A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems

R.L.M. Schils[1,*], A. Verhagen[1], H.F.M. Aarts[1] and L.B.J. Šebek[2]

[1]*Agrosystems Research, Plant Research International, P.O. Box 16, 6700 AA Wageningen, The Netherlands;*
[2]*Applied Research, Animal Sciences Group, P.O. Box 2176, 8203 AD Lelystad, The Netherlands; *Author
for correspondence (e-mail: rene.schils@wur.nl; fax: +31-317-423110)*

Abstract

Ruminant livestock systems are a significant source of greenhouse gases (GHGs). Thus far, mitigation options for GHG emissions mainly focused on a single gas, and are treated as isolated activities. The present paper proposes a framework for a farm level approach for the full accounting of GHG emissions. The methodology accounts for the relevant direct and indirect emissions of methane, nitrous oxide and carbon dioxide, including carbon sequestration. Furthermore, the potential trade-off with ammonia volatilisation and nitrate leaching are taken into account. A ruminant livestock farm is represented with a conceptual model consisting of five pools: animal, manure, soil, crop and feed. The carbon and nitrogen inputs, throughputs and outputs are described, and the direct emissions are related to the carbon and nitrogen flows. The indirect emissions included in the methodology are mainly carbon dioxide emissions from energy use and nitrous oxide emissions related to imported resources and nitrogen losses. The whole farm approach is illustrated with a case of two dairy farms with contrasting livestock density and grassland management. It is shown that the inclusion of carbon sequestration and all indirect emissions have a major impact on the GHG budget of the farm. For one farm, the effect of four mitigation options on the GHG emissions was quantified. It was concluded that a whole farm approach of full accounting contributes to a better insight in the interactions between the carbon and nitrogen flows and the resulting emissions, within and outside the farm boundaries. Consequently, the methodology can be used to develop efficient and effective mitigation strategies.

Introduction

In the European Union, the agricultural sector contributes approximately 10% to the total greenhouse gas (GHG) emissions (EUROSTAT 2003). Although national targets have been formulated for the reductions under the Kyoto protocol, specific targets for the agricultural sector have yet to be defined. In 1995, agriculture emitted 470 Tg CO_2-equivalents, of which 56% originated from nitrous oxide (N_2O), 36% from methane (CH_4) and 8% from carbon dioxide (CO_2) (Freibauer 2003). Emissions from ruminant animal husbandry, as a result of enteric fermentation and manure management, accounted for 39% of the total emissions. Emissions from grassland soils contributed 17% to the total emissions. Assuming that all ruminant animal husbandry is located on

grassland soils, the overall emissions from the ruminant livestock sector can be estimated roughly at 56% of the total agricultural emissions.

So far, research has focussed on identifying the sources, and reviewing individual mitigation options, either to reduce GHG emissions, e.g., Mosier et al. (1998); Velthof et al. (1998); Brown et al. (2001), or to sequester carbon (C) in the soil, e.g., Smith et al. (1998); Vleeshouwers and Verhagen (2002). However, most of these studies focus on a single gas, and the mitigation options are viewed as isolated activities. Effective mitigation strategies can only be developed within a whole farm approach (Oenema et al. 2001b). It ensures that interactions between the carbon and nitrogen (N) cycles are taken into account, and reveals the trade-offs between emissions of the different GHGs. Also, the possible effect of GHG mitigation strategies on other environmentally relevant emissions, like ammonia and nitrate, can be assessed better in a whole farm approach. Moreover, farmers will more readily adopt mitigation strategies if these are tailored to their specific farming system.

The structure of the common GHGs reporting framework (IPCC 1997) consists of six sectors and therefore does not stimulate an integrated approach, as the emissions resulting from agricultural activities are not confined to one sector. For instance, in the current accounting procedures, indirect carbon dioxide or nitrous oxide emissions due to resource use are mainly reported in the energy sector. However, the responsibility for resource utilisation, and the possible options for mitigation, is a management decision taken at the farm level. Therefore, a whole farm approach should not only include all direct emissions, but all indirect emissions as well.

The objective of this paper is to develop a farm level full accounting method for ruminant livestock systems. The method will be illustrated with a case of two dairy systems with contrasting intensity and grassland management.

Methodology

Current IPCC guidelines

The Intergovernmental Panel on Climate Change (IPCC) has defined the guidelines for the reporting of national inventories of GHG emissions (IPCC 1997). Emissions are calculated by multiplication of activities with an emission factor.

For the agricultural sector, the IPCC defines four groups of activities, of which only domestic livestock and soils are relevant for dairy farming. The domestic livestock category comprises methane emissions from enteric fermentation and methane and nitrous oxide emissions from manure management. The emissions of nitrous oxide that have to be reported under the IPCC guidelines are direct soil emissions from mineral fertiliser, manure, grazing and biological fixation, and indirect soil emissions through nitrate leaching or ammonia volatilisation.

Other relevant emissions from dairy farms, such as carbon dioxide emissions from fuel combustion or land use change are reported under the energy or land use change sector, respectively.

Whole farm approach

In this paper, we consider GHG emissions at the farm level. A ruminant livestock farm is defined as an enterprise that transforms external resources, as feed and mineral fertiliser, into the commodities milk and meat (Figure 1). Internally, a dairy farm is described with a conceptual model consisting of five pools, i.e., (1) animal, (2) manure, (3) soil, (4) crop and (5) feed. Inputs and outputs are designated to or derived from the relevant pools, respectively. The inner nutrient cycle (animal–soil–crop) represents the grazing cycle, with direct herbage intake by animals and direct faeces and urine excretion to the soil, whereas the outer nutrient cycle (animal–manure–soil–crop–feed) represents the housing system. Feeding losses, occurring in the stable, are returned to the manure pool, whilst grazing and harvest losses are returned to the soil pool.

