Available online at www.sciencedirect.com
SCIENCE DIRECT®
Agriculture, Ecosystems and Environment 112 (2006) 233–240
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Disaggregated greenhouse gas emission inventories from agriculture via a coupled economic-ecosystem model

Henry Neufeldt[a,*], Michael Schäfer[b], Elisabeth Angenendt[b], Changsheng Li[c], Martin Kaltschmitt[a], Jürgen Zeddies[b]

[a] Institute for Energy and Environment, Torgauer Str. 116, D-04347 Leipzig, Germany
[b] Department of Farm Management, University of Hohenheim, D-70593 Stuttgart, Germany
[c] Institute for the Study of Earth, Oceans, and Space, Morse Hall, University of New Hampshire, Durham, NH 03824, USA

Available online 23 November 2005

Abstract

Estimates of regional greenhouse gas emissions from agricultural systems are needed to evaluate possible mitigation strategies with respect to environmental effectiveness and economic feasibility. Therefore, in this study, we used the GIS-coupled economic-ecosystem model EFEM–DNDC to assess disaggregated regional greenhouse gas (GHG) emissions from typical livestock and crop production systems in the federal state of Baden-Württemberg, Southwest Germany. EFEM is an economic farm production model based on linear programming of typical agricultural production systems and simulates all relevant farm management processes and GHG emissions. DNDC is a process-oriented ecosystem model that describes the complete biogeochemical C and N cycle of agricultural soils, including all trace gases.

Direct soil emissions were mainly related to N_2O, whereas CH_4 uptake had marginal influence (net soil C uptake or release was not considered). The simulated N_2O emissions appeared to be highly correlated to N fertilizer application ($R^2 = 0.79$). The emission factor for Baden-Württemberg was 0.97% of the applied N after excluding background emissions.

Analysis of the production systems showed that total GHG emissions from crop based production systems were considerably lower (2.6–3.4 Mg CO_2 eq ha^{-1}) than from livestock based systems (5.2–5.3 Mg CO_2 eq ha^{-1}). Average production system GHG emissions for Baden-Württemberg were 4.5 Mg CO_2 eq ha^{-1}. Of the total 38% were derived from N_2O (direct and indirect soil emissions, and manure storage), 40% were from CH_4 (enteric fermentation and manure storage), and 22% were from CO_2 (mainly fertilizer production, gasoline, heating, and additional feed). The stocking rate was highly correlated ($R^2 = 0.85$) to the total production system GHG emissions and appears to be a useful indicator of regional emission levels.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Greenhouse gas emissions; Coupled economic-ecosystem model; Agricultural production systems; Stocking rates

1. Introduction

In Germany, agriculture contributes nearly 10% to the total greenhouse gas (GHG) emissions (DESTATIS, 2001). Therefore, it is important to develop strategies, which effectively mitigate GHG emissions from agricultural systems. Mitigation strategies imply improved management systems related to technical and organizational innovations and political measures capable of directing agricultural practices towards a more sustainable land use. In particular, GHG mitigation measures that concomitantly aim at increased resource use efficiency, in order to achieve synergistic effects, have the potential of being accepted (Oenema et al., 2001). However, to be successful all GHG mitigation measures strongly rely on farmer acceptance, especially due to the unfamiliarity with the issue of climate change (Oenema et al., 2001). Therefore, next to effectively reducing CO_2, CH_4, and N_2O emissions, the main radiative forcing gases emitted from agricultural systems, mitigation

* Corresponding author. Tel.: +49 341 2434 418; fax: +49 341 2434 433.
E-mail address: henry.neufeldt@ie-leipzig.de (H. Neufeldt).

0167-8809/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2005.08.024

strategies must consider socioeconomic factors. In particular, revenues and social constraints, such as regional habits or traditions, are important to obtain acceptance by farmers.

While measurement of GHG fluxes is feasible at the farm scale, at the regional scale only models allow to estimate GHG emissions from agriculture. However, neither economic nor ecosystem models alone can provide an integrated estimate of the economic and environmental effects of different mitigation options. Therefore, it is necessary to couple economic farm production models with ecosystem models. While the economic model simulates how agricultural policies (e.g. subsidies, laws) and the socioeconomic framework (prices, labor, etc.) influence farmer decisions on management options and land-use intensity in function of expected revenues, the ecosystem model uses the information on land-use distribution and intensity to simulate GHG emissions as a function of climate, soil, and management specific parameters. This approach not only allows for an integrated estimation of regional GHG emissions from farms and agricultural soils but also to ex ante simulate both the economic and environmental effects of different mitigation policies.

On a regional level, so far only Antle et al. (2002) and Schneider and McCarl (2003) have used coupled economic-ecosystem models to evaluate agricultural climate change policies. Antle et al. (2002) coupled the process-oriented CENTURY model to an economic production model to study C sequestration costs. Schneider and McCarl (2003) combined EPIC with an agricultural sector model to investigate land management adaptation to different US carbon price policies. Recently, Pacini et al. (2004) and Münier et al. (2004) used economic-ecosystem modeling to evaluate differences between conventional and organic farming systems in Tuscany, and to assess the effects of extensification on biotope fragmentation at landscape level in Denmark, respectively. All described modeling approaches showed a high potential for evaluating the environmental effectiveness and the economic viability of policy and management options for a wide range of applications.

In this study, we describe how the economic farm production model EFEM (Angenendt, 2003) was coupled with the process-oriented ecosystem model DNDC (Li, 2000) to simulate disaggregated agricultural GHG emissions from the federal state of Baden-Württemberg, Southwest Germany.

