input in the field corrected for both N emission and N uptake. In peat soils, net nitrogen mineralization is calculated as a function of soil wetness class (drainage) and land use	First order kinetics related to three biologically active nitrogen pools (microbial biomass, active humus and passive humus) with decomposition rates regulated by clay content, N availability, soil temperature, and soil moisture.
(De)nitrification	Fraction of net N input (N input minus NH3 emission, uptake and immobilization) as a function of soil type and soil wetness class	Process-oriented modelling of nitrification and denitrification sequence ($NO_3^- \rightarrow NO_2 \rightarrow N_2O \rightarrow N_2$) Process depends on moisture content, oxygen content, ammonium content, nitrate content, soil temperature and pH. Details are given in Li (2007).
N_2O and NOx emission	Emission fractions due to nitrification and denitrification	See above on (de)nitrification

Nernst (Stumm & Morgan, 1996) and Michaelis-Menten (Paul & Clark, 1989) equations to track microbial activities at hourly and daily time steps. These two equations are coupled via a so-called ‘anaerobic balloon’. The size of the ‘balloon’ is defined by the modelled redox potential from the Nernst equation. The soil substrates are allocated based on the calculated aerobic and anaerobic parts of the soil. With the Michaelis-Menten equation, redox reactions can be calculated based on the calculated substrate concentrations. This gives again a new redox potential. DNDC includes two parts. The first part predicts soil temperature, moisture, pH, redox potential, and substrate (ammonium, nitrate and DOC) concentrations. This part is driven by the input parameters about climate, soil, and management. The second part predicts N_2O, NO, N_2, NH_3, and CH_4 fluxes. These emissions are calculated using nitrification, denitrification, and fermentation sub-models with input parameters estimated in the first part of the model. The model has a site mode and regional mode. Because for this chapter, N_2O fluxes were simulated on plot scale, the site mode of the model was used.

3.2.4 Model parameterization and verification

For DNDC, the use of default values for all model parameters resulted in unrealistic hydrological dynamics and crop uptake. DNDC was therefore parameterized with measured data and coefficients valid for the Dutch situation. INITIATOR was specifically developed and, in its standard configuration, already parameterized for the Dutch situation (De Vries *et al.*, 2003b). Calibration of both models towards the N_2O measurements was not done because it would make valid comparison with the measurements and between models impossible. Verification with independent measurements was done for both models to determine whether modelled N_2O emissions were realistic.

Parameterization of DNDC

For both research plots, simulation with default DNDC parameters gave unrealistic results of groundwater level and water-filled pore space (WFPS), which seriously affected N_2O emissions. Input parameters driving the simulation of the groundwater level and WFPS in DNDC are the mean highest groundwater level (MHW, m), WFPS at wilting point, WFPS at field capacity, and hydraulic conductivity (m hr^{-1}). Both plots have an MHW of 0 m, because in winter the groundwater level can reach surface level for days and they often become nearly flooded (Velthof *et al.*, 1996a). The essential difference between the plots is the mean lowest groundwater level (MLW, m). Unfortunately, DNDC does not use MLW as an input parameter. Using measured values of WFPS at wilting point, WFPS at field capacity, hydraulic conductivity, and 0 for the MHW, the model simulated a continuously saturated soil and a groundwater level permanently at the surface. Therefore, the MHW for both plots was parameterized with a simulated WFPS for 27 dates between 15 May 2001 and 28 June 2002 (Jacobs *et al.*, 2003), using the detailed hydrological model SWAP (Van Dam, 2000). The MHW input parameter of DNDC was parameterized by searching for the smallest residual error between WFPS values simulated with DNDC and WFPS values simulated with SWAP. After the parameterization, the best-fitted MHWs were 0.60 m for the dry plot and 0.49 m for the wet plot. Velthof and Oenema (1995) measured WFPS on the same plots on 34 dates for the year 1992. The best-fitted MHWs were used to simulate the WFPS for 1992 and compared with the measured WFPS. The model also adequately simulated

WFPS for this year; the root mean squared error decreased by 24% for the dry plot and 50% for the wet plot compared to the default model run (data not shown).

After parameterization of WFPS, the grass died at the end of every simulation year. This problem was solved by changing the default crop parameters of DNDC. Four default crop parameters for perennial grass differ from measured parameters in Dutch grasslands: maximum grain production (kg dry matter ha^{-1}), water requirement (kg water for producing 1 kg dry matter), maximum leaf area index (LAI), and accumulative degree-days of maturity (TDD, °C). The default values for these crop parameters were adapted to (for the Dutch situation) more realistic values (Table 3.3). Other default crop parameters, such as the root-shoot distribution, were close to measured values.

The default C/N ratio for the above-ground biomass of perennial grass in DNDC, i.e., 35, is larger than C/N ratios measured in Dutch grasslands, which are generally around 16 (Lantinga, 1985). However, using smaller C/N ratios caused the grass to completely disappear at the end of every simulation year, even when nitrogen inputs were very large. Apparently, DNDC assumes that grassland is less efficient in N use than Dutch grassland is. With a C/N ratio of 16, the nitrogen demand for the first half of every year increased to more than 600 kg N ha^{-1}. DNDC was originally developed for simulating arable crops. Apparently, the root turnover in DNDC is too fast for perennial grasslands. The default (fixed) C/N ratio of 35 for leaf and stem biomass was therefore used, which means a corresponding C yield of 4.1 t C ha^{-1} yr^{-1} (117 kg N from grass cut x 35) for the dry plot and 4.4 t C ha^{-1} yr^{-1} (125 kg N from grass cut x 35) for the wet plot. As DNDC calculates with a constant C content of 40% this corresponds with a yield of about 10.5 t dry weight grass ha^{-1} yr^{-1}, which is realistic for Dutch grasslands (Elgersma *et al.*, 1998; Oenema *et al.*, 2005).

<u>Model verification</u>

Upscaling of the N_2O emission measurements to yearly emission estimates of the entire plot was needed in order to compare the measurements with the model outputs. The target scale (the daily and annual emission from an entire plot) is larger than the

Table 3.3 Adaptations to the crop parameters in DNDC.

Adapted parameter	Default DNDC	Adapted for Dutch fen meadow landscape	Source
Maximum grain production (kg dry matter ha^{-1})	200	245	Barrett *et al.* (2004) Elgersma *et al.* (1998)
Water requirement (kg water for producing 1kg dry matter)	350	354	Smid *et al.* (1998)
Maximum LAI	3	5	Lantinga (1985)
Accumulative degree days of maturity or TDD (ºC)	2500	1650	Calculated for simulated years (±165 days x 10ºC)

measurement scale. The measurement support was one hour and the surface area covered by the flux chamber was approximately 0.5 m^2. For spatial upscaling, the plot emission was estimated as the arithmetic mean of the N_2O emissions from the ten locations. The measured emissions were compared with the emissions simulated with DNDC on a daily scale. Measured and modelled trends and peaks in emissions were compared and deviations between the minimum and maximum emissions were calculated. To verify annual N_2O emissions, the measurements also had to be scaled up in time. Previous research (Velthof *et al.*, 1996a) showed that N_2O emissions in the growing season are significantly larger than N_2O emissions outside the growing season. Therefore the dataset was split into 'growing season' and 'off-season'. The growing season for grasslands is defined as the period between 1 March and 1 October (Van Dijk *et al.*, 2005). As defined in de Gruijter *et al.* (2006), the average N_2O emission was computed as

$$\hat{\mu} = \frac{O_G}{O_G + O_O} \times \hat{\mu}_G + \frac{O_O}{O_G + O_O} \times \hat{\mu}_O \qquad (3.1)$$

where $\hat{\mu}$ is the estimate of the annual average N_2O emission, O_G is the number of days in the growing season, O_O is the number of days in the off-season, $\hat{\mu}_G$ and $\hat{\mu}_O$ are the estimates of the average N_2O emission in the growing season and off-season, respectively. The variance of the estimation error was computed as

$$Var(\hat{\mu} - \mu) = \left(\frac{O_G}{O_G + O_O} \right)^2 \times \frac{S_G{}^2}{n_G} + \left(\frac{O_O}{O_G + O_O} \right)^2 \times \frac{S_O{}^2}{n_O} \qquad (3.2)$$

where $Var(\hat{\mu} - \mu)$ is the variance of the estimation error of the annual N_2O emission, $S_G{}^2$ is the sample variance of N_2O emissions in the growing season, n_G is the number of measurement dates in the growing season, $S_O{}^2$ is the sample variance of N_2O emissions in the off-season, and n_O is the number of measurement dates in the off-season. The standard error was computed as the square root of Eq. (3.2) and for each plot, it was verified if the simulated annual N_2O emissions from DNDC and INITIATOR were within the confidence intervals of the measured annual N_2O emissions.

3.2.5 Analysis of temporal resolution effects

For 2001 through 2006, differences between the simulated annual N_2O emissions from DNDC and INITIATOR were compared and the years with the largest difference in simulated N_2O emissions were selected for further analysis. For these years, it was analysed which inputs with high temporal variation caused the differences. Next, a three-step analysis was used to trace the effect of high-resolution temporal variation of these inputs on the annual N_2O emission using DNDC. This high-resolution temporal variation cannot be included in INITIATOR due to its annual temporal resolution.

Step 1: Identification of high-resolution variables and their interactions

All input variables that require input at a high temporal resolution in DNDC, e.g. daily temperature, were selected for further analysis. Interactions of these variables that, based on literature, can have a combined effect on N_2O emission (e.g. the combination of rainfall and fertilizer N input) were selected as well.

Step 2: Selection of key variables and variable interactions

Many variables (e.g. manure application) not only affect N_2O emissions on the day itself, but have a prolonged effect and may influence daily N_2O emissions for periods of weeks or months after the actual event. Therefore, N_2O emissions are often more strongly correlated with the aggregate value of such a variable over the previous period than with the variable value at the day of N_2O measurement. To identify the period over which the variable values need to be aggregated, correlations between daily N_2O emission and values of variables aggregated over varying periods were explored. For each variable and variable interaction, identified in Step 1, the optimum aggregation period with the largest correlation coefficient was determined for use in further analysis.

The temporal variation in variable values over the different years was analysed by comparing the values of the variables among the different years. The analysis was done for four seasons separately. For instance, if in the year 2002 relatively more grazing occurred in spring as compared to other years the variable 'grazing' in spring 2002 was classified as 'high'. For the year with the lowest value of the same parameter, a classification 'low' was assigned. A similar analysis was made for the variable interactions based on a multiplication of the variable values.

The variables and variable interactions classified 'high' of 'low' for the years with the largest differences in annual N_2O emission simulated by DNDC compared to INITIATOR were identified as 'key' variables and variable interactions. These 'key' variables and variable interactions can be the main cause of differences in simulated N_2O emission between the two models and consequently show the effect of difference in temporal resolution of the models.

Step 3: Analysis of the effects of temporal variation in key variables on N_2O emission

To identify the influence of the identified key variables and variable interactions on the differences in annual N_2O emission between DNDC and INITIATOR and analyse the effect of the within-year temporal variation in variable values temporal distribution of the key variables and interactions was manipulated.

Two different methods were used to manipulate the temporal variation in key variables. In the first method, a key variable for a season that was classified as 'high' was substituted for the same variable from a year with a 'low' classification for that season. The advantage of this 'switch' method is that the key variables keep a natural variation, but the disadvantage is that annual totals of the variables could also change. If that was the case, INITIATOR was run as well with the new annual total value of the variable for comparison. In the second method, the within-year distribution of key variables was changed while keeping the annual totals equal. This was done by increasing a variable in a specific season while proportionally decreasing this variable in the other seasons or vice versa. Key variable interactions were manipulated as well by changing the distribution of the variables over the year and thereby influencing the variable interactions.

3.2.6 Comparison of simulated annual average emission factors with the IPCC default values (Tier 1) and Dutch values (Tier 2)

Using the simulated annual N_2O emissions, emission factors were computed, following the IPCC Tier 1 (default values) and Tier 2 (national values) approaches. N_2O emission factors based on DNDC and INITIATOR results for the six simulation years were estimated using the available management and climate data. The N_2O emission factor, EF_{ij}, for model *i* and year *j* was calculated as:

$$EF_{ij} = \frac{N_2O_{ij} - BackgroundN_2O}{Ninput_j} \tag{3.3}$$

where N_2O_{ij} is the N_2O emission (kg N_2O–N ha^{-1} yr^{-1}) for model *i* and year *j*, *BackgroundN₂O* is the measured background emission (kg N_2O–N ha^{-1} yr^{-1}), and $Ninput_j$ (kg N ha^{-1} yr^{-1}) is the N input by fertilization, manure application, and manure due to grazing in year *j*. The N input by deposition was not included, in line with common practice when calculating N_2O emission factors from measurements (IPCC, 2006). A similar approach was used by De Vries *et al.* (2005) to estimate emission factors with INITIATOR based on national N_2O emission estimates. In this research no unfertilized plots were considered, but Velthof *et al.* (1996a) measured the background emissions for an unfertilized wet and an unfertilized dry plot from the same farm during two years with a measured background emission of 8.6 kg N_2O-N ha^{-1} yr^{-1} for the dry plot and 2.0 kg N_2O-N ha^{-1} yr^{-1} for the wet plot.

3.3 Results

3.3.1 Verification

Fig. 3.2 shows daily N_2O emissions modelled with DNDC and the N_2O measurements for both plots. Box plots indicate the error caused by spatial variation of ten N_2O measurements. While for the dry plot, only 58% of the modelled emissions for the measurement days falls between the minimum and maximum measured emission, the trend of the simulations is similar to the trend in measured emissions. DNDC in general overestimated the fluxes of N_2O compared to the measurements. For the wet plot, the model fit was satisfactory for spring and summer, while the autumn fit was poor. DNDC modelled larger emissions in autumn than measured.

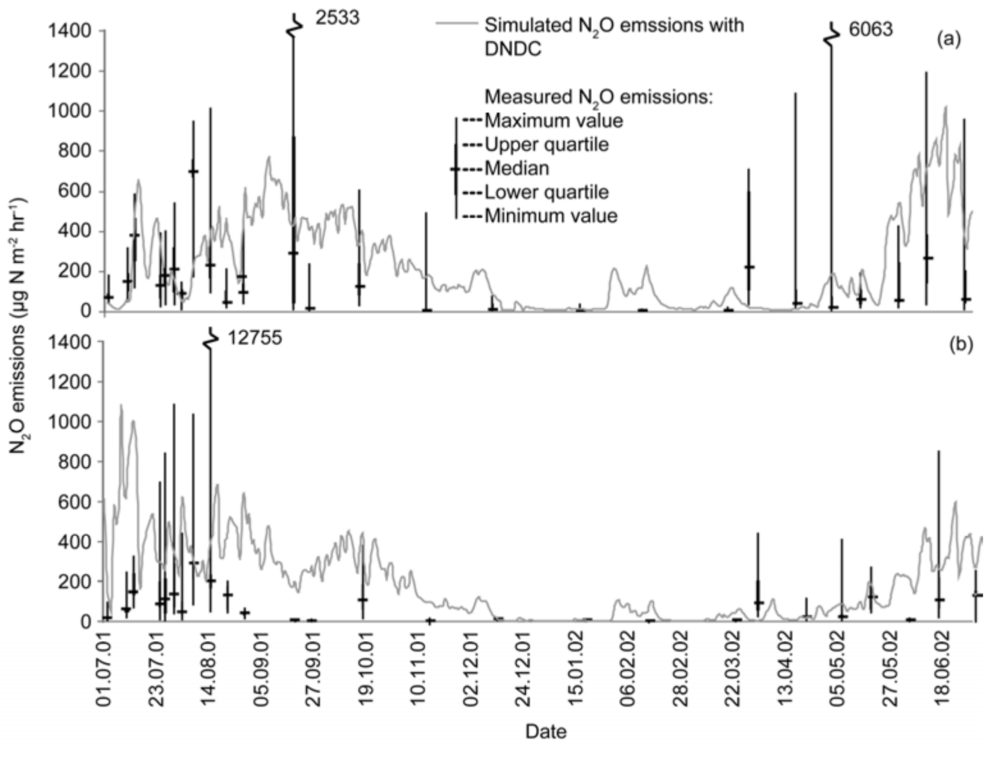

Fig. 3.2 Measured and modelled N_2O emissions for the (a) dry plot and (b) wet plot from 1 July 2001 through 30 June 2002. The values between the lower and upper quartile represent the 50% confidence interval.

In Fig. 3.3 yearly totals, estimated from 1 July 2001 through 30 June 2002, of the N_2O emissions are shown. For both plots, the estimates from INITIATOR and DNDC are within the confidence intervals of the measurement estimates and therefore not statistically significantly different from the measurements. Verification does not reject either of the two models and neither does it show that one of the two is more accurate than the other.

3.3.2 Analysis of temporal resolution effect

For the dry plot, the largest difference of modelled annual N_2O emissions between DNDC and INITIATOR was found for 2003 with a higher estimate from INITIATOR than from DNDC (Fig 3.4a). On the contrary, in 2004 the emission estimated with DNDC was much larger than the emission estimated by INITIATOR. For the wet plot (Fig 3.4b), for only one of the six simulation years (2003) the estimated N_2O emission of INITIATOR was larger than the estimated N_2O emission of DNDC. The trends of the differences between DNDC and INITIATOR were the same as for the dry plot. Because the years 2003 and 2004 showed the largest differences between the modelled N_2O emissions for both plots, these years were important in the subsequent analysis of the temporal resolution effect.

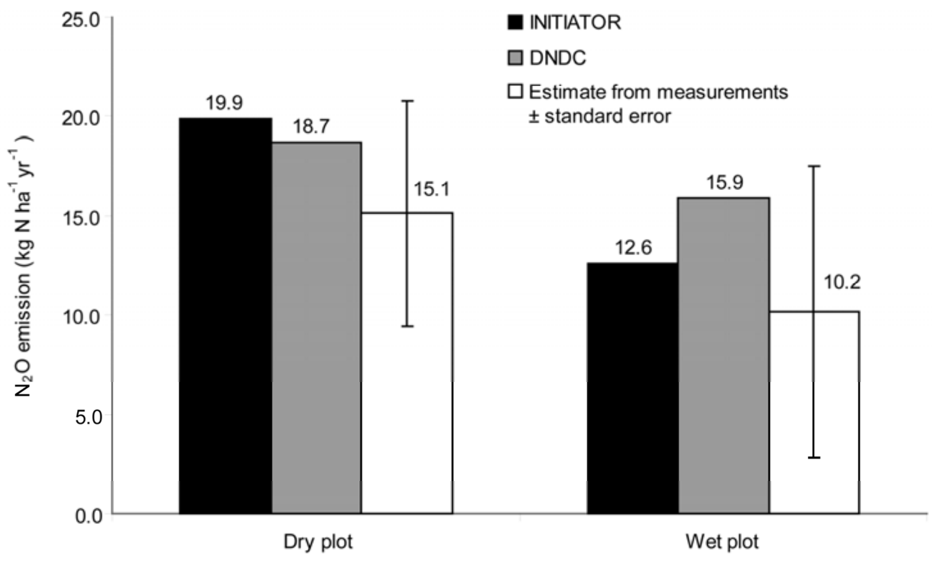

Fig. 3.3 Total annual N_2O emission for the period 1 July 2001 through 30 June 2002 estimated with INITIATOR, DNDC and estimates based on measurements.

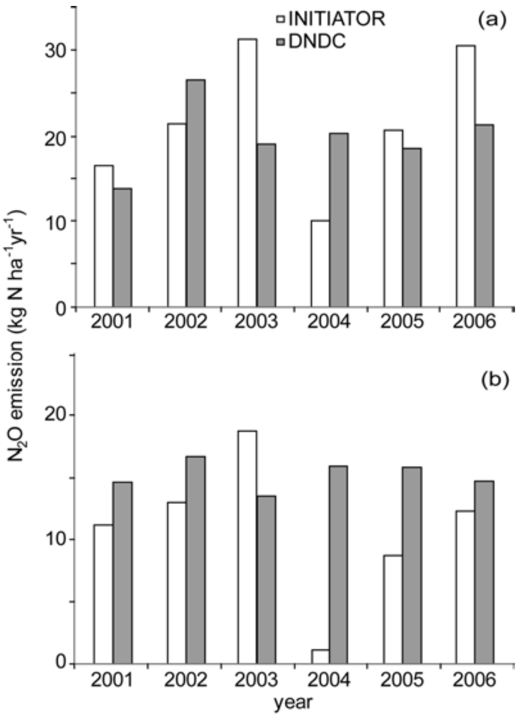

Fig. 3.4 Annual N_2O emissions estimated with INITIATOR and DNDC for 2001 through 2006 for the (a) dry plot and (b) wet plot

Step 1: Identification of high-resolution variables and their interactions

The variables with high temporal resolution in DNDC are rainfall, temperature, N removal due to mowing, N input due to fertilization, N input due to manure application, and N input due to grazing. All interactions of rainfall and N inputs (rainfall & fertilization, rainfall & manure application, rainfall & grazing) were selected for analysis in Step 2, because the interaction of rainfall and N application is known to trigger N_2O emissions (Flechard *et al.*, 2007; Jones *et al.*, 2007; Smith *et al.*, 2003). Because grass residues can also be a source of enhanced emissions, the interaction between rainfall & mowing was also used in Step 2 (Velthof *et al.*, 1996a). Finally, interaction between rainfall & temperature was selected as well, because high temperature in combination with rainfall can cause N_2O emission peaks (Skiba & Smith, 2000).

Step 2: Selection of key variables and variable interactions

All variables identified in Step 1, except temperature, were severely skewed and were therefore log-transformed prior to further analysis. The N_2O emission was also log-transformed. The temporal aggregation results are shown in Table 3.4 for the dry plot.

Management variables (fertilization, manure, grazing, and mowing) have a larger prolonged effect on N_2O emissions than meteorological variables (temperature and rainfall). The daily N_2O emission was best correlated ($r^2 = 0.65$) with the interaction between rainfall summed over 12 prior days and temperature summed over 10 prior days.

In Table 3.5, the results of the analysis of the seasonal variable values between the years are presented. The table shows that 'high' and 'low' variable values correspond to large differences in simulated yearly N_2O emission for summer rainfall, winter temperature, autumn grazing, interaction between rainfall & temperature, and interaction between rainfall & mowing. These variables were therefore identified as key variables in explaining the effects of temporal variation on simulated N_2O emissions. The same analysis was also performed for the wet plot (data not shown). The identified key variables for the wet plot were summer rainfall, spring fertilization, and autumn mowing. The key variable interactions were rainfall & temperature and rainfall & mowing.

Step 3: Analysis of the effects of temporal variation in key variables on N_2O emission

The results of this analysis are given in Table 3.6. Switching the variable distributions between years hardly affected the INITIATOR results due to the small differences in change in yearly total variable values. DNDC, however, strongly reacted to switching the variable distributions between years. Exchanging summer rainfall for the years 2003 and 2004 caused for both plots a large increase of N_2O emission in 2003 and a large decrease of N_2O emission in 2004. For the other substituted variables, the effect was less pronounced.

Table 3.4 Number (nr) of days over which variable values are aggregated (day itself + previous days) to obtain the largest correlation coefficients (r^2) with daily N_2O emission with DNDC (dry plot).

Variable	Optimal nr of days	Variable	Optimal nr of days	r^2
Variables				
Rainfall	10			0.15
Temperature	27			0.48
Manure	115			0.14
Fertilization	160			0.31
Grazing	41			0.21
Mowing	85			0.38
Interactions between variables (variable * variable)				
Rainfall	12	Temperature	10	0.65
Rainfall	9	Manure	121	0.22
Rainfall	10	Fertilization	162	0.44
Rainfall	10	Grazing	48	0.28
Rainfall	10	Mowing	102	0.52

For 2003, which originally had a dry summer, making the summer wetter and the other seasons drier increased the emission for the dry plot by 27% and for the wet plot by 23%. For 2004, which originally had a wet summer, making the summer drier and the other seasons wetter decreased the emission for the dry plot by 11% and for the wet plot by 3%.

Table 3.5 Relative value of variables in different years by season; 'high' indicates relatively high variable values as compared to other years and 'low' indicates relatively low values as compared to 2001-2006 average. Bold numbers in boxes represent key variables and key interactions.

Dry Plot	2001	2002	2003	2004	2005	2006
Seasonal contribution of variable						
Rainfall						
Spring	high	medium	high	low	high	high
Summer	high	medium	**low**	**high**	high	medium
Autumn	low	low	medium	low	low	high
Winter	high	high	high	high	medium	low
Temperature						
Spring	low	high	high	medium	medium	low
Summer	medium	low	high	medium	low	medium
Autumn	high	low	low	low	medium	high
Winter	medium	high	**low**	**high**	medium	low
Manure						
Spring	medium	medium	medium	low	medium	high
Summer	low	high	medium	low	medium	medium
Autumn	high	medium	medium	low	high	low
Winter	high	low	high	low	medium	medium
Fertilization						
Spring	medium	low	medium	high	medium	medium
Summer	low	high	high	high	medium	high
Autumn	high	high	medium	low	high	high
Winter	high	high	medium	medium	low	low
Grazing						
Spring	low	high	medium	low	medium	medium
Summer	high	high	medium	low	high	high
Autumn	low	low	**low**	**high**	low	low
Winter	low	low	high	medium	low	low
Mowing						
Spring	low	low	high	medium	high	low
Summer	high	medium	medium	low	medium	low
Autumn	low	medium	low	medium	low	high
Winter	low	low	low	low	low	high
Variable Combinations						
Rainfall & Temperature	high	high	**low**	**high**	high	high
Rainfall & Manure	high	high	high	low	high	medium
Rainfall & Fertilization	high	medium	medium	low	high	high
Rainfall & Grazing	low	high	high	low	high	high
Rainfall & Mowing	low	low	**low**	**high**	medium	high

[1]Temperature
[2]Fertilization

Table 3.6 Change in emissions calculated by DNDC as result of manipulation experiments of within-year temporal distribution for a number of key variables and interactions.

Dry Plot	2001	2002	2003	2004	2005	2006
Switch method: Variables substituted between 2003 and 2004						
Rain in summer	-	-	+62%	-37%	-2%	+1%
Temperature in winter	-	-	+3%	-6%	0%	+2%
Grazing in autumn	-	-	0%	+1%	-2%	-1%
Changing intra-annual distribution while keeping annual totals equal						
More rain in summer 2003	-	-	+27%	+1%	0%	+2%
Less rain in summer 2004	-	-	-	-11%	-2%	+1%
Temperature & Rain larger in 2003	-	-	+330%	+12%	+4%	+3%
Temperature & Rain smaller in 2004	-	-	-	-83%	-3%	0%
Wet Plot	2001	2002	2003	2004	2005	2006
Switch method: Variables substituted between 2003 and 2004						
Rain in summer	-	-	+39%	-25%	-3%	-1%
Fertilization in spring	-	-	-2%	0%	0%	0%
Mowing in spring	-	-	+1%	-9%	-3%	+1%
Changing intra-annual distribution while keeping annual totals equal						
More rain in summer 2003	-	-	+23%	+2%	+2%	+2%
Less rain in summer 2004	-	-	-	-3%	-3%	-2%
Temperature & Rain larger in 2003	-	-	+78%	+7%	+5%	+5%
Temperature & Rain smaller in 2004	-	-	-	-74%	-5%	-3%

- not applicable (nothing was changed compared to the original run)

Increasing the interaction of rainfall and temperature in 2003 led to a dramatic increase in N_2O emissions (more than three times the original emission for the dry plot, see Table 3.6). The effect of decreasing the interaction rainfall & temperature in 2004 was a large decrease in N_2O emissions for both plots. Manipulation of the key variables and variable interactions in 2003 or 2004 sometimes also affected the emissions in 2005 and 2006 due to differences in N content of the soil which is passed on to the next year (Table 3.6).

3.4 Discussion

3.4.1 Parameterization and verification

Default parameters of DNDC yielded unrealistic results, particularly for the soil hydrology. Problems with the parameterization of field capacity and wilting point for DNDC have also been observed by Beheydt *et al.* (2007). However, accurate simulation of soil moisture is a key requirement for reliable simulation of N_2O emissions (Frolking *et al.*, 1998). Therefore, parameterization is essential. After parameterization, the WFPS corresponded to the measured WFPS in 1992, 2001, and 2002, which were all average in terms of summer rainfall. The model was assumed to perform well for years with wet and dry summers, too. Jagadeesh Babu *et al.* (2006) indicate the use of default crop parameters in DNDC as a potential source of errors, but they could not adjust these parameters due to lack of data. Tonitto *et al.* (2007) adjusted the crop parameters for their research in Illinois in the same way as in this research.

Although not every simulated daily emission fell between the minimum and maximum measured value for the dry plot, the patterns were similar (Fig. 3.3). The annual modelled fluxes were within the borders of the confidence intervals of the measured fluxes (Fig. 3.4).