The emissions of the GHGs methane, nitrous oxide and carbon dioxide, as well as the emissions of ammonia and nitrate are related to carbon and nitrogen flows and environmental conditions. Therefore, we take the relevant carbon and nitrogen flows through the system as our starting point. The method is a static account of annual flows and emissions.
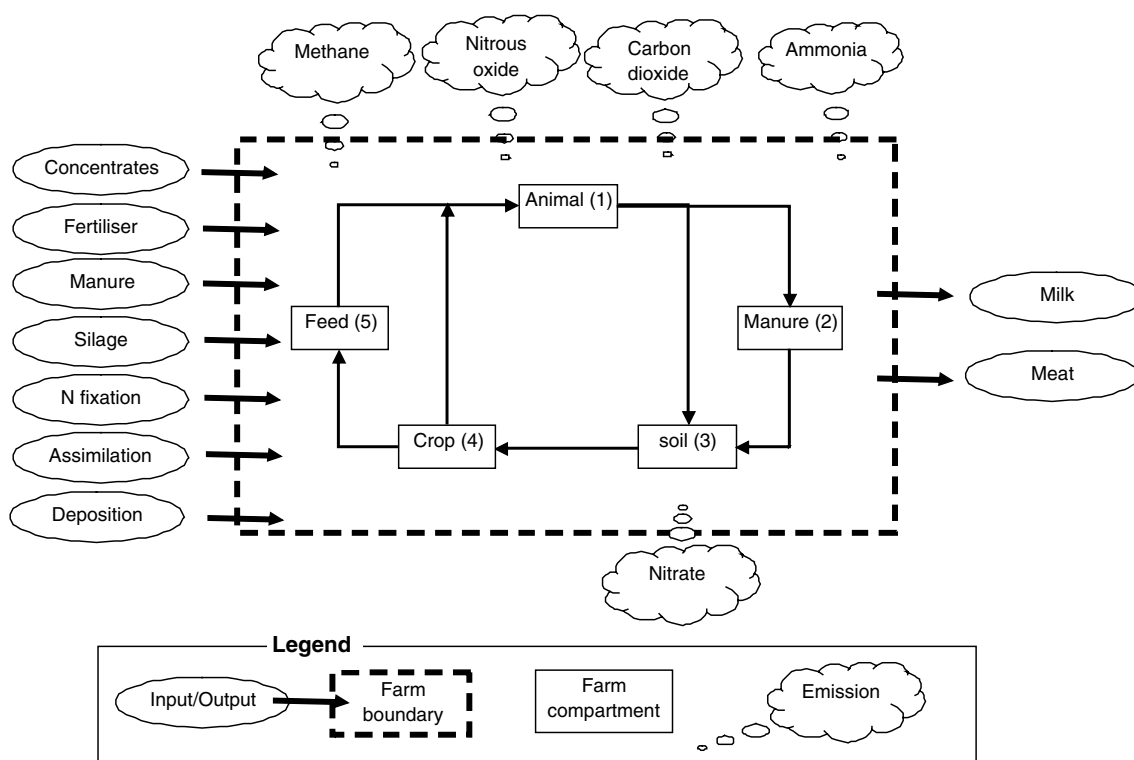
Figure 1. Carbon and nitrogen flow diagram of a ruminant livestock system. The numbers in the farm compartments correspond with the explanation in the text.

Direct emissions

For the sake of simplicity, Figure 1 only shows the main nutrient flows within the boundaries of the farming system, and the inputs, outputs and losses. The individual processes and the associated carbon and nitrogen losses are described here, and are summarised in Table 1.

(1) Animals convert carbon and nitrogen from imported concentrates and forages, and home-grown grass and forage crops into milk and meat. The most important associated GHG emission is methane, due to enteric fermentation. Minor emissions of nitrous dioxide, directly from the rumen, may occur. The excretion of faeces and urine, both in the field and in the stable, causes emissions of methane, nitrous oxide and ammonia, due to fermentation, nitrification, denitrification and ammonia volatilisation, respectively. Silage feeding involves the use of fuel operated machinery,

which leads to direct carbon dioxide and nitrous oxide emissions.

(2) Excreta from housed animals are mostly stored before application to the field. Depending on the type of manure, storage system and period, emissions of methane, nitrous oxide and ammonia will occur. In general, stable and storage emissions of these three gases are higher than pasture emissions, due to the direct contact between faeces and urine in stable and storage. Manure application is mainly associated with ammonia, nitrous oxide and carbon dioxide losses, depending on application method, application time and manure type.

(3) The soil pool is by far the largest carbon and nitrogen stock within a dairy farm. A diverse range of organic and inorganic nutrients is cycled within the soil pool, but we restrict our concept to the net input, net output and net accumulation. The carbon balance of the soil is an essential component of the full accounting system of GHGs. Soil and crop management,

Table 1. Direct emissions of methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), ammonium (NH_3) and nitrate (NO_3), grouped per farm compartment.

