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The impact of grassland ploughing on CO_2 and N_2O emissions in the Netherlands

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Abstract

The contribution of ploughing permanent grassland and leys to emissions of N_2O and CO_2 is not yet well known. In this paper, the contribution of ploughing permanent grassland and leys, including grassland renovation, to CO_2 and N_2O emissions and mitigation options are explored. Land use changes in the Netherlands during 1970–2020 are used as a case study. Three grassland management operations are defined: (i) conversion of permanent grassland to arable land and leys; (ii) rotations of leys with arable crops or bulbs; and (iii) grassland renovation. The Introductory Carbon Balance Model (ICBM) is modified to calculate C and N accumulation and release. Model calibration is based on ICBM parameters, soil organic N data and C to N ratios. IPCC emission factors are used to estimate N_2O-emissions. The model is validated with data from the Rothamsted Park Grass experiments. Conversion of permanent grassland to arable land, a ley arable rotation of 3 years ley and 3 years arable crops, and a ley bulb rotation of 6 years ley and one year bulbs, result in calculated N_2O and CO_2 emissions totalling 250, 150 and 30 ton CO_2-equivalents ha^{-1}, respectively. Most of this comes from CO_2. Emissions are very high directly after ploughing and decrease slowly over a period of more than 50 years. N_2O emissions in 3/3 ley arable rotation and 6/1 ley bulb rotation are 2.1 and 11.0 ton CO_2-equivalents ha^{-1} $year^{-1}$, respectively. From each grassland renovation, N_2O emissions amount to 1.8 to 5.5 ton CO_2-equivalents ha^{-1}. The calculated total annual emissions caused by ploughing in the Netherlands range from 0.5 to 0.65 Mton CO_2-equivalents $year^{-1}$. Grassland renovation in spring offers realistic opportunities to lower the N_2O emissions. Developing appropriate combinations of ley, arable crops and bulbs, will reduce the need for conversion of permanent pasture. It will also decrease the rotational losses, due to a decreased proportion of leys in rotations. Also spatial policies are effective in reducing emissions of CO_2 and N_2O. Grassland ploughing contributes significantly to N_2O and CO_2 emissions. The conclusion can be drawn that total N_2O emissions are underestimated, because emissions from grassland ploughing are not taken into account. Specific emission factors and the development of mitigation options are required to account for the emissions and to realise a reduction of emissions due to the changes in grassland ploughing.

Introduction

The increasing concentration of greenhouse gases in the atmosphere is an international environmental concern. In Kyoto in 1997, many governments agreed to reduce the emissions of the greenhouse gases CO_2 and others, such as nitrous oxide (N_2O) and methane (CH_4). The main sources for CH_4 are enteric fermentation and animal manure (Van Den Pol-Van Dasselaar et al. 1999). For N_2O the focus is on the effects

Table 1. Strategic grassland management operations that include ploughing in the Netherlands.

Conversion of permanent grassland	Ploughing permanent grassland to arable land for continuous cropping of silage maize or to rotations of ley with arable crops, leguminous crops and bulbs.
Rotation with leys	Land use with temporary grassland (EU 1999) in combination with arable crops or bulbs. Most common cropping systems: – Arable crops/fodder crops, a rotation of 3 years ley and 3 years arable crops (Aarts et al. 2000a, b) – Bulb crops, like tulip, lily and gladiolus, a rotation of 6 years ley with 1 year bulbs
Renovation of permanent grassland	Ploughing in spring or autumn, immediately followed by reseeding in order to improve sward quality or introduce new (higher yielding or more resistant) varieties of mainly perennial rye-grass.

of application of manure and fertilisers (Freibauer and Kaltschnitt 2003; Olivier et al. 2003).

Agricultural activities are responsible for up to 40% of the estimated global emission of 14 Mton of N_2O into the atmosphere (Prather et al. 1995). A similar contribution of agriculture to national N_2O-emissions is found in the Netherlands (Anonymous 1997). To ensure compliance with the Kyoto agreement it is essential to identify major sources and practices that lead to production and emission of greenhouse gases.

Agricultural activities affect the emission of CO_2 through oxidation of soil organic matter (Smith et al. 2001) and by sequestration of CO_2 in soil organic matter (Conant et al. 2001). Land use changes by ploughing permanent grassland for arable cropping or establishing ley-arable rotations have only recently been identified as an important regulating management factor in CO_2 emissions (Sauerbeck 2001; Guo and Gifford 2002; Del Galdo et al. 2003). Also, large losses of soil organic N, caused by land use changes, have been reported (Whitehead et al. 1990; Whitmore et al. 1992; Hoffmann 1999; Bhogal et al. 2000). Corresponding large emissions of N_2O seem likely. The effect of land use changes on CH_4 emissions will be marginal (Van Den Pol-Van Dasselaar et al. 1999). Few countries consistently report their emissions (UNFCCC 2000). The contribution of grassland ploughing to overall N_2O emissions is not quantified yet.

This paper reports quantification of the contribution of grassland ploughing including grassland renovation to CO_2 and N_2O emissions. Options to reduce such emissions will be explored. The Netherlands will be used as a case study, because significant land use changes have occurred since 1970 and are expected during the next 15 to 20 years. A simple simulation model (ICBM, Andrén and Kätterer 2001) will be used to estimate the C and N release and associated CO_2 and N_2O emissions from ploughed grassland on a field scale in combination with IPCC emission factors.