The simulated N inputs and outputs to soil were compared with measurements on nitrogen inputs and outputs at other sites in the Dutch fen meadow landscape to analyse differences between modelled and measured nitrogen flows (Table 3.7). For both DNDC and INITIATOR, measured N inputs of fertilizer and manure were used. The N deposition used by INITIATOR was based on estimates by an emission deposition model, whereas DNDC used the measured N concentration in rain (mg N l^{-1}). Mineralization and accompanied subsidence of the surface layer has been observed in both plots (Beuving & Van den Akker, 1996). Kuikman *et al.* (2005) estimated that the mineralization is about 363 kg N ha^{-1} yr^{-1} for the dry and about 136 kg N ha^{-1} yr^{-1} for the wet plot. For the dry plot, both models estimated a smaller mineralization, although INITIATOR is closer to the estimate of Kuikman *et al.* (2005) and DNDC largely underestimates the mineralization. For the wet plot, the modelled mineralization rates are closer to the estimate of Kuikman *et al.* (2005). INITIATOR represents differences between mineralization rates of the dry and the wet plot better than DNDC.

The N outputs by DNDC are generally too small, particularly for the net crop removal and denitrification (total emissions of N_2, N_2O, and NO_2). The latter value was influenced by underestimation of mineralization in the dry plot. Furthermore, DNDC simulates a strong N accumulation in the soil, which seems unrealistic in view of the underestimated mineralization. The N outputs by INITIATOR are more in line with the measurements; only N leaching is significantly underestimated. DNDC simulates N_2O emissions quite independently from the estimated N uptake and N leaching. A crucial difference between both models is the much smaller N_2O/N_2 ratio estimated by INITIATOR due to the much larger estimated denitrification. Measurements by Van Beek (2004b) are between the DNDC estimate and the INITIATOR estimate for denitrification. Denitrification measurements by De Klein and Logtestijn (1994); 4-16 kg N ha^{-1} yr^{-1}) from grassland on peat soil are close to the DNDC estimate, although these measurements were only limited to the topsoil (<20 cm). These findings show that analysis of the N balance provides valuable information about measured and modelled N flows for both plots. For the objectives of this study, however, the balance was only used to show differences between modelled and measured N flows.

Table 3.7. N balance with annual averages for the validation period from 1 July 2001 to 30 June 2002 (kg N ha^{-1} yr^{-1}). Comparison of simulated and measured N inputs and outputs to the soil.

	Dry Plot			Wet Plot		
	DNDC	INITIATOR	Measurements	DNDC	INITIATOR	Measurements
Nitrogen inputs to soil						
Fertilizer	104	104	104[a]	110	110	110[a]
Manure (applied & grazing)	187	187	187[a]	264	263	263[a]
Deposition	39	39		39	39	
N fixation	21	25		3	25	
N mineralization	178	298	363[b]	136	93	136[b]
Total	529	654		484	530	
Nitrogen outputs to soil						
NH_3 volatilization	27	27	39[c]	36	37	66[c]
Grass loss (cut & grazed)	83	240	221[a]	174	248	424[a]
N leaching	55	6	38[d]	12	4	38[d]
Denitrification, of which:	22	381	126-213[e]	19	242	
-N_2O emissions	*19*	*20*		*16*	*13*	
-NO emissions	*2*	*6*		*2*	*4*	
-N_2 emissions	*2*	*358*		*1*	*227*	
Total	209	652		240	531	
Nitrogen change in soil	+320	+2		+311	-1	

[a] Information from farmer (K. Van Houwelingen, personal communication, 2008)
[b] Kuikman *et al.* (2005)
[c] Sonneveld *et al.* (2008)
[d] Van Beek *et al.* (2004a)
[e] Van Beek *et al.* (2004b)

3.4.2 Analysis of temporal resolution effect

In three steps, the effect of high-resolution temporal variation on N_2O emissions was analysed. For the variables manure, fertilization, and mowing the largest correlation with daily N_2O emission was found using the sum of the variable over a period of more than two months (Table 3.4). For the estimation of the annual N_2O emission it is, therefore, not necessary to know the exact dates of these events. The effect of these events on N_2O emission is prolonged and N levels in the soil are enhanced for several months; thus knowing the months in which the events occur is sufficient to estimate the annual N_2O emission. Rainfall gave the best correlation when using the sum of the prior ten days for the dry plot. Apparently, it takes about ten days for the hydrology in the field to return to the initial situation and the effect of rainfall on N_2O emission is noticeable for more than a week.

The analysis of the temporal resolution effects showed for both plots that changes in the rainfall dataset have the largest effect on annual N_2O emission. The dry plot is more sensitive to summer rainfall than the wet plot. Apparently, the high water levels in the ditches surrounding the wet plot cause the plot to keep a certain wetness even in dry summers. Note that the summer in 2003 was dry and the summer of 2004 was wet (Fig. 3.1). Climatological studies indicate that the frequency of these extreme wet and dry years will increase (KNMI, 2006). This study showed that the estimation of the annual N_2O emission is very sensitive to seasonal changes in rainfall. Especially the amount of rainfall in summer affects annual N_2O emissions. Temperatures are high in summer and nitrogen is applied in spring or summer. Nitrogen application in spring also causes high nitrogen levels in summer due to the prolonged effect. These conditions are needed for N_2O emission peaks, together with a certain wetness of the soil. Because for the research plots the conditions for temperature and nitrogen application are always met in summer, the amount of rainfall is probably the decisive condition for N_2O emission. Large summer rainfall amounts causes large summer N_2O emissions and a large annual N_2O emission, and vice versa. Jones *et al.* (2007) also found large N_2O emissions due to large rainfall amounts in the growing season. Flechard *et al.* (2007) observed N_2O emission factors, which were consequently smaller for dry years than for other years. For boreal sub humid climates, Grant *et al.* (2006) already advised to decrease emission factors for dry years.

3.4.3 Inclusion of finer temporal resolution into low temporal-resolution models

Ideally, countries would use Tier 3 methods to accurately simulate their N_2O emissions, but limited data availability makes this difficult. However, in this thesis, information from Tier 3 methods was used at small spatial extents (parcels) to improve Tier 2 methods. For instance, the proportion of summer rainfall is not considered in the low temporal-resolution model INITIATOR. The analysis of the temporal resolution effects shows that the proportion of summer rainfall can potentially have a large effect on annual N_2O emission. Therefore, the INITIATOR model can be improved by adjusting the N_2O emissions for years with a relatively low or high summer rainfall (Table 3.5). For years with 'medium' summer rainfall (Table 3.5) the emissions were not adjusted, but for years with 'low' or 'high' summer rainfall, a linear adjustment was made proportional to the deviation from the normal summer rainfall.

For both plots, this temporal resolution effect was estimated to be 12.9% (± 4.5%). For instance, the annual emission increases by 12.9% when the summer rainfall has a share of 26% of the annual rainfall and decreases by 12.9% when the share is 24% of the annual rainfall. The adjusted N_2O emissions are given in Fig 3.5. The annual estimated emissions slightly improved; the root mean squared error between DNDC and INITIATOR decreased by 13% for the dry parcel and by 2% for the wet parcel, but differences in results between the models still remain (Fig. 3.5). INITIATOR estimated on average larger N_2O emissions for the dry plot and DNDC estimated on average larger N_2O emissions for the wet plot. This is probably because INITIATOR puts more emphasis on N_2O emission due to mineralization from the dry plot, while DNDC puts more emphasis on N_2O emission due to denitrification caused by the high WFPS from the wet plot. Accordingly, differences in modelled annual N_2O emissions are not only caused by differences in temporal resolution, but also by differences in model concepts.

3.4.4 Comparison of simulated annual average emission factors with the IPCC default values (Tier 1) and Dutch values (Tier 2)

Table 3.8 shows that the emission factors for DNDC and INITIATOR for the dry plot over the six simulation years are very similar. These emission factors were derived assuming a constant background emission. The emission in 2004 simulated by INITIATOR was

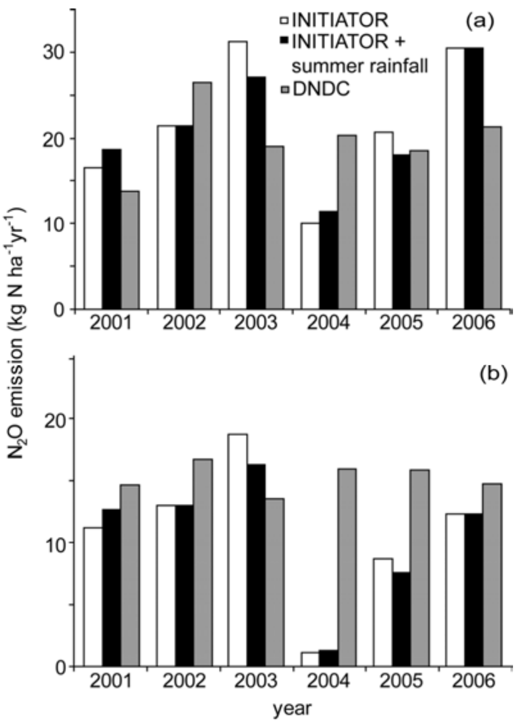

Fig. 3.5 Annual N_2O emissions estimated with INITIATOR and DNDC for 2001 through 2006 for the (a) dry plot and (b) wet plot (see also Fig. 3.4) compared with updated INITIATOR estimates, which take into account the effect of relatively low or high amounts of summer rainfall.

smaller than the background emission, causing a negative emission factor. The large emission factors for DNDC in 2004 are caused by the large summer rainfall.

Table 3.8 Nitrogen inputs and estimated annual N_2O emission factors derived from the simulated N_2O emissions of DNDC and INITIATOR.

	2001	2002	2003	2004	2005	2006
Dry Plot						
N input due to manure and fertilizer (kg N ha^{-1} yr^{-1})	224	401	399	86	386	376
DNDC N_2O emission factor	2.3%	4.4%	2.6%	13.6%	2.6%	3.4%
INITIATOR N_2O emission factor (%)	4.5%	3.8%	6.6%	3.0%	3.7%	6.7%
Wet Plot						
N input due to manure and fertilizer (kg N ha^{-1} yr^{-1})	328	414	438	68	315	285
DNDC N_2O emission factor (%)	3.9%	3.5%	2.6%	20.6%	4.4%	4.5%
INITIATOR N_2O emission factor (%)	3.2%	3.0%	4.5%	-1.1%	2.6%	4.3%

The default Tier 1 value for the N_2O emission factor according to the updated IPCC Guidelines (IPCC, 2006) is 1% for the application of manure and fertilizer on both mineral and organic soils, based on results of a global N_2O emission inventory of Bouwman *et al.* (2002). The emission percentages used in the Dutch Tier 2 approach are also 1% for mineral soils but 2% for organic soils. This value is mainly based on measurements during a two year experimental study by Velthof and Oenema (1995), who measured N_2O emissions from managed grassland in the Netherlands on two mineral soils (sand and clay) and two peat soils (similar to the research in this chapter, a dry and a wet plot). These authors calculated N_2O emission factors near 1% for the mineral soils but near 2% and 4% for the 'wet' and 'dry' peat soils, respectively. The larger values were caused by the larger C and N turnover rates and shallower groundwater levels in peat soils, leading to larger denitrification rates. It is clear that the DNDC and INITIATOR estimates are closer to the national value than the IPCC default value. Note, however, that the differences between the DNDC and INITIATOR estimates and the national value are still substantial.

3.5 Conclusions

Comparison of predictions obtained with the high temporal resolution model DNDC and the low temporal resolution model INITIATOR enabled an assessment of the effect of temporal resolution on annual N_2O emission. However, differences between modelled N_2O emission are also influenced by differences in model concepts and these differences are hard to separate from those caused by differences in temporal resolution. Results point to the important role of distribution of rainfall within a year for estimating annual N_2O emissions from intensively managed grasslands in the fen meadow landscape. In years with a relatively large summer rainfall, N_2O emission estimated with DNDC was larger than estimated with INITIATOR. In years with a relatively small summer rainfall, the opposite occurred. One important conclusion from this work is therefore that low temporal resolution inventory models such as INITIATOR (and other Tier 2 methods) may be improved for intensively managed grasslands on peat soils by adjusting N_2O emission estimates for years with relatively dry summers and wet summers. More research is needed to analyse to what degree these conclusions may be extrapolated to other ecosystems.

The analysis used to identify key variables and variable interactions showed that not the daily values of these variables are important for predicting daily and annual N_2O emissions, but the average of the variables over weeks or even months. Aggregates over longer periods showed the largest correlation with daily N_2O emissions. Especially for management variables, the largest correlations were found using the average of months or even longer. Because of this prolonged effect, the exact dates of nitrogen application are not important for estimating annual N_2O emissions for intensively managed grasslands on peat soils. It is sufficient to know in which month the application took place. This will greatly simplify upscaling efforts of N_2O emissions.

The emission factors estimated from DNDC and INITIATOR varied largely between the models and between years. It is therefore recommended to estimate emission factors over a large time period (decades) and to be cautious with years with very large of very small summer rainfall.


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4

Uncertainty propagation analysis of an N_2O emission model at the plot and landscape support

Abstract

Uncertainties associated with agricultural N_2O emissions are large. The goal of this work was (i) to quantify the uncertainties of modelled N_2O emissions caused by model input uncertainty at point and landscape support, and (ii) to identify the main sources of input uncertainty at both scales. For the Dutch fen meadow landscape, a Monte Carlo uncertainty propagation analysis was performed using the INITIATOR model. Spatial auto- and cross-correlation of uncertain numerical inputs that are spatially variable were represented by the linear model of coregionalization. Bayesian Maximum Entropy was used to quantify the uncertainty of spatially variable categorical model inputs. Stochastic sensitivity analysis was used to analyse the contribution of groups of uncertain inputs to the uncertainty of the N_2O emission at point and landscape support. The average N_2O emission at landscape support had a mean of 20.5 kg N_2O-N ha^{-1} yr^{-1} and a standard deviation of 10.7 kg N_2O-N ha^{-1} yr^{-1}, producing a relative error of 52%. At point support, the relative error was on average 78%, indicating that upscaling decreases uncertainty. Soil inputs and denitrification and nitrification inputs were the main sources of uncertainty in N_2O emission at point support. At landscape support, uncertainty in soil inputs averaged out and uncertainty in denitrification and nitrification inputs was the dominant source of uncertainty. Experiments at landscape scale are needed to assess the spatial variability of these fractions and analyse how a more realistic representation influences the uncertainty budget at landscape scale. This research confirms that results from uncertainty analyses are often scale dependent and that results for one scale cannot directly be extrapolated to other scales.

Based on: Nol, L., Heuvelink, G.B.M. and Veldkamp, A, De Vries, W., Kros, H.
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4.1 Introduction

In the past century, fossil fuel consumption has rapidly grown due to industrialisation and increasing traffic. In agriculture, the use of nitrogen (N) fertilizers and manure with high N content rapidly increased (Vitousek *et al.*, 1997). These processes seriously increased the levels of N in the environment (Galloway *et al.*, 2008; IPCC, 2007b). In the Netherlands, this has led to emissions of nitrous oxide (N_2O) and ammonia (NH_3), biodiversity loss, eutrophication of surface water and pollution of groundwater (Bakker & Berendse, 1999; De Vries *et al.*, 2001; Gulati & Van Donk, 2002; Kroeze *et al.*, 2003; Ozinga *et al.*, 2009; Van Dyck *et al.*, 2009). The most recent National Inventory Report of the Netherlands (Van der Maas *et al.*, 2008) identifies uncertainty about N_2O emission from agriculture as the main source of uncertainty in the total annual GHG budget. Ramírez *et al.* (2008) reached the same conclusion using a Monte Carlo (MC) uncertainty analysis on Tier 2 level. However, these studies did not analyse the causes behind the large uncertainty in N_2O emission from agricultural soils.

The MC method is commonly used to analyse how uncertainties propagate in ecosystem models and cause uncertainty in model outputs (Rypdal & Winiwarter, 2001). Attractive properties of the method are the easy implementation, the general applicability and the resulting entire probability distribution of the model output (Heuvelink, 1998a). It can also reach a given level of accuracy, by using a sufficient large number of MC runs. Uncertainty propagation analysis on N_2O emissions using MC simulation has been performed for various ecosystems and models. For instance, DNDC was used to estimate the uncertainty in N_2O emissions from Chinese rice paddies (Li *et al.*, 2004) and Finnish peatlands (Alm *et al.*, 2007). In the Netherlands, de Vries *et al.* (2003b) performed an uncertainty analysis of all major N flows using the INITIATOR model. However, this research was limited to non-spatial model inputs, whereas spatial model inputs such as soil type and land use also influence the uncertainty in GHG prediction (Mosier, 1998; Pihlatie *et al.*, 2004; Saggar *et al.*, 2004). There is a need for a systematic uncertainty analysis on different spatial scales (Boyer *et al.*, 2006; Yates *et al.*, 2007), taking uncertainty in all major inputs and spatial auto- and cross-correlation between these inputs into account.

In this chapter, the approach and results of an uncertainty analysis using MC simulation of an N_2O emission model for the Dutch fen meadow landscape are described, including all relevant management, soil, and emission model inputs. This landscape was selected since the largest uncertainties associated with N_2O emissions are found for peat soils in the Netherlands (Van der Maas *et al.*, 2008). The study was carried out both at point and landscape support with the aims to (i) quantify the uncertainty of N_2O emission estimates of an N emission model due to uncertain model inputs at point and landscape support, and (ii) identify the main sources of input uncertainty at both scales.

4.2 Materials and methods

4.2.1 The model INITIATOR

INITIATOR (version 3.2) is a simple integrated N model developed for the Netherlands (§1.3.2). De Vries *et al.* (2003b) provide an extensive description. An extended version of INITIATOR can simulate CO_2 emissions from soils, CH_4 emissions, NH_3 emissions and N_2O emissions from housing systems, and leaching and runoff of P, base cations and heavy metals (De Vries *et al.*, 2005), but here the focus is on N_2O emissions from soils, notably peat soils. INITIATOR uses 48 model inputs to model N_2O emission from soils. Model inputs are defined as initial conditions, boundary conditions, and model parameters.

Data on manure application from cattle in stables, grazing cattle, pigs and poultry (kg N ha^{-1}) are privacy-sensitive and not easily available, therefore, pre-processing with a spatial manure distribution module was used (De Vries *et al.*, 2009). A so-called GIAB-database (Naeff, 2003) was used to assess the number of animals per animal type and stable system for each Dutch farm. First, these data were aggregated in INITIATOR to the municipality level. Secondly, the manure excretion in meadows and stables (kg N yr^{-1}) was estimated and distributed over the grasslands in the municipality and rescaled to a 250 m resolution, while taking into account differences in soil type, land use and hydrology. If the amount of manure application was greater than the EU legal permitted N load, the excess is exported to neighbouring areas with shortages. In INITIATOR, the manure application (kg N ha^{-1} yr^{-1}) was also used to estimate the amount of synthetic fertilizer used. Synthetic fertilizers were assumed to be added to the grassland, which already received manure application, up to the legally permitted N load.

N mineralisation in peat soils, which is largely due to drainage, was assessed from the CO_2 emission. In INITIATOR, the CO_2 emission was calculated as a function of thickness and organic matter content of the peat layer, soil wetness and land use (De Vries *et al.*, 2005; De Vries *et al.*, 2009). Using the C/N ratio of the peat layer, the N mineralization was modelled. The maximum N uptake by grassland and cropland was calculated by multiplying the crop or grass yield with the % N in crop or grass, which is a function of total N input. The categorical model inputs land use, soil type and soil wetness were

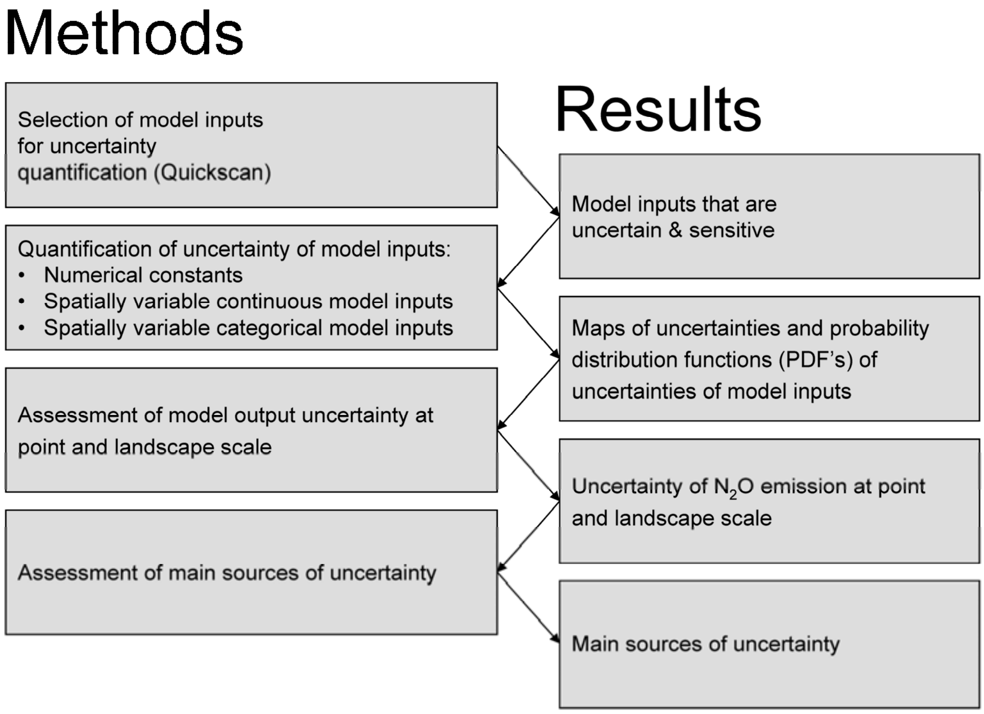

Fig. 4.1 Flow chart of uncertainty analysis methods and results

used for stratification and estimation of continuous input variables such as grass yield and emission factors.

4.2.2 The Dutch fen meadow landscape

The Dutch fen meadow landscape is located in the western part of the Netherlands (§1.2). Nowadays, 81% of the land cover in the fen meadow landscape is grassland (GeoDesk, 2006). Most grassland is intensively managed and owned by dairy farmers. However, more and more grassland is extensively managed and higher groundwater regimes are applied to reduce soil subsidence. The fen meadow landscape is predominately located on peat soils according to the Dutch soil map 1:50,000 (De Vries *et al.*, 2003a). The area covers about 1000 km^2.

A flow diagram of used methods and intended results is presented in Fig. 4.1. The methods will be discussed in the next sections.

4.2.3 Selection of model inputs for uncertainty quantification (Quickscan)

Not all model inputs were included in the MC uncertainty propagation analysis. Only those inputs that have a large uncertainty and to which the model is sensitive were taken into account. Janssen *et al.* (2005) and Petersen *et al.* (2003) reported the use of a 'quickscan' for selecting the main sources of uncertainty. The developed quickscan was intended to qualitatively classify all types of uncertainty (e.g. model context, model inputs, stakeholder involvement); however in this chapter the focus is on uncertainty due to uncertainty in model inputs. Other types of uncertainty are treated in the other chapters of this thesis and in Kroon *et al.* (2008). The quickscan was adapted for use in this research. The first step in the quickscan approach was to create a table listing all model inputs, their level of uncertainty and their level of sensitivity. A qualitative approach was used for simplicity and transparency. The second step was to determine the level of uncertainty of the inputs using literature research, measurements of different model inputs in the fen meadow landscape, and interviews with experts. The developers of the INITIATOR model, which have detailed knowledge about the processes causing N2O emission in the Dutch fen meadow landscape, were also consulted. The last step of the quickscan was to determine the level of sensitivity of the inputs. This was partly derived by interpreting the model structure and components, partly from interviews with experts, and partly from test runs with INITIATOR.

4.2.4 Input uncertainty quantification of selected model inputs

The uncertainties of model inputs selected using the quickscan were characterized with probability distribution functions (PDFs, Heuvelink *et al.*, 2007). The spatial support of the inputs and the method used to adjust the inputs to the model resolution (in space and time) influence their uncertainty. The estimation and representation of input uncertainty also depends on the measurement scale of the input (e.g. continuous numeric or categorical) and whether the input is constant or variable in space, as described below.

<u>Numerical constants</u>

Uncertain numerical constants are characterized by a continuous PDF, which quantifies the probability that the uncertain variable takes a value in any given interval. Common shapes for continuous PDFs are the normal, lognormal, and uniform distribution. In case of multiple uncertain numerical constants, statistical dependence between uncertain inputs may need to be considered, because this can have a marked effect on the outcome of the uncertainty propagation analysis. For normally distributed inputs, statistical dependence between two variables is specified by the Pearson's correlation coefficient.

Spatially variable continuous model inputs

An uncertain numerical model input that varies in space can be represented by the basic model:

$$Z(\mathbf{x}) = m(\mathbf{x}) + \varepsilon(\mathbf{x}) \tag{4.1}$$

where $Z(\mathbf{x})$ is the variable at location $\mathbf{x}$, $m(\mathbf{x})$ is a known trend and $\varepsilon(\mathbf{x})$ is an unknown stochastic residual. The residual $\varepsilon(\mathbf{x})$ may be spatially autocorrelated, usually characterized with the semivariogram $\gamma(\mathbf{h})$:

$$\gamma_\varepsilon(\mathbf{h}) = \frac{1}{2}\mathrm{E}\left[\left(\varepsilon(\mathbf{x}) - \varepsilon(\mathbf{x}+\mathbf{h})\right)^2\right] \tag{4.2}$$

where E is the mathematical expectation and $\mathbf{h}$ is the lag distance (m). Note that second-order stationarity was assumed in Eq. (2), by letting γ depend only on the separation distance $\mathbf{h}$ and not on the locations $\mathbf{x}$ and $\mathbf{x}+\mathbf{h}$ (Oliver & Webster, 2007). If there are two (or more) uncertain spatial variables Z_1 and Z_2, then spatial cross-correlation may need to be specified as well, using the cross-semivariogram $\gamma_{12}(\mathbf{h})$

$$\gamma_{12}(\mathbf{h}) = \frac{1}{2}\mathrm{E}\left[\left(\varepsilon_1(\mathbf{x}) - \varepsilon_1(\mathbf{x}+\mathbf{h})\right)\left(\varepsilon_2(\mathbf{x}) - \varepsilon_2(\mathbf{x}+\mathbf{h})\right)\right] \tag{4.3}$$

To guarantee positive-definiteness of two correlated spatial variables, the linear model of coregionalization (LMCR) is often imposed (Goovaerts, 1997; Lark & Papritz, 2003; Vašát *et al.*, 2010):

$$\gamma(\mathbf{h}) = \begin{bmatrix} \gamma_{11}(\mathbf{h}) & \gamma_{12}(\mathbf{h}) \\ \gamma_{21}(\mathbf{h}) & \gamma_{22}(\mathbf{h}) \end{bmatrix} = \sum_{i=1}^{m} \begin{bmatrix} a_{11i} & a_{12i} \\ a_{21i} & a_{22i} \end{bmatrix} \cdot f_i(\mathbf{h}) = \sum_{i=1}^{m} A_i \cdot f_i(\mathbf{h}) \tag{4.4}$$

where the $f_i(\mathbf{h})$ are one-dimensional variogram structures, m is the number of structures, and where each of the matrices A_i is symmetric and positive-definite. The LMCR model can easily be extended to three variables and more.

Spatially variable categorical model inputs

For a spatially variable categorical model input *C* with categories c_i (i =1,..., n_c) the uncertainty about its value at some location **x** is characterized by a discrete PDF:

$$P(C(\mathbf{x}) = c_i) = \pi_i(\mathbf{x}) \quad (4.5)$$

where $P(C(\mathbf{x}) = c_i)$ is the univariate probability that variable *C* falls in category c_i at location *C* or shortly $\pi_i(\mathbf{x})$. The bivariate probability is given by:

$$P(C(\mathbf{x}) = c_i \text{ and } C(\mathbf{y}) = c_j) = \pi_{ij}(\mathbf{x}, \mathbf{y}) \quad (4.6)$$

Bayesian Maximum Entropy (BME) was used to quantify uncertain categorical spatial variables. BME has proven to be a powerful method for spatial prediction and mapping categorical variables (Bogaert, 2002; Brus *et al.*, 2008). The method combines 'hard' data (observations) with 'soft' data (maps). BME consists of two steps: (i) estimation of the unconditional multi-point PDF at the prediction location and at neighbouring observation location and (ii) conditioning the unconditional multi-point PDF on the observations at locations in the local neighbourhood of the prediction location. The entropy (*H*) is a measure of the prediction accuracy:

$$H = -\sum_{i=1}^{n_c} \pi_i \log \pi_i \quad (4.7)$$

The minimum value of the entropy is 0 and occurs when one possible outcome has probability 1, the maximum entropy value is log n_c, which occurs when all outcomes have equal probability (Brus *et al.*, 2008). The larger the entropy, the larger the uncertainty in model input *C*.