2. Material and methods

2.1. EFEM

The Economic Farm Emission Model (EFEM) is an economic farm production model that simulates crop and livestock production systems (Angenendt, 2003; Schäfer et al., 2004). The model is based on linear programming of typical agricultural production systems at farm level and simulates all relevant farm management processes including mechanization, animal and crop production, animal housing, manure management, farm N cycle, and a complete business calculation (Fig. 1). The mathematical up-scaling algorithm described in Kazenwadel and Doluschitz (1998) is used to

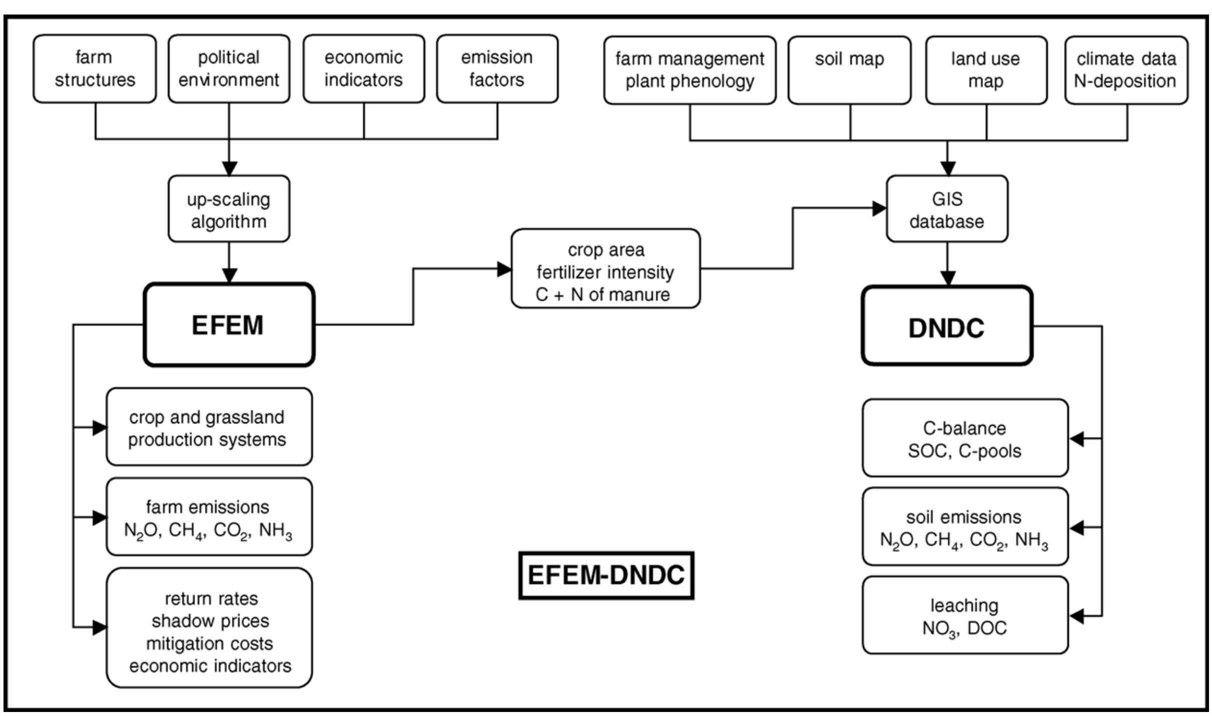

Fig. 1. Flow diagram of EFEM–DNDC.

account for a regionally representative distribution of the production systems. Input parameters include statistical data of the production systems, such as land area distribution, planted crops, number and type of animals, N fertilization, farm structures, costs, and revenues (KTBL, 1993, 2000, 2002; MLR, 1998; ZMP, 2001a,b,c,d; DESTATIS, 2001), indicators of the political environment, such as subsidies and laws (MLR, 1997, 2000, 2001; BMVEL, 2002a,b), and emission factors (IPCC, 1997; Döhler et al., 2002; Bareth and Angenendt, 2003). Details of the different regional groups (RGs), which are composed of several adjacent municipals with similar environmental conditions, and typical production systems in Baden-Württemberg are given in Table 1.

The model simulates farm emissions of CO_2, CH_4, N_2O, and NH_3 from fossil fuels, mineral fertilizers, additional feed, ruminant enteric fermentation, and manure management, and provides economic parameters, such as gross margin, shadow prices, and mitigation costs.

2.2. DNDC

The DeNitrification DeComposition model (DNDC) is a process-oriented agroecosystem model that simulates the entire biogeochemical C and N cycle of agricultural soils (Li, 2000). The model requires information on land use and management, plant phenology, soil characteristics, N deposition, and climate (Fig. 1). Regional datasets were prepared using the soil survey map of Baden-Württemberg at a scale of 1:200,000 (LGRB, 2002), the CORINE land cover map at a scale of 1:100,000 (DESTATIS, 1997), an interpolated climate map based on daily temperature and precipitation data for the year 2000 from all weather stations in Baden-Württemberg (DWD, 2002), and the borders of the RGs. All maps were processed and merged using ArcView GIS (ESRI, 1996). A detailed description of the dataset preparation is given in Neufeldt (2005). All files necessary to run DNDC version 8.0 in the regional mode (DNDC, 2002) were prepared based on the attributes of the datasets. Planting, harvesting, and fertilization dates were derived from plant phenological data of the region (DWD, 2003) and expert knowledge. The default crop growth parameters were adjusted to produce realistic yields. To better reflect the soils of the region, the default soil hydraulic and textural properties were adapted based on LGRB (2002).