Farm component		CH_4	N_2O	CO_2	NH_3	NO_3
1. *Animal*		•	•			
Input	Concentrate					
	Intake silage		•	•		
	Intake grazing					
Output	Milk					
	Meat					
	Excretion stable	•	•		•	
	Excretion pasture	•	•		•	
2. *Manure*		•	•		•	
Input	Excretion stable	•	•		•	
	Import					
	Feeding losses					
Output	Application		•	•	•	
	Export					
3. *Soil*		•	•	•		•
Input	Excretion pasture	•	•		•	
	Application		•	•	•	
	Mineral fertiliser		•	•	•	
	Harvest losses				•	
	Grazing losses				•	
	Biological fixation		•			
Output	Crop uptake					
4. *Crop*						
Input	Crop uptake					
Output	Harvest		•	•		
	Harvest losses				•	
	Grazing					
	Grazing losses				•	
5. *Feed*			•		•	
Input	Harvest		•	•		
	Import					
Output	Intake silage		•	•		
	Feeding losses					

Relevant emissions for each farm component are marked with •.

in relation to soil type and climate, determine whether there is a net carbon sequestration or a net carbon loss.

4) Grass and forage crops take up nutrients from the soil pool and atmosphere, which are then withdrawn from the crop pool by grazing or mechanised harvests. Harvest and grazing losses are returned to the soil pool, but these pathways also lead to ammonia volatilisation losses.

5) Harvested grass and forage crops are stored in the feed pool, together with imported feeds. Conservation losses are a source for a variety of nitrogen losses, among other ammonia and nitrous oxide. Feeding losses are directed to the manure pool.

Indirect emissions

In the full accounting approach, we include indirect emissions of GHGs. Firstly, indirect emissions of nitrous oxide occur outside the system boundaries after nitrogen is emitted through volatilisation, leaching or runoff. Secondly, energy use is responsible for indirect emissions of carbon dioxide, nitrous oxide and methane. So, the full accounting of indirect GHG emissions requires an account of the direct and indirect energy use on a dairy farm. The direct energy use consists of electricity use and fuel use. The direct carbon dioxide and nitrous oxide emissions due to on-farm fuel combustion were already accounted for in the previous paragraph.

The indirect GHG emissions are related to the production process of electricity and fuel. Furthermore, the energy use and the associated GHG emissions during the production of imported resources have to be accounted for. In this respect, we distinguish (i) purchased goods, i.e., fertiliser, concentrate, silage and manure, (ii) services, e.g., contractors, and (iii) buildings and machinery.

Implementation

The described full accounting procedure has been implemented in a Microsoft EXCEL spreadsheet. The procedure is currently being incorporated as a GHG module within the FARMIN model (Van Evert et al. 2003).

Case study

Farm data

Data were selected from two dairy systems at one site, but with contrasting livestock density and grassland management. The original experiment is described extensively in Schils et al. (2000a, b). The experiment consisted of a comparison between a grass/clover and grass/fertiliser-N dairy system, from May 1990 until April 1993 (Table 2). The soil is a calcareous marine light clay, reclaimed from the sea in 1957 and under grass since 1971. On a total area of 40.6 ha, 33 paddocks were established with mixed swards of perennial ryegrass and white clover.

Table 2. Some characteristics of the grass/fertiliser-N and grass/clover dairy system (Schils et al. 2000a, b).

	Grass/ fertiliser-N	Grass/ clover
Pasture area (ha)	34.4	40.6
Dairy cows (#)	59	59
Stocking rate[a] (LU ha^{-1})	2.2	1.9
Concentrates (kg cow^{-1} year^{-1})	1815	1830
Milk (kg FPCM[b] cow^{-1} year^{-1})	8095	8294
Nitrogen application[c] (kg ha^{-1} year^{-1})	275	69
Biological N fixation[d] (kg ha^{-1} year^{-1})	0	176

[a]LU = Livestock Unit: 0–1 year = 0.3, 1–2 year = 0.6, cow = 1.0; [b]FPCM = Fat and Protein Corrected Milk production; [c]including inorganic N from slurry; [d]calculated as white clover DM yield * 54 kg N (van der Meer and Baan Hofman 1989).

Approximately two thirds of the paddocks were ploughed, cultivated and sown with a seed mixture of perennial ryegrass and white clover. The other paddocks were direct-drilled. In order to have similar sward ages in both systems, an approximately equivalent proportion of the area was renewed on the grass/fertiliser-N farm.

One farm manager was responsible for both herds, which were housed under one roof, but in independent units with separated silage clamps and slurry storage facilities, cubicles, feeding passages and milk tanks. The dairy herds consisted of Holstein-Friesian cows, calving from October to April.

A farm management system was used to record all data, i.e., mineral fertiliser use, grazing management, silage production, feed intake, milk production, milk sales, milk quality, animal weights, animal health and fertility. Regularly, samples were taken at crucial points in the farm nutrient cycle. Sampling methods and analytical schemes are described in the original papers. In short, measurements were carried out on animals (weight), milk (fat and protein), manure (DM, crude ash, NH_3–N and total-N), fresh and ensiled grass (DM, crude ash, crude fibre, crude protein and NH_3), grass and grass/clover swards (botanical composition), soil (organic matter) and drain water (nitrate).

Direct emission factors

The emission factors for methane, nitrous oxide, carbon dioxide and ammonium were derived from literature (Table 3), whereas carbon sequestration and nitrate leaching were derived from on-site measurements.

Nitrogen losses during conservation were derived from dry matter losses (PR 1997), assuming a nitrogen loss proportional to the loss of dry matter. Nitrogen losses from conservation are a mixture of ammonia and nitrogen oxides (Maw et al. 2002). As we had insufficient quantitative data to distinguish between the nitrogen losses, we assumed a 50:50 ratio between ammonia and nitrogen oxides.