Material and methods

Grassland management operations

There was 1 Mha of intensively managed grassland in the Netherlands in 2001. Most grassland here is used for grazing and cutting, with 5–7 cuts per annum, and an annual application of 250–450 kg ha^{-1} of N in animal manure and mineral fertilisers. *Lolium perenne* L. is the dominant species, with a ground cover of 60 to 95% in most grasslands. Production varies between 10 and 16 tons of dry matter $year^{-1}$ (CBS 2000). Each year 5–10% of the total grassland area is ploughed (Anonymous 2000a). Although there is some variation in practice, three 'strategic grassland management operations' can be distinguished: (i) conversion of permanent grassland to arable cropping systems, (ii) rotation of ley with other crops, and (iii) renovation of permanent grassland. These operations are described in Table 1.

Changes in land use between 1970 and 2020

Developments between 1970 and 2020 are shown in Table 2. During a period of 50 years, three major developments can be identified:

1. The acreage of grassland decreased over the whole period 1970–2000 and will decrease further from 2000 to 2020, due to urbanisation, expansion of infrastructure, natural habitat recreation, recreational use and an increase in fodder maize production

Table 2. Acreage developments concerning permanent grassland, leys, bulbs and fodder maize between 1970 and 2020 in the Netherlands. Bold numbers are based on surveys and statistics (CBS 2000). All data in thousands of hectares.

Land use ↓ Year →	1970	1980	1990	1995	2000	2020
Total grassland	**1345**	**1198**	**1095**	**1050**	**1010**	850
Permanent grassland	**1310**	**1160**	**1060**	**1010**	**920**	640
Ley	**35**	**38**	**35**	**40**	**90**	210
Ley-arable 3/3: ley	10	10	10	15	30	90
Ley-arable 3/3: arable	10	10	10	15	30	90
Total bulb area	**12**	**14.5**	**17**	**17.5**	**22.5**	30
Ley-bulbs 6/1: ley	25	25	25	30	60	120
Ley-bulbs 6/1: bulbs	4	4	4	5	10	20
Total maize area	**5**	**140**	**200**	**235**	**250**	250
Land use change:						
Conversion of permanent grassland for maize	0	100	60	20	0	0
Conversion of permanent grassland for leys	0	0	0	5	50	120
Annual ley area ploughed up in rotations	7	7	7	10	20	60
Annual grass area for grassland renovation[1]	**20**	**40**	**50**	**50**	**50**	30

[1]Grassland renovation is exclusively in autumn until 2000. Trend analysis and implementation of manure policy will change grassland renovation gradually to spring (25 000 ha in 2020) and less in autumn (5000 ha).

(CBS 2000; MHSPE 2001). In the period 2000–2020, the area of permanent grassland is expected to decrease faster than the total grassland area;

2. There has been a large increase in the maize growing area (CBS 2000) and in grassland renovation (Anonymous 2000a) until about 2000. The total maize area from 2000 and onwards is expected to remain constant. Grassland renovation will decrease proportionally with the decrease in the area of permanent grassland;
3. There will be an increase in the total area receiving ley management, as a result of an expected increase in ley-arable rotations due to a stimulation of organic farming (MANMF 2001), ley-maize rotations (Aarts et al. 2000a, b) and an increase in ley-bulb rotations. The latter wil be caused partly by switch from continuous cropping to ley-bulb rotations and an increase in the total area (MHSPE 2001) after 2000.

Modelling C and N losses

Model concept

The effects of the three management operations and their growth and decline in land of area on the emission of CO_2 and N_2O is calculated with a simple model for net accumulation and release of soil organic C and N. The principles of this model are shown in Figure 1 and are based on Jenkinson et al. (1987) and Jenkinson (1988). Soil organic C and N accumulate relatively quickly under young pastures (Whitehead et al. 1990; Hassink and Neeteson 1991) and continue to accumulate at a lower rate in older pastures as well (Jenkinson et al. 1987). Grassland ploughing enhances the release of C and N following decomposition of soil organic matter (e.g., Strebel et al. 1988; Whitehead et al. 1990; Whitmore et al. 1992; Campbell et al. 2001). This may continue for a relatively long time before equilibrium conditions are reached (Kortleven 1963; Allison 1973; Richter et al. 1989; Schlesinger 1991).

In ley-arable rotations the processes of accumulation and release of soil organic C and N occur subsequently and repeatedly. This annual accumulation and release affect the actual equilibrium level of organic matter that is reached after several decades. As a consequence, the new equilibrium range of soil organic C and N, when permanent grassland is converted to a ley-arable or a ley-bulb rotation, depends on the number of grassland years in the rotation. Thus, in the ley-bulb rotation with 6 ley years out of 7, C and N still accumulate and this leads to higher soil organic C and N contents than ley-arable rotations with 3 ley years out of 6.

The loss of soil organic C and N in rotations, until equilibrium is reached, consists of two processes: (i) the release caused by the conversion of permanent grassland to arable land or ley: an ‘actual’ loss is distinguished from a ‘potential’ loss. The ‘actual’ loss is real and takes place following decrease of soil organic N and C. The ‘potential’ loss is a potential N and C