4.2.5 Assessment of uncertainty at point and landscape support

The propagation of uncertainty in the N_2O emission calculated with INITIATOR caused by uncertainty in model inputs was analysed using MC simulation. During the MC simulation, random drawings from the PDF of the uncertain inputs were generated and the model was run for each of the drawings (Heuvelink, 1998a). Many of the numerical constants were stratified based on categorical data, meaning that their PDF depends on the value of a categorical variable. Therefore the MC simulation followed a nested approach (Finke *et al.*, 1999) in which first the categorical variables are simulated, after which the numerical constant is simulated, conditional to the simulated categorical variables. Sequential Gaussian simulation (Goovaerts, 1997) was used to generate realizations from spatially distributed and spatially correlated variables. For spatially distributed categorical variables, BME was used to draw from the conditional

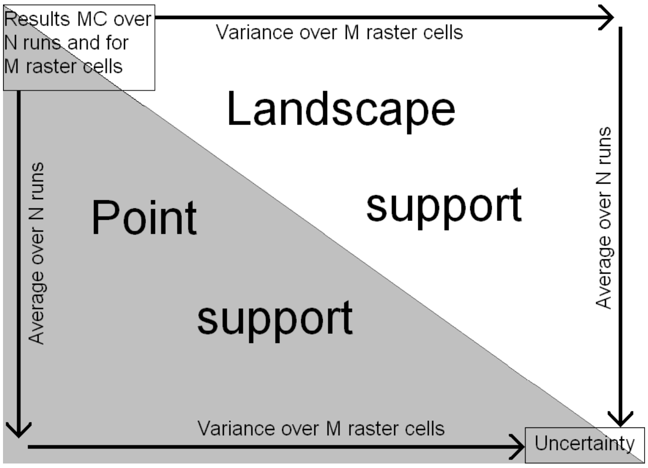

Fig. 4.2 Approaches to estimate uncertainty at point and landscape support.

multi-point PDFs. Repeated sampling and model running yielded a sample of simulated N_2O emissions, of which summary statistics were computed to assess the uncertainty propagation. To verify that the number of MC runs was sufficient and produced stable results, scatter plots of standard deviations at point support of independent MC analyses were made.

At point support, the MC analysis was performed for every node of a dense grid covering the study area, using a spatial resolution of 250 m. Maps of the associated uncertainties in N_2O emissions associated uncertainties were made, to identify spatial patterns and hotspots. Because spatial correlation was taken into account, the N_2O emission and associated uncertainty could also be aggregated to the landscape scale (Heuvelink & Pebesma, 1999). For every MC simulation, first the variance of the N_2O emission for the fen meadow landscape was computed. Next, the average over all MC simulations was used to characterize the model output uncertainty at landscape support. The model output uncertainty at point support, which was characterized by calculating the variance over MC runs for each point location, was also averaged to enable comparison with the model output uncertainty at landscape support (Fig 4.2).

4.2.6 Assessment of the main sources of uncertainty

The main sources of uncertainty were determined with a stochastic sensitivity analysis (Saltelli *et al.*, 2000). This method assesses the contribution of distinct uncertainty sources to uncertainty in the predicted N_2O emission. With this method, it is not only possible to analyse the contribution of individual inputs, but also of groups of uncertain inputs on the uncertainty of the N_2O emission. For each group of uncertain inputs, the bottom marginal variance (BMV) is calculated; which is the variance reduction that results from only assuming uncertainty in one group of inputs, compared to the total variance (Jansen, 1998b; Li & Wu, 2006). Differences between the BMV at point and landscape support were also analysed.

4.3 Results

4.3.1 Selection of model inputs for uncertainty quantification

The quickscan results are discussed for seven groups including all model inputs used to simulate agricultural N_2O emissions, following Table 4.1.

Soil: Soil type was considered a very sensitive input to INITIATOR, because many other INITIATOR inputs depend on it. Also, the uncertainty in soil type was large. Soil type is derived from the Dutch soil map 1:50,000 (De Vries *et al.*, 2003a; Steur & Heijink, 1991), but large parts of the map were already established in the 1960s and 1970s. Although soil types hardly change over a few decades, (drained) peat soils do (Kempen *et al.*, 2009; Van Kekem, 2004). In the western part of the Netherlands, peat soils are generally thick (§1.2). The peat soils exist of eutrophic or mesotrophic peat mixed with clay minerals. When peat in the topsoil oxidizes, clay minerals will accumulate and the soil type will transform into a mineral soil. Van Amstel *et al.* (2000) also reported a large uncertainty about the area occupied by peat soils. Thus, soil type was included in the uncertainty propagation analysis.

Data from auger points were used to determine the spatial variability in soil properties. The soil properties bulk density, organic matter content, C/N ratio, thickness of the peat layer and (if present) thickness of the mineral cover layer all turned out to have a large spatial variation, which in turn causes large uncertainties when the density of sampling points is small. However, N_2O emission was only sensitive to organic matter content in INITIATOR. It was therefore decided to include only the soil property soil organic matter in the uncertainty propagation analysis.

Land use and hydrology: INITIATOR is sensitive to land use because many INITIATOR inputs depend on it. The uncertainty in land use is small, because accurate, up-to-date information is available (GeoDesk, 2006). Therefore, this model input was not considered uncertain. The mean lowest groundwater level (MLW) and mean highest groundwater level (MHW) are uncertain, but in INITIATOR the groundwater table is mainly used to distinguish between three soil wetness classes: wet, moist and dry. Due to this crude division, much of the uncertainty about the groundwater table is eliminated. For example, in the fen meadow landscape, groundwater table is uncertain

Table 4.1 Quickscan with qualitative analysis of uncertainty of all model inputs used in INITIATOR and the sensitivity of modelled N_2O emission for all inputs (legend: from ++ very uncertain/sensitive to −− not uncertain/sensitive). Arrows indicate the selected inputs.

Model input (unit)	Unc[a]	Sens[b]	Model input (unit)	Unc[a]	Sens[b]
Soil			Deposition of NH (kg N ha^{-1} yr^{-1})	++	O
Soil type (-)	++	++	Fraction of N deposition taken up by vegetation (-)	+	−
Bulk density (%)	++	+	Nitrification and denitrification in soils		
Organic matter content (%)	++	++	Emission factor of N_2O due to soil denitrification (-)	++	++
C/N ratio (-)	++	+	Emission factor N_2O due to soil nitrification (-)	++	++
Thickness of peat layer of shallow peat soils (cm)	++	O	Fraction of soil N, which is denitrified (-)	++	++
Mineral cover depth of shallow peat soils (cm)	++	O	Fraction of soil N, which is nitrified (-)	++	++
Total depth of peat layer of peat soils (cm)	++	O	Fraction of soil N, which is immobilized (-)	+	O
Land cover			Fraction of soil N, which is denitrified in nature areas (-)	O	−
Land cover type (-)	O	++	Fraction of soil N, which is nitrified in nature areas (-)	O	−
% Nature area covered by deciduous forest (%)	O	−	Uptake by vegetation		
% Nature area covered by spruce (%)	O	−−	Yield of grass or maize (kg dry matter ha^{-1})	++	++
% Nature area covered by pine (%)	O	−−	% N in grass yield (%)	++	++
% Nature area covered by heath (%)	O	−−	Yield of crops (not grass or maize) (kg fresh matter ha^{-1})	++	−
% Nature area covered by grass (%)	O	−	Dry matter content of crops (%)	O	−
Hydrology			Fraction of N from grazing cattle taken up by vegetation (-)	+	−
Mean highest groundwater level (MHW)	++	+	Min. N deposition on nature areas (kg ha^{-1} yr^{-1})	+	−
Mean lowest groundwater level (MLW)	++	+	Max. N deposition on nature areas (kg ha^{-1} yr^{-1})	+	−
Groundwater table (-)	+	+	Density of stem wood in nature areas (kg m^{-3})	O	−
Precipitation excess (mm)	O	−	Fraction min. N content in stem wood in nature areas (-)	O	−
Manure management			Fraction max. N content in stem wood in nature areas (-)	O	−
N in applied cattle manure (kg N ha^{-1} yr^{-1})	++	++	Growth rate of stem wood in nature areas (m^3 ha^{-1} yr^{-1})	O	−
N in applied pig manure (kg N ha^{-1} yr^{-1})	−	++	Fraction of N taken up by vegetation of total applied N (-)	++	+
N in applied poultry manure (kg N ha^{-1} yr^{-1})	−	++	Fraction of max. N uptake (min. need for crops) (-)	++	+
N in manure from grazing cattle (kg N ha^{-1} yr^{-1})	++	++	Organic products (e.g. compost, sewage sludge)		
N in applied fertilizers (kg N ha^{-1} yr^{-1})	++	O	Total organic products input (kton)	+	−
Max. permitted manure application (kg N ha^{-1} yr^{-1})	−−	++	Organic matter in organic products (% dry matter)	+	−
Deposition			N in organic products (% dry matter)	+	−
Deposition of NO (kg N ha^{-1} yr^{-1})	++	O	Fraction NH_4^+ in organic products (-)	+	−

[a] Uncertainty
[b] Sensitivity

because at many locations it is uncertain if the table is I or II, but since in INITIATOR these tables fall in the same soil wetness class (i.e., wet), there is little uncertainty about the soil wetness class at these locations. Consequently, hydrological parameters were not included in the uncertainty propagation analysis

Manure management: Input data on the amount of applied N (kg N ha^{-1} yr^{-1}) are relevant, because the area consists mainly of intensively managed grassland. Due to limited data availability, pre-processing and other causes, these inputs are very uncertain. Data from interviews on the application of animal manure at comparable farms on peat soils in the Northern Frisian woodlands (Sonneveld *et al.*, 2008) also demonstrate large uncertainties. The Frisian manure application data was compared with default INITIATOR inputs from the GIAB-database for 215 grassland parcels in the Northern Frisian woodlands. The average applied cattle manure was 98 kg N ha^{-1} with a random error (i.e., standard deviation) of 142 kg N ha^{-1} and the average applied N during grazing was 52 kg N ha^{-1} with a random error of 58 kg N ha^{-1}. Because pigs and sheep are not common in the fen meadow landscape, the uncertainty of these two inputs is low for this area and not relevant. Thus, only N in applied cattle manure and in manure from grazing cattle were considered uncertain and quantified for the uncertainty propagation analysis.

Atmospheric deposition: Atmospheric deposition plays an important role in the N budget in natural areas, such as forests. In the Netherlands, however, the N inputs by management and cattle to grasslands are much larger than N inputs by atmospheric deposition (Van der Maas *et al.*, 2008). In the fen meadow landscape, the proportion of natural areas is much smaller (7%) than the proportion of grassland (81%). Therefore, the model is only moderately sensitive to atmospheric deposition and this input was not taken into account in the uncertainty analysis.

Denitrification and nitrification in soils: N_2O emission is in INITIATOR described as a function of nitrification and denitrification. In INITIATOR, the amount of nitrification of NH_4^+ to NO_3^- and further denitrification of NO_3^- to N_2 are modelled as fractions of N input to soil and depending on soil type, land use, and hydrology. During these nitrification and denitrification processes, a certain amount of N is assumed to be leaked as N_2O emission (Firestone & Davidson, 1989). The model uses denitrification and nitrification fractions, being the fraction of N nitrified to NO_3^- and the fraction of N denitrified to N_2, and N_2O emission factors, being the ratio of N_2O emission to total N ($N_2O + NO_X + N_2$) emission to simulate these N_2O emissions. As expected, De Vries *et al.* (2003b) showed that the uncertainty in N_2O emissions is largely determined by the uncertainty of these parameters, especially for peat soils. These parameters were therefore considered in the uncertainty propagation analysis.

Uptake by vegetation: Because the fen meadow landscape is mainly covered by grassland, the model is not very sensitive to inputs that are used to estimate the N uptake in nature areas or maize, being the only crop that is cultivated in this landscape. Therefore, only the uncertainty of grass yield was considered. Because of the large N inputs to grasslands, N is usually not a limiting factor for N uptake and usually grasslands can reach a maximum N uptake. The model inputs grass yield and % N in grass are multiplied in INITIATOR to calculate the maximum N uptake. These two inputs were classified as sensitive and consequently included in the uncertainty propagation analysis.

Organic products: INITIATOR simulates the N input from four types of organic products: sugar beet waste, kitchen and garden compost, mushroom compost and sewage sludge. The contribution of N from organic products to the soil is small compared to the contribution of N from animal manure (Velthof, 2004). The sensitivity of the model was therefore assumed negligible for organic products.

In summary, ten model inputs (Table 4.1) were selected by the quickscan and used in the MC uncertainty analysis. How the PDFs of these model inputs with a high uncertainty (++) and a high sensitivity (++) were obtained, is discussed in the next section.

4.3.2 Uncertainty quantification of selected model inputs

Soil type: Soil type as used by INITIATOR has 13 categories in the Netherlands. The fen meadow landscape consists mainly of the categories thick peat and thin peat, although categories peaty clay, clay, peaty sand, sand and water/urban also occur. BME was used to estimate multi-point PDFs and to simulate maps of soil type for use in the MC simulation, following the approach of Brus *et al.* (2008). The map with dominant soil types, being the soil type with the highest probability of occurrence at a given location, resulting from BME is presented in Fig. 4.3. In the largest part of the study area, thick peat soils are dominant, although thin peat soils and clay soils also occur. The entropy map is given in Fig. 4.4. Areas with low entropy mainly coincide with areas where detailed soil surveys were carried out.

Organic matter content of peat soils (%): INITIATOR requires the organic matter content up to the depth of the mean lowest groundwater level (MLW) to estimate the amount of carbon and nitrogen available for mineralization. In all cases, the depth of the MLW is less than 120 cm. For each soil type, the distribution of organic matter content at 0–20 cm, 20–50 cm and 50–120 cm depth was modelled geostatistically using data from

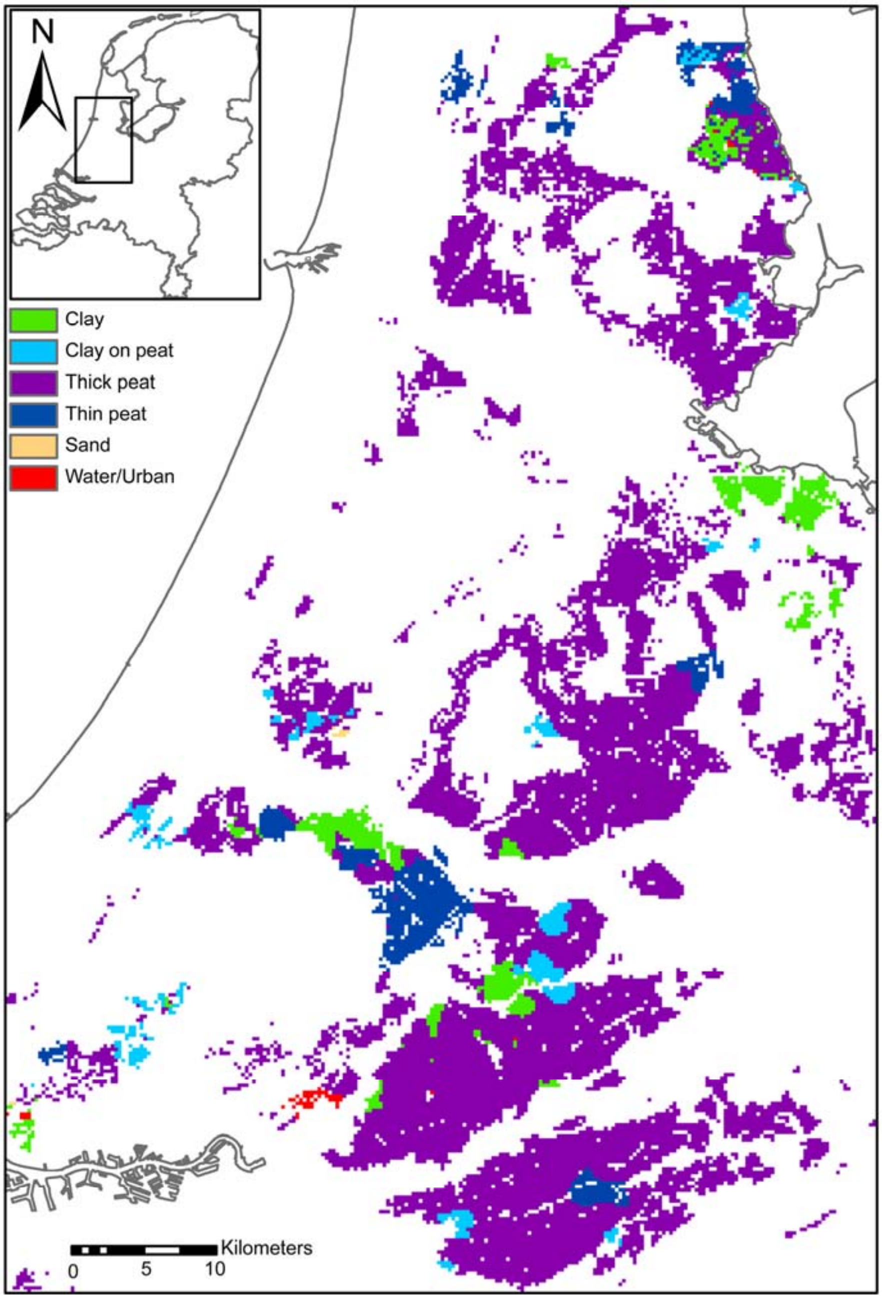

Fig. 4.3 Dominant soil types estimated with Bayesian Maximum Entropy for the fen meadow landscape. Inset: Location of Dutch fen meadow landscape.

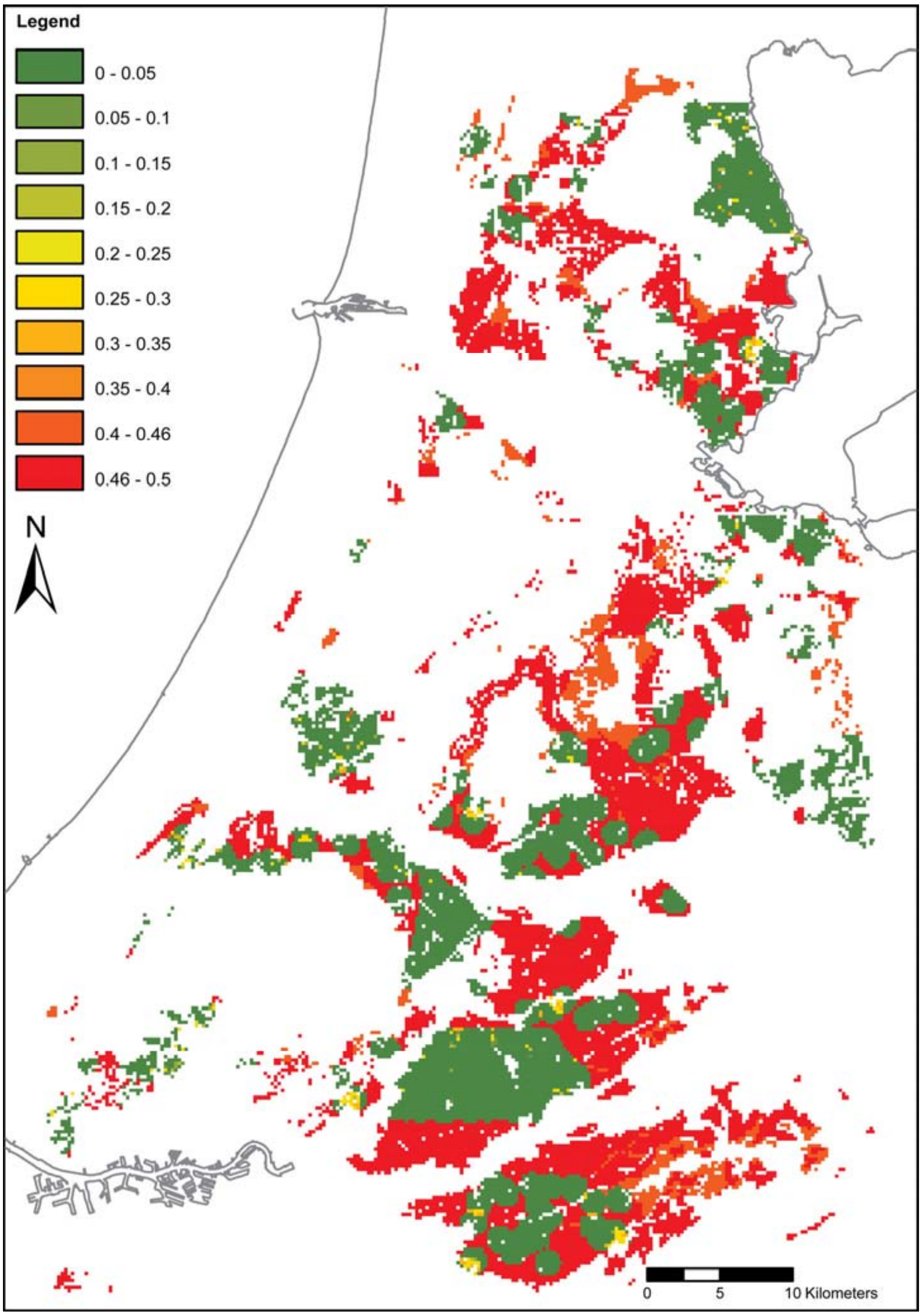

Fig. 4.4 Entropy (–) estimated with Bayesian Maximum Entropy for the fen meadow landscape.

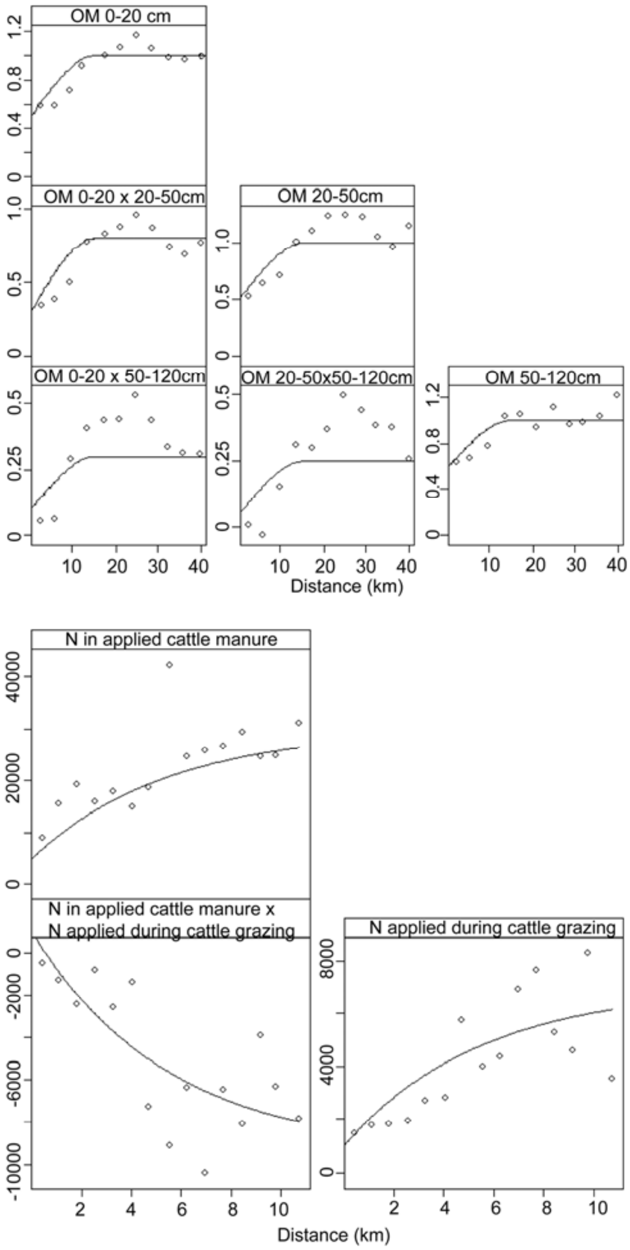

Fig. 4.5 Semivariograms and cross-semivariograms of (a) standardized log-transformed organic matter content at three depths: 0–20 cm, 20–50 cm and 50–120 cm and of (b) residuals in nitrogen in applied cattle manure and nitrogen in manure from grazing cattle. Circles are experimental semivariogram values; solid line represents the fitted LMCR model.

the Dutch soil information database (Alterra, 2009; Van der Pouw & Finke, 1999). Because organic matter content depends on soil type, PDFs were made for every depth and for every soil type. All distributions were skewed and organic matter content was therefore log-transformed. Semivariograms and cross-semivariograms of standardized residuals (i.e., after subtracting soil type dependent means and dividing by soil type dependent standard deviations) are presented in Fig 4.5a. The with BME simulated maps of soil type were subsequently used for simulation of the organic matter content for the three different depths using LMCR. For each point, the simulated values for different depths were weighted for the soil profile from 0 cm to MLW and summed up to get an organic carbon content for 0 to MLW for each MC run and for each point. After back transformation, the simulated values were truncated for values larger than 100%. The average and standard deviation of organic matter content over all MC runs are presented in Fig. 4.6.

Nitrogen inputs by cattle manure application and cattle grazing: To assess the uncertainty in N inputs by cattle manure application and cattle grazing, interview data from the Northern Frisian woodlands (Sonneveld *et al.*, 2008) were used. These data were used because there were no data from the fen meadow landscape and because the two landscapes have comparable N management data. All 215 dairy farms on peat soils from this research were selected and compared the spatial data on N in applied cattle manure (kg N ha^{-1} yr^{-1}) and N applied during grazing (kg N ha^{-1} yr^{-1}) with spatial data derived by INITIATOR based on the GIAB database for the Northern Frisian woodlands. Semivariograms and cross-semivariograms of the differences (errors) between these databases were calculated (Fig. 4.5b). By assuming that the errors observed in the Northern Frisian woodlands are comparable to those in the fen meadow landscape, the semivariograms and cross-semivariograms were used to generate random drawings of the errors in N inputs by cattle manure application and cattle grazing in the MC analysis (Goovaerts, 2001). For each MC run and each point in the study, the default value from INITIATOR based on the GIAB database was augmented with the random drawn error. Values were truncated at zero to rule out negative values.

Fractions of soil N which are denitrified and nitrified: The fractions of available N in the soil that are denitrified and nitrified depend on soil type, land use and soil wetness class. For wet soils, the denitrification fraction is large and the nitrification fraction small. For dry soils, it is the opposite. Values for the denitrification fraction range from 0 in dry sandy soils to 1 in wet peat soils or wet clay soils. The nitrification fraction has a smaller variability. Its values range from 0.4 for wet peat soils to 1 in well-drained pH neutral soils. Both parameters were assumed to be normally distributed with parameter

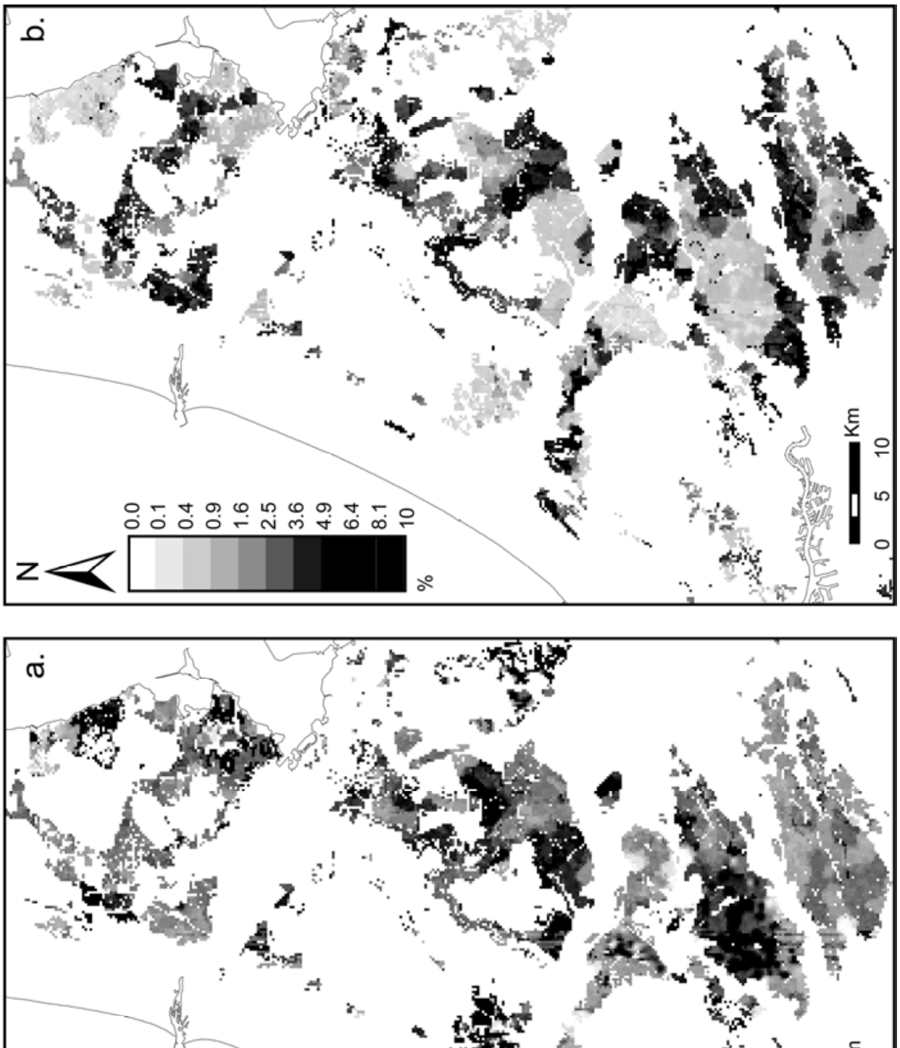

Fig. 4.6 Average (a) and standard deviation (b) of organic matter content (%) for 0 cm until mean lowest groundwater level (MLW) for the fen meadow landscape.