Carbon sequestration was calculated from the change in organic matter content, measured in the topsoil (0–5 cm) in 1989, 1991 and 1993. Soil carbon was calculated as 58% of soil organic matter (Kurmies 1949). The soil density was assumed to be 1.3 kg l^{-1}. The sampled paddocks were grouped into undisturbed grass swards, sod

Table 3. Emission factors (EF) for the quantification of the direct emissions.

	EF	Unit	Equation to calculate emission	IPCC	Reference
Methane (kg CH$_4$)					
Enteric fermentation					
Dairy cows	0.01	cow^{-1} year^{-1}	50 + EF* milkproduction	●	Corré 2002
Heifers	65	animal^{-1} year^{-1}	EF* animal number	●	Corré 2002
Calves	25	animal^{-1} year^{-1}	EF* animal number	●	Corré 2002
Grazing excreta	0.11	m^{-3}	EF* excretion in pasture		De Mol and Hilhorst 2003
Manure in storage	2.93	m^{-3}	EF* excretion in stable	●	De Mol and Hilhorst 2003
Soil	−0.6	ha^{-1} year^{-1}			Van Den Pol-Van Dasselaar 1998
Nitrous oxide (g N)					
Rumen	0.05	(kg N)$^{-1}$	EF* intake-N		Velthof and Oenema 1997
Soil	900	ha^{-1} year^{-1}		●	Velthof and Oenema 1997
Grazing	25	(kg N)$^{-1}$	EF* (N-excretion pasture − NH$_3$ loss)	●	Velthof and Oenema 1997
Manure in storage	0.05	(kg N)$^{-1}$	EF* excretion in stable	●	Velthof and Oenema 1997
Manure application	5	(kg N)$^{-1}$	EF* (N in manure − NH$_3$-loss)	●	Velthof and Oenema 1997
Mineral fertiliser	10	(kg N)$^{-1}$	EF* (N in fertiliser − NH$_3$-loss)	●	Velthof and Oenema 1997
Biological fixation	5	(kg N)$^{-1}$	EF* fixed N	●	Velthof and Oenema 1997
Silage	15	(kg NO$_3$-N)$^{-1}$	EF* silage-NO$_3$		Velthof and Oenema 1997
Fuel	1	GJ^{-1}	EF* energy use through fuel		Velthof and Oenema 1997
Carbon dioxide					
Carbon sequestration (kg C)					
Ploughing	−5178	kg ha^{-1}			Schils et al. 2000a
Undisturbed grass	+1994	kg ha^{-1}			Schils et al. 2000a
Sod seeded grass/clover	+1442	kg ha^{-1}			Schils et al. 2000a
Renewed grass	+2046	kg ha^{-1}			Schils et al. 2000a
Renewed grass/clover	+1519	kg ha^{-1}			Schils et al. 2000a
Fuel (kg CO$_2$)	73	GJ^{-1}	EF* energy use through fuel		Van Dasselaar and Pothoven 1994
Ammonium (g N)					
Manure in storage and housing	80	(kg N)$^{-1}$	EF* N-excretion in stable		Oenema et al. 2000b
Grazing excreta	77	(kg N)$^{-1}$	EF* N-excretion pasture		Bussink 1992, 1994
Manure application	60	(kg NH$_3$-N)$^{-1}$	EF* N in manure		Huijsmans et al. 2001
Mineral fertiliser	20	(kg N)$^{-1}$	EF* fertiliser application		Sommer and Jensen 1994
Harvest and grazing losses	30	(kg N)$^{-1}$	EF* harvest and grazing losses		Oenema et al. 2001a
Conservation losses	55	(kg N)$^{-1}$	EF* harvested silage		PR 1997
Nitrate (kg N)					
Grass	20	kg ha^{-1}			Schils 1994
Grass/clover	24	kg ha^{-1}			Schils 1994

Category is marked with ● when relevant for the IPCC accounting system.

seeded grass/clover swards, ploughed grass swards and ploughed grass/clover swards. The organic matter content of the sampled paddocks was plotted against the sward age relative to the year of sward renovation (Figure 2). However, the exact age of the undisturbed grass and sod seeded grass/clover swards was not available, so their age was calculated relative to the first sampling date. From these data, carbon loss from the topsoil after ploughing was calculated at 5.2 t ha^{-1}. The average carbon sequestration varied from 1.4 to 2.0 t ha^{-1} year^{-1}, depending on sward type. It has to be realised that calculations based on the topsoil of 0–5 cm overestimate the carbon dioxide exchange with the atmosphere. With grassland renovation, a lot of organic matter is ploughed to a depth of 20 to 25 cm.