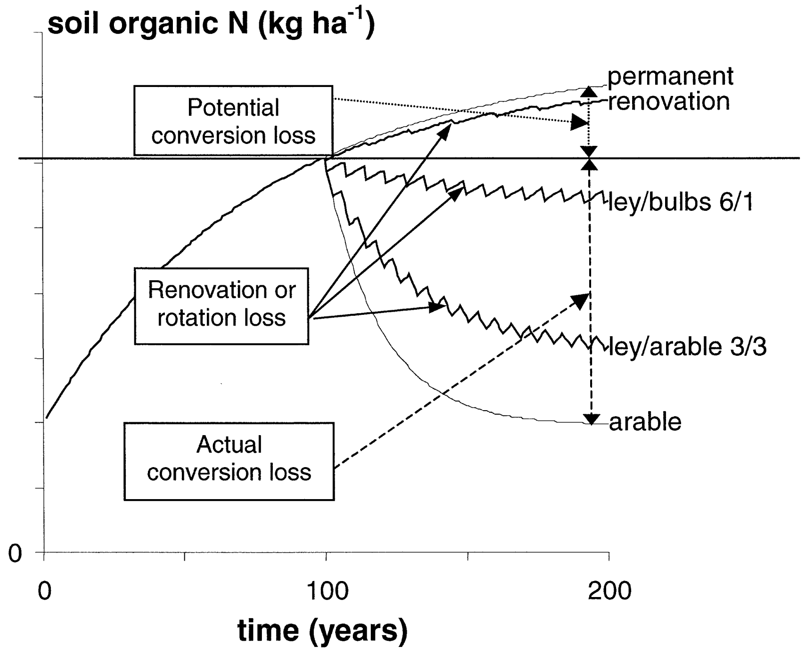

Figure 1. Patterns of soil organic N accumulation and losses on permanent grassland over time for situations with and without regular renovation by ploughing and patterns of soil organic N decrease when 100 year old grassland is ploughed and converted to arable or ley arable systems with different rotational length. 'Actual' losses from conversion, rotation and renovation and a so-called 'potential' loss are distinguished. The latter represents the continued N accumulation until equilibrium conditions are reached.

sequestration which would have taken place when the conversion of grassland had not been executed. (ii) The release caused by the specific configurations of the ley-arable or ley-bulb rotations (Loiseau et al. 1994): the rotational releases for N can best be calculated from the equilibrium condition. In rotation, there is no net change in C assumed, since C is released during the arable years but immobilised during the grassland period. Any loss of N, however, would have to be compensated for by new input and immobilisation of N and would result in N_2O emissions that depend on the specific source of N and emissions along the production chain of N sources, i.e., fertiliser or manure (Velthof et al. 1997).

During the brief fallow period associated with grassland renovation, soil organic C and N decrease sharply. When the grass sward is re-established, accumulation continues. Here the equilibrium condition eventually equals the C and N content in undisturbed pasture, although it may take more time before it is reached. In the case of grassland renovation, there is no net change in C assumed, comparable to ley-arable rotations.

To quantify the effect of ploughing on accumulation and release of soil organic C and N, the factors sward age, soil type, ley-arable rotation and renovation are taken into account. The effects due to specific arable crops (cereals, root crops, etc.), the choice and application rate of manure and other fertilisers and site conditions (climate, soil conditions, pH, drainage) are neglected, although it is known that they affect C and N accumulation and release as well (Jenkinson et al. 1987; Whitehead et al. 1990; Whitmore et al. 1992; Loiseau et al. 1994).

The model

The Introductory Carbon Balance Model (ICBM; Kätterer and Andrén 1999) is used to quantify the amounts of C and N which are accumulated or released under grassland and arable land, by simulating soil organic N turnover and assuming a constant C to N ratio in soil organic matter. Kätterer and Andrén (1999) defined two organic C pools: young and old, with a high and low rate parameter, respectively, for C mineralisation and a humification parameter for throughput of mineralised C from the young to the old pool. The pools have been redefined for the ICBM as follows: a relatively unstable organic N pool (young) and a stable organic N pool (old), with their own de-

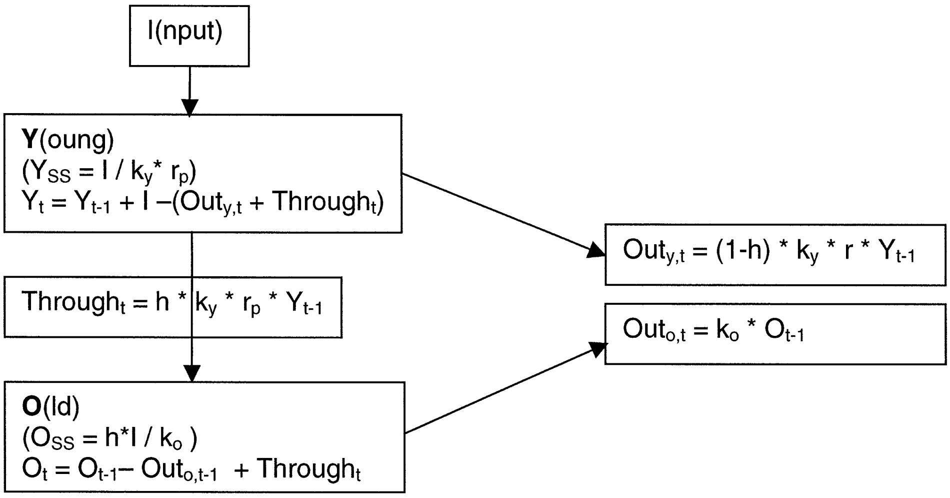

Figure 2. Structure of the Introductory Carbon Balance Model (ICBM) by Kätterer and Andrén (2001). State variables are Y_t and O_t, representing a young, unstable and an old, stable organic N pool, respectively (kg ha^{-1}) and their steady state condition (Y_{ss} and O_{ss}, respectively, kg ha^{-1}), k_y and k_o are decomposition rates for the young and old pool, respectively (kg ha^{-1} year^{-1}), h is the humification factor (–), r_p is the 'ploughing' coefficient (–). $Through_t$ is an internal flux, the throughput of N from the young to the old pool (kg ha^{-1} year^{-1}). External fluxes are $Out_{y,t}$, $Out_{o,t}$, the N release by the young and old N pools, respectively (kg ha^{-1} year^{-1}). t represents time (year).

composition rates and humification factor were defined as in Figure 2.