Table 4.2 Uncertainty in N_2O emission factors of due to nitrification and denitrification stratified by soil type and the uncertainty in fractions of soil nitrogen that is denitrified and nitrified stratified by soil type, soil wetness class, and land use for the fen meadow landscape (derived from De Vries *et al.*, 2003b).

Soil type	N_2O emission factor due to nitrification		N_2O emission factor due to denitrification		Soil wetness class[a]	Land use	Fraction of soil nitrogen which is nitrified		Fraction of soil nitrogen which is denitrified	
	mean	s.d.[b]	mean	s.d.[b]			mean	s.d.[b]	mean	s.d.[b]
Clay	0.01	0.004	0.04	0.013	Dry	Grass	0.98	0.013	0.75	0.075
						Maize	0.98	0.013	0.70	0.100
						Nature	0.98	0.013	0.60	0.100
					Moist	Grass	0.95	0.025	0.83	0.063
						Maize	0.95	0.025	0.75	0.075
						Nature	0.95	0.025	0.70	0.100
					Wet	Grass	0.90	0.025	0.89	0.045
						Maize	0.90	0.025	0.89	0.045
						Nature	0.95	0.025	0.90	0.050
					Very wet	Nature	0.80	0.050	0.95	0.025
					Extremely wet	Nature	0.65	0.075	0.95	0.025
Peat	0.02	0.005	0.07	0.025	Dry	Grass	0.95	0.025	0.88	0.375
						Maize	0.95	0.025	0.75	0.075
						Nature	0.98	0.013	0.85	0.075
					Moist	Grass	0.90	0.025	0.88	0.375
						Maize	0.95	0.025	0.83	0.063
						Nature	0.95	0.025	0.90	0.050
					Wet	Grass	0.85	0.025	0.94	0.020
						Maize	0.88	0.038	0.89	0.045
						Nature	0.90	0.050	0.95	0.025
					Very wet	Nature	0.65	0.013	0.95	0.025
					Extremely wet	Nature	0.05	0.100	0.95	0.025

[a] Soil wetness class is divided into three wetness classes: wet with a mean highest groundwater level (MHW) of less than 40 cm, moist with an MHW between 40 and 80 cm and dry with an MHW greater than 80 cm.
[b] s.d. = standard deviation

values determined by De Vries *et al.* (2003b; Table 4.2). Simulated values were truncated for values smaller than 0 and larger than 1 .

Emission factors of N_2O due to nitrification and denitrification: The fractions of N emitted as N_2O due to nitrification and denitrification processes are related to soil type. The uncertainty in these N_2O emission factors were assessed by De Vries (2003b) based on literature data, available empirical field evidence and model calculations, as shown in Table 4.2. The mean and standard deviation for the denitrification emission factors are larger than for the nitrification emission factors. All parameters were assumed to have a (truncated) normal distribution. Simulated values were truncated for values smaller than 0 and larger than 1.

Yield of grass and % N in grass: The grass yield in INITIATOR depends on soil type and soil wetness class (Table 4.3). The values of INITIATOR were derived from the average grass yields reported by Aarts *et al.* (2005). Reported uncertainties in yields (Aarts *et al.*, 2002; Aarts *et al.*, 2005; Ten Berge *et al.*, 2002) were used for the MC simulation. A normal distribution was assumed and the simulated values were truncated at zero to rule out negative values.

The % N in grass is assumed to be spatially constant. In INITIATOR, the grass yield and the % N in grass determine the uptake of N. The parameter value used for % N in grass is 3.08% (Schröder, 1998). The uncertainty of the % N in grass was derived from Ten Berge *et al.* (2002; Table 4.3) and the errors were assumed to be normally distributed. The simulated values were truncated at 0% to rule out negative values. The grass yield and % N in grass are positively correlated with an r value of +0.8 for Dutch soils occurring in the fen meadow landscape, as described by Ten Berge *et al.* (2002; Table 4.3). Thus, a bivariate (truncated) normal distribution for the yield and % N in grass was assumed.

Table 4.3 Uncertainty in yield of grass and % N in grass.

Land use	Soil type	Soil wetness class	Yield of grass (kg dm ha^{-1})		% N in grass (% of dm)		Correlation
			Mean	s.d.[a]	Mean	s.d.[a]	
	Peaty clay	moist	10000	500			
	Peaty clay	wet	9500	760			
Grass	Peat	moist	10000	1000	3.08[b]	0.372	0.78
	Peat	wet	9000	720			
	Clay	moist	11000	1210			

[a] From Ten Berge *et al.* (2002)

[b] INITIATOR uses one value for the % N in grass, there is no further subdivision.

4.3.3 Uncertainty in N_2O emissions at point and landscape support

In Fig. 4.7, the standard deviation of the N_2O emission at point support of 100, 250, and 500 MC runs are plotted against the standard deviation of the N_2O emission at point support of another 100, 250, and 500 MC runs. Theoretically, when the results of an infinite number of MC runs is plotted against the results of another infinite number of MC runs the result will be a 1:1 line. Because the results of the 500 MC runs are already close to the 1:1 line, 1000 runs were considered sufficient to get a stable outcome with a small MC sampling error.

The map of the average N_2O emission is almost similar to the map of a reference run in which average values of model inputs are used (Fig. 4.8). The average N_2O emission for the entire fen meadow landscape is 19.7 kg N_2O-N ha^{-1} yr^{-1}. This is larger than the IPCC Tier 1 and Tier 2 estimates for the area, which were 13.0 and 14.5 kg N_2O-N ha^{-1} yr^{-1},

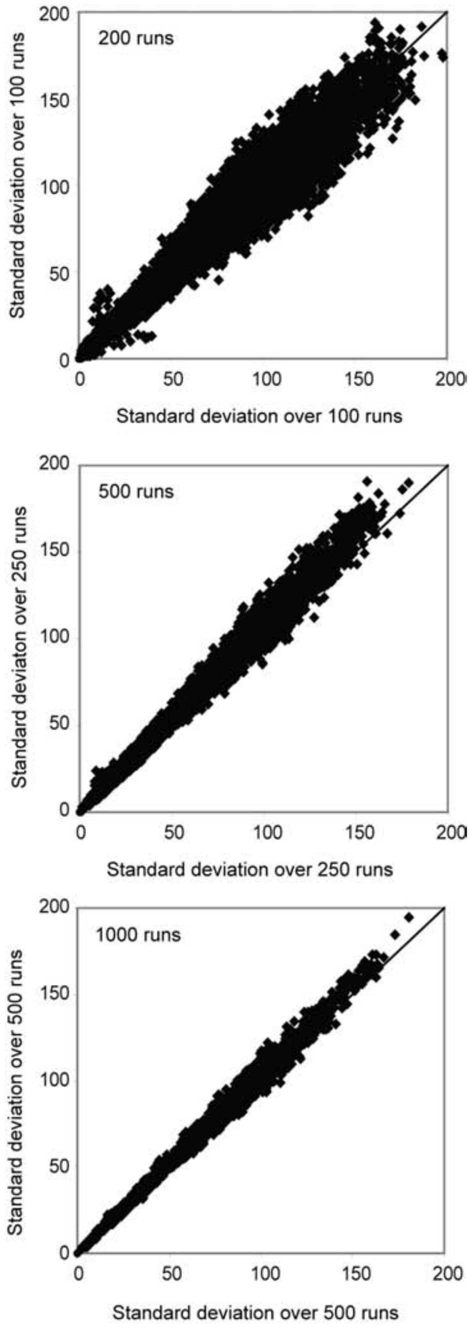

Fig. 4.7 Scatter plots of standard deviations of N_2O emission (kg N_2O-N ha^{-1} yr^{-1}) over MC runs on point scale for two independent MC analyses: (a) 100 runs, (b) 250 runs, (c) 500 runs.

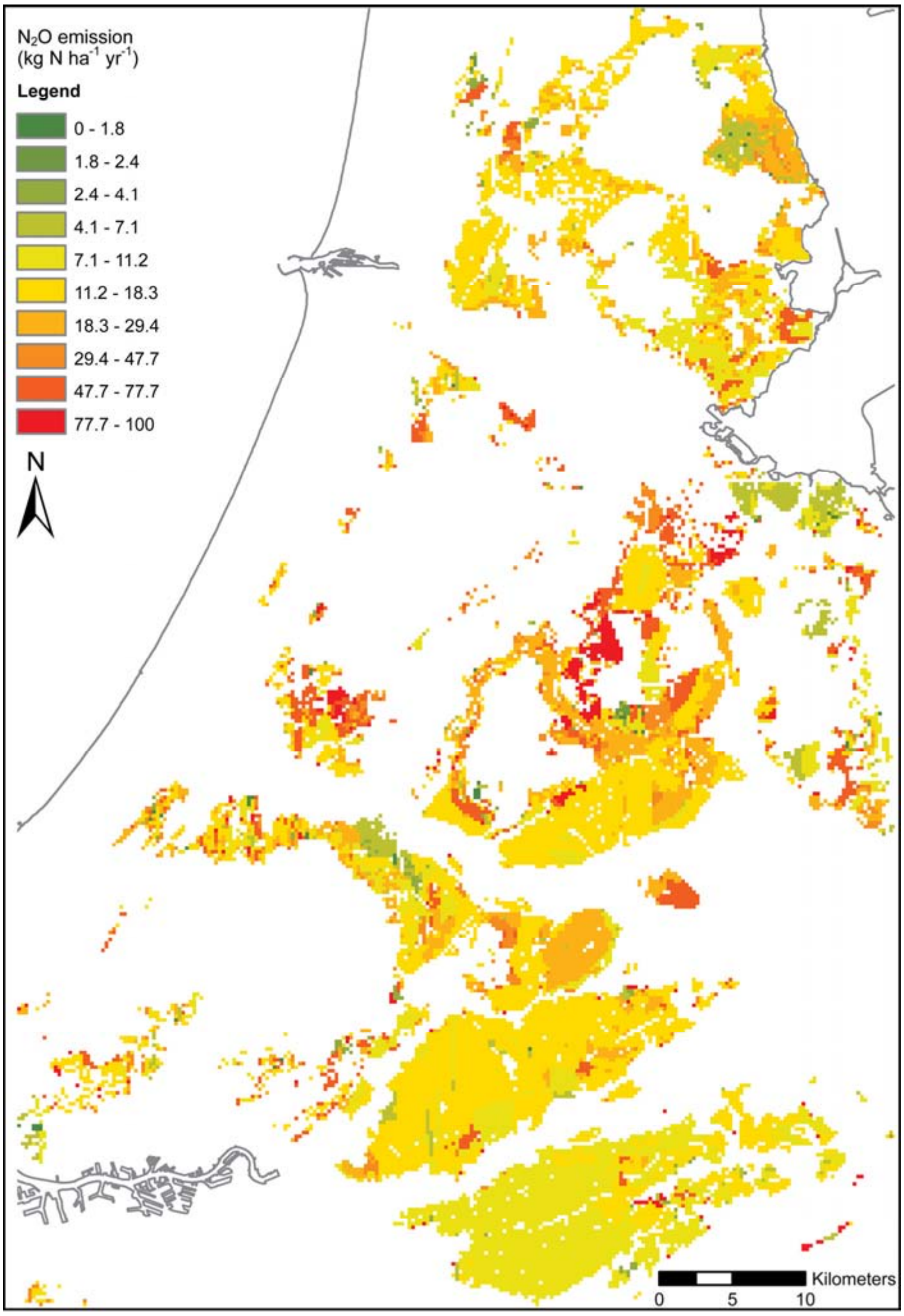

Fig. 4.8 N_2O emission (kg N_2O-N ha^{-1} yr^{-1}) simulated with INITIATOR for the reference run for the fen meadow landscape. The legend has a logarithmic scale.

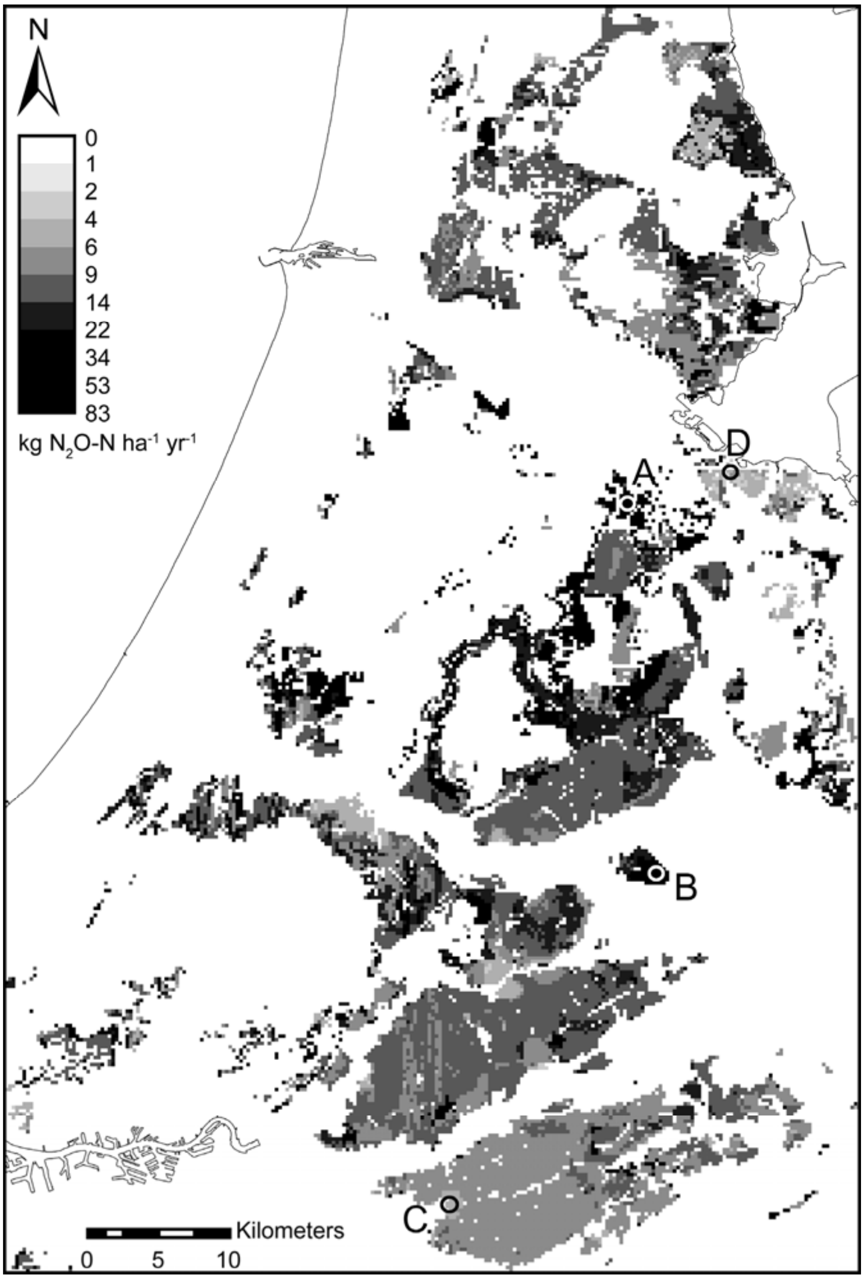

Fig. 4.9 Standard deviations of N_2O emission (kg N_2O-N ha^{-1} yr^{-1}) of the Monte Carlo simulation for the fen meadow landscape. The legend of this map has a logarithmic scale. Circles accompanied by the letters A, B, C, and D refer to example locations discussed in the main text.

respectively (§3.3.3). Velthof *et al.* (1996a) measured emissions in the fen meadow landscape which are comparable to the results presented here; 2.0 kg N_2O-N ha^{-1} yr^{-1} for an unfertilized and mown plot and 38.5 kg N_2O-N ha^{-1} yr^{-1} for a fertilized and grazed plot. Also Van Beek *et al.* (2009) measured comparable emissions with 11.8 kg N_2O-N ha^{-1} yr^{-1} for wet drained peat soils and 29.8 kg N_2O-N ha^{-1} yr^{-1} for dry drained peat soils.

The N_2O emission standard deviation map is presented in Fig 4.9. The areas with a high standard deviation are largely coinciding with large N_2O emissions. The average standard deviation of the MC simulation at point support is 15.8 kg N_2O-N ha^{-1} yr^{-1}. The average N_2O emission over all runs at landscape support is 20.5 kg N_2O-N ha^{-1} yr^{-1} with a standard deviation of 10.7 kg N_2O-N ha^{-1} yr^{-1}. The distribution is only slightly skewed (skew < 0.5) and the 95% confidence interval is 4.3–39.5 kg N_2O-N ha^{-1} yr^{-1}

4.3.4 Main sources of uncertainty

A stochastic sensitivity analysis was executed for the four variable groups as identified in the quickscan: 1) soil, 2) manure management, 3) nitrification and denitrification in soils and 4) uptake by vegetation (see Table 4.1). The share of different groups of inputs in the uncertainty of the N_2O emission at point support and at landscape support is presented in Fig. 4.10. The uncertainty at point support is much higher than at landscape support. At point support, the input groups soil and nitrification and denitrification in soils both have a large share in the uncertainty. Clearly, the group nitrification and denitrification in soils has by far the largest share in the uncertainty at landscape support.

4.4 Discussion

4.4.1 Input uncertainty quantification

The focus of this research was on the uncertainty in modelled N_2O emissions caused by the uncertainties in model inputs. The contribution of model structural uncertainty was ignored. Due to the large number of INITIATOR inputs, a quickscan was used to select which model inputs were relevant for the uncertainty analysis. Gottschalk *et al.* (2007) used a similar approach to estimate which inputs should be used for the uncertainty propagation analysis of the simulation of net ecosystem exchange. A possible disadvantage of the quickscan approach is that inputs that have not been selected have an influence on the N_2O emission, causing an underestimation of the output uncertainty. The main advantage of the quickscan is that it is time efficient. The alternative is to include more inputs or even all inputs in the uncertainty analysis.

However, including spatial auto- and cross-correlations of these inputs will become a very time consuming and complex process, while the extra identified uncertainty is probably limited compared to other sources of uncertainty.

4.4.2 Uncertainty of N_2O emissions at point support

There was no simulated systematic error, because the difference between the results of a reference run with average parameter values and the average over the MC runs was negligible (r^2 = 0.95). This is probably caused by the approximate linearity of N process descriptions in INITIATOR.

It is important to realize that different factors dominate the uncertainty at different locations. To illustrate this aspect, two locations with a large uncertainty in N_2O emission and two locations with a small uncertainty in N_2O emission were selected (Fig. 4.9). The uncertainty of N_2O at locations A and B is large. The soil type for both locations is most probably thick peat (Fig. 4.3), but the entropy is large for location A (H = 0.5) and small for location B (H = 0.0; Fig. 4.4). At location A, various soil types will be predicted during the MC simulation and therefore the uncertainty in the organic matter content is large (Fig. 4.6). At location B, the organic matter content is large and the uncertainty in the organic carbon content is considerable, because the standard deviation of organic matter content is large for thick peat soils. The uncertainty in nitrification and denitrification variables was also large for both locations, because standard deviation is large for grass on peat soils with moist conditions (Table 4.2). At

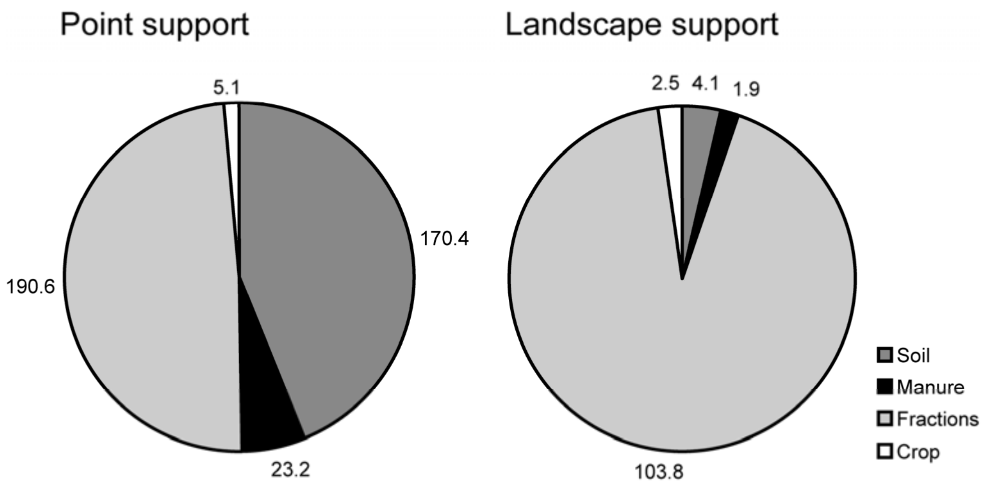

Fig. 4.10 Contribution of groups of uncertain inputs to: (a) variance at point support and (b) variance at landscape support.

location C, the uncertainty of N_2O emission is small, although the dominant soil type is thick peat soil. The MLW is close to surface level (data not shown), which causes low mineralization rates which in turn result in small N_2O emissions. The uncertainty of the N_2O emission at location D is small, because it is highly probable (H = 0.0, see Fig. 4.4) that the dominant soil type is not peat, but clay (Fig. 4.3). Therefore, the organic matter content and the uncertainty in organic matter content are small (Fig. 4.6). The land use at location D is grassland and the uncertainty in nitrification and denitrification variables is small for grass on clay soils compared to grass on peat soils (Table 4.2).

4.4.3 Uncertainty of N_2O emission at landscape support

The N_2O emission from the fen meadow landscape is large (on average 20.5 kg N_2O-N ha^{-1} yr^{-1}) compared to other countries and other landscapes. This is due to the typical landscape with drained peat soils, combined with large N inputs to soil (Velthof *et al.*, 1996a).

Results of this study showed that the modelled uncertainties in N_2O emissions are quite considerable and scale-dependent for the Dutch fen meadow landscape. It is generally known that biogeochemical processes are scale-dependent. One of the main reasons is that different processes operate and interact at different scales (Heuvelink, 1998b; Veldkamp *et al.*, 2001). In the uncertainty propagation analysis, this scale aspect was incorporated by aggregating point support data to the landscape support. It is also known that aggregation of spatial data usually leads to a lower uncertainty and to linearization of relationships (Heuvelink & Pebesma, 1999; Kok & Veldkamp, 2001). This aggregation effect is reflected in the decrease of the calculated uncertainty from point support (c.v. = 78%, s.d. = 15.8 kg N_2O-N ha^{-1} yr^{-1}) to the aggregated landscape support (c.v. = 52%, s.d. = 10.7 kg N_2O-N ha^{-1} yr^{-1}). A similar large uncertainty of N_2O emissions has been found by many researchers (Brown *et al.*, 2001; Nevison, 2000; Olsthoorn & Pielaat, 2002). A further decrease of the coefficient of variation is foreseen at even coarser aggregated scales, such as country scale. In the Dutch National Inventory (Van der Maas *et al.*, 2008), the uncertainty of direct N_2O emissions from agriculture is estimated as 61%, which is larger than the c.v. obtained at the landscape scale. The 61% value is however, a conservative estimate, because the IPCC emission factors used were assumed to have large uncertainties.

The contribution of uncertainty sources to the output uncertainty depend on the model output considered (Kros *et al.*, 1999) and are also scale dependent. For instance, the uncertain soil inputs have a larger share at point support than at landscape support. These soil inputs and associated errors are spatially variable, which means that errors partially average out at the landscape support. The degree of averaging out depends on the nugget variance and spatial correlation length of the uncertain soil inputs. In our case, spatial correlation was not very strong and much of the uncertainties in soil inputs therefore ceased at landscape support. This did not happen with the uncertainties about the nitrification and denitrification variables. Just as De Vries *et al.* (2003b), it was found that at landscape support uncertainty in N_2O emission was mainly due to uncertainty in nitrification and denitrification variables. These variables were taken constant in space and hence did not average out at landscape support. For instance, when an MC run simulates a large value of the denitrification emission factor for grasslands on wet peat soils, this emission factor is attributed to all grasslands on wet peat soils in the fen meadow landscape and will therefore result in a large total N_2O soil emission for the landscape. This may not be very realistic. The quantification of the spatial variability of these variables and inclusion of this spatial variability in models is therefore crucial, especially for large (national, continental) scales. The large uncertainty considering nitrification and denitrification variables is found by many researchers and research is focussing on decreasing the uncertainty of emission factors (Beheydt *et al.*, 2007; Flechard *et al.*, 2007; Olsthoorn & Pielaat, 2002). However, at point support soil parameters are also a large source of uncertainty. Therefore, for point support predictions, decreasing the uncertainty of soil parameters can also contribute to the improvement of the N_2O emission inventory. Although these soil parameters were spatially variable in the model, these are often assumed to be constant in time. Especially for the fen meadow landscape, this assumption is unrealistic and using soil data that were collected a few decades ago for the estimation of current emissions can involve large uncertainties (Kempen *et al.*, 2009; Van Kekem, 2004).

4.5 Conclusions

Although in this research only the ten most important input uncertainties were taken into account, the uncertainty is substantial and ranges between 50% and 80%. In fact, these are underestimates of the true uncertainty, because there are more uncertainties, such as the uncertainty in model structure. Chapter 4 gives more information about the uncertainty in model structure. Clearly, there is an urgent need to reduce the uncertainties of simulated N_2O emissions, including model uncertainties. One possibility might be by model comparison strategies. The uncertainty is scale dependent and decreases when data are aggregated. The contribution of uncertainty sources is also scale dependent. Spatial variables can average out with upscaling (i.e., soil inputs), while variables that are constant in space cannot. Not only improvement of nitrification and denitrification variables can decrease uncertainties of N_2O emissions, but at point support, also the improvement of soil data can.

Translation: “Fen meadow pact: You are out of luck, because we are not going away!”

5

Uncertainty in future N_2O emission due to land use change

Abstract

Better insight in the possible range of future N_2O emissions can help to construct mitigation and adaptation strategies and to adapt land use planning and management to climate objectives. Socio-economic developments and related land use change in the area are expected to be large in future and have major impacts on N_2O emission. The goals of this study are to estimate changes in N_2O emissions for the period 2006–2040 under different scenarios for the Dutch fen meadow landscape and to quantify the share of different emission sources. Three scenarios were constructed and quantified based on the Story-And-Simulation approach. The rural production and the rural fragmentation scenarios are characterized by globalization and a market-oriented economy; in the rural production scenario dairy farming has a strong competitive position in the study region while under the rural fragmentation scenario agriculture is declining. Under the rural multifunctionality scenario, the global context is characterized by regionalization and stronger regulation towards environmental issues. Farmers will receive subsidies to manage wet meadows extensively as high nature valued farmland. Under the rural production scenario, the N_2O emission decreased between 2006 and 2040 by -7%. Due to measures to limit peat mineralization and policies to reduce agricultural emissions, the rural multifunctionality scenario shows the largest decrease in N_2O emissions (-44%). Under the rural fragmentation scenario, in which the dairy farming sector is diminished, the emission decreased by -33%. Compared to other uncertainties involved in N_2O emission estimates, the uncertainty due to possible future land use change is relatively large and assuming a constant emission with time is therefore not appropriate.

Based on: Nol, L., Verburg, P.H. and Moors, E.J.
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5.1 Introduction

The uncertainty of greenhouse gas (GHG) emission inventories is usually high (IPCC, 2007a; Van der Maas *et al.*, 2008), especially inventories of the GHG nitrous oxide (N_2O) (EPA, 2009; Ramírez *et al.*, 2008). Uncertainty can be located in: context, model structure, model technique, model inputs, model parameters, and model outputs (Walker *et al.*, 2003). For emission of N_2O, uncertainty is mainly originating from model input data, from model parameters due to errors in measurements underlying emission factors, and from model structure due to a lack of knowledge of emission processes. However, it is not only the uncertainty in the current state of N_2O emissions that is relevant to assess, but the uncertainty in future N_2O emissions is important too. Uncertainty in future N_2O emissions is mainly caused by uncertainties in land use. Human-induced changes in land use are driven by socio-economic developments. Better insight in the possible range of trends in N_2O emission can help to construct mitigation and adaptation strategies and link land use planning and land use management to climate objectives (del Prado *et al.*, 2010).