Nitrate leaching through drain water was measured on 40% of the paddocks. The average nitrogen loss was 20 kg ha^{-1} on grass/fertiliser-N swards and 24 kg ha^{-1} on grass/clover-N swards (Schils 1994).
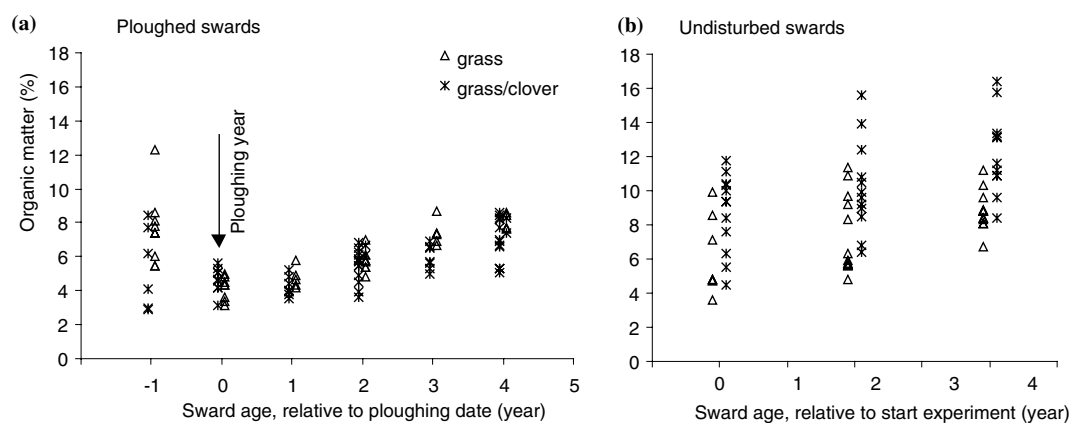
Figure 2. Changes in organic matter content (0–5 cm) in relation to sward age, for (a) ploughed swards, and (b) undisturbed swards.

Table 4. Emission factors (EF) for the quantification of the indirect greenhouse gas emissions in the case on clay soil.

	EF	Unit	IPCC	Reference
Carbon dioxide (kg CO_2)				
Fuel*				
Electricity	67	GJ^{-1}		Van Dasselaar and Pothoven 1994
Indirect energy	67	GJ^{-1}		Van Dasselaar and Pothoven 1994
Fertiliser nitrogen	56	GJ^{-1}		Van Dasselaar and Pothoven 1994
Nitrous oxide (g N)				
Fuel*				
Electricity	1	GJ^{-1}		Velthof and Oenema 1997
Indirect energy	1	GJ^{-1}		Velthof and Oenema 1997
Nitrate leaching	25	$(kg\ NO_3\text{-}N)^{-1}$	•	IPCC 1997
Ammonia volatilisation	5	$(kg\ NH_3\text{-}N)^{-1}$	•	IPCC 1997
Purchased concentrate	10	$(kg\ N)^{-1}$		Velthof and Oenema 1997
Purchased silage	20	$(kg\ N)^{-1}$		Velthof and Oenema 1997
Purchased fertiliser	5	$(kg\ N)^{-1}$		Velthof and Oenema 1997

*Included in direct emission factor; Category is marked with • when relevant for the IPCC accounting system.

Indirect emission factors

The energy use itself was taken from the original paper (Schils et al. 2000a), which used the energy values of Hageman (1994). The indirect emissions related to energy use were categorised in production and transport of fuel, electricity use and indirect energy (Table 4).

In the international literature, the emission factors for carbon dioxide combine the direct and indirect emission. Therefore we follow that approach and do not explicitly assign an indirect carbon dioxide emission for fuel combustion. The carbon dioxide emission from electricity use and indirect energy use was taken from Van Dasselaar and Pothoven (1994), which is based on a combined energy production from oil and gas. As the production of mineral fertiliser nitrogen is mainly based on gas, the emission factor is lower.

Indirect nitrous oxide emissions from on-farm fuel use were included in the direct emissions, similar to the approach with carbon dioxide. The emissions from electricity use and indirect energy use were derived from Velthof and Oenema (1997). Nitrous oxide emissions resulting from nitrate leaching and ammonia volatilisation were adopted from IPCC (1997). The nitrous oxide emissions associated with the production of imported concentrates, silage and mineral fertiliser were taken from Velthof and Oenema (1997).

Methane emissions from oil and gas production, transport and distribution are not accounted for as

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Table 5. Direct and indirect emissions per ha of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) for the grass-fertiliser-N and grass/clover farm.

	Grass/ fertiliser-N	Grass/ clover
Methane (kg CH_4)		
Enteric fermentation	268	229
Grazing excreta	2.7	2.4
Manure in storage	92	72
Soil	−0.6	−0.6
Total	363	303
Total (CO_2-equivalents)	7623	6362
Nitrous oxide (kg N)		
Rumen	0.02	0.02
Soil	0.9	0.9
Grazing	2.9	2.6
Manure in storage	0.01	0.01
Manure application	0.7	0.6
Mineral fertiliser	2.0	0.2
Biological fixation	0	0.88
Silage	0.0	0.0
Fuel	0.004	0.003
Total direct	6.61	5.10
Nitrate leaching	0.5	0.55
Ammonia volatilisation	0.3	0.2
Purchased mineral fertiliser	1.0	0.1
Purchased concentrate	0.8	0.6
Purchased silage	0.2	0.0
Electricity	0.01	0.01
Indirect energy use	0.05	0.03
Total indirect	2.8	1.5
Total	9.4	6.6
Total (CO_2-equivalents)	4597	3237
Carbon dioxide (kg CO_2)		
Carbon sequestration	−6468	−4898
Fuel	263	219
Total direct	−6205	−4679
Electricity	428	365
Indirect energy use	3153	2234
Total indirect	3582	2599
Total (CO_2-equivalents)	−2623	−2080
Overall total (CO_2-equivalents)	9597	7519

the emission factors for indirect energy, derived from Spakman et al. (2003), are lower than 1×10^{-6} kg CH_4 MJ^{-1}.

GHG emissions

According to the IPCC methodology, the total emission was 10.7 kt CO_2 ha^{-1} $year^{-1}$ on the grass/fertiliser-N farm and 8.7 kt CO_2 ha^{-1} $year^{-1}$ on the grass/clover farm. Methane contributed approximately 70% and nitrous oxide 30% to the total GHG emission. About 95% of the total

emissions were due to direct emissions. It has to be realised that in this paper the IPCC derived emissions are based on the same emission factors as the full accounting approach. Therefore, the difference between the two methods only reflects the different sources included in the inventory.