DNDC simulates a full carbon (C) and nitrogen (N) balance, including different C and N pools, and the emissions of all relevant trace gases from soils (Li, 2000). However, for this study only CH_4 and N_2O fluxes were considered, because the DNDC version used did not correctly model the proportions of different plant compartments (roots, shoots, grain). The modeling of the partitioning of assimilates is essential, since it alters the litter and root inputs to the soil and thus the C balance. DNDC addressed the emission range within the homogeneous map polygons (equivalent to the number of datasets) by simulating each polygon with an upper and a lower value for soil C, pH, texture, and bulk density. These values were derived from the range given in the attributes of the soil survey map (LGRB, 2002).

2.3. Model coupling

DNDC requires information on land area and N fertilizer rates (mineral and organic) of the different crops for each polygon but EFEM only provides this information in aggregated form for the RGs. The land areas and fertilizer rates of the different crops were spatially distributed based on the georeferenced CORINE (DESTATIS, 1997) land-use

Table 1
Agricultural land area, N fertilizer input (N_{min}, N_{org}), stocking rates per livestock unit[a], gross margins, and total GHG emissions of the regional groups (RG) and agricultural production systems in Baden-Württemberg

Code	Agricultural land area[b] (km^2)					N_{min} (kg N ha^{-1})	N_{org} (kg N ha^{-1})	Livestock (LU ha^{-1})	Gross margin (€ ha^{-1})	GHG (kg CO_2 eq ha^{-1})
	Total	Cropland	Grassland	Vineyards	Orchards					
RG1	2377	1781	455	105	36	104	28	0.43	1290	4062
RG2	2033	1235	521	116	160	84	26	0.42	1620	3842
RG3	1215	217	988	4	7	29	54	0.88	1020	4305
RG4	2320	1184	1136	0	0	59	41	0.64	950	3676
RG5	536	49	484	0	3	20	104	1.54	1890	8165
RG6	2514	1635	870	0	9	84	65	0.96	1510	5883
RG7	1769	852	911	1	5	63	53	0.84	1160	4439
RG8	1917	1542	361	10	3	104	47	0.68	1330	4120
Baden-Württemberg	14681	8495	5726	236	223	77	47	0.71	1310	4504
Fruit/grapes	696	231	6	236	223	112	1	0.01	3860	2590
Cash crops	3124	3124	0	0	0	134	2	0.02	690	2940
Cash crops/poultry	819	819	0	0	0	141	3	0.05	650	3396
Cattle/sheep	8444	2723	5721	0	0	42	66	1.03	1260	5198
Pigs	1599	1599	0	0	0	99	75	1.01	1990	5307

[a] One livestock unit (LU) is equivalent to 500 kg live weight.
[b] Luvisols (31%), Cambisols (19%), Vertisols (12%), Leptosols (11%), Regosols (9%), Fluvisols (6%), Gleysols (5%), Planosols (2%), Histosols (2%), Anthrosols (1%), and Podzols (1%). *Source*: Neufeldt (2005).

categories. This database interface provided DNDC with the necessary information on crop area and N application rates for each dataset (Fig. 1).

However, prior to coupling the two models via the database interface, inconsistencies between the land areas in EFEM and CORINE had to be corrected to properly assign crop areas and fertilizer amounts to the polygons. The inconsistencies occurred because crop areas in EFEM are based on the official agricultural accounting (SLBW, 2000), which registered a considerably lower amount of agricultural lands in Baden-Württemberg (14,681 km^2) than CORINE (18,683 km^2). A correction factor based on the ratio between the different land-use categories in CORINE and EFEM was applied to account for the inconsistencies. A detailed discussion on the effects of the correction procedure is given in Neufeldt (2005).

There are some limitations to the spatial distribution of annual crops within each RG since EFEM does not provide georeferenced information, and CORINE only distinguishes between cropland, grassland, vineyards, and orchards. Hence, the exact location of different annual crops within the RGs is not known, and it was therefore necessary to assume that all annual crops found in any RG occurred on all of its cropland polygons.

The regional mode of DNDC8.0 does not account for grazing. This limitation was addressed by assuming that the corresponding amounts of N from animal droppings in each RG were added as manure. The model version used also did not account for varying manure application rates. This may lead to inconsistent manure inputs for specific crops, but on the average the input reflects the RGs' activity data correctly.

2.4. Model validation

EFEM has been validated in Schäfer et al. (2004) by comparing the modeled distribution of different production systems within each RG with official agricultural accounting (SLBW, 2000). The average coefficient of variation was 10% for the production systems and 3% for the RGs. Table 2 compares the modeled crop distribution on cropland with data from SLBW (2000), suggesting that EFEM simulates land-use distribution and thus the driving forces behind agricultural decision-making processes quite well. Grassland, vineyards, and orchards were not considered here, because these categories are not changed in the short-term.

DNDC was validated for N_2O only, because the impact of CH_4 on GHG emissions from soil is negligible. Fig. 2 shows a scatterplot of measured versus simulated annual N_2O emissions from a series of long-term field studies in Germany (Kaiser et al., 1998a,b; Schmädeke, 1998; Schmidt, 1998; Kammann, 2001; Ruser et al., 2001; Teepe et al., 2000; Sehy et al., 2002). The studies covered all relevant crops (except for vineyards and orchards) planted in Baden-Württemberg. The scatterplot shows a close correlation between measured and simulated emissions ($R^2 = 0.73$). However, the regression equation given in Fig. 2 indicates that DNDC generally underestimates N_2O emissions. Therefore, all simulated soil N_2O emissions were adjusted to the regression equation to compensate for the underestimation.