Scenarios are a commonly used tool to address the role of uncertainties in future developments (Peterson *et al.*, 2003). In the IPCC special report on emissions scenarios (SRES) four global scenarios addressing two main uncertainties that were supposed to influence emissions were presented: economic (A) vs. environmental (B) orientation and global (1) vs. regional (2) orientation (IPCC, 2000b). The market-driven scenarios (A1 and A2) are expected to have higher GHG emissions until 2040 compared to the environment driven scenarios (B1 and B2). The higher GHG emissions in the market-driven scenarios are caused by large economic growth, large energy demand, large-scale dairy farming, little attention to nature protection, and little mitigation policies. The Millennium Ecosystem Assessment (Carpenter *et al.*, 2005) under authority of UNEP constructed four global scenarios focusing on ecosystem services. Key driving forces under these scenarios were the approach to sustainability, the focus on economy and the social policy. The projected global changes between 1995 and 2050 vary considerably between -14% and +57% for N_2O emission and between -28% and +161% for the all GHG emissions. UNEP (2007) also constructed four scenarios for their Global Environmental Outlook (GEO-4) based on environmental, social, and economic drivers. They did not distinguish between different GHG's. Generally, their estimates are more conservative than the Millennium Ecosystem Assessment emission estimates (between -23% and +109% for global GHG emissions and between -39% and +70% for the European GHG emissions).

At regional scales, many researchers studied the trends in future GHG emissions using different scenarios. Socio-economic developments are relevant to asses because they can cause changes in climate, but also in land use, including changes in land cover or changes in management practices. However, land use change is often ignored in emission inventories, although it can significantly influence future GHG emissions (Verburg & Van Der Gon, 2001). One example of how management practices influence GHG emissions is provided by Smith *et al.* (2008). The study used the SRES scenarios to estimate the GHG mitigation potential of various agricultural practices. They concluded that improved cropland and grassland management (e.g. efficient nutrient management, lower grazing intensity, water management) and restoration of degraded lands and cultivated organic soils were the most prominent measures and that they could potentially reduce the global GHG emissions by 20% in 2030. Another example is from Leip *et al.* (2008), who estimated the effect of agricultural measures on future N_2O emissions at the regional scale. Results showed that only a small fraction of increased N fertilizers would go into increased yield, while most of it would be emitted to the environment. It is, therefore, important to research the possible effects of land use change.

Assessment of uncertainty in future GHG emissions is especially important in regions with rapid land use change and with high and uncertain GHG emissions. An example of such a region is the Dutch fen meadow landscape. This landscape is an area with peat soils. Due to the low bearing capacity and moist conditions of these soils, the main land cover in the area is grassland. These grasslands are usually intensively managed by dairy farmers; they are fertilized with manure and synthetic fertilizers, grazed, and mown. High N inputs to the soil by N fertilizers, manure, and cattle droppings cause high N_2O emissions. Especially the high C content and moist conditions of the peat soils are optimal for N_2O emission (Ramírez *et al.*, 2008; Velthof & Oenema, 1995). The peat soils also emit N_2O themselves, due to mineralization; the organic C in the soil is emitted as CO_2, whereas the organic N in the soil is emitted due to nitrification and denitrification as N_2O. The fen meadow landscape is thus a hotspot of N_2O emission and the sources of soil-bound N_2O emission can be split into mineralization, manure application, grazing, synthetic fertilizer application, N-fixation by crops such as clover, and deposition (De Vries *et al.*, 2003b; IPCC, 2000a; IPCC, 2006; Kroeze *et al.*, 2003).

The uncertainty of N_2O emissions in this region is large due to uncertainties in biophysical and management factors (Brown *et al.*, 2001; Nevison, 2000; Olsthoorn & Pielaat, 2002). In Chapter 4, a Monte Carlo analysis of N_2O emissions was performed with an integrated N model, including uncertainty in different input variables, autocorrelation in model inputs, and correlation between model inputs. They estimated, for this region, the uncertainty (coefficient of variation) of agricultural N_2O emission to be approximately 52%. On top of this large uncertainty, land use is also rapidly changing due to expanding cities, the difficult competitive position of dairy farms and subsidence of peat soils (Koomen *et al.*, 2008; Kuikman *et al.*, 2005). The region is facing many future challenges, such as implementing natural conservation policies like the national ecological network (NEN), dealing with urban expansion, meeting (recreational, commercial) needs of citizens, coping with the effects of climate change,like flood risk and droughts (Beniston *et al.*, 2007; MNP, 2006; MNP, 2007). These future changes in the fen meadow landscape are likely to have major impacts on the N_2O emissions.

The goals of this paper are (i) to develop specific scenarios for land use change in the Dutch fen meadow landscape, (ii) to estimate changes in N_2O emission for the period 2006–2040 under these different scenarios for the Dutch fen meadow landscape and quantify the share of different emission sources in the scenarios and (iii) to assess the uncertainty of N_2O emissions due to the diverging scenario conditions and to compare this uncertainty to other sources of uncertainty in N_2O emission inventories. This comparison is to understand the full range of uncertainty in order to better target future improvements in emission estimates. To achieve these objectives first plausible storylines for scenarios of land use change will be constructed using plausible storylines based on interviews with stakeholders and experts. As a second step, this cognitive knowledge will be translated into quantitative modelling of N_2O emissions.

5.2. Methods

5.2.1 Case study area

The Dutch fen meadow landscape was formed in the Holocene because peat swamps came into existence in the western part of the Netherlands (Fig. 5.1). Since medieval times, the area has been cultivated for agriculture. This landscape has a surface area of approximately 1000 km^2 according to the occurrence of peat soils on the Dutch soil map (1:50,000; Stiboka, 1969).

The region's main land cover is grassland (89%) for intensive dairy farming. The grassland is intersected by many ditches to drain the peat soils. Recently, large parts of the grassland area are taken out of production and purchased by nature organizations. General properties of the fen meadow landscape for the year 2006 are in Table 5.1. About 86% of the area consists of thick peat soils of more than 50% peat in the upper 0.80 m of the soil profile combined with a peat layer that runs deeper than 1.20 m.

5.2.2 Scenario construction

Scenarios were constructed following the widely used and accepted Story And Simulation (SAS) method introduced by Alcamo et al. (2009). The Millennium Ecosystem Assessment (Carpenter *et al.*, 2005), the Global Environmental Outlook (UNEP, 2007), PRELUDE (EEA, 2007; Volkery *et al.*, 2008) and a local scenario study by Kok (2006) are examples of studies which have used an approach similar to the SAS method. The construction of scenario storylines is part of the SAS method, which is a participatory and iterative process where the storylines are a result of this process (Kok *et al.*, 2006; Lorenzoni *et al.*, 2000; Patel *et al.*, 2007; Xiang & Clarke, 2003). Note that

Table 5.1 Properties of the Dutch fen meadow landscape for the reference year 2006

Property	Value
Soil distribution	
Clay	4%
Thick peat	86%
Thin peat	4%
Peaty clay	2%
Water/Urban	3%
Land use distribution	
Grassland	89%
Crops	3%
Natural area	5%
Urban	3%
Groundwater	
Mean highest groundwater level (MHW)	-0.12 m
Mean lowest groundwater level (MLW)	-0.69 m
Agricultural management	
Average cattle manure application	151 kg N ha^{-1} yr^{-1}
Average cattle manure during grazing	35 kg N ha^{-1} yr^{-1}
N_2O emission	
Total agricultural emission	20.2 kg N_2O-N ha^{-1} yr^{-1}
N_2O emission sources	
Manure	18%
Grazing	4%
Fertilization	19%
Fixation	1%
Deposition	4%
Mineralization	43%
Leaching	12%

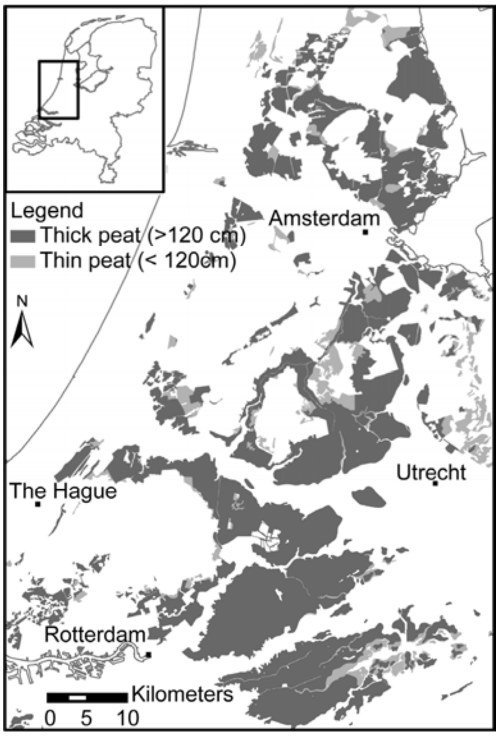

Fig. 5.1 Location of peat soils within the Dutch fen meadow landscape. Inset: Location of the fen meadow landscape in the Netherlands.

the constructed scenarios were chosen to represent a range of possible developments without one scenario being more likely than the other, because the objective was to identify the entire range of possible future N_2O emissions and accordingly the upper or lower limit of possible future emissions.

Interviews with experts and stakeholders

The *first* step in the SAS method is an iterative process of interviewing experts and stakeholders and constructing participatory qualitative and quantitative scenarios. Nineteen experts and stakeholders from different research areas and organizations related to the region (e.g. farmers, rural advisory companies, nature organizations, and dairy experts) were interviewed. They were presented with open questions about expected trends for the period 2006–2040 in climate, land use, policy, demography, economy, nature protection, and agriculture in the fen meadow landscape Most questions started with: “What future developments/trends do you expect in ...?”. These open questions triggered the respondents to answer with causal relations (“If...then...”), which were helpful for constructing the scenarios.

Construction of qualitative scenario storylines

As a *second* step, scenarios for the fen meadow landscape were constructed. These scenarios were primarily based on answers to the questionnaires. Based on frequently heard answers, concepts of scenarios were constructed and presented again to the experts and stakeholders. This iterative process continued until the scenarios were considered plausible and consistent. Physical and financial conditions together with the causal relations stated by the respondents were taken into account to achieve consistency in the scenarios. Additionally, a relation with well-known scenarios at global and national scale was established to enable the quantification and plausibility of the constructed scenarios (Carpenter *et al.*, 2005; EEA, 2007; IPCC, 2000b; MNP, 2006; MNP, 2007; UNEP, 2007). Currently available policy plans that are relevant for the region were also accounted for. Land use change and climate change are mostly driven by the same overall socio-economic changes and associated policies. Some of the land use changes anticipated in the scenarios are accounting for adaptation measures to climate changes. In order to ensure internal consistency of the scenarios an approach was chosen that accounts for both land use change and climate change within the scenarios.

Translation in main scenario drivers

Many stakeholders and experts were not familiar with the model inputs or could only indicate if the model inputs would be higher or lower under a certain scenario. To bridge the gap between qualitative storylines and quantitative model inputs, an intermediate step was made. In this *third* step of the SAS method, drivers relevant for modeling the scenarios using an N_2O emission model were specified in more detail. The choice of these drivers was made in close cooperation with experts. In this *third* step of the SAS method, literature and models were used to provide numerical data on these drivers (IPCC, 2000b; KNMI, 2006; Koomen *et al.*, 2008; MNP, 2002; MNP, 2006; MNP, 2007; VROM, 2004). The constructed scenarios were presented to 14 of the interviewed stakeholders and experts to check if the storylines were consistent and if the underlying assumptions were credible. This iterative process was especially important in harmonizing the qualitative and quantitative scenarios.

To incorporate effects of climate change, scenarios from the KNMI (2006) were used consistent with the storylines. This national meteorological institute constructed four climate change scenarios for the Netherlands using global circulation models (GCMs) and climate models for Western Europe. For the Netherlands, they identified two main uncertainties concerning climate: change or no change in the air circulation patterns and a temperature increase of +1ºC or +2ºC in 2050 (MNP, 2002; MNP, 2006; MNP, 2007).

To translate the storylines to changes in land use, the Dutch LANDS project (Koomen *et al.*, 2008) was used to account for changes in urban land use and land use change scenarios from MNP (2007) were used for changes in rural land use.

5.2.3 Modelling N_2O emissions

The *last* step is the simulation of N_2O emission.

<u>Quantification of the scenarios for modelling N_2O emissions</u>

The model INITIATOR was used to simulate N_2O emissions under the different scenarios. INITIATOR (Integrated NITrogen Impact Assessment Tool On a Regional Scale, version 3.2) is an integrated nitrogen (N) model (De Vries *et al.*, 2003b), which is constructed for the Netherlands. De Vries et al. (2003b) provide an extensive description of this model, which is relatively simple and transparent compared to biogeochemical models, such as DNDC (Li *et al.*, 1992) and DayCent (Parton *et al.*, 1998). INITIATOR can simulate CO_2 emissions, CH_4 emissions, NH_3 emissions, and N_2O emissions from stables, soils, leaching, and runoff; however, this research focuses on the emission of N_2O from soils. The model uses annual time steps and a spatial resolution of 250m. INITIATOR assumes that N_2O emission from soils is a function of denitrification and nitrification in soils, soil N input, and uptake of N (De Vries *et al.*, 2003b). INITIATOR has the advantage that mineralization of peat soils is specifically taken into account in the model.

First, soil subsidence is modelled based on the mean lowest groundwater level (MLW), the depth of the peat layer and the occurrence of a clayey top layer. Secondly, the CO_2 emission is estimated based on soil subsidence, organic carbon content, and bulk density. At last, the N mineralization is modelled based on the CO_2 emission and the C/N ratio of the soil. The year 2006 is used as reference year, because all model inputs were available for this year.

Approximately one hundred model inputs (input and model parameters) are used to estimate the N_2O emission. In Chapter 3 was analyzed how large the magnitude of the uncertainty of model inputs are and analyzed the sensitivity of modelled N_2O emission for these model inputs. Key model inputs are soil type, organic matter content, N in applied cattle manure, N in manure from grazing cattle, fraction of soil N that is denitrified, fraction of soil N that is nitrified, emission factor of N_2O due to soil denitrification, emission factor of N_2O due to soil nitrification, yield of grass and % N in grass yield. These results were used to prioritize the importance of the model inputs. In this *fourth* step of the SAS method, quantitative scenarios with all relevant model inputs for the model INITIATOR were drawn up in detail based on the information collected in earlier steps.

<u>Modelling with INITIATOR for 2006-2040</u>

After the definition and specification of the scenarios, both spatial and non-spatial model inputs for the reference year 2006 and for 2040 under the different scenarios were available. However, to model N_2O emissions for the entire period 2006–2040, model parameters for all years in-between were needed as well. To quantify these model parameters, the changes in the scenarios between 2006 and 2040 were assumed to be linear. An example is urbanization; pixels which are non-urban in 2006 and urban in 2040 were grouped into 33 even classes (i.e. 33 years between 2006 and 2040) based on the distance to urban areas. The first class represents the pixels closest to the urban areas in 2006 and these pixels were assumed to change to urban area in 2007. Thus, every class represents pixels undergoing urbanization in a specified year. When all model inputs were quantified for all years, the N_2O emissions were simulated with INITIATOR. Emissions from soils in urban areas were not taken into account; therefore, the spatial extent of the fen meadow landscape is assumed to decrease due to urbanization. An uncertainty range of plausible future N_2O emissions was made based on the simulated future N_2O emissions.

Comparison of sources of uncertainty
The uncertainty in future N_2O emissions was compared to other sources of uncertainty in N_2O emissions for the fen meadow landscape, such as uncertainty due to model inputs, model structure, and land cover databases. This comparison is based on values attained from other studies and literature. To indicate the relative importance of these sources of uncertainty compared to the range of future emissions, the coefficient of variation (c.v.) was estimated for each source and compared.

5.3 Results

5.3.1 Results of scenario building process

Similar to the SRES scenarios (IPCC, 2000b), the scenario storylines are characterized by two axis that relate to the dominant differences between the scenarios (Fig. 5.2). The respondents unanimously answered that relatively extreme scenarios would be best applicable for the goal of this research; which is to quantify the full range of possible future N_2O emissions. They believe that, for the global context, the IPCC A1 economic growth & globalization scenario and the B2 environmental protection & regionalization scenario were the two most divergent SRES scenarios. The vertical axis

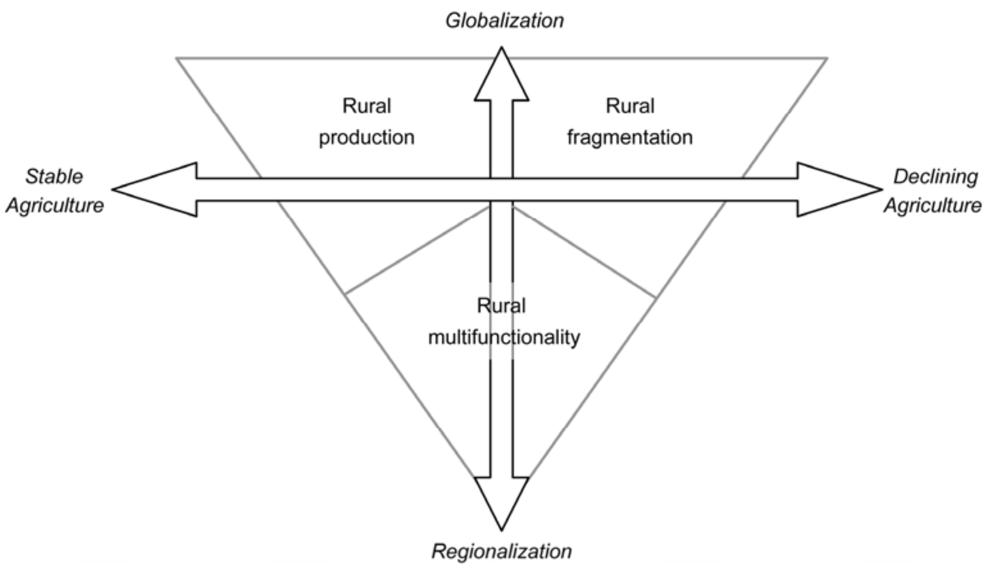

Fig. 5.2 Schematic overview of the three scenarios for the Dutch fen meadow landscape. The y-axis represents the socio-economic drivers at global and national scale. The x-axis represents agricultural drivers at landscape scale

in Fig. 5.2 represents these SRES scenarios. According to respondents, the assumed conditions in the A1 scenario could lead to two alternative futures for the fen meadow landscape, which represents the horizontal axis: one scenario in which dairy farming continues and has a strong competitive position and one in which dairy farming is not able to compete with other regions and declines. These first two steps of the SAS method resulted in the construction of three scenario storylines for the fen meadow landscape: the rural production scenario, the rural fragmentation scenario, and the rural multifunctionality scenario (Fig. 5.2).

Five drivers that differ under the three scenarios were identified to be most important for the fen meadow landscape: External drivers and threats, socio-economic developments including land use change, governmental intervention, and agricultural practices. The storylines, which were based on the respondents' answers, were connected to literature, and data. Basic assumptions for these drivers under the three scenarios are listed in Table 5.2. Because the rural production and the rural fragmentation scenario are both based on the A1 scenario, many global and national drivers are similar. However, at the landscape level, differences become clear. Because the rural multifunctionality scenario is derived from the B2 scenario, many global and national drivers differ from the other two scenarios. For instance, climate change and sea level rise are more dramatic in the rural production and rural fragmentation scenarios than in the rural multifunctionality scenario.

Rural production. Under this scenario, the world develops into A1 direction (IPCC, 2000b) with continued globalization, limited regulation, and emphasis on market economy. In the Netherlands, administration, like spatial planning, becomes the responsibility of lower authorities, like municipalities and farmers. The pressure on space is large, especially in the western part of the Netherlands, because of a population growth due to immigration and a because of decreasing household size. Maintenance and protection of natural areas is not seen as a priority for the Dutch government and is mainly depending on private initiatives. Biofuel will be imported in this scenario. So there is no demand for local production of biofuel in this region. Dairy farming in the fen meadow landscape has a strong competitive position because of its location close to the market. The farms will increase in size (upscaling) in order to be competitive. Grassland is used intensively, meaning it will be heavily fertilized and frequently mown. The grassland area is drained to increase yield and to maintain bearing power. The groundwater levels maintain at the same depth below the soil surface; this means in practice, that they are regularly lowered to compensate for soil subsidence. Technological innovations will increase productivity and efficiency. Floods will be a large threat, due to soil subsidence and rapid sea level rise (Aerts *et al.*, 2008).

Salt seepage, droughts, and heavy rain showers will also be threats, especially for agriculture (KNMI, 2006).

Rural fragmentation. In this scenario, the region also develops in a context of continued globalization, limited regulation, and emphasis on market economy (A1). Therefore, the global and national context is the same as in the first scenario. In contrast to that scenario, dairy farming in the fen meadow landscape has a weak competitive position and declines. Daily fresh milk will be imported mainly from Poland and Russia. Within the Netherlands, the northern provinces Groningen and Friesland have a stronger competitive position due to better possibilities for upscaling. Only a few large-scale intensive farms will be able to survive in the fen meadow landscape. To decrease soil subsidence and drainage costs, groundwater levels will be raised at locations where dairy farming has stopped. Nature organizations do not have enough capital to purchase and manage all former agricultural areas, consequently, areas will become fallow and reed and willow vegetation will take over. The area of deciduous forest will nearly double. Besides, land abandonment and high water levels will lead to new peat swamps and the landscape will have a less open character. Probably entire polders are used for water storage, to cope with flood risks (Aerts *et al.*, 2008). Some polders will be managed as residential and recreational parks.

Rural multifunctionality. The world develops similar as in the B2 scenario (IPCC, 2000b) with focus on regional development and strong regulation towards environmental concerns. In the Netherlands, population will decrease and economic growth will decline. Production subsidies, however, are largely replaced by subsidies to enhance agro-ecological qualities. Provincial and national authorities will be more powerful, instead of farmers or municipalities. They make clear choices on spatial planning and land use, because they recognize the problems associated with climate change. Urbanization will be within or adjacent to existing urban areas and green and blue buffers will be constructed around cities. At regional scale, there will be fewer changes in land use as compared to the other scenarios. Dairy farming can survive in the fen meadow landscape, although the grassland area will be used more extensively. Instead of the current strategy in which ditch water levels are adapted to the function of the polder, the strategy “Function follows water level” will be implemented. Groundwater levels are raised at low-lying meadows; the land use will change into nature. Drainage will be continued at higher located meadows, which are still used for dairy farming.

Table 5.2 Basic assumptions under the main drivers of the three scenario storylines for the period 2006-2040.

<table>
<tr><th>Rural production</th><th>Rural fragmentation</th><th>Rural multifunctionality</th></tr>
<tr><td colspan="3">External drivers and threats</td></tr>
<tr><td colspan="3"><u>Climate</u></td></tr>
<tr><td colspan="2">Increase of 2ºC between 1990 and 2050 and a strong change in atmospheric circulation (W+ scenario KNMI). Small decrease and more variation in annual precipitation (summer -19%, winter +14.2%)[1]</td><td>Increase of 1ºC between 1990 and 2050 and a weak change in atmospheric circulation (G scenario KNMI). Increase in annual precipitation (summer +2.8%, winter +3.6%)[1].</td></tr>
<tr><td colspan="3"><u>Sea level rise</u></td></tr>
<tr><td colspan="2">+40 cm (including 5 cm soil subsidence)[1,2]. Increased salt seepage in drained grasslands and increased flood risks.</td><td rowspan="2">+0.20 cm (including 5 cm soil subsidence)[1,2]. The strategy ‘Function follows water level’ is implemented to cope with flood risks and soil subsidence.</td></tr>
<tr><td></td><td>Entire polders are used for water storage.</td></tr>
<tr><td colspan="3">Socio-economic developments</td></tr>
<tr><td colspan="3"><u>Economic growth</u></td></tr>
<tr><td colspan="2">2.9% per year for the Netherlands[3]</td><td>2.3% per year for the Netherlands[3]</td></tr>
<tr><td colspan="3"><u>Population</u></td></tr>
<tr><td colspan="2">19.7 million in the Netherlands[4]</td><td>15.8 million in the Netherlands[4]</td></tr>
<tr><td colspan="3"><u>Social coherence</u></td></tr>
<tr><td colspan="2">Weak, emphasis on individual freedom[3]</td><td>Strong, emphasis on regional</td></tr>
<tr><td colspan="3"><u>Economic orientation</u></td></tr>
<tr><td colspan="2">Free market prevails[3,5]</td><td>Government intervenes[3,5]</td></tr>
<tr><td colspan="3">Governmental intervention</td></tr>
<tr><td colspan="3"><u>Common Agricultural Policy (CAP)</u></td></tr>
<tr><td colspan="2">CAP subsidies and cohesion policy are phased out by 2030[6]</td><td>CAP subsidies: increase of 10%, linked to environmental and social targets (production subsidies are replaced by nature subsidies). Export subsidies are eliminated.[6]</td></tr>
<tr><td colspan="3"><u>Spatial policy</u></td></tr>
<tr><td colspan="2">Less restrictive policies[3]</td><td>Restrictive policies for rural</td></tr>
<tr><td colspan="3"><u>Nature protection policy</u></td></tr>
<tr><td colspan="2">Protection of most valuable areas only. Acquisition by private owners and organisations[3].</td><td rowspan="2">Large areas are protected; nature restoration and land reclamation for new nature[3]. Acquisition by national government[3].</td></tr>
<tr><td></td><td>Large areas become unmanaged nature reserves.</td></tr>
<tr><td colspan="3"><u>National ecological network (NEN)</u></td></tr>
<tr><td>The NEN is fragmented, which causes a risk of decreasing biodiversity.</td><td>Many peat swamps come into existence; the planned ecological links between the natural areas are not finished.</td><td>The NEN is finished in 2018[7] to preserve biodiversity.</td></tr>
</table>

Water management		
Continued drainage of peat soils; consequently salt seepage increases[1]. In general due to continuing drainage of peat soils, the mineralization of peat soils continues.	Continued drainage of peat soils at large scale farms; consequently salt seepage increases [1]. Groundwater levels are raised in abandoned areas. Large areas become wetter and change into peat swamps.	Water levels are managed by local water boards[8] following 'Function follows water level'. Groundwater levels are raised in wet areas, the mineralization of peat soils decreases.
Land use and land cover changes		
Land cover change (map)		
The total urban area in the Netherlands increases with 190,000 ha between 2010 and 2040[5]. Urban sprawl (recreational and residential parks) in rural areas, strong increase in low-density dwellings[8].		Concentration of urban areas near existing urban areas.[8] More lakes and natural areas.
.	More swamps. Large-scale farms on clay-on-peat soils.	
Land use change (map)		
Small decline in agricultural land use.	Strong decline of agricultural land use.[4,8]	Small decline in agricultural land use[8].Increase of natural areas at low areas; especially flowery hay lands and bird meadows.
Agricultural practices		
Agricultural sector		
Industrial dairy farming and greenhouse farming[8] and upscaling of farms[9].		More extensive small-scale farming[8]
Fertilization		
Optimal fertilizer rates at large scale farms.		Fertilizer rates decline by 50%.
Animals		
In the Netherlands: Dairy cows +25%[4] and pigs -5%[4]		The Netherlands: Dairy cows -15%[4] and pigs -55%[4]. Similar trend in the fen meadow landscape.
Similar trend in the fen meadow landscape.	A large increase in cows in Northern provinces, consequently the amount of cows in the fen meadow landscape decreases.	

[1] KNMI (2006)
[2] Kabat *et al.* (2009)
[3] MNP (2002)
[4] MNP (2006)
[5] MNP (2007)
[6] De Vries *et al.* (2008)
[7] VROM (2004)
[8] Koomen (2008)
[9] Provinces (2009)

Farmers will receive subsidies to manage the wet meadows as high nature valued farmland e.g. as meadow bird reserves or flowery hay lands. Because farmers have to pay for GHG emissions of their farm, they consider measures to reduce emissions; e.g. by using submerged drains (Pleijter & Van den Akker, 2007), by changing the cattle's diet, and by building low-emission stables. The NEN will be completed in 2018 as planned and nature is combined with recreation and biofuel cultivation of reed or willow vegetation. New lakes will be made, because they have a large recreational value and can contribute to preserve biodiversity.

5.3.2 Model results

All model inputs for INITIATOR were quantified in order to model N_2O emissions. Most model inputs could be directly quantified based on the scenarios, but some model inputs needed extra work. Therefore, the assumptions underlying these inputs are presented (Table 5.2).