State variables: Y_{SS}, O_{SS} = the amounts of 'Young' and 'Old' soil organic N under the steady state condition, respectively (kg ha^{-1}).

Y_t, O_t = the amounts of 'Young' and 'Old' soil organic N at time = t, respectively (kg ha^{-1}).

Fluxes: $Out_{y,t}$, $Out_{o,t}$, = the N release by 'Young' and 'Old' organic N pools (kg ha^{-1} year^{-1}).

$Through_t$ = the N throughput from the 'Young' to the 'Old' organic N pool (kg ha^{-1} year^{-1}).

Model parameters: k_y, k_o = decomposition rate constants for the 'Young' and 'Old' soil organic N (year^{-1}).

I = the annual input of N (kg ha^{-1} year^{-1}).

H = the humification factor, the amount of 'Young' organic N that is transferred into 'Old' organic N (-).

r_p = ploughing coefficient, defined by Andrén and Kätterer (2001) as the 'external influence coefficient' (-).

Model calibration

Soil organic N (and C) content depends on the assigned decomposition rates (k_y and k_o) and the N input level (I). The stable organic N pool is assumed to be comparable to the old organic matter pool from Kätterer and Andrén (1999), k_o = 0.006 is used and the humification factor is set at 0.1.

Hassink (1994) reported 0.1% and 0.15% N as minimum soil organic N values on young grassland after a long period of arable cropping in the layer 0–20 cm for sand and clay, respectively. Related to these contents, soil organic N is set at 3000 and 4000 kg N per ha, for sand and clay respectively. The theoretical maximum of SON in Figure 1 is realised on old permanent grassland, with amounts of SON of 0.21% and 0.42% for sand and clay, respectively in the layer 0–10 cm (Hassink 1994). Assuming these organic N contents over the top layer of 0–20 cm, the total amount of soil organic N is set at 6000 and 12000 kg N per ha for sand and clay, respectively.

Soil Nitrogen Supply on permanent grassland under grazing conditions is about 200 kg N ha^{-1} year^{-1} on sand and clay soils (Vellinga and André 1999). This agrees well with data from immobilisation ranges as found by Whitehead et al. (1990), Hassink and Neeteson (1991) and Hassink (1995b). Annual net input of N on grassland is set at 200 kg ha^{-1}. Annual net N input on arable land is set at 100 kg ha^{-1}.

Verberne et al. (1990) and Hassink (1994) reported lower decomposition rates on clay soils than on sandy soils as a result of physical protection. The overall decomposition rates of $(Out_{y,t}+Out_{o,t})/(Y_{ss}+O_{ss})$, 200/6000 and 200/12000 for sand and clay, respec-

Table 3. Data on soil organic N, C to N ratio, humification factor, N inputs and rate parameters to be used in the ICBM model (Andrén and Kätterer 2001) for simulating C and N release of conversion of permanent grassland to arable land and leys.

Parameter	Sand	Clay	
Soil organic N, minimum	3000	4000	(Hassink 1994)
Soil organic N, maximum	6000	12000	(Hassink 1994)
Input grassland	200	200	(Hassink 1995b; Vellinga and André 1999)
H	0.1	0.1	(Andrén and Kätterer 2001)
C:N-ratio	15	10	(Hassink 1994)
Ratio k_{sand}:k_{clay}	2	1	(Verberne 1990; Hassink 1994; Vellinga and André 1999)
R_p	3	3	(Koornneef 1945; Allison 1973; Whitmore et al. 1992)
K_o	0.006	0.003	(Andrén and Kätterer 2001)
$Y_{t=0}$	600	1000	*Calculated with model simulation*
$O_{t=0}$	2000	4000	*Calculated with model simulation*
Y_{ss}	3333	6667	*Calculated with model simulation*
O_{ss}	2040	4125	*Calculated with model simulation*
K_y	0.06	0.03	*Calculated with model simulation*
Input arable	100	100	*Calculated with model simulation*

Table 4. Data of N losses in stubble and root, extra N uptake and reduced inputs of fertiliser N in rotations of leys with arable crops and bulbs.

Parameter	Value (kg ha^{-1})	Rationale	Reference
$N_{stubble,root}$	300	for permanent grassland and 6 year old ley	Whitehead et al. (1990)
	200	for 3 year old ley	
$N_{uptake,extra}$	25	1 year bulbs	–
	100	3 years arable: $1 \times 50 + 2 \times 25$	
	700	permanent arable in 25 years: $(3 \times 50) + (22 \times 25)$	
Reduced N_{input}	25	In bulbs, every rotation	van Dam (personal communication)
	100	$50 + 2 \times 25$ in 3 arable years	Van Dijk (1997)
	150	$100 + 2 \times 25 = 150$ in years 1–3 after ploughing	

tively, indicate a 2:1 ratio. So, k_o for clay is adjusted to 0.003, k_o for sand is kept at 0.006.

Grassland ploughing enhances release of soil organic N. Results from long term experiments of grassland conversion to arable land show decomposition rates between 5 and 12% (Koornneef 1945; Allison 1973; Whitmore et al. 1992). Thus the net decomposition rate of soil organic matter is about three times faster under arable than under grassland conditions, the value of r_p is set at 3.

Simulation runs to find the decomposition rate k_y and the partitioning between Y and O were carried out for a 300 year period with 100 year grassland on previous arable land, followed by 200 years of arable management. Parameter values were chosen in order to realise a stable model, i.e., the values of Y and O should be about the same at t=0 and t=300 years. The results are shown in Table 3.