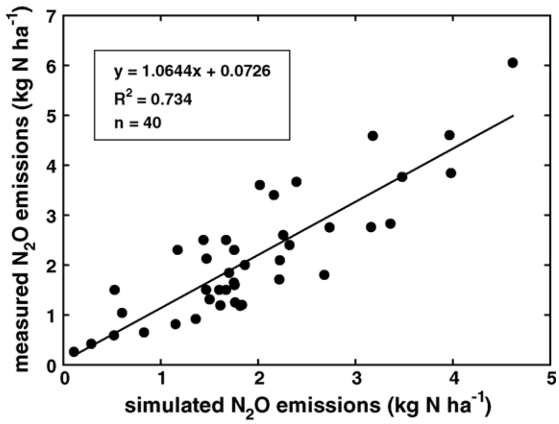

Fig. 2. Comparison of measured annual fluxes of N_2O from grassland and the most common crops on mineral soils with simulated emissions using DNDC.

3. Results and discussion

3.1. Soil GHG fluxes and N fertilization

Total N input rates ranged from around 250 kg N ha^{-1} for sugar beet and silage crops to 41 kg N ha^{-1} for set-aside (Table 3). The N input levels were based on crop requirements and the average manure production. However, set-aside only received N fertilizer because DNDC did not allow varying organic N application rates for different crops planted on the same polygon. Grassland did not receive any mineral N and comparatively low organic N amendments, because the average stocking rates in Baden-Württemberg are low enough (0.71 LU ha^{-1}) to be maintained at a low grassland productivity and thus for organic N to cover nutrient requirements. Vineyards and orchards were fertilized with mineral N only, because the average fruit and grape producing farms do not contain any livestock. The

Table 2
Comparison of the crop distribution (%) on cropland in Baden-Württemberg from modeling with EFEM and from the official agricultural accounting (SLBW, 2000)

	Winter cereals	Spring cereals	Set-aside	Silage crops	Rapeseed	Root crops
EFEM	43.4	26.1	9.4	9.2	8.3	3.6
Agricultural accounting	41.3	26.9	7.9	12.2	8.1	3.6

Table 3
Modeled N_2O, CH_4, and total GHG[a] emissions, mineral and organic N fertilization rates (N_{min}, N_{org}), and N_2O emission factors[b] (EF_{N_2O}) of different crops in Baden-Württemberg

Crops	Land area[c] (km^2)	N_2O (kg N ha^{-1})	CH_4 (kg C ha^{-1})	GHG (kg CO_2 eq ha^{-1})	N_{min} (kg N ha^{-1})	N_{org} (kg N ha^{-1})	EF_{N_2O} (%)
Winter cereals[d]	4501	2.83 ± 0.57	−1.37 ± 0.99	1340 ± 305	144	42	1.17
Spring cereals [e]	2695	1.94 ± 0.49	−1.24 ± 0.96	910 ± 266	107	42	0.86
Set-aside	974	0.89 ± 0.27	−1.25 ± 0.96	399 ± 158	0	41	0.56
Silage crops [f]	935	3.34 ± 0.64	−1.17 ± 0.84	1594 ± 335	195	52	1.09
Rapeseed (*Brassica napus* ssp. *oleifera*)	863	2.17 ± 0.39	−1.25 ± 0.94	1022 ± 216	154	41	0.77
Sugar beet (*Beta vulgaris* ssp. *rapacea*)	292	2.53 ± 0.48	−1.04 ± 0.93	1203 ± 260	221	30	0.75
Potatoes (*Solanum tuberosum*)	98	2.11 ± 0.42	−0.55 ± 0.52	1012 ± 219	166	40	0.70
Grassland [g]	6992	1.17 ± 0.64	−1.53 ± 1.30	527 ± 348	0	56	0.66
Grapes (*Vitis vinifera*)	858	1.81 ± 0.60	−1.49 ± 0.97	840 ± 319	80	0	1.21
Fruits[h]	475	1.45 ± 0.79	−1.43 ± 1.30	666 ± 421	60	0	1.68
Baden-Württemberg	18683	1.89 ± 0.57	−1.39 ± 1.09	882 ± 308	76	45	0.97

[a] GHG = N_2O-N × 44/28 × 310 + CH_4-C × 16/12 × 21; calculation based on emission factors from IPCC (1997).
[b] EF_{N_2O} = (N_2O-$N_{emission}$ − N_2O-$N_{background}$)/(N_{min} + N_{org}) × 100.
[c] Land area according to CORINE (DESTATIS, 1997). Note the difference to Table 1, which is based on the official agricultural accounting (SLBW, 2000).
[d] Includes winter wheat (*Triticum aestivum*), winter barley (*Hordeum vulgare*), and rye (*Secale cereale*).
[e] Includes spring wheat (*Triticum aestivum*), spring barley (*Hordeum vulgare*), oats (*Avena sativa*), and grain maize (*Zea mays*).
[f] Includes silage maize (*Zea mays*) and grass (*Lolium* spp., *Festua pratensis*, *Dactylis glomerata*)/clover (*Trifolium* spp.) silage.
[g] Mainly ryegrass (*Lolium perenne*), fescue (*Festuca pratensis*), timothy-grass (*Phleum pretense*), cocksfoot grass (*Dactylis glomerata*), and white clover (*Trifolium repens*).
[h] Mainly apples (*Malus domestica*) and some pears (*Pyrus communis*), plums (*Prunus domestica*), and cherries (*Prunus avium*).

small discrepancy between Tables 1 and 3 for mineral and organic N added to total Baden-Württemberg (77 + 47 and 76 + 45 kg N ha^{-1}, respectively) is due to the differences between the areas covered by different land-use categories in the official agricultural statistics (SLBW, 2000) and CORINE (DESTATIS, 1997).