<u>Future changes in model inputs</u>

The major land use change in the rural production and the rural fragmentation scenarios is urbanization. In the rural fragmentation scenario, new nature is also abundant, because agricultural grassland will be either replaced by urban area or will be abandoned and taken over by deciduous forest. In the rural multifunctionality scenario, nature restoration and land reclamation for new nature is the major land use change, which is mainly due to the completion of the NEN (Fig. 5.3). In this scenario, the nature reserves are predominantly extensively managed meadows. They are classified as nature in Fig. 5.3, because nature organizations own these areas. In the rural production scenario, groundwater tables were assumed to remain the same as in the reference year. In fact, this means that groundwater tables are lowered annually to compensate for soil subsidence. In the rural fragmentation scenario, the groundwater levels are raised 2 cm per year in areas covered by deciduous forest, mainly alder and willow, which can stand wet conditions. In the rural multifunctionality scenario, the groundwater levels are increased in all low-lying areas (lower than 1.5 m below mean sea level (MSL)). This rise in groundwater level is assumed to be related to the absolute location of the area compared to MSL, for instance, areas which are located 1.5 m below MSL were assumed to have a rise in groundwater level of 0.5 cm per year, while areas which are located 6 m below MSL were assumed to have a rise in groundwater level of 2 cm per year.

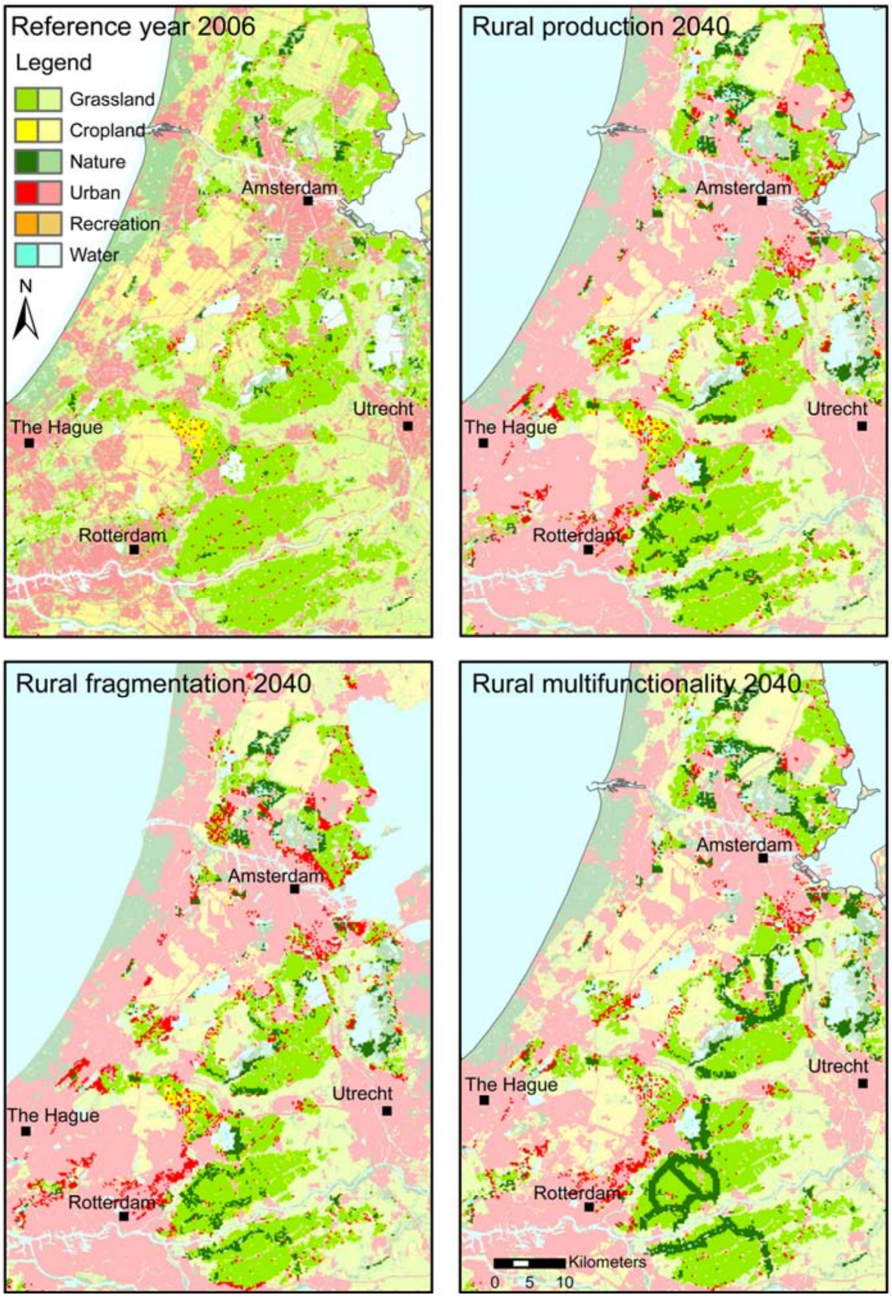

Fig. 5.3 Land use under different scenarios for (a) the reference year 2006, (b) the rural production scenario in 2040, (c) the rural fragmentation scenario in 2040 and (d) the rural multifunctionality scenario in 2040.

Changes in N_2O emission

Under all scenarios, the soil subsidence was considerable. The rural production scenario had the largest soil subsidence of 20.7 cm on average, while the rural multifunctionality scenario had the smallest soil subsidence of 17.6 cm as a result of the higher groundwater levels. In the top layer, due to oxidation of peat, mineral parts will be left over that will lead to a gradual evolvement from a peat layer into a clay layer (Table 5.3).

Table 5.3. Distribution of soil types in the Dutch fen meadow landscape for 2006 and for 2040 under different scenarios.

	Reference year[1]	Rural production	Rural fragmentation	Rural multifunctionality
Soil type	2006	2040	2040	2040
Clay	4%	4%	3%	4%
Thick peat	86%	65%	67%	68%
Thin peat	4%	3%	3%	3%
Peaty clay	2%	13%	7%	11%
Water/Urban	3%	15%	20%	13%

[1] See also Table 5.1

All scenarios show a decrease in aggregated N_2O emissions (Fig. 5.4). However, the decrease in the rural production scenario is caused by rapid urbanization, which causes a decrease of the area of agricultural land. Therefore, this scenario shows a small increase of +4% in N_2O emission per hectare of agricultural land. For the period 2006 to 2025, the trends in N_2O emissions under the rural fragmentation and in the rural multifunctionality scenarios are comparable. However, between 2026 and 2040 the N_2O emissions under these two scenarios diverge. Under the rural multifunctionality scenario, the N_2O emission continues to decrease to 1110 t N_2O-N yr^{-1} in 2040, whereas the emission under the rural fragmentation scenario decreases less rapidly and is assumed to be 1336 t N_2O-N yr^{-1} in 2040. The decrease in the rural multifunctionality scenario can be mainly attributed to the policy on agricultural management, while the decrease in the rural fragmentation is mainly due to a decrease in nitrogen mineralization, because of increased groundwater levels. The rise in groundwater levels clearly reduces emissions in the first decade, but the extra rise in groundwater level in the following decades shows less effect.

The rapid urbanization under the rural production scenario is also visible in the spatial distribution of N_2O emissions by pixels with zero emission around Amsterdam and around The Hague (Fig. 5.5). Average N_2O emission in rural areas increases due to intensification of agriculture. Under the rural fragmentation scenario, many locations have low or zero emission due to a strong decrease in dairy farms and due to urbanization. The few remaining dairy farms are located in the centre of the fen

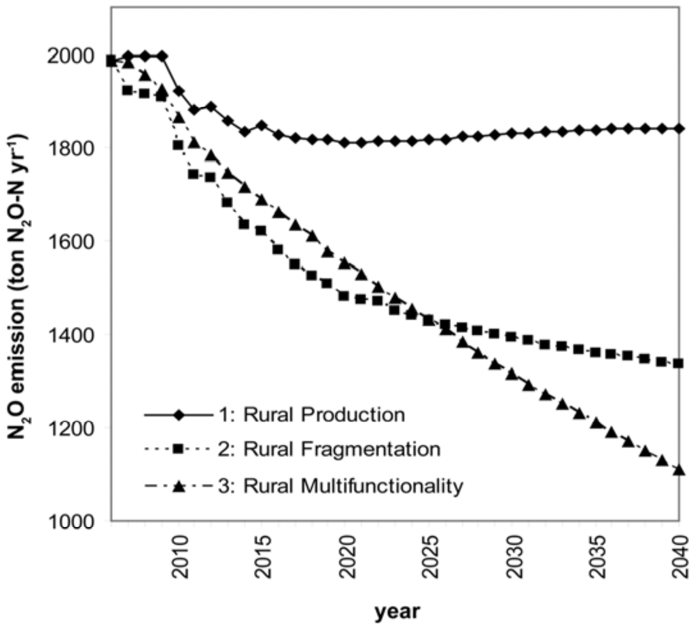

Fig. 5.4 N_2O emission (ton N_2O-N yr^{-1}) between 2006 and 2040 under different scenarios.

meadow landscape. Under the rural multifunctionality scenario, the NEN is clearly visible by its low emissions. These emissions are small because of the absence of agricultural practices (fertilization, manure application, and grazing) and low mineralization rates due to high groundwater levels. The eastern part and a small area in the northwest part of the fen meadow landscape emit more N_2O than the rest of the landscape, because these parts are located at higher altitudes and are therefore assumed to be better drained and more suitable for intensive dairy farming.

<u>Emission sources</u>

While the total aggregated emissions differs considerable between the scenarios (Fig. 5.4), their shares among N_2O emission sources stay quite similar (Fig. 5.6). This shows that the assumptions under the scenarios are strongly correlated. For instance, intensive agriculture in the fen meadow landscape is only possible on land with deep groundwater levels to bring about enough bearing capacity. Due to deep drainage, oxidation and mineralization of the soil will be large. Large emissions from agricultural management are therefore closely related to large emissions from mineralization. Under all scenarios, mineralization remains the major source of emission, although the total amount of emission due to mineralization decreases under all scenarios. Under the rural multifunctionality scenario, the emission due to mineralization even halves.

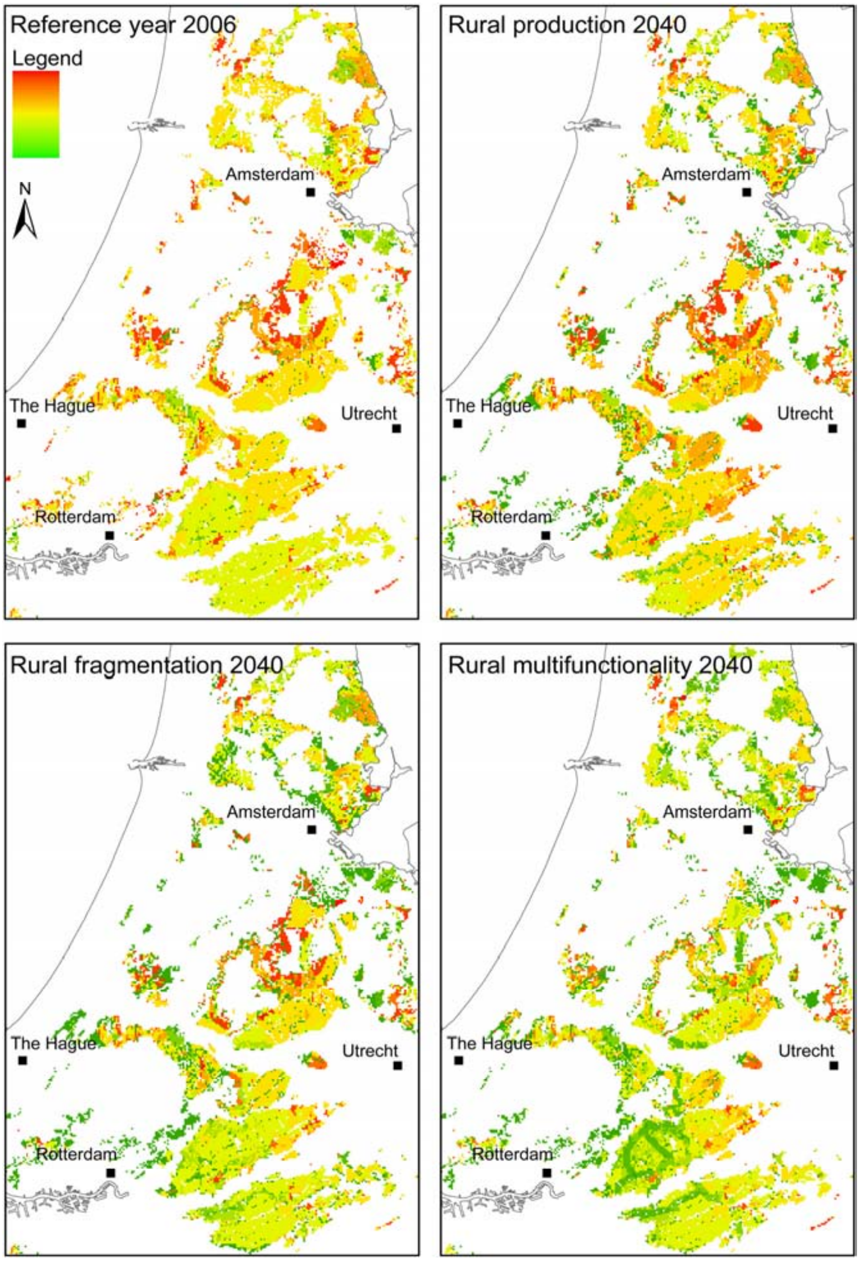

Fig. 5.5 Maps of N_2O emissions from the Dutch fen meadow landscape for (a) reference year 2006, (b) the change in emission in the rural production scenario in 2040, (c) the change in emission in the rural fragmentation scenario in 2040 and (d) the change in emission in the rural multifunctionality scenario in 2040

Comparison with other sources of uncertainty

Table 5.4 presents an overview of estimates in uncertainty in N_2O emission inventories based in three different studies for the same area. Although the different uncertainty sources are difficult to compare due to differences in scale of assessment, the coefficient of variation provides an indication of their relative importance. Compared to the other uncertainties, the uncertainty due to differences in possible land use changes is a significant source. However, the largest source of uncertainty in emissions is due to uncertainties in model inputs (especially emission factors and soil parameters) at point scale, which also affects landscape scale estimates. More details on the different sources of uncertainty can be found in the chapters referred to in Table 5.4.

5.4. Discussion

5.4.1 Scenario construction process

Research on future trends and GHG emission at landscape scale is usually focused on one part of the Story And Simulation approach; either on thorough scenario construction or on the simulation of biophysical properties. Garb *et al.* (2008) also pinpointed to the growing imbalance between environmental modelling of scenarios and a proper social analysis of scenarios. Scenario developers are mainly focusing on the construction of plausible and consistent scenarios for simulating social-economic developments and land use change (Rounsevell *et al.*, 2005; Soliva & Hunziker, 2009; Tress & Tress, 2003); while GHG researchers mainly simulate future GHG emissions by estimating the effect of one or more specific measures (Johnson *et al.*, 2007; Oenema *et al.*, 2001; Weiske *et al.*, 2006). For the fen meadow landscape both parts of the SAS approach are equally important to determine the range of future emissions. These parts are also strongly linked, because N_2O emission is strongly related to land use. Therefore, this research did not only focus on the estimation of possible future N_2O emission, but also on the construction of plausible and coherent scenarios in close cooperation with stakeholders and experts. In this way, stakeholders are also “owner” of the constructed scenarios and they are more open to adopt the study’s results (Mahmoud *et al.*, 2009). The outcomes of this study can be used as a platform for discussion on adaptation and mitigation and can enhance decision-making processes. Kok (2009) stated that although the SAS method combines advances of qualitative and quantitative scenarios, the link between these qualitative and quantitative scenarios is still weak. To strengthen this link, qualitative scenarios were translated to main drivers before model inputs were quantified.

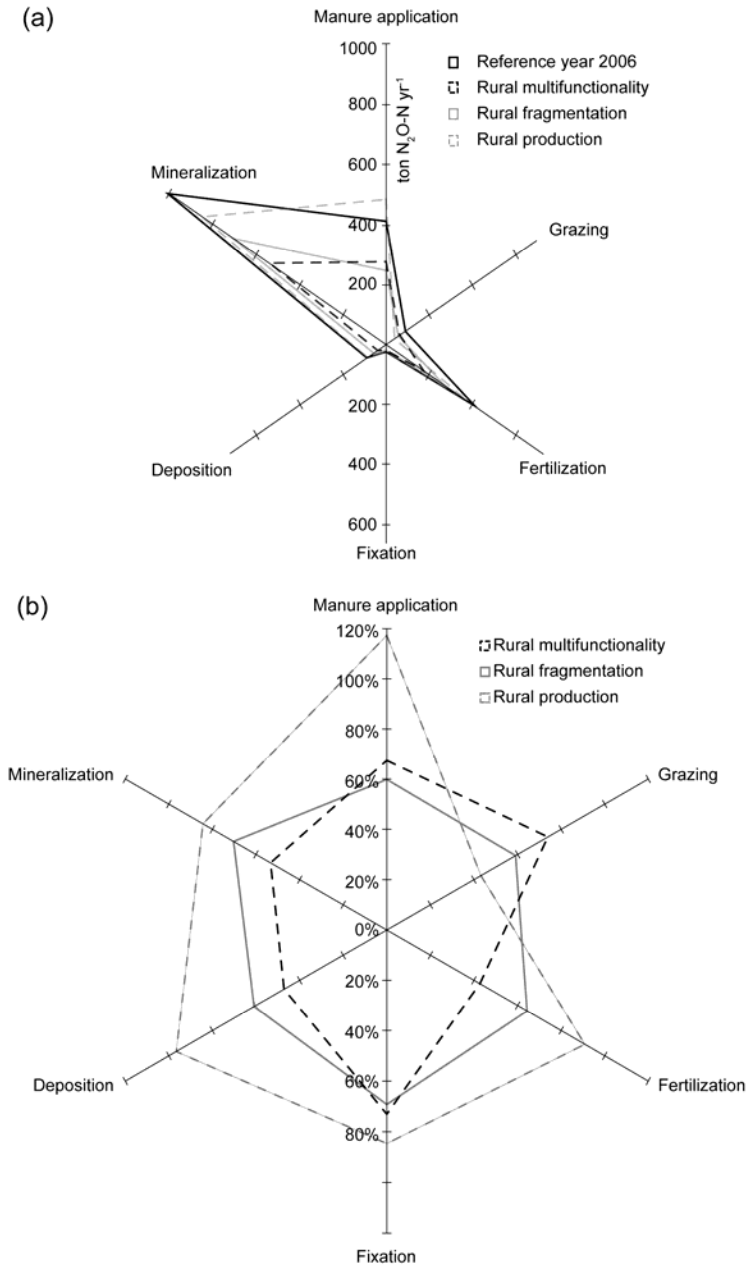

Fig. 5.6 Distribution of sources of N_2O emission (a) in the reference year 2006 and in 2040 under different scenarios and (b) under different scenarios compared to the reference year. The emission sources of the reference year 2006 were all set at 100%.

Table 5.4 Sources of variability for N_2O emission from the Dutch fen meadow landscape and their coefficient of variation (C.V.) and, if applicable, their range of C.V.'s at different spatial scales.

Sources of variability	Scale	C.V.	Range
Variability due to inventory method/model			
- due to model formulation (using Tier 3a, Tier 3b)[a]	Parcel	32%	8%-123%
- due to inventory method (using Tier 1, Tier2a,Tier2b, Tier 3a)[b]	Polder	33%	21%-41%
- due to inventory method (using Tier 1, Tier 2a) [b]	Polder	6%	4%-9%
- due to inventory method (using Tier 1, Tier 2a) [b]	Landscape	7%	7.0%-7.4%
Variability due to model inputs[c]			
Variability due to all model inputs, divided into:	Point	78%	
- due to emission factors	Point	32%	
- due to soil parameters	Point	30%	
- due to manure management parameters	Point	11%	
- due to crop parameters	Point	5%	
Variability due to all model inputs, divided into:	Landscape	52%	
- due to emission factors	Landscape	35%	
- due to soil parameters	Landscape	7%	
- due to manure management parameters	Landscape	5%	
- due to crop parameters	Landscape	5%	
Variability due to variability in land cover data[b]			
- using Tier 1, Tier 2a, Tier 2b, Tier 3a	Polder	6%	3%-14%
- using Tier 1, Tier 2a	Polder	4%	2.9%-4.4%
- using Tier 1, Tier 2a	Landscape	8%	8.0%-8.2%
Variability in time[a]			
- due to between-year variation in models (using Tier 3a, Tier 3b)	Parcel	30%	7%-54%
Variability due to future scenarios			
- due to land use change induced by socio-economic developments	Landscape	26%	

[a] Chapter 3 of this thesis
[b] Chapter 2 of this thesis
[c] Chapter 4 of this thesis

Land use change results from scenarios of the LANDS project (Koomen et al., 2008), were applied, because this project has incorporated climate change in the scenarios and it has a strong focus on the 'Randstad' in the Netherlands, which is largely corresponding to the location of the fen meadow landscape. In their global economy scenario, derived from the IPCC SRES A1 scenario, agriculture will drastically reduce around the cities of Amsterdam and Utrecht in 2030 while there is a strong increase in urban land use, recreational area, and nature reserves. In their regional community scenario, derived from the IPCC SRES B2 scenario, the decrease in agricultural area is less pronounced and the focus is in on preserving open areas for recreation and on new opportunities for farming. Because the LANDS project is mainly focused on socio-economic developments and urban land use, land use change scenarios from MNP (2007) were used for rural land use. De Nijs et al. (2004) also constructed land use change scenarios based on IPCC scenarios; however, they did not include climate change effects. In their 'Individual World' scenario, agricultural subsidies are diminished and therefore the agricultural area will sharply decrease. This land will be left fallow or bought by nature conservation organizations for nature protection and by private investors to build rural estates. This 'Individual World' scenario is closely related to our rural fragmentation scenario. In their study, the increase in natural areas for the year 2030 will be larger, especially in the northern part of the landscape. This is mainly caused by classification differences, e.g. green rural residential areas are classified as natural area, whereas LANDS classifies them as urban. Rounsevell et al. (2005) estimated land use change under the IPCC scenarios at European scale until 2080, using a simple supply/demand model. In 2080, the Dutch agricultural area is assumed to decline by 29% under the B2 scenario. For our rural multifunctionality scenario a comparable decline in agricultural area of 30% was simulated; however, this decline is already reached in 2040. This can be explained by the large pressure on space in the fen meadow landscape compared to the rest of the country. The same applies when comparing land use change in other scenarios to the study of Rounsevell et al. (2005). For instance, in both studies the area of grassland declines under all scenarios due to urbanization and the increase of natural areas.

5.4.2 Implications of the model results

The large and uncertain N_2O emissions are typical for the Dutch fen meadow landscape (Langeveld *et al.*, 1997; Velthof, 1997) and emphasize the need to research uncertainties in future N_2O emissions for this landscape. Roelandt *et al.* (2007) estimated future N_2O emissions from Belgium until 2050. They used simple statistical models, which required land use data, climate data, and N management data. Roelandt et al. (2007) concluded that N_2O emissions from Belgian agricultural soils will be more affected by changes in agricultural land cover than by other factors that affect emissions. In this study, it was found that although the decline in agricultural land cover does not differ much between the scenarios (between 21% and 30%), the differences in estimated N_2O emission between the scenarios are considerable (between -44% and -7%). The differences in land use change (land cover and land management) between the scenarios had much a larger effect on N_2O emissions than differences in climate conditions between the scenarios. The small difference between temperatures has no influence on N_2O emissions; whereas the differences in N input and ground water level have a large influence on N_2O emissions. The differences between the rural production scenario and the other scenarios (Fig. 5.4) can be attributed to the difference in the dairy farming sector. The rural production scenario showed a decrease in aggregated emissions, whereas it showed a small increase in emission per hectare. The clayey peat soils and peaty clay soils are more favorable for urban expansion due to a larger bearing capacity than thick peat soils, whereas the thick peat soils together with an intensification of agricultural use have the highest emission potential. Therefore, the trend in N_2O emission per hectare can be opposite to the trend at landscape scale.

The importance of the different sources related to agricultural management (manure application, fertilization, and grazing) differ between the scenarios (Fig. 5.6). Under the rural fragmentation scenario, these emission sources all have a small share, because dairy farming is outcompeted by other regions. Under the rural multifunctionality scenario, the share of fertilization is low, due to measures to reduce fertilizer application while the ratio grazing/manure application is larger compared to the other scenarios due to an increase in grazing time. The assumptions underlying the scenarios are strongly correlated. For instance, if groundwater levels are raised, the mineralization will be reduced but the area is also less suitable for intensive dairy farming; therefore, a small N_2O emission from mineralization is correlated to a small N_2O emission from fertilization (Fig. 5.6). Measures to mitigate agricultural N_2O emissions should not focus on the effect of one source of N_2O emissions, but should focus on the interplay between the different sources. A raise in groundwater levels does therefore not only decrease soil subsidence, decrease salt seepage and decrease flood risks, but can also contribute to mitigation of N_2O emissions in two ways: by decreasing the mineralization rate and by decreasing agricultural N inputs. The disadvantage of higher groundwater levels is an increased CH_4 emission (Hargreaves & Fowler, 1998; Hendriks *et al.*, 2007; Van den Pol- van Dasselaar *et al.*, 1999).

The change in soil types in the fen meadow landscape between 2006 and 2040 is remarkable. Many peat soils in the fen meadow landscape already have a clayey top layer. If, over the years, this layer becomes thicker than 40 cm, the soil is classified as a peaty clay soil (Table 5.3). The rate of this mineralization process is positively related to the rate of soil subsidence. The process of peat oxidation is also discussed in Nol *et al.* (subm.), Finke *et al.* (1996), and Van Kekem *et al.* (2005). Lately, this change in soil type has been recognized in the Netherlands and therefore the provinces of Utrecht (Stouthamer *et al.*, 2008) and Drenthe (Kempen *et al.*, 2009) have updated their soil database. In these new soil databases, many former peat soils with a thin mineral top layer are now classified as peat soils with a thick mineral top layer and former peat soils with thick mineral layers are now classified as mineral soils. The process of peat mineralization and the resulting decline of peat soils create difficulties for N_2O emission inventories; soil type can no longer be assumed as a static parameter, it is changing in time and depending on the rate of mineralization. As a consequence, the amount of N_2O emitted from these landscapes is not linearly related to variables, like agricultural area and management intensity, but also depending on the driving forces of the mineralization rate.

Examples of comparable areas with comparable soil types and hydrology can be found in Germany (Augustin *et al.*, 1998; Goldberg *et al.*, 2010), Finland (Alm *et al.*, 2007), Canada (Wray & Bayley, 2007), Denmark (Blicher-Mathiesen & Hoffmann, 1999). However, most of these landscapes have lower N_2O emissions because they are not used for agriculture or the N-input to these landscapes is lower. Most of these landscapes are wetlands, while the fen meadow landscape in the Netherlands is drained for agricultural purposes.

This research focused on the soil-bound N_2O emissions. However, if one is interested in the full GHG balance and in the most favorable scenario in terms of GHG mitigation, this study should be extended with N_2O emissions from stables, leaching, and runoff and also from open water, urban, and industrial areas. In the Netherlands, about 61% of the total N_2O emission is originating from agriculture (Van der Maas *et al.*, 2009). The other sources of N_2O emission are mainly from point sources, such as industrial processes and solvents, which are easier to measure and result in more accurate estimates than dispersed sources, such as agriculture. Agricultural soils in the Netherlands are responsible for 91% of the N_2O emissions from agriculture, therefore N_2O emissions from agricultural soils are identified as a key source in the National Inventory Report and are for a large part responsible for the uncertainty in the overall GHG estimates (Van der Maas *et al.*, 2009).

In a full GHG balance, CO_2 and CH_4 emissions should also be included (Brink *et al.*, 2001; Luo *et al.*, 2010). The N_2O emission under the rural production scenario would probably increase faster when stable N_2O emission was included because of the increase in cattle combined with a decrease in grazing time. The CO_2 emission will probably stay high under this scenario due to continued draining of the peat soils. Under the rural fragmentation scenario, the decrease in N_2O emission will, to a some extent, be counterbalanced by an increase in CH_4 emissions due to raised groundwater levels and resulting peat swamps in large parts of the fen meadow landscape (Hendriks *et al.*, 2007). In time, the CO_2 emission will decrease due to a decrease in peat mineralization. Carbon will perhaps even be sequestered in 2040. The N_2O emission from stables under the rural multifunctionality scenario will probably decrease due to a decrease in cattle numbers and an increase in grazing time. The CO_2 and CH_4 emission in the rural multifunctionality scenario will probably be in between the emissions for the rural production and rural fragmentation scenarios, given the development of groundwater levels in this scenario.