It is no surprise that the full accounting approach leads to a considerably different distribution between the three GHGs and between direct and indirect emissions (Table 5). The carbon and nitrogen flows are the starting point for the calculation of the GHG emissions in the full accounting approach. For a better understanding, the nitrogen cycle of the grass-fertiliser-N based dairy system is shown in Figure 3.

Excluding carbon sequestration, the total emission was 16.1 and 12.4 kt CO_2 ha^{-1} $year^{-1}$ on the grass/fertiliser-N and grass/clover farm, respectively. The average contribution of methane, nitrous oxide and carbon dioxide to the total emission was 49, 27 and 24%, respectively (Figure 4). The direct methane and nitrous oxide emissions account for 69% of the total emissions, while the direct carbon dioxide emissions from on-farm fuel combustion are only 1–2% of the total emissions. The indirect emissions of nitrous oxide and carbon dioxide are 30–35% of the emissions. Carbon sequestration was approximately 5.7 kt CO_2, thereby reducing the overall emission of GHGs by 37%.

As the stocking rate was 15% lower on grass/clover than on grass/fertiliser-N, it is obvious that for most activities the direct emissions per ha approximately follow the difference in stocking rate. The use of white clover results into a more than proportional reduction because the emission factor for biologically fixed nitrogen is 50% lower than for mineral fertiliser nitrogen (Table 3). Due to the lower milk production per ha on the grass/clover farm, the direct emission per kg milk was only 10% lower on the grass/clover farm than on the grass/fertiliser-N farm.

The use of white clover had a marked effect on the indirect emissions of nitrous oxide and carbon dioxide, especially due to reduced mineral fertiliser use. Compared to grass/fertiliser-N, the indirect emission on the grass/clover farm was 32% lower per ha and 22% lower per kg milk.

Carbon sequestration was 30% higher on the grass/fertiliser-N swards than on the grass/clover swards. Firstly, due to the higher proportion of
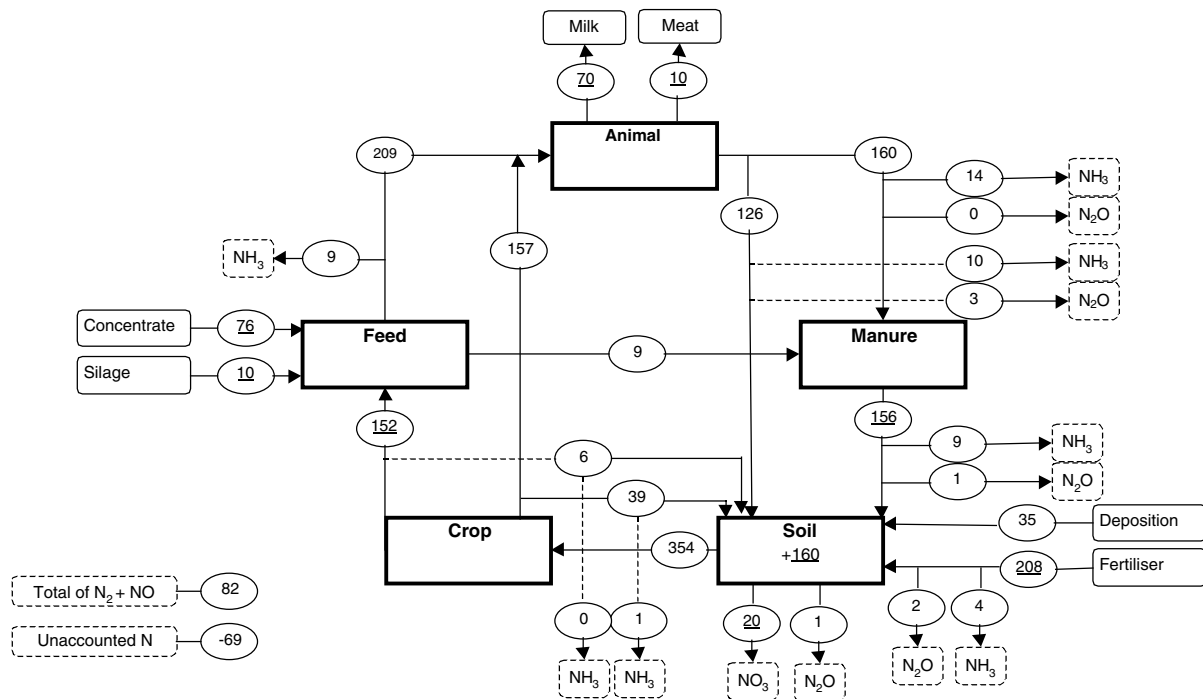
Figure 3. Nitrogen cycle of the grass/fertiliser-N farm (kg N ha^{-1} year^{-1}). Measured data are underlined. For reasons of clarity, emissions of dinitrogen (N$_2$) and nitric oxide (NO) are not assigned to the different farm compartments, but are shown as total emission only.
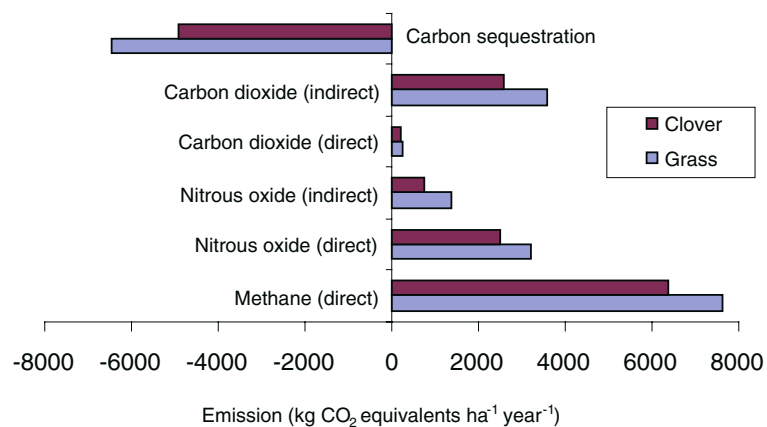