Average N_2O emissions from Baden-Württemberg were 1.89 (±0.57) kg N_2O-N ha^{-1} after correcting the simulation results for the validated emissions. When considering the average background emission of 0.72 (±0.26) kg N_2O-N ha^{-1}, established with DNDC by simulating all datasets as ‘‘fallow’’, modeled N_2O emissions were 31% lower than the UBA (2002) estimate for Baden-Württemberg (1.7 kg N_2O-N ha^{-1}), using the IPCC method (1997). Since EFEM obtained the same value as UBA (2002) when applying the IPCC emission factors to the region, only soil specific factors can explain the difference. This emphasizes the need for large-scale soil maps as input data to reliable process-oriented ecosystem models, in order to address GHG emissions from soils at sub-national scales. Similarly, Freibauer (2003) found considerable discrepancies between N_2O emissions from soils using the IPCC method and based on a regression model that was especially designed for European regions, suggesting that the IPCC method may only be valid at continental scales.

Nitrous oxide emissions ranged from less than 1 kg N_2O-N ha^{-1} to more than 3 kg N_2O-N ha^{-1}, and showed a close correlation to total N fertilizer application rates ($R^2 = 0.79$). This is a well-established relationship shown, e.g. by Kaiser and Ruser (2000), who compared several long-term measurement trials of the most frequently planted crops in Germany. After subtracting the background emissions (0.66, 0.80, 0.84, and 0.44 kg N_2O-N ha^{-1} for cropland, grassland, vineyards, and orchards, respectively), emission factors for N_2O (EF_{N_2O}) were between 0.56% for set-aside and 1.68% for orchards. Emission factors published in Kaiser and Ruser (2000) varied strongly between crops and sites, ranging from 0.53 to over 15%, but the average EF_{N_2O} for the most important crops were between 1 and 2.4%. Kaiser and Ruser (2000) did not, however, consider background emissions, suggesting that the range modeled by DNDC is realistic. For Baden-Württemberg EF_{N_2O} was 0.97%, which is between the IPCC value of 1.25% (IPCC, 1997), and the value of 0.77%, derived for German soils based on 88 long-term field trials (Lægreid and Aastveit, 2002). Since N_2O emissions vary considerably from one year to another due to different climatic conditions, simulations considering a series of years would be necessary to estimate long-term EF_{N_2O}. The obtained results may therefore only be valid for the year 2000. The low EF_{N_2O} of Lægreid and Aastveit (2002) however, which is based on a multi-year analysis of N_2O emissions, indicates that the IPCC value is probably, nevertheless, too high for the study region.

Methane fluxes ranged from −0.55 (±0.52) kg CH_4-C ha^{-1} to −1.53 (±1.30) kg CH_4-C ha^{-1} and showed no clear correlation to any of the input parameters (Table 3). The large flux ranges for each crop indicate that the amplitude of soil input parameters may be important, especially texture, because it determines the soil moisture content (Li et al., 2002). Average CH_4 uptake for Baden-Württemberg was 1.39 (±1.09) kg CH_4-C ha^{-1}. Freibauer (2003) reported an uptake of only 0.5 (±0.5) kg CH_4-C ha^{-1} for European agricultural soils based on 66 long-term field trials, the average value presented here being about 60% higher. On the other hand, Boeckx and Van Cleemput (2001)

Table 4
GHG emissions (kg CO_2 eq ha^{-1}) from typical agricultural production systems for different emission sources in Baden-Württemberg

Management systems	Fruit/grapes	Cash crops	Cash crops/poultry	Cattle/sheep	Pigs	Baden-Württemberg
N_2O soil direct[a]	783 (30)	1016 (35)	1269 (38)	789 (15)	1284 (24)	918 (20)
N_2O soil indirect[b]	307 (12)	395 (13)	442 (13)	449 (9)	703 (13)	458 (10)
N_2O others[c]	420 (16)	531 (18)	590 (18)	236 (5)	401 (8)	345 (8)
CH_4 ruminants	31 (1)	16 (1)	29 (1)	2452 (47)	150 (3)	1433 (32)
CH_4 manure management	9 (0)	40 (1)	73 (2)	623 (12)	368 (7)	411 (9)
CH_4 soil	−39 (−2)	−37 (−1)	−37 (−1)	−41 (−1)	−36 (−1)	−39 (−1)
CO_2 plant production[d]	1059 (41)	953 (32)	956 (28)	403 (8)	940 (18)	640 (14)
CO_2 animal husbandry[e]	10 (0)	17 (1)	38 (1)	277 (5)	1488 (28)	328 (7)
Total	2581 (100)	2932 (100)	3359 (100)	5186 (100)	5299 (100)	4494 (100)

Values in parenthesis are percent of total emissions within the production systems.
[a] Includes emissions from atmospheric deposition because the direct soil N_2O emissions are modeled by DNDC.
[b] Leaching and runoff.
[c] Manure storage and fertilizer production.
[d] Fertilizer production, gasoline, pesticides, and drying.
[e] Additional feed and energy input.

estimated an uptake of 1.7 kg CH_4-C ha^{-1} for agricultural soils of Germany, suggesting comparable results. Nevertheless, since methane uptake by soils only leads to a negligible reduction of GHG emissions, total soil GHG emissions were nearly completely related to N_2O emissions.