Nitrogen from stubble and roots, additional N uptake and reduced fertiliser inputs are summarised in Table 4. Vergeer and Bussink (1999) predicted an additional N demand of about 300 kg N ha^{-1} for grassland renovated in autumn, caused by N losses during the brief fallow period. Ernst and Berendonk (1990) and Adams and Jan (1999) reported greater N losses for late autumn renovation compared with early autumn renovation. A 3:1 ratio is used for N loss by autumn and spring renovation, respectively.

N_2O and CO_2 losses

Nitrogen loss is partly emitted as N_2O. A grass residue emission factor (stubble and roots) of 1.25% is used (IPCC 1997). For released N after ploughing up grassland or grassland in rotations, no specific emission factor has been defined. A combination of emission factors defined for direct and indirect N losses is used: 1.25% for direct emission (equivalent to the emission factor for mineral fertiliser) and 2.5% for indirect N losses by nitrate leaching (IPCC 1997). N_2O is converted to CO_2-equivalents by using the Intergovernmental Panel on Climate Change's GWP of

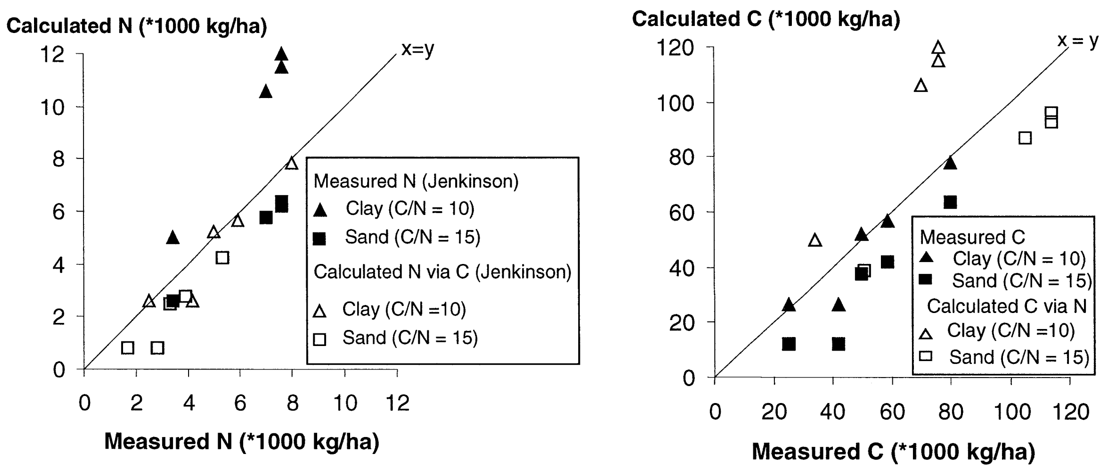

Figure 3. Measured and calculated N (left graph) and C amounts (right graph) from Rothamsted experiments (Jenkinson 1988) and simulations with the ICBM model (Andrén and Kätterer 2001). Closed dots are measured N and C data from the Rothamsted experiments compared with model results. Open dots are calculated N and C from measured C and N data by using C/N ratios of 10 and 15 for sand and clay, respectively compared with model results.

310 for a time horizon of 100 years. Emissions are calculated as follows:

CO_2-emission = C loss * 44/12 (kg)

N_2O-emission = N loss * (0.0125 + 0.025) * 44/28 * 310 (kg CO_2-equivalents)

N_2O emissions of 3% from field measurements with slurry and fertiliser applications were reported by Scanlon and Kiely (2003). Freibauer and Kaltschnitt (2003) developed a fertilizer-based model with the same order of magnitude of N_2O emissions.

Model validation

Data for C and N contents obtained in the long-term Rothamsted experiments (Jenkinson 1988) are used to validate the used ICBM model. The N contents are converted to C and vice versa using C to N ratios of 10 and 15 for sand and clay, respectively. Comparison of simulation results with experimental data results in a correlation (R^2) of 0.72 and 0.60 for N and C, respectively (Figure 3).

Large C losses of 55 to 65% of the total C under pasture are reported in a meta-analysis by Guo and Gifford (2002). Simulation runs with the ICBM model show C losses of 50–60% when old permanent grassland is converted to arable land.

Results

Losses of C and N from conversion

The net C and N losses that occur when converting permanent grassland to arable land or ley-arable rotations are calculated for 50 and 100 year old grassland on sand and clay, respectively, representing accumulated emissions from the moment of ploughing until a new equilibrium is established. The calculated 'actual' and 'potential' N losses are 50–70% higher with clay soils compared with sand (Figure 4). However, with the higher C to N ratio on sand, C losses are similar for sand and clay. Greenhouse gas emissions in terms of CO_2-equivalents from clay soils are still 25% higher on clay than on sand (Figure 4). The total contribution of N to the total CO_2-equivalents emission is 25 and 33% on sand and clay, respectively.

The effect of sward age at ploughing on the sum of actual and potential loss is small. However, ploughing older swards leads to larger actual losses and smaller potential losses, compared to ploughing younger swards (Figure 4).

Actual and potential losses of C and N are less where there is a smaller proportion of arable periods in the rotation and are lowest with grassland renovation, when the arable period is minimal. In the case of a 1 to 6 rotation with bulbs and with renovation, accumulation still continues on relatively young swards (Figure 4).