Figure 4. Direct and direct GHG emissions of the grass/clover and grass/fertiliser-N system.

swards renovated with ploughing. Secondly, due to the higher organic matter accumulation on undisturbed grass swards, compared to the sod-seeded grass/clover swards (Figure 2).

Considering all emissions, including carbon sequestration, the total global warming potential was 11.1 kt CO$_2$ ha^{-1} year^{-1} on the grass/fertiliser-N farm and 9.1 kt CO$_2$ ha^{-1} year^{-1} on the grass/clover farm, or 0.70 and 0.63 kg CO$_2$ kg milk^{-1}, respectively.

Ammonia and nitrate emissions

The total ammonia volatilisation losses were 47 kg N ha^{-1} year^{-1} from the grass/fertiliser-N farm

and 37 kg N ha^{-1} year^{-1} from the grass/clover-N farm. The major losses occurred from housing and storage (29%), grazing (22%) and manure application (18%). As stated earlier, the average nitrate leaching losses were 20 kg N ha^{-1} on grass/fertiliser-N swards and 24 kg N ha^{-1} on grass/clover-N swards.

Mitigation options

A set of four potential options for mitigation of GHG emissions were selected from Oenema et al. (2001b), i.e., (i) reduced mineral fertiliser use, (ii) reduced grazing, (iii) increased milk production per cow, and (iv) reduced grassland renovation (Table 6). Primarily, options (i), (ii) and (iii) are aimed at nitrous oxide, option (iii) is aimed at methane, while option (iv) is aimed at carbon sequestration. The effects of the mitigation options were only calculated for the grass/fertiliser-N farm. The calculated effects are only based on changes in volumes, while it is arguable that emissions per unit will change at other levels of inputs. Furthermore, it is assumed that the farmer already applies Good Agricultural Practice.

Reduction of the mineral fertiliser use by 15% results into a 5% reduction of the direct nitrous oxide emissions. The indirect emissions are also reduced due to lower mineral fertiliser purchases and lower nitrogen losses. However, the gain is partly offset by the reduced grass yield of 7.5 kg DM per kg applied N (Unwin and Vellinga 1994), which has to be compensated by silage import. The indirect carbon dioxide emissions are 2% lower.

The overall effect of a 15% reduced mineral fertiliser input is a decrease of 0.02 kg CO_2 kg milk^{-1}.

Reduction of grazing time from 20 to 16 h d^{-1} has a marked effect on direct nitrous oxide emissions from animal excreta during grazing and mineral fertiliser. However, due to the increased manure storage, the methane emissions from manure management increase to the same extent. Furthermore, there is more fuel consumption due to the increased application of manure and silage harvests. The overall effect is almost nil.

An increased milk production per cow of 500 kg year^{-1} requires an increased concentrate input of 235 kg year^{-1} (CVB 2002), but the total number of cows and replacement stock can be reduced. The more efficient milk production reduces the methane and nitrous oxide emissions by approximately 4%. Furthermore, there are small changes in the mineral fertiliser and slurry application, and silage making, which leads to an increased fuel use. The indirect energy use, hence the carbon dioxide emissions, is lower with fewer cows. The aggregated effect of an increased milk production of 500 kg cow^{-1} year^{-1} is a reduction of 0.03 kg CO_2 kg milk^{-1}.

Finally, reduction of the proportion of renovated grassland from 5 to 0%, increases carbon sequestration by 230 kg C ha^{-1}. Due to a poorer sward quality, the yields are assumed to be 2% lower (Schils et al. 2002) which requires higher silage imports. On the other hand, increasing soil organic matter also increases the soil nitrogen supply, which in turn reduces the amount of mineral fertiliser required (PR 1997). On the

Table 6. Effect of mitigation options on direct and indirect emissions on grass/fertiliser-N farm.

	Present	Less mineral fertiliser	Less grazing	More milk per cow	No grassland renovation
Methane	7623		+289	−281	
Nitrous oxide (direct)	3220	−151	−273	−73	−10
Nitrous oxide (indirect)	1381	−34	−29	−88	+24
Carbon dioxide (direct)	263		+55	+10	−10
Carbon dioxide (indirect)	3582	−82	−5	−11	−4
Carbon sequestration	−6468				−843
Total (kg CO_2 ha^{-1})	9597	−267	+37	−443	−843
Total (kg CO_2 kg FPCM^{-1})[*]	0.70	−0.02	0.00	−0.03	−0.06
Ammonia volatilisation (kg N ha^{-1})	57	−0.6	+3.4	−1.1	0
Nitrate leaching (kg N ha^{-1})	20	−1.5	−1.8	−2.1	0

[*]FPCM = Fat and Protein Corrected Milk; GHG emissions of present situation are expressed in CO_2-equivalents per ha. Results of scenarios are relative to control.

whole, the emission is reduced by 0.06 kg CO_2 kg milk^{-1}. In this calculation, the positive effect of 'no renovation' on nitrous oxide emission (Estavillo et al. 2002) has not been taken into account.