3.2. Production system GHG emissions

Average GHG emissions from agriculture were 4.5 Mg CO_2 eq ha^{-1}, 38% of which came from N_2O, 40% from CH_4, and 22% from CO_2 (Table 4). According to the official statistics (SLBW, 2003), agricultural N_2O and CH_4 emissions in Baden-Württemberg for the year 2000 were 1.6 Mg CO_2 eq ha^{-1} and 2.1 Mg CO_2 eq ha^{-1}, respectively, suggesting good agreement with the model results. CO_2 emissions from agriculture are not specified in SLBW (2003).

Cash crop and crop/poultry farms emitted 2.9 and 3.4 Mg CO_2 eq ha^{-1}, respectively (Table 4). The systems showed a rather similar distribution of GHG emissions since poultry only has a small share of the total production (Table 1). Nitrous oxide accounted for 66–68% of total GHG emissions, close to three quarters of which were derived from direct and indirect soil emissions while the rest was related to fertilizer production and manure storage. Carbon dioxide contributed to total GHGs with 29–33%, mainly coming from fertilizer production, gasoline, pesticides, and drying. Methane only had share of 1–2% of total GHGs. The results are comparable with those presented by Löthe (1999), who estimated 2.6 Mg CO_2 eq ha^{-1} for a cash crop farm in Kraichgau (a region in the northwest of RG1) after recalculation with IPCC (1997) emission factors and global warming potentials.

Fruit and grape producing farms showed the lowest GHG emissions with 2.6 Mg CO_2 eq ha^{-1}. The emission distribution was similar to that of crop and crop/poultry farms because no animals are kept (Table 1). However, the proportion of CO_2 was higher because of increased gasoline use, whereas soil N_2O emissions were lower due to lower N fertilizer rates.

Compared to systems dominated by crop production, GHG emissions from livestock production systems were nearly twice as high, ranging from 5.2 to 5.3 Mg CO_2 eq ha^{-1}. In cattle and sheep farms (95% cattle), 59% of GHG emissions were related to CH_4 from enteric fermentation and, to a lesser extent, manure management. Nitrous oxide emissions were lower than those from crop producing systems, mainly because of reduced emissions from grasslands and fertilizer production. Carbon dioxide emissions were also lower than in crop production systems, owing to reduced emissions from fertilizer production, gasoline, pesticides, and crop drying, whereas CO_2 emissions from animal husbandry exceeded those of crop systems by an order of a magnitude. The results correspond well to GHG emissions reported for different dairy production systems in Baden-Württemberg, ranging from 4.3 to 13.2 Mg CO_2 eq ha^{-1} (Wetterich and Haas, 1999; Müller, 2002; Angenendt, 2003).

Pig fattening farms were the most GHG intensive production systems in Baden-Württemberg. From these farms 46% of GHGs were related to CO_2, predominantly coming from additional feed and heating of animal housings, and CO_2 emissions from plant production. Nitrous oxide emissions were the highest of all production systems and contributed to total GHGs with 45%. Soil N_2O emissions clearly predominated due to the high N fertilizer input. Methane emissions contributed with 9% to GHG emissions, coming predominantly from manure management. A pig fattening farm in Kraichgau described by Löthe (1999) only emitted 3.5 Mg CO_2 eq ha^{-1} but the results may not be comparable since EFEM estimated 5.1 Mg CO_2 eq ha^{-1} for the farm parameters given.

3.3. Regional GHG emissions

GHG emissions varied strongly between the RGs, ranging from 3.7 Mg CO_2 eq ha^{-1} in RG4 to 8.2 Mg CO_2 eq ha^{-1} in RG5. The high emissions in RG5, the Allgäu region, are related to high stocking rates (Table 1).

This is consistent with results of Trunk (1995) and Bareth and Angenendt (2003), who estimated an average of 8.3 and 8.6 Mg CO_2 eq ha^{-1}, respectively, for intensive dairy farms in that region. Emissions in RG6 were slightly lower, because, next to intensive cattle and pig producing farms, crop production is important. In the regions with average GHG emissions (RG3, RG7, RG8) mixed crop and livestock production systems prevail. The regions with low emissions are characterized by low stocking rates due to crop, fruit, and grape production systems (RG1, RG2) or due to extensive grazing systems (RG4).

The different regional emission levels were thus highly correlated to the stocking rates per livestock unit ($GHG = 3890 \times LU\ ha^{-1} + 1696$; $R^2 = 0.85$; $p < 0.01$). Based on these results, stocking rates seem to be a good indicator of overall agricultural GHG emissions in Baden-Württemberg, for they are easily available from agricultural statistics and can explain most of the emission variation. Further research is necessary to verify whether the regression equation can be directly applied to other regions in Germany and Europe or whether adaptations are required due to regional differences in land-use systems and intensity.

4. Conclusions

According to DNDC, N_2O is responsible for most soil GHG emissions, and is highly correlated to N fertilization. Due to the significance of soil factors for N_2O emissions, high resolution soil maps are required to adequately address GHG emissions at sub-national scales.

Analysis of the production systems with EFEM shows that the distribution of GHGs strongly depends on the presence of livestock, and that stocking rates appear to be a useful indicator of total GHG emission levels.