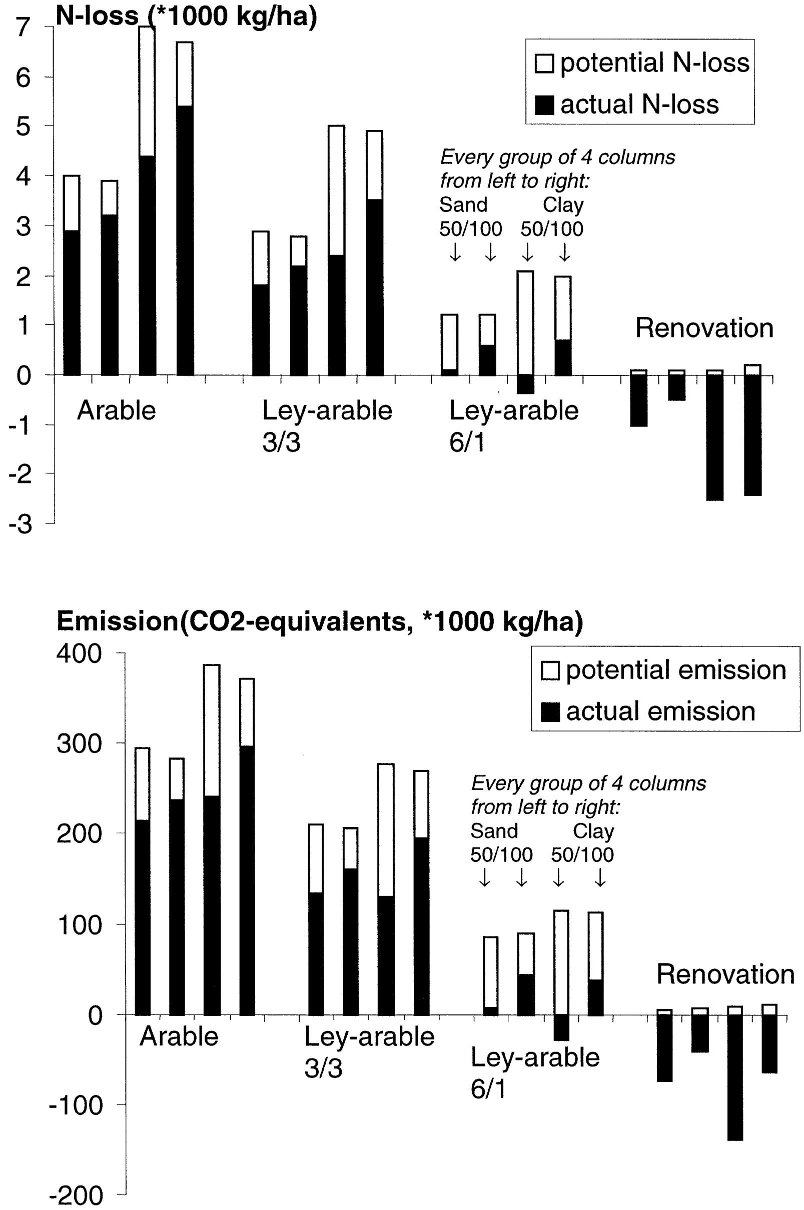

Figure 4. Actual and potential conversion N-losses and emissions in CO_2-equivalents (both in 1000 kg ha^{-1}) when grassland on sand and clay of 50 and 100 years old is ploughed and used as permanent arable land, 3/3 ley-arable rotations, 6/1 ley-bulb rotations and grassland renovation. Per group of 4 columns from left to right: sand of 50 and 100 year old, respectively and clay of 50 and 100 years old, respectively. Numbers are presented as total losses and emissions.

Losses of N in rotation and renovation

For 3/3 ley-arable rotations, average N losses are estimated at 120 kg N ha^{-1} $year^{-1}$ and emissions in CO_2-equivalents are estimated at 2.1 tons ha^{-1} $year^{-1}$ (Table 5). Losses and greenhouse gas emissions in the case of bulbs are 5 times higher due to a longer ley period and a decreased opportunity to utilise the released N, and are 600 kg N ha^{-1} and 11 tons of CO_2-equivalents ha^{-1} $year^{-1}$, respectively. Losses caused by grassland renovation are 100 and 300 kg N ha^{-1} for spring and autumn renovation, respectively. The total greenhouse gas emission in CO_2-equivalents

Table 5. Simulated annual rotational N losses (1000 kg ha^{-1} year^{-1}) and N_2O emissions (expressed as CO_2-equivalents; 1000 kg ha^{-1} year^{-1}) of rotations of ley-arable crops (3 years ley, 3 years arable) and ley-bulbs (6 years ley, 1 year bulbs) and by renovation in autumn and spring (once in 15 years).

	Ley-arable 3/3	Ley-bulbs 6/1	Renovation
	Rotational N loss (1000 kg ha^{-1})		
Sand and clay	0.12	0.60	
Spring renovation			0.1
Autumn renovation			0.3
	Rotational emission (CO_2-equivalents, 1000 kg ha^{-1})		
Sand and clay	2.1	11.0	
Spring renovation			1.8
Autumn renovation			5.5

caused by grassland renovation ranges between 1.8 and 5.5 tons ha^{-1} (Table 5).

Emissions of CO_2 and N_2O from land use changes between 1970 and 2020

Carbon dioxide and N_2O-emissions due to land use changes (Table 2) were calculated on a per hectare basis and presented as amounts emitted over the period between ploughing and a newly established equilibrium condition for soil C and N (Figure 4). The potential C- and N-losses are shown separately. Land use changes before 1970 are not included. To include long-term effects, calculations on C and N dynamics are presented up to 2100 (Figure 5).