5.4.3 Uncertainty Assessment

This study was focused on the uncertainty due to future land use change. However, other uncertainties such as uncertainty due to model inputs, uncertainty due to model structure, and uncertainty due to spatial and temporal upscaling can also cause uncertainty in modelled N_2O emissions (Table 5.4). Rapid land use change and the question if dairy farming can be sustained contribute to the variation in future emissions estimated for the fen meadow landscape. It is important to account for such changes in designing policies for emission reduction. The importance of land use change and the implications on uncertainty of future emission estimates varies between landscapes and between countries, e.g., the results of this study are different from the findings of Dendoncker *et al* (2008) who estimated for Luxembourg that uncertainty due to diverging scenarios is small as compared to uncertainty resulting from data processing.

5.5. Conclusion

This study combines theory and models from social and natural sciences to make an assessment of future emissions of N_2O in the western part of the Netherlands. By means of the Story And Simulation method, stakeholders and experts were consulted to construct future scenarios for the fen meadow landscape. The main scenario drivers were translated to model inputs and a biogeochemical model was used to simulate N_2O emissions under the different scenarios. The participatory and iterative method for building scenarios resulted in a series of plausible scenarios that were accepted by a wide range of experts and stakeholders.

Changes in future N_2O emission from agricultural soils in the fen meadow landscape may range between 1110 (-44%) and 1839 (-7%) t N_2O-N yr^{-1} for 2040 compared to the emission in 2006. The scenario in which dairy farming in the area will continue and intensify (rural production scenario) causes the largest N_2O emissions, although urbanization will rapidly decrease the size of the fen meadow area. The scenario in which dairy farming continues in an extensive way (rural multifunctionality) has lower N_2O emissions than the scenario in which the dairy farming sector is marginalized (rural fragmentation). For the fen meadow landscape, sources of N_2O emission are strongly and positively related to each other. When implementing mitigation strategies to reduce N_2O emissions from one source, N_2O emissions from other sources are also reduced, which should be accounted for in designing policies. As compared to other sources of uncertainty in N_2O emission inventories the uncertainty due to future changes in land use is high. Therefore, the uncertainty of N_2O emission for the fen meadow landscape, as result of possible diverging land use change trajectories should be accounted for in mitigation and adaptation strategies.

6

Synthesis and conclusions

6.1 Uncertainty and N_2O emission inventories

6.1.1 Main findings

In this thesis, the uncertainties in inventories of the GHG N_2O were assessed for a peat area in the Netherlands, the Dutch fen meadow landscape. An overview of the main conclusions is given in this chapter. The importance of the different sources of uncertainty and the relationships between the different sources of uncertainty is discussed. In addition, the relevance of these findings for science and society will be discussed. The main findings of the research presented in the previous chapters are:

1. Uncertainties in emission inventories are affected by spatial scale effects;
    - The choice of a certain land cover database (with a specific spatial resolution) can have large effects on N_2O inventories; differences in estimated surface areas of landscape elements between different land cover databases sometimes exceed 20% for the fen meadow landscape while each landscape element has its own emission characteristics (§2.4).
    - At polder scale, the differences in estimated N_2O emissions were larger between the inventory techniques than between land cover data. At landscape scale, the opposite applies because errors in land cover data were mainly systematic (bias) and errors in inventory techniques were mainly random. Bias is consistently in the same direction and does not cancel out when estimates are scaled up; therefore, at larger scales these systematic errors are more distinct compared to random errors in emission factors (§2.4).

2. Besides issues of spatial upscaling, uncertainties can also be related to temporal upscaling;
    - Data on the distribution of rainfall within a year is crucial for estimating annual N_2O emissions from intensively managed grasslands in the fen meadow landscape. In years with a relatively large summer rainfall, N_2O emission estimated with a high temporal resolution model was larger than estimated with a low temporal resolution model. In years with a relatively small summer rainfall, the opposite occurred (§3.5).
    - Low temporal resolution models such as INITIATOR (and other Tier 2 methods) may be improved for intensively managed grasslands on

peat soils by adjusting N_2O emission estimates for years with relatively dry summers or wet summers (§3.5).

- Exact timing of nitrogen application is not important for estimating annual N_2O emissions for intensively managed grasslands on peat soils, because the application has a prolonged effect of weeks or even months. Therefore, more detailed information about timing of nitrogen application does not directly yield more accurate results. It is sufficient to know in which month the application took place (§3.5).
- Emission factors estimated from the two models (INITIATOR and DNDC) varied largely between the models and between years. It is therefore recommended to derive emission factors over a large period of time (decades) and to be cautious with emission factors from years with very large of very small summer rainfall (§3.5).

3. Uncertainty also results from uncertainty in model inputs;
    - The uncertainty in N_2O emission in the Dutch fen meadow landscape due to model inputs is substantial and ranges between 52% at landscape scale and 78% at point scale (§4.5).
    - The contribution of uncertainty sources is scale-dependent. Non-systematic uncertainty in spatial variables (such as soil inputs) can average out (i.e., decrease) with upscaling, while for variables that are constant in space the uncertainty remains the same (§4.5).

4. Uncertainty in estimates of future emissions can originate from differences in land use change induced by future socio-economic developments;
    - Changes in future N_2O emissions from agricultural soils in the fen meadow landscape ranges between -875 (-44%) and -144 (-7%) t N_2O-N yr^{-1} for 2040 compared to the emission in 2006. A scenario in which dairy farming will continue and intensify (‘rural production’ scenario) causes the largest N_2O emissions, even though urbanization rapidly decreases the spatial extent of the fen meadow area. The scenario in which dairy farming continues in an extensive mode (‘rural multifunctionality’) has smaller N_2O emissions than the scenario in which the dairy farming sector has almost disappeared (‘rural fragmentation’), because the former scenario employs measures to decrease peat mineralization and policies to reduce agricultural emissions (§5.5).
    - For the fen meadow landscape, sources of N_2O emission are strongly and positively related to each other. When implementing mitigation

strategies to reduce N_2O emissions from one source, N_2O emissions from other sources are in many cases also reduced (§5.5).

- Given the significant uncertainty in future emissions compared to other uncertainties, the uncertainty in land use change should be accounted for in mitigation and adaptation strategies (§5.5).

6.1.2 Sources of uncertainty

In this thesis, various sources of uncertainty in N_2O emission inventories were discussed. Large uncertainties in N_2O emission estimates (at point support) were found as a result of uncertainty in model inputs at point support (Tables 5.4; 6.1). These model inputs can be divided into emission factors, soil parameters, manure management parameters, and crop parameters. At landscape support, especially emission factors are a large source of uncertainty, because other factors partially cancel out when scaling up. This was also found for many other ecosystems and countries (Mosier *et al.*, 1998; Payraudeau *et al.*, 2007; Ramírez *et al.*, 2008). At point support, not only emission factors are a main source of uncertainty, but soil parameters as well. For Germany, Jungkunst (2006) found that soil properties influenced N_2O emissions at site scale, while no relation was found at national scale.

Table 6.1 Simplified version of Table 5.3; different sources of uncertainty for N_2O emission from the Dutch fen meadow landscape, their scale, and their coefficient of variation (C.V.)

Sources of uncertainty	support	resolution	extent	C.V.
Uncertainty due to:				
- all key model inputs	point	250m	f.m.l.[b]	78%
- all key model inputs	f.m.l.[b]	f.m.l.[b]	f.m.l.[b]	52%
- N_2O measurements; choice of the regression method[a]	point	point	point	40%
- emission factors	f.m.l.[b]	f.m.l.[b]	f.m.l.[b]	35%
- inventory method (using Tier 1,Tier2a,Tier2b,INITIATOR)	0.2-100m	0.2-100m	polder	33%
- emission factors	point	250m	f.m.l.[b]	32%
- model formulation (using INITIATOR and DNDC)	parcel	parcel	parcel	32%
- soil parameters	point	250m	f.m.l.[b]	30%
- between-year variation in INITIATOR and DNDC	parcel	parcel	parcel	30%
- socio-economic developments and land use change	point	250m	f.m.l.[b]	26%
- manure management parameters	point	250m	f.m.l.[b]	11%
- land cover data (using Tier 1, Tier 2a)	0.2-100m	polder	f.m.l.[b]	8%
- inventory method (using Tier 1, Tier 2a)	1-25m	polder	f.m.l.[b]	7%
- soil parameters	f.m.l.[b]	f.m.l.[b]	f.m.l.[b]	7%
- land cover data (using Tier 1,Tier2a,Tier2b,INITIATOR)	0.2-100m	0.2-100m	polder	6%
- inventory method (using Tier 1, Tier 2a)	0.2-100m	0.2-100m	polder	6%
- crop parameters	point	250m	f.m.l[b]	5%
- manure management parameters	f.m.l.[b]	f.m.l.[b]	f.m.l.[b]	5%
- crop parameters	f.m.l.[b]	f.m.l.[b]	f.m.l.[b]	5%

[a]Kroon *et al.* (Kroon *et al.*, 2008)
[b]f.m.l. = fen meadow landscape

Although this thesis deals with the effect of uncertainty in soil parameters on uncertainty in N_2O emissions, the similarity is that soil parameters have more influence on N_2O emissions at small scale than at large scale. For the fen meadow landscape, the uncertainty in soil parameters is mainly caused by changes in parameters due to mineralization of peat soils. Most Dutch soil data were derived in the 1960's and 1970's. However, peat soils are subject to change and therefore soil parameters derived from these data for the fen meadow landscape have large uncertainties. Recently, fieldwork and research have started to update the Dutch soil data and soil maps. When the updated soil map is available and used to derive soil parameters, the uncertainty due to soil parameters can be reduced. In the Netherlands, many data on manure management parameters are available. For countries which do not have as detailed manure management data, the uncertainty due to manure management parameters will probably be larger. Uncertainties due to the inventory method or model used are also considerable. The uncertainty due to model formulation was estimated as 32%, but it should be noted that this uncertainty estimate was based on a comparison of two models only. To improve the reliability of the uncertainty estimate, other models should be included too. When comparing Tier 1 and Tier 2a methods, the uncertainty due to inventory method is underestimated, because these methods have the same model structure and produce similar results. The uncertainty due to uncertainty in land cover data is also quite small; however, this uncertainty is systematic and does not average out when aggregating. This uncertainty is relatively easy to reduce by using high-resolution land cover data for landscapes with many linear landscape elements. The variation due to between-year variation in models is considerable (30%). However, the uncertainty between years modelled by INITIATOR was larger (45%) than modelled by DNDC (14%). The uncertainty due to socio-economic developments and land use change was estimated as 24%, future projections for 2040 ranged between 1.1 and 1.8 kt N_2O-N yr^{-1}. This uncertainty source is an outsider compared to the other sources, because it does not directly influence current N_2O inventories.

The uncertainty due to measurement errors or limitations in measurement equipment was not assessed in this thesis. However, many researchers that work on this theme and indicate that measurement error can be a large source of uncertainty. Especially in the Dutch fen meadow landscape, where many measurement campaigns are being executed (Hendriks *et al.*, 2007; Kroon *et al.*, 2008; Schrier-Uijl *et al.*, 2008). For instance, Kroon *et al.* (2008) showed that the choice of regression method used for closed chamber measurements considerably influences N_2O emission estimates. Estimates of an exponential regression method and a linear regression method differ up to 40%.

Uncertainty in inventory data can also be a result of processes that are not incorporated in N_2O emission inventories. These processes are ignored because they are unknown or because modellers think they are not relevant. For instance, the effect of dredging of ditches is usually not incorporated in emission inventories, whereas recent measurements suggest that this can be an important source of GHG emission (Rietra *et al.*, 2009). Research on which processes are relevant and which are not and on whether the relevant processes are described properly by the model, is important.

Less important uncertainty sources are the variability in crop parameters and in manure management, mainly because in the Netherlands much high-resolution up-to-date information about these model inputs is available. The uncertainty due to variability in land cover data is also small compared to other uncertainty sources. However, as mentioned above, this uncertainty source is systematic and does not cancel out by aggregation; while it is easy to reduce by using high-resolution land cover data.

6.1.3 Uncertainty interactions

Most uncertainties in N_2O emission inventories are spatially autocorrelated, related to each other, and related to the scale of inventory. In this section, some important identified interactions are discussed.

The preceding chapters showed that for N_2O emission inventories, spatial and temporal uncertainties are related. At the extent of a polder, the temporal variation and uncertainty at field support can be large, while at polder support small-scale variation can average out (because e.g. farmers fertilize at different days). The systematic error of overestimating the grassland area (Chapter 2) has probably a larger effect on high-temporal resolution models than on low-temporal resolution models. These high-temporal resolution models usually include many spatially explicit inputs, which are necessary to include processes with large temporal and spatial dependencies. An example of such a process is fertilization; since weather, soil moisture content (temporal variables), land use, and groundwater table (spatial variables) can all influence the N_2O emission.

Another important interaction exists between spatial uncertainty and model input uncertainty. Much of the uncertainty within the model inputs originates from spatial variation (Chapter 4). Most model inputs were measured at a different spatial scale than the scale at which the model describes processes. Therefore, aggregation and disaggregation were necessary. For (dis)aggregation assumptions are needed based on the relation between the measurement and model scale, which causes an increase in uncertainty in model outcomes. The same applies for the temporal scale. In Chapter 4, the LGN4 land use database was used as input for INITIATOR. However, in Chapter 2, it was shown that the systematic error in the LGN4 database because of the omission of ditches is about +18% at landscape scale. Therefore, the estimated emission in Chapter 4 is probably an overestimation of the real N_2O emission. Unfortunately, more accurate land cover data used in Chapter 2 did not have the proper extent or did not include sufficient detail in land cover categories and could therefore not be used as input for INITIATOR at landscape scale.

Uncertainty in model structure is, of course, closely related to uncertainty in model inputs. The model structure defines which inputs are used. Different N_2O emission models rely much on the same model inputs, however the spatial and temporal scale of the models and corresponding inputs can be different, with consequences for the uncertainty. For example, DNDC and INITIATOR (Chapter 3) both need management parameters, but the input for INITIATOR is the amount of N applied by grazing cows in kg N ha^{-1} yr^{-1}, whereas DNDC needs the number of grazing cows (heads ha^{-1}) and the dates and number of hours that they grazed. A disadvantage of the use of the same data for different models is that if a model input contains bias, this bias is propagated by all models, resulting in bias in the N_2O emission, which is undiscovered because all models suffer from the same bias.

Sources of N_2O emission in the fen meadow landscape are likely to change in the future. How they change and in which direction depends on socio-economic developments and land use change. How the uncertainty will change in future is uncertain as well. The reduction of uncertainty from different sources depends on investments in scientific modelling and measurement techniques, on change of sources due to e.g. policy measures or market orientation, and on unforeseen processes. In future, unforeseen processes can also influence the uncertainty in N_2O inventories. For instance, a financial crisis can cause a bankruptcy of farmers, which can cause a large decrease of N input to soils and consequently of N_2O emissions. These developments and forces may be dependent on changes in society at large. To give an idea of these processes, the storylines presented in Chapter 5 were translated in terms of developments of the uncertainty in emission inventories. All assumption are based on a thought experiment in which the driving factors of the scenarios are translated into changes that are likely to affect the practice of emission inventory. In Table 6.2 an overview of possible changes in uncertainty of future N_2O emissions is given. Whereas technological innovations can decrease measurement uncertainty and improve our knowledge of N_2O emission processes, the scale discrepancy between the scale at which N_2O is measured and at which it affects climate change (global) will probably also in next decades cause uncertainties to be considerable.

6.1.4 Implications for uncertainty and full GHG balance

The discussion has mainly focused on the uncertainty in N_2O emission inventories; however, CO_2 and CH_4 are also important GHG sources in the fen meadow landscape. The uncertainty in CO_2 and CH_4 is usually much smaller than in N_2O (Jacobs *et al.*, 2007; Ramírez *et al.*, 2008; Van der Maas *et al.*, 2009). Recommendation to decrease the uncertainty in N_2O emission estimates can also affect the uncertainty in CO_2 and CH_4 estimates. In Chapter 2, the effect of overestimation of grassland area on N_2O emission is shown. In the suggested field map, ditches, ditch banks, and grassland were distinguished. These data were used by Schrier-Uijl (2010) in combination with CH_4 emission measurement on the landscape elements. The effect of overestimation of grassland and underestimation of ditches and ditch banks by regular land cover data is even larger for CH_4 inventories than for N_2O inventories. The emissions of CH_4 from ditches and ditch banks are much larger than from the grassland and are responsible for about 64% of the terrestrial CH_4 emissions. This means that the CH_4 emission is strongly underestimated when using regular land cover databases for CH_4 inventories. Inventories from conventional land cover databases are 12–46% smaller (depending on the database) than inventories based on accurate data on ditch and ditch bank areas from field maps. CO_2 emission is expected to be smaller when using a field map, because CO_2 is mainly emitted due to mineralization (in aerobic environments). It is also important to estimate CO_2 and CH_4 emissions for the scenarios in Chapter 5. For example, in the rural fragmentation scenario, large areas will be abandoned by dairy farmers and will become swamps. As a result, the N_2O emission will decrease, but the CH_4 emission will increase. Hendriks (2006) measured emissions from an abandoned peat meadow in the fen meadow landscape with a groundwater level of about 10 cm below surface. N_2O emissions were absent, but CH_4 emissions were larger than compared to intensively managed peat meadows. The peat meadow acts as a sink of CO_2. An important difference between N_2O, CO_2, and CH_4, is that N_2O is very strongly linked to management, whereas CO_2 and CH_4 to a much smaller degree. Fertilization, manure application, and grazing directly influence N_2O emissions. In general, when the N input stops, N_2O emissions quickly decrease to negligible amounts (Hendriks *et al.*, 2007; Schrier-Uijl *et al.*, 2010). When groundwater levels are increased in the fen meadow landscape CH_4 emissions will increase, whereas CO_2 respiration can become larger than the CO_2 emission.

Table 6.2 Overview of possible changes in uncertainty sources for future scenarios until 2040 (§5.3.1) based on a thought experiment (– is a decrease in uncertainty, O is no change in uncertainty, + is an increase in uncertainty)

	Rural production	Rural fragmentation	Rural multifunctionality
Measurement uncertainty			
	(O) Uncertainty will decrease, due to technological innovations in measurement techniques; on the other hand, environmental issues do not have priority and investments in GHG research will be minimal, which will increase uncertainty.	(O) Uncertainty will decrease, due to technological innovations in measurement techniques; on the other hand, environmental issues do not have priority and investments in GHG research will be minimal, which will increase uncertainty.	(–) Uncertainty will decrease, because environmental issues have high priority; on the other hand, innovations in measurement techniques are lacking.
Spatial uncertainty			
	(–) At the landscape scale, uncertainty will decrease, due to technical innovations in mapping techniques (GIS). At the field scale, uncertainty will decrease because grazing will decrease and grazing of cattle is a main source of spatial uncertainty at field scale.	(O) At the landscape scale, uncertainty will decrease, due to technical innovations in mapping techniques (GIS). However, due to the fragmentation of the landscape, uncertainty will increase. New swamps will on the other hand have higher uncertainties in CH_4.	(–) At landscape scale, uncertainty will slightly decrease. At field scale, uncertainty will decrease, because of smaller agricultural N inputs for soils with large N_2O emission potentials.
Temporal uncertainty			
	(O) Uncertainty will stay large, because the temporal variation will also stay large; agricultural N inputs to soil will be large. However, new continuous measurement techniques will improve knowledge on processes driving temporal variation.	(–) Uncertainty will decrease because agricultural N inputs to soil will largely stop and mineralization of N will decrease due to higher groundwater levels. New continuous measurement techniques will improve knowledge on processes driving temporal variation.	(–) Uncertainty will decrease, because agricultural N inputs are decreased.
Model structure			
	(O) Uncertainty will decrease slightly, because of a few new insights and a few new models. Because of a lack of resources for GHG research, development goes slow.	(+) Uncertainty will increase, because model development cannot anticipate fast changes in land use and ecosystems.	(–) Uncertainty will decrease, because of new insights and new models. However, when new sources of uncertainty are identified, overall uncertainty can increase.
Model input uncertainty			
	(O) Uncertainty will decrease due to new measurement techniques, which are closer to the spatial and temporal scale of interest.	(+) Uncertainty will increase, because new model inputs are defined due to the new situation in the area.	(–) Uncertainty from N inputs will decrease, because the management will be less intensive.
Other uncertainty			
	(+) New sources of uncertainty will probably be identified by new measurement and model techniques. Unforeseen processes can cause an increase or decrease in the uncertainty of N_2O inventories.		

Not only other GHGs (CO_2 and CH_4) are related to N_2O emission, but also NH_3 emission and NO_3^- leaching. Climate policies to reduce N_2O emission can increase NH_3 emissions (Oenema *et al.*, 2009; Sonneveld *et al.*, 2008). In the Netherlands, application of manure in wet periods is a common measure to reduce NH_3 emissions. However, as a consequence of this, N_2O emission increases. The N_2O emission in sandy regions in the Netherlands is much smaller than in the fen meadow region. The N applied to sandy soils is for a large part leached as NO_3^- (Boumans *et al.*, 2007).

6.2 Relevance and research perspectives

The Dutch fen meadow landscape is a unique area. This area is a hotspot of N_2O emissions in combination with large uncertainties in N_2O emissions. Therefore, it is difficult to extrapolate outcomes of this thesis directly to other landscapes and other countries. However, some results from this thesis are generally applicable.

6.2.1 The National Inventory Report (NIR)

In the NIR of the Netherlands for 2007 (Van der Maas *et al.*, 2009), direct and indirect N_2O emissions from agriculture were identified as the two most important sources of uncertainty in Dutch GHG emissions at Tier 2 level. Although the shares on the Dutch GHG balance are small (both 2%), their uncertainty levels (61% for direct and 206% for indirect agricultural N_2O emissions) makes them the most important uncertainty sources of GHG emission. In this thesis, suggestions were given to cope with these large uncertainties. Using accurate data on grassland area for estimating the N_2O emission from the cultivation of histosols and adapting N_2O emission estimates from intensively managed grasslands for years with a very dry summer or a very wet summer are straightforward measures to decrease the uncertainty in the national inventory.

For annual emission estimates at landscape and national extent, it may not always be the best option to use models with a high temporal resolution. Many high-resolution parameters, which have a large effect on daily N_2O emission, have negligible effects on annual N_2O emission. For example, fertilization can cause an emission peak; however, on annual scale it is sufficient to know the total annual quantity to estimate the annual N_2O emission. Therefore, countries that want to use Tier 3 methods for reporting annual GHG emissions, should carefully examine the trade-off between the increase in uncertainty due to the inclusion of processes with a high temporal resolution and high-resolution data on the one hand and the improvement of the GHG estimate due to inclusion of these processes on the other hand. They should be aware that many processes that are important at small spatial and temporal scales are less important at larger scales, because data values can average out in space and time.

6.2.2 Landscape elements

Landscapes with many linear elements will suffer more from over- and underestimation of landscape elements and land use types than landscapes with large landscape units and less linear or small elements. In landscapes with linear elements, the systematic error caused by underestimation of the area of linear elements should be estimated. Results can be corrected for this effect or higher resolution data can be used.

6.2.3 Methodology

Computers are increasingly better suited for simulation with high-resolution spatial data. Monte Carlo uncertainty analysis can also be executed more easily with fast computers. The combination of Monte Carlo analysis and (new) methods of estimating and simulating categorical data and auto-correlated and spatially correlated model inputs (Chapter 4) is innovative. Many environmental models include spatial information and include categorical model inputs. When ignoring auto-correlation in spatial model inputs, the uncertainty will be underestimated. When ignoring (spatial) correlation between model inputs the uncertainty will be underestimated or overestimated. For spatially explicit categorical data, Bayesian Maximum Entropy (BME, Bogaert, 2002; Christakos, 1990a; Christakos, 1990b) is a very useful tool in uncertainty propagation analysis.

For the fen meadow landscape, the Monte Carlo uncertainty analysis could probably be improved when groundwater level is also included as an uncertain parameter. The choice of uncertain parameters was based on a quickscan (Table 4.1). Because the INITIATOR model uses groundwater classes and soil wetness classes almost everywhere instead of groundwater levels, the model was assumed not as sensitive for groundwater level as for other variables. Therefore, the Monte Carlo analysis was executed as described in Chapter 4. However, when results of the Monte Carlo analysis were assessed, the fact that the highest groundwater level (MHW) was used in the estimation of the mineralization rate and the mineralization was identified as a large source of uncertainty indicated that the analysis points to a possible improvement by including uncertainty in the MHW.

Generally, the INITIATOR model performed better than the DNDC model for the fen meadow landscape. This is probably due to the fact that INITIATOR was developed for Dutch situations. DNDC had to be parameterized extensively to acquire reliable outcomes (Chapter 3). Alm (2007) experienced the same problems with DNDC for a peat area in Finland. Unfortunately, most N_2O emission models are not suitable for simulating the specific situation of the fen meadow landscape. When the Netherlands decides to report N_2O emissions at Tier 3 level, DNDC (or a similar model) should be better equipped to simulate N_2O emissions from the Dutch fen meadow landscape or

INTIATOR (or a similar model) should be upgraded to Tier 3 level. The model comparison (Chapter 3) could be improved by including more models.

6.2.4 Emission factors

Throughout this thesis, it was indicated that the source of uncertainty depends on scale. The uncertainty in emission factors found is large, especially at landscape support (Fig. 4.10, Table 6.1), but for Tier 1 and Tier 2 inventory methods this is in fact quite common (Olsthoorn & Pielaat, 2002; Van der Maas *et al.*, 2009). In INITIATOR, the emission factors are divided into denitrification and nitrification emission factors and distinguished based on soil type (Table 4.2). To improve emission factors in Tier 1 and 2 inventories, many suggest to divide these into more classes with smaller uncertainty intervals. Soil temperature and soil moisture content are usually measured in N_2O emission campaigns and could probably improve the use of emission factors. However, for many countries measurement data are lacking to make (more) reliable divisions in emission factors. The division in INITIATOR between emission factors for denitrification and nitrification is understandable, because these are two different processes. However, these different emission factors cannot be based on measurements, because most measurements cannot distinguish between these two processes. It may be more effective to divide emission factors based on measurement strategies. The shape of the probability distribution of the emission factors can also be improved. INITIATOR assumes a uniform distribution of the emission factors, while a normal or lognormal distribution would probably be more realistic, based on uncertainty management advice (IPCC, 2000a; Olsthoorn & Pielaat, 2002).

6.2.5 Soil parameters

At landscape support, the largest sources of uncertainty are the emission factors, while at point support uncertainty in soil parameters is equally important (Fig. 4.10; Table 6.1). This means that when a study focuses on point support, e.g. when the objective is to indicate hotspots of N_2O emissions (locations with large N_2O emissions), the uncertainty could easily be decreased by improvement of soil data. When the objective of a study focuses on landscape support, e.g., when the objective is to assess the N_2O emission of the fen meadow landscape, improvement of soil data will hardly decrease the uncertainty in the N_2O emission estimates and only improvement of emission factors can significantly decrease uncertainty. This type of scale dependent uncertainty analysis can also be used for other GHGs and other environmental models. Sometimes uncertainties can be reduced with relatively small effort. A result can be that at a certain spatial scale, uncertainties mainly arise from sources that can be improved with relatively small effort. Chapter 4 has also shown that soil type cannot be assumed as a stationary parameter in time for the Dutch fen meadow landscape. For most landscapes and ecosystems, soil type does not change within a few decades, however, drained peat soils do. It is therefore important that Dutch soil map 1:50,000 is up-to-date (Kempen *et al.*, 2009). Much environmental research makes use of soil data. When such research takes place in areas with drained peat soils, it should include a decline in peat soils due to mineralization (as was done in Chapter 5) and it should use up-to-date soil data. A strong linkage was made between environmental science and socio-economic studies. Most research on future projections is only focusing on one part, but by using the Story-And-Simulation method, projected socio-economic developments and land use change could be translated into model inputs for INITIATOR.

6.2.6 The future of the fen meadow landscape

A recent development in the fen meadow landscape is the enormous increase in fodder maize cultivation (from about 960 ha in 2000 to about 1940 ha in 2009). This development is contrary to what most experts and stakeholders expected and what most policy makers have in mind. The area loses its openness and its specific character. Maize cultivation also increases mineralization rates, consequently soil subsidence increases and N_2O and CO_2 emissions increase. The ideal picture of the fen meadow landscape for many Dutch people is small-scale dairy farms with cows grazing in the meadows, like it was in the 1950s. Nowadays, small-scale dairy farms are not profitable in this area unless they are subsidized (Chapter 5, 'rural multifunctionality scenario'). Large-scale farms can be profitable (Chapter 5, 'rural production scenario'); however, the area will remain a hotspot of N_2O emission and in the long run the peat will disappear. When the focus is on reduction of GHG emissions in combination with conservation of the dairy farming sector, dairy farming is only possible on the higher (more clayey) parts of the area, while the lower parts of the areas should be rewetted.

6.3 Main conclusion

Uncertainty matters. Therefore, the uncertainty in GHG emissions should be quantified. This thesis made a considerable contribution to the uncertainty estimation of N_2O emissions. The quantification is complex due to scale effects and spatial and temporal correlations; however, this research lays a foundation for proper uncertainty management in future GHG modelling and IPCC inventories. Especially given the recent debate on the reliability of the IPCC reports, proper uncertainty quantification is of vital importance.