Coupling the economic farm production model EFEM with the process-oriented ecosystem model DNDC hence allows for a realistic simulation of disaggregated soil, production system, and regional GHG emissions from agricultural systems. Simulations of different scenarios will therefore allow to evaluate the environmental effectiveness and the economic viability of possible GHG mitigation measures at regional scales.

Acknowledgements

This study was carried out within grants KA 895/3-1 and ZE 164/17-1 of the German Research Foundation (DFG).

References

Angenendt, E., 2003. Entwicklung eines ökologisch-ökonomischen Models für extensive Futterbaubetriebe zur Abbildung der Emissionen klimarelevanter Gase aus der Landwirtschaft und zur Bewertung von Verminderungsstrategien. Agrimedia Verlag, Bergen.

Antle, J., Capalbo, S., Mooney, S., Elliott, E.T., Paustian, K.H., 2002. Sensitivity of carbon sequestration costs to soil carbon rates. Environ. Pollut. 116, 413–422.

Bareth, G., Angenendt, E., 2003. Ökonomisch-ökologische Modellierung von klimarelevanten Emissionen aus der Landwirtschaft auf regionaler Ebene. Berichte über Landwirtschaft, Zeitschrift für Agrarpolitik und Landwirtschaft 81, 29–56.

Boeckx, P., Van Cleemput, O., 2001. Estimates of N_2O and CH_4 fluxes from agricultural lands in various regions in Europe. Nutr. Cycl. Agroecosyst. 60, 35–47.

BMVEL, 2002a. Agenda 2000—Tierprämien. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft, Berlin.

BMVEL, 2002b. Agenda 2000—Pflanzlicher Bereich, Agrarumweltmaßnahmen. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft, Berlin.

DESTATIS, 1997. Daten zur Bodenbedeckung für die Bundesrepublik Deutschland. Statistisches Bundesamt, Wiesbaden.

DESTATIS, 2001. Statistisches Jahrbuch 2001. Statistisches Bundesamt, Wiesbaden.

Döhler, H., Eurich-Menden, B., Dämmgen, U., Osterburg, B., Lüttich, M., Bergschmitt, A., Berg, W., Brunsch, R., 2002. Ammoniak Emissionsinventar der deutschen Landwirtschaft und Minderungsszenarien bis zum Jahr 2010. Umweltbundesamt Texte 05/02, Berlin.

DNDC, 2002. User's Guide for the DNDC Model. University of New Hampshire, Durham.

DWD, 2002. Klimatologische Daten im DWD. Deutscher Wetterdienst, Offenbach.

DWD, 2003. Die Phänologie im DWD. Deutscher Wetterdienst, Offenbach.

ESRI, 1996. ArcView GIS. Environmental Systems Research Institute Inc., Redlands, CA.

Freibauer, A., 2003. Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. Eur. J. Agron. 19, 135–160.

IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, Intergovernmental Panel on Climate Change, Paris.

Kaiser, E.A., Ruser, R., 2000. Nitrous oxide emissions from arable soils in Germany—an evaluation of six long-term field experiments. J. Plant Nutr. Soil Sci. 163, 249–260.

Kaiser, E.A., Kohrs, K., Kücke, M., Schnug, E., Heinemeyer, O., Munch, J.C., 1998a. Nitrous oxide release from arable soil: importance of N-fertilization, crops and temporal variation. Soil Biol. Biochem. 30, 1555–1563.

Kaiser, E.A., Kohrs, K., Kücke, M., Schnug, E., Munch, J.C., Heinemeyer, O., 1998b. Nitrous oxide release from arable soil: importance of perennial forage crops. Biol. Fertil. Soils 28, 36–43.

Kammann, C., 2001. Die Auswirkung steigender atmosphärischer CO_2 Konzentrationen auf die Flüsse der Klimaspurengase N_2O und CH_4 in einem Grünlandökosystem. Ph.D. Thesis, Justus-Liebig University, Giessen.

Kazenwadel, G., Doluschitz, R., 1998. Modellierung auf Regionsebene durch Hochrechnung auf der Basis einzelbetrieblicher Kennzahlen. Z. Agrarinformatik 1, 2–8.

KTBL, 1993. Spezielle Betriebszweige in der Tierhaltung. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt.

KTBL, 2000. Taschenbuch Landwirtschaft 2000/2001. Daten für die Betriebskalkulation in der Landwirtschaft, Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt.

KTBL, 2002. Betriebsplanung Landwirtschaft 2002/2003. Daten für die Betriebskalkulation in der Landwirtschaft. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt.

Lægreid, M., Aastveit, A.H., 2002. Nitrous oxide emissions from field-applied fertilizers. In: Petersen, S.O., Olesen, J.E. (Eds.), Greehouse Gas Inventories for Agriculture in the Nordic Countries. DIAS Report, Plant Production, vol. 81, pp. 122–134.

LGRB, 2002. Bodenübersichtskarte von Baden-Württemberg 1:200000. Landesamt für Geowissenschaften und Rohstoffe von Baden-Württemberg, Freiburg.

Li, C.S., 2000. Modeling trace gas emissions from agricultural ecosystems. Nutr. Cycl. Agroecosyst. 58, 259–276.

Li, C., Qiu, J., Frolking, S., Xiao, X., Salas, W., Moore, B., Boles, S., Huang, Y., Sass, R., 2002. Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000. Geophys. Res. Lett. 29, 1972 doi: 10.1029/2002GL015370.

Löthe, K., 1999. Strategien zur Verminderung von Gasemissionen aus verschiedenen landwirtschaftlichen Betriebssystemen. Wissenschaftsverlag Vauk, Kiel.