Total annual emissions of CO_2 and N_2O increased sharply between 1970 and 1980 from about 0.5 Mton to 1.7 Mton CO_2-equivalents and are predicted to decrease to 1.0 Mton in 2005. Total greenhouse gas emissions remain fairly constant until 2020 and will gradually decrease to about 0.5 Mton in 2090.

Following the initial increment from 0.25 to 0.65 Mton between 1970 and 1980, N_2O-emissions remain fairly constant at 0.5–0.6 Mton CO_2-equivalents. Before the year 2000 N_2O emissions can be mainly attributed to grassland renovation and conversion of grassland to maize. From 2000 on, rotations of ley with arable crops and bulbs gradually become the major emitters. From 1995 until roughly 2050, the anticipated conversion of grassland into ley systems is a major contributor to N_2O-emissions from grassland ploughing.

The CO_2-emissions caused by grassland conversion to arable land and ley management increased sharply from 0.25 Mton in 1970 to 1.1 Mton in 1980. Between 1980 and 2005, annual CO_2-emissions decrease to 0.4 Mton and then remain constant until 2020. From 2020 onwards CO_2-emissions slowly decline to about nil, because no further land use changes after 2020 are used in the calculations.

Potential losses range from 0.4 Mton during the period 1980–2000, to 0.2 Mton during the period after 2020 and represent the potential sink strength of the grassland without the conversion to arable and ley management.

Uncertainty analysis

To analyse the effects of variation and uncertainty in model parameters on the calculated emissions, an uncertainty analysis was conducted (Table 6). Conversion losses are more than proportionally affected by a reduction of k_y and k_o, as a result of a large change in equilibrium levels of soil organic N. Losses due to conversion are less than proportionally affected by an increase of k_y and k_o, changes in r_p or in C to N ratios, the N_2O-emission factor and in the distribution of land use changes over sandy and clayey soils.

Changes in k_y/k_o and C to N ratios have hardly any effect on rotation and renovation losses. They are more strongly affected by changes in r_p. If one assumes that the rate parameter k_y* r_p is decreasing over time (see Yang 1996), then very high emissions in the first year after ploughing are followed by a sharp decline in emissions in later years. Losses due to total conversion are not affected by a variable rate k_y*r_p, but emissions are much greater in the year immediately after ploughing and decline sharply in later years, than with a constant rate parameter. With bulbs and grassland renovation, a variable k_y*r_p will lead to greater losses. Effects are comparable to those using an increased r_p, that is constant over time. In the case of a 3/3 ley-arable rotation, the very high losses in the first year may be compensated by lower losses in the second and third year, indicating that total losses may remain unchanged.

Discussion

Grassland renovation and land use change converting permanent grassland to arable land and leys have led and still lead to significant emissions of greenhouse

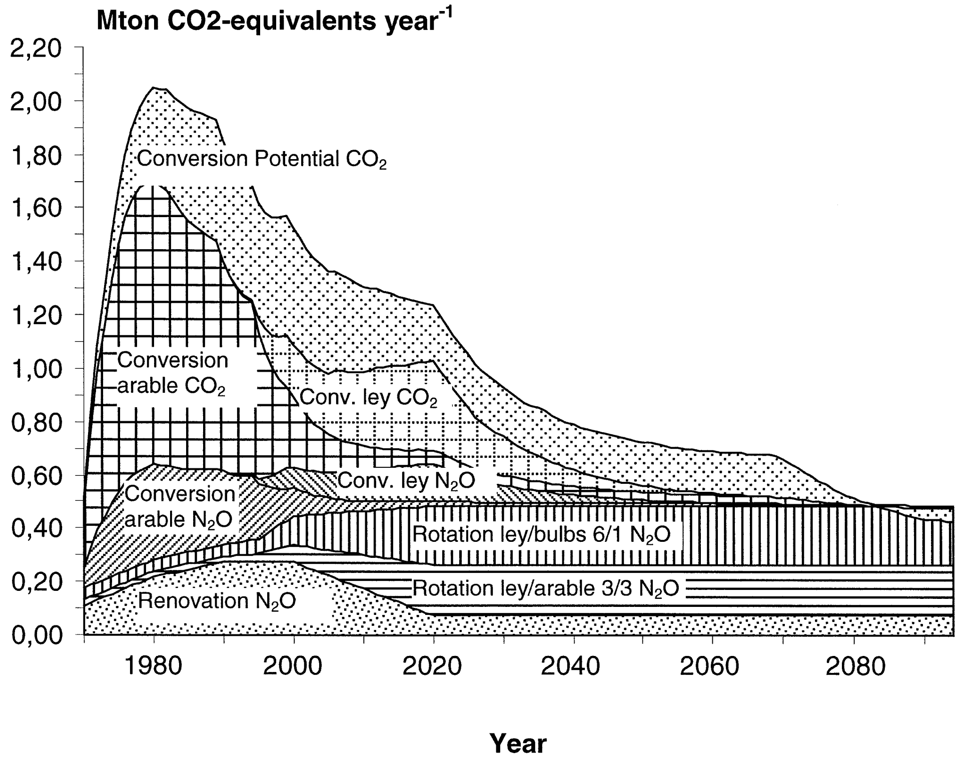

Figure 5. Emission of N_2O by ploughing permanent grassland for renovation and by ploughing ley in rotations, and emission of N_2O and CO_2 caused by conversion of permanent grassland to arable cropping (maize) and ley systems. The actual conversion emission is split up for C and N and in ploughing between 1970 and 2000 for maize and between 1995 and 2020 for ley systems. The potential CO_2 emission is combined for all conversions in the whole period 1970–2020. All emissions are expressed as CO_2-equivalents in Megatons ha^{-1} year^{-1}. Results based on Figure 3, Table 5 and acreage developments of Table 2.