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Annex

Model and Input Parameters in INITIATOR

Model and input parameters	SE[1]	Description
Areal parameters		
OPP	Yes	Surface area of pixel (250 m x 250 m = 6.35 ha)
PROV	Yes	Province
MESTGEB	Yes	Manure district
REGIO	Yes	Hydrological region
BOU	Yes	Distribution of crop types
Soil parameters and CO_2 background emission		
SOIL	Yes	Soil type
PTRHOalt	Yes	Bulk density of peat layer until MLW
PTOMalt	Yes	Organic matter of peat layer until MLW
PTCNalt	Yes	C/N ratio of peat layer until MLW
PTLD/VEENTOT	Yes	Thickness of peat layer of thin peat soils
PTLDCOV/VEENDEK	Yes	Mineral cover depth of soil profile
PTLDtot/VEENALL	Yes	Total depth of peat layer, also for thick peat soils
frox	No	Oxidation fraction of peat
frC	No	Fraction organic carbon of peat
CNmo	No	C/N ratio micro-organisms for decomposing the substrate
DAmo	No	Dissimilation – Assimilation ratio of micro-organisms)
Pfrim [1,2]	No	Min and max fraction immobilization of N
Landuse		
VEG	Yes	Vegetation type (grass, maize, other crop, or nature)
frNAT_deciduous	Yes	Fraction area deciduous in nature
frNAT_spruce	Yes	Fraction area spruce in nature
frNAT_pine	Yes	Fraction area pine in nature
frNAT_heath	Yes	Fraction area heath in nature
frNAT_natural grass	Yes	Fraction area grass in nature
N management parameters		
Ninam[1]	Yes	N in manure from cow stables, without application emission
Ninam[2]	Yes	N in manure from pig stables, without application emission
Ninam[3]	Yes	N in manure from poultry stables, without application emission
Ninam[4]	Yes	N in manure from grazing cows, without application emission
Nkmini	Yes	N in fertilizers
Muit[1]	Yes	N production in cow stables
Muit[2]	Yes	N production in pig stables
Muit[3]	Yes	N production in poultry stables
frwg	Yes	fraction N uptake of N due to grazing
PfN2Oemh[1,2]	Yes	Min and max fraction N_2O emission from stables
PfNOxemh[1,2]	Yes	Min and max fraction NOx emission from stables
PfN2emh[1][1,2]	Yes	Min and max fraction N_2 emission from stables for cows
PfN2emh[2][1,2]	Yes	Min and max fraction N_2 emission from stables for pigs
PfN2emh[3][1,2]	Yes	Min and max fraction N_2 emission from stables for poultry
PfNH3emg[1,2]	Yes	Min and max NH_3 from grazing
PfNH3emf[1,2]	Yes	Min and max NH_3 emission from fertilizers
LMestAdv	Yes	Manure advice for animal manure and fertilizers
Lfrwamorg [1]	Yes	Fraction organic N in cow manure
Lfrwamorg [2]	Yes	Fraction organic N in pig manure
Lfrwamorg[3]	Yes	Fraction organic N in poultry manure
Deposition		
NDEP	Yes	Deposition of NOx and NHx
NHDEP	Yes	Deposition of NHx
NODEP	Yes	Deposition of NOx

frwdep	No	Fraction uptake N of N deposition
PNdepmin[1,2]	No	Min and max fraction deposition min
PNdepmax[1,2]	No	Min and max fraction deposition max
<u>Ammonia emissions</u>		
fNH3ema	No	Fraction NH_3 emission from animal manure application
PfNH3emh[1][1,2]	No	Min and max NH_3 emission from housing of cows
PfNH3emh[2][1,2]	No	Min and max NH_3 emission from housing of pigs
PfNH3emh[3][1,2]	No	Min and max NH_3 emission from housing of poultry
<u>N_2O emissions</u>		
N2Oref	Yes	Reference N_2O =1
PfrN2Ode[1,2]	Yes[2]	Min and max fraction N_2O emission factor due to denitrification soil
PfrN2Oni[1,2]	Yes[2]	Min and max fraction N_2O emission factor due to nitrification soil
Pfrni[1,2]	Yes[2]	Min and max fraction nitrification of soil N
Pfrdes[1,2]	Yes[2]	Min and max fraction denitrification of soil N
<u>Yield grass and crops</u>		
LBYIELD[1..5]	Yes[2]	Fresh yield crops
BDS[1..5]	Yes[2]	Dry weight crops
ctNB	Yes[2]	% N in crops
LNfi	Yes[2]	N fixation
LctN	Yes[2]	% N in grass
LYIELD	Yes[2]	Yield grass
LfrNmin	Yes[2]	Fraction mineral N/total N in vegetation
<u>Lfrup</u>		
<u>Nature fractions</u>		
Nfric [1..5]	No	Fraction interception precipitation per vegetation type
Nrhost [1..5]	No	Density of stem wood per vegetation type
Nstmin[1..5]	No	Min N content stem wood
Nstmax[1..5]	No	Max N content stem wood
LNkrgc[1..5]	Yes[2]	Growth rate constant
PNfrni[1,2]	Yes[2]	Min and max fraction nitrification soil
PNfrdes[1,2]	Yes[2]	Min and max fraction denitrification soil
PNfrdedi[1,2]	Yes[2]	Min and Max denitrification ditch
PNfrdegw[1,2]	Yes[2]	Min and Max denitrification groundwater
<u>Hydrology (Precipitation, transpiration, evapotranspiration, leaching and runoff)</u>		
PREC	Yes	Precipitation
gt	Yes	Groundwater table
GHG	Yes	Mean Highest Waterlevel, MHW
GLG	Yes	Mean Lowest Waterlevel, MLW
GTPL	Yes	Groundwater table in symbols
NN	Yes	Precipitation excess
frro(1)	Yes	Fraction horizontal transport water out of layer 0-5 cm
frro(2)	Yes	Fraction horizontal transport water out of layer 5-20 cm
frro(3)	Yes	Fraction horizontal transport water out of layer 20-50 cm
frro(4)	Yes	Fraction horizontal transport water out of layer >50 cm
frlel(4)	Yes	Fraction leaching vertical transport out of layer >50 cm
Lfrrol[1]	Yes[2]	Fraction runoff of soil layer 0-5 cm
Lfrrol[2]	Yes[2]	Fraction runoff of soil layer 5-20 cm
Lfrrol[3]	Yes[2]	Fraction runoff of soil layer 20-50 cm
Lfrrol[4]	Yes[2]	Fraction runoff of soil layer 50 cm-deeper
Lfrlel[4]	Yes[2]	Fraction leaching soil layer 50 cm- deeper
NEs[1..5]	No	Evaporation soil of vegetation type
LNEtref[1..5]	Yes[2]	Reference transpiration vegetation type
Pfrdedi[1,2]	Yes[2]	Min and max denitrification ditch

Pfrdegw[1,2]	Yes[2]	Min and max denitrification groundwater
Pfrtr [1…5] [1,2]	Yes[2]	Fraction transpiration of precipitation per vegetation type
PcNO3min [1,2]	Yes[2]	Min and max percentage mineral NO_3^- in precipitation
Organic products (e.g. compost, sewage sludge)		
LOMinoptot[1..4]	No	Organic matter input due to organic products
LOMop[1..4]	No	Organic matter %
LNop[1..4]	No	N content
LfrNminop[1..4]	No	Ammonia fraction
Lfrwop[1..4]	No	N efficiency
LfNH4emaop[1..4]	No	Ammonia emission
Lfrhop[1..4]	No	Humification fraction

[1] SE = Spatial explicit

[2] Yes, because depending on soil type, vegetation type and/or soil wetness class

Summary

Nitrous oxide (N_2O) is a long-lived greenhouse gas (GHG) with a large global warming potential. While it has a modest share of about 8% in the total global GHG balance, the uncertainty of N_2O emission inventories are large. The major source of N_2O emission on global and national scale is agriculture. A hotspot of agricultural N_2O emission is the Dutch fen meadow landscape; therefore, it is worthwhile to focus on N_2O emissions from this landscape for improving uncertainty estimates in GHG inventories. The main objective of this PhD thesis is to quantify the uncertainty of N_2O emission inventories for the Dutch fen meadow landscape.

After the general introduction (Chapter 1), Chapter 2 analyses how different land cover representations introduce systematic errors into the results of regional N_2O emission inventories. Landscape representations based on land cover databases differ significantly from the real landscape. Using a land cover database with high uncertainty as input for emission inventory analyses can cause propagation of systematic and random errors. Surface areas of grassland, ditches, and ditch banks were estimated for two polders in the Dutch fen meadow landscape using five land cover representations: four commonly used databases and a detailed field map, which most closely resembles the real landscape. These estimated surface areas were scaled up to the Dutch fen meadow landscape. Based on the estimated surface areas agricultural N_2O emissions were estimated using different inventory techniques. All four common databases overestimated the grassland area when compared to the field map. This caused a considerable overestimation of agricultural N_2O emissions, ranging from 9% for more detailed databases to 11% for the coarsest database. The effect of poor land cover representation was larger for an inventory method based on a process model than for inventory methods based on simple emission factors. Although the effect of errors in land cover representations may be small compared to the effect of uncertainties in emission factors, these effects are systematic (i.e.,, cause bias) and do not cancel out by spatial upscaling. Moreover, bias in land cover representations can be quantified or reduced by careful selection of the land cover database.

Chapter 3 focused on the effect of temporal resolution of an inventory method on N_2O emission estimates. Most countries use a one-year-resolution emission factor approach to estimate terrestrial N_2O emissions as part of their national GHG inventory, either by applying default values (Tier 1 method) or nationally derived values (Tier 2 methods). This method employs an annual temporal resolution and uses yearly averaged inputs to

predict emission. Little attention has so far been paid to the effect of the temporal resolution of the approach (e.g. day, season, year) on N_2O emission estimates. The effect of lumping temporal variation can be very large due to daily or seasonal variations of processes causing N_2O emissions. Therefore, annual N_2O emissions from a model (DNDC) with daily time steps were compared with those of a model (INITIATOR) with annual time steps. N_2O emissions were simulated for two intensively managed grassland plots in the Dutch fen meadow landscape in the period 2001-2006. The years with the largest differences in model results were used in to estimate the effect of the within-year temporal distribution of rainfall, fertilization, and manure application on the annual N_2O emission. Emission factors based on DNDC and INITIATOR N_2O results for the six simulation years were estimated using the available management and climate data. Annual N_2O emissions from the investigated grasslands were sensitive to rainfall distribution within the year, especially to summer rainfall. It is recommended to adjust Tier 2 N_2O emission estimates from intensively managed grasslands on peat soils in the temperate climate zone for relative summer rainfall.

The goal of Chapter 4 was (i) to quantify the uncertainties of modelled N_2O emissions caused by model input uncertainty at point and landscape scale (i.e., resolution), and (ii) to identify the main sources of input uncertainty at both scales. A Monte Carlo uncertainty propagation analysis using the INITIATOR model was performed. Spatial auto- and cross-correlation of uncertain numerical inputs that are spatially variable were represented by the linear model of coregionalization. Bayesian Maximum Entropy was used to quantify the uncertainty of spatially variable categorical model inputs. Stochastic sensitivity analysis was used to analyse the contribution of groups of uncertain inputs to the uncertainty of the N_2O emission at point and landscape scale. The average N_2O emission at landscape scale had a mean of 20.5 kg N_2O-N ha^{-1} yr^{-1} and a standard deviation of 10.7 kg N_2O-N ha^{-1} yr^{-1}, producing a relative error of 52%. At point scale, the relative error was on average 78%, indicating that upscaling decreases uncertainty. Soil inputs and denitrification and nitrification inputs were the main sources of uncertainty in N_2O emission at point scale. At landscape scale, uncertainty in soil inputs averaged out and uncertainty in denitrification and nitrification inputs was the dominant source of uncertainty. Experiments at landscape scale are needed to assess the spatial variability of these fractions and analyse how a more realistic representation influences the uncertainty budget at landscape scale. This research confirms that results from uncertainty analyses are often scale dependent and that results for one scale cannot directly be extrapolated to other scales.

In Chapter 5, insight is provided in the possible range of future N_2O emissions that can help to construct mitigation and adaptation strategies and to adapt land use planning to climate objectives. For the Dutch fen meadow landscape, changes in land use induced by socio-economic developments are expected to be large in future and have major impacts on N_2O emission. The goals of this study are to estimate changes in N_2O emissions for the period 2006–2040 under different scenarios and to quantify the share of different emission sources. Three scenarios were developed and quantified based on the Story-And-Simulation approach. The rural production and the rural fragmentation scenarios are characterized by globalization and economic growth; however, in the fen meadow landscape under the rural production scenario dairy farming has a strong competitive position and under the rural fragmentation scenario agriculture is declining. Under the rural multifunctionality scenario, the global context is characterized by more regionalization and environmental protection. Under the rural production scenario, the N_2O emission decreased between 2006 and 2040 with 7%. Due to measures to decrease peat mineralization and policies to reduce agricultural emissions, the rural multifunctionality scenario shows a larger decrease in N_2O emissions (-44%) as compared to the rural fragmentation in which the dairy farming sector is diminished (-33%). Compared to other uncertainties involved in N_2O emission estimates, the uncertainty in future socio-economic developments and land use change is relatively large and assuming a constant emission with time is therefore not appropriate.

Chapter 6 is a synthesis of the results and main findings from Chapters 2-5. All types of uncertainty, discussed in Chapter 2-5 are ranked and relations between uncertainties are described. The implications for uncertainty on the full GHG are given and the research perspectives are discussed. At last, some future perspectives for the fen meadow landscape are given.

Samenvatting

Lachgas (N_2O) is een broeikasgas (BKG) dat lang in de atmosfeer blijft voordat het wordt afgebroken. Lachgas heeft verder een 310 keer zo groot potentieel om de aarde op te warmen als koolstofdioxide (CO_2). Hoewel het gas een middelmatig aandeel heeft van ongeveer 8% in de totale BKG balans, zijn de onzekerheden van lachgasemissie-inventarisaties groot. De grootste bron van lachgasemissie op mondiale en nationale schaal is landbouw. Een hotspot van lachgasemissies uit landbouw is het Nederlandse veenweidegebied waardoor het waardevol is om voor het verbeteren van onzekerheidsberekeningen in BKG-inventarisaties te focussen op dit landschap. Het belangrijkste doel van dit proefschrift is om de onzekerheid van lachgasemissie-inventarisaties voor het Nederlandse veenweidegebied te kwantificeren.

Na de algemene introductie (Hoofdstuk 1), is er in Hoofdstuk 2 geanalyseerd hoe verschillende representaties van landbedekking systematische fouten veroorzaken in regionale inventarisaties van lachgasemissie. Representaties van databases die informatie over landbedekking bevatten verschillen significant van het werkelijke landschap. Wanneer een dergelijke database met informatie over landbedekking onzekerheden bevat en wordt gebruikt als invoer voor emissie-inventarisaties, kan er voortplanting optreden van systematische en toevallige fouten. In dit tweede hoofdstuk zijn de oppervlaktes grasland, sloten en slootkanten gemeten en berekend voor twee polders in het Nederlandse veenweidegebied. Dit is gedaan met behulp van vijf verschillende representaties van landbedekking: vier veelgebruikte databases en een gedetailleerde veldkaart welke het beste overeenkomt met het werkelijke landschap. Deze oppervlaktes zijn opgeschaald naar het hele veenweidegebied en gebruikt om lachgasemissies uit landbouw te bereken met behulp van verschillende inventarisatietechnieken; variërend van simpele methodes gebaseerd op emissiefactoren tot complexere methodes gebaseerd op een procesmodel. Alle vier de veelgebruikte databases overschatten het oppervlakte grasland vergeleken met de veldkaart. Dit zorgde voor een aanzienlijke overschatting van de lachgasemissies uit landbouw, variërend van 9% voor de meest gedetailleerde database tot 11% voor de grofste database. Het effect van een slechte representatie van landbedekking was groter voor een inventarisatiemethode gebaseerd op een procesmodel dan voor een simpele inventarisatiemethode. Hoewel het effect van fouten in representaties van landbedekking relatief klein is ten opzichte bijvoorbeeld het effect van fouten in emissiefactoren, zijn deze effecten systematisch (d.w.z. ze veroorzaken bias) en wegen

niet tegen elkaar op door ruimtelijke opschaling (wat wel voor emissiefactoren geldt). De systematische fouten in representaties van landbedekking kunnen worden gekwantificeerd en verminderd met een zorgvuldige selectie van de juiste database.

Hoofdstuk 3 gaat over het effect van temporele resolutie van een inventarisatiemethode op lachgasemissieschattingen. De meeste landen gebruiken een emissiefactorenbenadering met een temporele resolutie van een jaar om hun terrestrische lachgasemissies te schatten als deel van hun nationale BKG-inventarisatie; door middel van standaardwaarden (Tier 1 methode) of nationaal afgeleide waarden (Tier 2 methode). Deze Tier methodes gebruiken een temporele resolutie van een jaar en daarvoor worden gemiddelde waardes over een jaar gebruikt om de emissies te schatten. Het effect van de temporele resolutie (bijvoorbeeld dag, seizoen, jaar) van een methode op lachgasemissieschattingen heeft tot nu toe weinig aandacht gehad. Het effect van het samenvoegen van temporele variatie kan erg groot zijn door dagelijkse variatie of seizoensvariatie van processen die zorgen voor lachgasemissie. Daarom is de jaarlijkse lachgasemissie van een model met dagelijkse tijdstappen (DNDC) vergeleken met een model met jaarlijkse tijdstappen (INITIATOR). De lachgasemissie is gesimuleerd voor twee intensief beheerde weilanden in het Nederlands veenweidegebied voor de periode 2001 t/m 2006. De jaren met de grootste verschillen in modelresultaten zijn gebruikt om het effect van de temporele distributie van neerslag en bemesting met kunstmest en dierlijke mest binnen een jaar op de jaarlijkse lachgasemissieschatting te bepalen. Emissiefactoren, gebaseerd op lachgasemissieberekeningen van DNDC en INITIATOR voor de zes simulatiejaren, zijn berekend met behulp van beschikbare beheers- en klimaatsdata. Jaarlijkse lachgasemissies van de onderzochte weilanden waren gevoelig voor neerslagverdeling binnen het jaar, zeker de hoeveelheid neerslag in de zomer heeft een grote invloed gehad op de jaarlijkse N_2O emissie. Er wordt aangeraden om de Tier 2 emissieschattingen voor intensief beheerde weilanden op veengronden aan te passen voor de relatieve neerslag in de zomer en opzichte van de neerslag in de andere seizoenen.

Het doel van Hoofdstuk 4 was ten eerste om de onzekerheden van gemodelleerde lachgasemissies veroorzaakt door onzekerheid ten gevolge van modelinvoer op punt- en landschapschaal (d.w.z. resolutie) te kwantificeren en ten tweede om de belangrijkste bronnen van invoeronzekerheid op beide schalen te identificeren. Een Monte Carlo onzekerheidsanalyse werd uitgevoerd met behulp van INITIATOR. Ruimtelijke auto- en crosscorrelatie van onzekere numerieke invoergegevens die ruimtelijke variabel zijn, zijn bepaald met het “lineair model of coregionalization” (LMCR). De “Bayesian Maximum Entropy” (BME) methode is gebruikt om de onzekerheid van ruimtelijk variabele categorische invoergegevens te kwantificeren.

Een stochastische gevoeligheidsanalyse is gebruikt om de bijdrage van groepen onzekere invoergegevens op de onzekerheid in de lachgasemissieberekening op punt- en landschapschaal te analyseren. De gemiddelde emissie van N_2O op landschapschaal is 20,5 kg N_2O-N ha^{-1} yr^{-1} en de standaard deviatie is 10,7 kg N_2O-N ha^{-1} yr^{-1}, dus de relatieve fout is 52%. Op puntschaal, is de relatieve fout gemiddeld 78%. Opschaling verlaagt dus de onzekerheid. Invoergegevens over bodem en denitrificatie en nitrificatie zijn de belangrijkste bronnen van onzekerheid op puntschaal. Op landschapschaal wegen de onzekerheden in bodemgegevens tegen elkaar op en is de groep denitrificatie- en nitrificatiegegevens de dominante bron van onzekerheid. Experimenten op landschapschaal zijn nodig om de ruimtelijke variabiliteit van deze emissiefracties te bepalen. Dit onderzoek stelt vast dat resultaten van onzekerheidsanalyses vaak schaalafhankelijk zijn en dat resultaten op een bepaalde schaal niet direct geëxtrapoleerd kunnen worden naar andere schalen.

In Hoofdstuk 5 is inzicht verworven in de reeks van mogelijke toekomstige lachgasemissies dat kan helpen om mitigatie- en adaptatiestrategieën op te stellen en om landgebruikplanning aan te laten sluiten bij klimaatsdoelstellingen. In het Nederlandse veenweidegebied zullen veranderingen in landgebruik, voortkomend uit sociaaleconomische ontwikkelingen, naar verwachting in de toekomst groot zijn en een groot effect hebben op de lachgasemissie. De doelstellingen van dit onderzoek waren om veranderingen in lachgasemissies voor de periode 2006-2040 voor verschillende scenario's te voorspellen. Drie scenario's zijn ontwikkeld en gekwantificeerd op basis van de zogenaamde "Story-And-Simulation" methode. De landelijke productie- en versnipperingscenario's worden gekenmerkt door globalisering en economische groei, maar in het veenweidegebied is er onderscheid tussen beide scenario's. In het landelijke productiescenario heeft de melkveesector een sterke concurrentiepositie terwijl in het landelijke versnipperingscenario de landbouw in het gebied afneemt. Het derde scenario is het landelijke multifunctionaliteitscenario waarin de mondiale context wordt gekenmerkt door regionalisering en milieubescherming. Volgens het landelijke productiescenario daalt de lachagsemissie tussen 2006 en 2004 met 7%. Door maatregelen om mineralisatie van het veen te verlagen en beleid om emissies uit landbouw verminderen, laat het landelijke multifunctionaliteitscenario de grootste afname van lachgasemissie zien (44%) vergeleken met het landelijke versnipperingscenario (33%) waarin de melkveesector toch ook sterk is afgenomen. De onzekerheid over toekomstige sociaaleconomische ontwikkelingen en veranderingen in landgebruik is vergeleken met andere onzekerheden in ramingen van de lachgasemissie relatief groot. De aanname dat emissies constant blijven in de tijd is dan ook niet juist.

Hoofdstuk 6 is tot slot een synthese van de resultaten en bevat de belangrijkste bevindingen uit de hoofdstukken 2 t/m 5. Alle soorten van onzekerheid, besproken in de eerdere hoofdstukken, zijn gerangschikt en de relaties tussen onderzekerheden worden beschreven. De gevolgen voor onzekerheid op de gehele BKG-balans worden besproken en perspectieven voor onderzoek worden besproken. Afsluitend zijn enkele toekomstperspectieven voor het veenweidegebied gegeven.

About the author

Curriculum Vitae

Linda Nol was born in Westzaan on September 27th, 1980. After she completed secondary school (VWO) in 1998 at the 'Saenredam College' in Zaandijk, she started the study 'Physical Geography' at the University of Amsterdam. For her MSc thesis, she did research on the effect of plastic covers on hydrology of abandoned fields in the Guadalentín Basin, Spain. As a spin-off of this project, an article was published in Soil Science Society of American Journal. After her graduation in 2003, she decided to start another MSc in 'Sustainable development' at the Utrecht University. In 2005, she started her PhD at the chair group 'Land Dynamics'. Since 2009, she works as a teacher soil science and GIS at the 'CAH University of Applied Science' in Dronten.

Linda is also an active volleyball player and is member of VV Zaanstad D1, which plays in the national 2nd division in 2009/2010.

List of publications

Jacobs C.M.J., Jacobs A.F.G., Bosveld F.C., Hendriks D.M.D., Hensen A., Kroon P.S., Moors E.J., Nol L., Schrier-Uijl A.P., Veenendaal E.M., 2007. Variability of annual CO_2 exchange from Dutch grasslands. Biogeosciences 4 (5): 803-816.

Nol L., Heuvelink G.B.M., De Vries W., Kros J., Moors E.J., Verburg P.H., 2009. Effect of temporal resolution on N_2O emission inventories in Dutch fen meadows. Global Biogeochemical Cycles 23 (GB4003).

Nol L., Heuvelink G.B.M., Veldkamp A., De Vries W., Kros H., accepted by Geoderma. Uncertainty propagation analysis of an N_2O emission model at the plot and landscape scale.

Nol L., Neubert, R., Vermeulen, A.T., Vellinga, O., Tolk, L., Olivier, J., Hutjes, R.W.A., Dolman, A.J., submitted to Landschap. De broeikasgasbalans van alle kanten.

Nol L., Verburg P.H., Moors E.J., submitted to Global Change Biology. Uncertainty in land use induced N_2O emission due to future socio-economic developments and land use change.

Nol L., Verburg P.H., Heuvelink G.B.M., Molenaar K., 2008. Effect of land cover data on nitrous oxide inventory in fen meadows. Journal of Environmental Quality 37 (3): 1209-1219.

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Van der Meulen E..S., Nol L., Cammeraat L.H., 2006. Effects of irrigation and plastic mulch on soil properties on semiarid abandoned fields. Soil Science Society of America Journal 70 (3): 930-939.

Verburg, P.H., Neumann, K., Nol, L., submitted. Challenges in using land use and land cover data for global change studies.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (4.3 ECTS)

- Review of methods for upscaling non-CO_2 emission estimates for agriculture; presented at SPAM discussion group (2006)

Writing of Project Proposal (4.3 ECTS)

- Upscaling and uncertainly analysis of N_2O emission inventories; analysis of the Dutch fen meadow landscapes (2005)

Laboratory Training and Working Visits (0.7 ECTS)

- N_2O Measurements; TNO-Jan Duyzer (2007)
- Grass system analysis, fertilization schemes, grazing regimes; Spruijt farm (fen meadow landscape), Zegveld (2007)
- Greenhouse gas tower measurements (EC); ECN-Petra Kroon, Petten (2007)

Post-Graduate Courses (7.7 ECTS)

- Advanced statistics; WGS (2005)
- Land science South Africa; PE&RC (2007)
- Statistical methods for spatial data analysis and modelling; BSIK, PE&RC (2007)
- Summerschool "Uncertainty in Environmental Modelling"; NitroEurope, Aberdeen, Scotland (2008)

Deficiency, Refresh, Brush-up Courses (1.7 ECTS)

- Techniques for writing and presenting a scientific paper; PE&RC (2006)
- Personal efficacy; WGS (2008)

Competence Strengthening / Skills Courses (4.7 ECTS)

- Scientific publishing; WGS (2005)
- PhD Competence assessment; WGS (2005)
- Uncertainty analysis; SENSE (2006)

Discussion Groups / Local Seminars and Other Scientific Meetings (6.8 ECTS)

- Spatial Modelling (SPAM) discussion group; monthly meetings (2005-2007)
- Climate Change and Soil-Water-Vegetation Interactions (CSI) discussion group; monthly meetings (2007-2010)
- BSIK CcSP MEI Discussion group; annual meetings (2005-2008)
- NBV-day: Soil and Climate, N_2O in the Netherlands? (2007)
- CcSP Mitigation meeting; oral presentation (2007)
- GEO & Environment Seminar Earth and Life sciences; Free University, A'dam; oral presentation (2008)
- Nitro-Europe Meeting; Wageningen; oral presentation (2008)
- NBV-day: Dag van de Wetenschap (Week van de Bodem) (2008)
- NWO Talent Day (2009)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.9 ECTS)

- PE&RC Annual meeting: the truth of science (2005)
- PE&RC Introduction weekend (2006)
- PE&RC 10th Anniversary (2007)
- PE&RC Annual meeting: collapse (2007)
- PE&RC Workshop on "scaling" (2008)
- PE&RC Evaluation committee TSP (2008)

International Symposia, Workshops and Conferences (7.6 ECTS)

- Soil & Water symposium; poster presentation (2006)
- Synergy in CcSP Research; oral presentation (2007)
- CcSP Conference Mid-term review; poster presentation (2007)
- NitroEurope Conference "Reactive Nitrogen and the European Greenhouse Gas Balance"; Ghent, Belgium; oral presentation (2008)
- 16th Nitrogen workshop; Turin, Italy; poster presentation (2009)

Courses in Which the PhD Candidate Has Worked as a Teacher (12 days)

- Integration course; LAD; 1.5 day
- Introduction course; LAD; 1 day
- Habitat analysis for ecosystems; LAD; 1 day
- Multifunctional land use; LAD; 1 day
- Soil classification in ISRIC; LAD; 2 days
- Multifunctional land use; LAD; 2 days
- Soil classification in ISRIC; LAD; 4 days
- Soil Structure and soil suitability; LAD; 2.5 days

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