MLR, 1997. Marktentlastung und Kulturlandschaftsausgleich (MEKA): Programm und Akzeptanz. Ministerium für Ernährung und ländlichen Raum Baden-Württemberg, Stuttgart.

MLR, 1998. Landwirtschaftliche Betriebsverhältnisse und Buchführungsergebnisse. Wirtschaftsjahr 1997/98. Heft 47. Ministerium für Ernährung und ländlichen Raum Baden-Württemberg, Stuttgart.

MLR, 2000. Richtlinie des Ministeriums Ländlicher Raum zur Förderung der Erhaltung und Pflege der Kulturlandschaften und von Erzeugungspraktiken, die der Marktentlastung dienen (Marktentlastungs- und Kulturausgleich MEKA II) vom 12.09.2000. Ministerium für Ernährung und ländlichen Raum Baden-Württemberg, Stuttgart.

MLR, 2001. Landwirtschaftliche Betriebsverhältnisse und Buchführungsergebnisse, Wirtschaftsjahre 2000/01. Heft 50. Ministerium für Ernährung und ländlichen Raum Baden-Württemberg, Stuttgart.

Müller, H.-U., 2002. Strategien zur Verminderung der Gasemissionen aus der Milchviehhaltung in einer intensiven Grünlandregion. Shaker Verlag, Aachen.

Münier, B., Birr-Pedersen, K., Schou, J.S., 2004. Combined ecological and economic modeling in agricultural land use scenarios. Ecol. Model. 174, 5–18.

Neufeldt, H., 2005. Carbon stocks and sequestration potentials of agricultural soils in the federal state of Baden-Württemberg, Southwest Germany. J. Plant Nutr. Soil Sci. 168, 202–211.

Oenema, O., Velthof, G., Kuikman, P., 2001. Technical and policy aspects of strategies to decrease greenhouse gas emissions from agriculture. Nutr. Cycl. Agroecosyst. 60, 301–315.

Pacini, C., Wossink, A., Giesen, G., Huirne, R., 2004. Ecological-economic modeling to support multi-objective policy making: a farming systems approach implemented for Tuscany. Agr. Ecosyst. Environ. 102, 349–364.

Ruser, R., Flessa, H., Schilling, R., Beese, F., Munch, J.C., 2001. Effect of crop-specific field management and N fertilization on N_2O emissions from a fine-loamy soil. Nutr. Cycl. Agroecosyst. 59, 177–191.

Schäfer, M., Angenendt, E., Neufeldt, H., Zeddies, J., 2004. Modellierung klimarelevanter Emissionen aus der Landwirtschaft Baden-Württembergs. Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus 39, 221–230.

Schmädeke, F., 1998. Lachgas- und Methanflüsse eines Gley-Auenbodens unter dem Einfluß einer Rapsfruchtfolge und in Abhängigkeit von der N-Düngung. Ph.D. Thesis, Georg-August University, Göttingen.

Schmidt, U., 1998. Einfluß von Bewirtschaftungsmaßnahmen und Umweltfaktoren auf Lachgas (N_2O)-Emissionen aus landwirtschaftlich genutzten Lößböden. Ph.D. Thesis, University of Hohenheim, Stuttgart.

Schneider, U.A., McCarl, B.A., 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. Environ. Resour. Econ. 24, 291–312.

Sehy, U., Ruser, R., Kaiser, E.A., Munch, J.C., 2002. Auswirkungen der Nutzungssysteme auf die Flüsse des klimarelevanten Spurengases N_2O von Ackerböden. Jahresbericht für Forschungsverband Agrarökosysteme München, GSF, Neuherberg.

SLBW, 2000. Sonderauswertung Landwirtschaftszählung 2000. Statistisches Landesamt Baden-Württemberg, Stuttgart.

SLBW, 2003. Statistische Berichte Baden-Württemberg: Emissionen klimarelevanter Gase (CO_2, CH_4, N_2O) in Baden-Württemberg. Statistisches Landesamt Baden-Württemberg, Stuttgart.

Teepe, R., Brumme, R., Beese, F., 2000. Nitrous oxide emissions from frozen soils under agricultural, fallow and forest land. Soil Biol. Biochem. 32, 1807–1810.

Trunk, W., 1995. Ökonomische Beurteilung von Strategien zur Vermeidung von Schadgasemissionen bei der Milcherzeugung—dargestellt für allgäuer Futterbaubetriebe. Verlag Dr. Kovač, Hamburg.

UBA, 2002. BMVEL/UBA-Ammoniak Emissionsinventar der deutschen Landwirtschaft und Minderungsszenarien bis zum Jahr 2010. Umweltbundesamt, Berlin.

Wetterich, F., Haas, G., 1999. Ökobilanz Allgäuer Grünlandbetriebe—Intensiv, extensivert, ökologisch. Verlag Dr. Köster.

ZMP, 2001. ZMP-Marktbilanz Vieh und Fleisch. Zentrale Markt- und Preisberichtstelle, Bonn.

ZMP, 2001. ZMP-Marktbilanz Eier und Geflügel. Zentrale Markt- und Preisberichtstelle, Bonn.

ZMP, 2001. ZMP-Marktbilanz Kartoffeln. Zentrale Markt- und Preisberichtstelle, Bonn.

ZMP, 2001. ZMP-Marktbilanz Getreide, Ölsaaten, Futtermittel. Zentrale Markt- und Preisberichtstelle, Bonn.