Table 6. Relative changes in CO_2 and N_2O emissions of conversion of permanent grassland, rotations of ley with arable crops and bulbs and grassland renovation, when parameters concerning organic matter dynamics, emission factors and areal developments are 50 and 150% of the standard value, respectively.

Parameter	Standard	Alternative (standard =100%)	Change in emission (standard = 100%)			
			Conversion	Rotation ley arable	Rotation ley bulb	Renovation
Organic matter dynamics						
Rate k_y, k_o	0.06/0.006	50–150	190–67	99–102	97–105	98–103
r_p constant	3	50–150	80–107	81–109	60–130	55–142
C/N ratio- constant over time	15; 10	50–150	65–135	100	100	100
C/N ratio- changing over time	15; 10	50–150	128–72	100	100	100
Emission factors						
N $\rightarrow$ N_2O	3.75%	50–50	86–115	50–150	50–150	50–150
Areal developments						
Sand share in ley rotations	50	50–150	106–94	100	100	100

gases compared to other sources of greenhouse gases from agriculture in the Netherlands. It is estimated that in 2000 approximately 1.7 Mton CO_2-equivalents of which 0.65 Mton from N_2O have been emitted as a result of ploughing grassland. However, these emissions are reported as only N_2O emissions from manure, fertilisers, ground and surface waters are included in the national inventory (Spakman et al. 1997). This is a clear underestimation of the reported agricultural N_2O emissions, estimated at 7.0 Mton CO_2-equivalents in 2003 (Olivier et al. 2003).

As no specific emission factors for grass sward residues or soil organic matter decomposition as a result of ploughing are available in the IPCC approach, the default emission factor of 1.25% for N in crop residues (IPCC 1997) is used. This leads to substantial N_2O emissions (Figure 5). Considerable short-term N_2O losses have been reported by Davies et al. (2001) and Estavillo et al. (2002). More accurate calculations will be possible in the future, as data from experiments and field trials will be available (Dolfing et al. 2004).

Analysis of historical data shows that land use changes as considered in this paper are not unique. Significant land use changes for the 19^{th} century are reported by Priester (1991) and Hoffmann (1999) in the Netherlands and Sweden, respectively. Trienekens (1985) and Whitmore et al. (1992) reported a large shift from grassland to arable land in the period 1940–1945. And today conversion of permanent grassland is continuing (Anonymous 2000a; Guo and Gifford 2002). Thus the presented case is not unique.

Although the datasets, calculations and forecasts in this paper do hold uncertainty and are analysed for Dutch conditions only, it can be concluded that the emissions as a result of land use changes and rotations with leys have been and still are substantial in other countries as well.

To account for such emissions of greenhouse gases as a result of the large scale application of grassland ploughing, it would help to develop either specific emission factors or response functions to be included in simple simulation models such as used in this paper.

Grassland management options to reduce emissions

The 1997 Kyoto agreement calls for lowering greenhouse gas emissions. In light of the significant contribution to CO_2 and N_2O emissions of land use changes and ploughing leys, identification of relevant mitigation options is an important issue. This is even more so because these emissions are not yet accounted for in many national inventories of greenhouse gas emissions.

Of the identified options, effects of less frequent grassland renovation and changing from autumn to spring renovation are already incorporated in the calculations. The introduction of minimum tillage by spike seeding (Roberts et al. 1989), reduced herbicide application (Tenuta and Beauchamp 1996), reduced fertiliser application and reduced grazing (Davies et al. 2001), may reduce greenhouse gas emissions even further. Yet, in the case of persistent weeds and unwanted grasses or a very deteriorated sward, spike seeding and omitting herbicides is not always an effective way to improve sward quality.

Another option is to develop appropriate combinations of ley, arable land and bulbs which will reduce the proportion of ley in the rotation to include more arable crops and bulbs and maintain soil fertility and soil organic matter contents. Such innovations will reduce the need for additional land use changes and as such reduce conversion losses, although the losses per hectare might increase, due to a lower equilibrium soil C status. Losses due to rotations will be reduced due to smaller accumulation during the ley period and a better utilisation of the slower N release during the arable period. To achieve this, dairy farmers, arable farmers and bulb growers will be required to cooperate intensively. Since there are many ways to combine crops in rotations, more precise quantitative effects are difficult to predict.

Spatial planning by governmental actions and policies also provides opportunities for emission reduction, e.g., by concentrating land use changes on sand instead of clay. Relevant is the so-called 'outplacement' of dairy farms to the traditional arable regions, as part of the Dutch policy to extensify dairy farming in heavily stocked and sensitive areas (Anonymous 2000b, c). These outplaced dairy farms require (additional) grassland. Combining this with ley-arable and ley-bulb rotations would decrease the need to plough up permanent grassland, as leys are established on former arable land.

Conclusions

Ploughing grassland for conversion to ley and arable land, ley rotations and for grassland renovation is responsible for considerable N_2O and CO_2 emissions in the Netherlands. In the case of land use change converting permanent grassland to arable land or ley, the emission of CO_2 is greater than that of N_2O (expressed as CO_2-equivalents). Emissions of N_2O and CO_2 are affected by land use changes for a period of more than fifty consecutive years.

The total current N_2O emissions from Dutch agriculture are underestimated with 0.65 Mton year^{-1} because the effects of grassland ploughing are ignored. The widespread use of ley arable systems and the fact that the historical and anticipated land use changes in the Netherlands are not unique emphasise the need for the development of emission factors or response functions that facilitate the transparent reporting of emissions associated with land use changes and the development of mitigation options.

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