The side effects on ammonia volatilisation and nitrate leaching were very generally positive. Only reduced grazing resulted in increased ammonia losses.

Discussion and conclusion

The whole farm approach is a powerful tool to develop GHG mitigation strategies for farming systems, taking into account the transfer of effects to other environmental issues. In our approach, we only considered side effects on nitrate leaching and ammonia volatilisation. The implementation of mitigation options in the farm case clearly demonstrated how one measure affects all emissions. In this paper, we only traced the most evident interactions. In reality, there are many more refined interactions. For instance, reduction of mineral fertiliser use could reduce the digestibility of grass, especially on peat soils, and hence increase methane emissions. The method can easily be extended to other relevant issues like water quality or heavy metals. Furthermore, inclusion of the cost and benefits of mitigation options are necessary when it comes to the final selection of measures and implementation on farms (Henry et al. 1995; De Haan 2001). We have not calculated the costs of the mitigation options for the specific case presented here, but earlier studies provide an indication of the costs of similar measures. Reduction of the fertiliser input reduced the income by 8 to 31 € ha^{-1} (Velthof et al. 2000b) while reduction of grazing time reduced the income even further, between 30 and 84 € ha^{-1} (Velthof et al. 2000a). Increased milk production on the other hand, led to an increased income, ranging from 65 to 89 € ha^{-1} (Velthof et al. 2000a). Similar studies for grassland renovation are not available. The benefits of refraining from grassland renovation can be quantified between 28 and 70 € ha^{-1}, but the effects on sward quality and yield are hard to quantify (Schils et al. 2002).

Inclusion of all direct and indirect emissions should lead to farmer's awareness that his or her management decisions not only affect the on-farm losses, but also the losses occurring earlier or later in the production chain. For that reason farmers should also be rewarded for achievements outside the farm gate. However, the IPCC inventory method is designed for reporting the progress in national emission abatement. Therefore it is not a suitable instrument to stimulate and record the farmer's GHGs mitigation efforts. Implementation of the full accounting and whole farm approach in policy would be a step further towards effective and efficient mitigation strategies. In recent years, these whole farm approaches have been implemented for nitrogen and phosphorus (Oenema et al. 2001a; Oborn et al. 2003). At this moment the IPCC methodology lacks the refinement that is necessary to reflect the wide range of mitigation options. For instance, the use of ammonium based mineral fertilisers (Flessa et al. 1996) or timing of mineral fertiliser and manure application (Stevens and Laughlin 2002) are not transformed into appropriate emission factors.

The whole farm approach was used to explore mitigation options, while the IPCC methods aims at reporting changes in GHG emissions. Both approaches serve their own specific objectives. In higher tiers of the IPCC reporting system, changes in farm management and the achieved emission reductions should be reflected in the national inventories. Both methods benefit from further refinement of the emission factors.

The developed methodology serves as a framework for a whole farm and full accounting approach. In the illustrated case we used two farms that were monitored closely over several years. Therefore, the carbon and nitrogen flows could be derived from on-site measurements. When performing studies with larger groups of farms, with generally fewer site-specific data available, more use of statistical data or models will be necessary. For Europe, the data needed to upscale the whole farm approach are available from databases like ELPEN (www.macaulay.ac.uk/elpen). The method is transparent and relatively easy to comprehend and will facilitate communication between scientists, farmers and policy makers.

The calculated emissions in the case studies were based on the average value of the emission factors. But the spatial and temporal variability in the underlying experiments for these emission factors is large. For example, for nitrous oxide and methane the variability of the emission factors may vary between 10 and 100%. Despite the high uncertainty, it is possible to compare and weigh

mitigation measures. The uncertainty itself should also be used as one of the selection criteria for mitigation options. Although for instance the direct fuel based carbon dioxide emissions are relatively low, mitigation options that reduce the operating hours of fuel operated machinery have a high certainty in outcome.

Carbon sequestration is included in the full accounting approach because article 3.3 of the Kyoto protocol gives the opportunity to use soil carbon sinks in the national GHG budget (UN-FCCC 1997). Although in the presented case, the impact of sequestration is only based on changes in the top soil (0–5 cm), and thus not entirely representative for most grassland situations, it is clear from other research (Soussana et al. 2004) that carbon sequestration in grasslands can make a substantial, although short-lived, contribution to reduce global warming.

Short-cycling carbon was not included as it is generally seen as not relevant for the greenhouse effect. It is reasoned that carbon dioxide emissions from animal respiratory or metabolic origin, manure management, conservation losses and soil respiration has been fixed by photosynthetic activity earlier in the farm cycle, and thus makes no net contribution to the greenhouse effect. However, it can be argued that improvements in the utilisation of short cycling carbon are useful as well. In the present situation of the grass/fertiliser-N farm the total carbon dioxide emissions from short cycling carbon was 15.4 t ha^{-1} year^{-1}. Minor improvements in the efficiency of feeding, manure or grassland management could reduce carbon dioxide emissions. This is illustrated in the case with the increased milk production per cow where the carbon dioxide emissions from short cycling carbon were reduced by 6%.

The presented framework for a whole farm approach contributes to a transparent evaluation of the effectiveness and efficiency of mitigation strategies. Including interactions between the various carbon and nitrogen flows and the resulting emissions inside and outside the farm boundaries is a necessity for a full accounting system.

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