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

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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$_2$O, whereas CH$_4$ uptake had marginal influence (net soil C uptake or release was not considered). The simulated N$_2$O 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$_2$O (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.

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$_2$O emissions, the main radiative forcing gases emitted from agricultural systems, mitigation
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...
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 CO₂, CH₄, N₂O, and NH₃ 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 CH₄ and N₂O 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...
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 km²) than CORINE (18,683 km²). 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 N₂O 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 N₂O emissions. Therefore, all simulated soil N₂O emissions were adjusted to the regression equation to compensate for the underestimation.

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

<table>
<thead>
<tr>
<th></th>
<th>Winter cereals</th>
<th>Spring cereals</th>
<th>Set-aside</th>
<th>Silage crops</th>
<th>Rapeseed</th>
<th>Root crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFEM</td>
<td>43.4</td>
<td>26.1</td>
<td>9.4</td>
<td>9.2</td>
<td>8.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Agricultural accounting</td>
<td>41.3</td>
<td>26.9</td>
<td>7.9</td>
<td>12.2</td>
<td>8.1</td>
<td>3.6</td>
</tr>
</tbody>
</table>
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 N₂O emissions from Baden-Württemberg were 1.89 (±0.57) kg N₂O-N ha⁻¹ after correcting the simulation results for the validated emissions. When considering the average background emission of 0.72 (±0.26) kg N₂O-N ha⁻¹, established with DNDC by simulating all datasets as “fallow”, modeled N₂O emissions were 31% lower than the UBA (2002) estimate for Baden-Württemberg (1.7 kg N₂O-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 N₂O 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 N₂O-N ha⁻¹ to more than 3 kg N₂O-N ha⁻¹, and showed a close correlation to total N fertilizer application rates (R² = 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 N₂O-N ha⁻¹ for cropland, grassland, vineyards, and orchards, respectively), emission factors for N₂O (EFₙ₂₀) 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 EFₙ₂₀ 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 EFₙ₂₀ 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 N₂O 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 EFₙ₂₀. The obtained results may therefore only be valid for the year 2000. The low EFₙ₂₀ of Lægreid and Aastveit (2002) however, which is based on a multi-year analysis of N₂O emissions, indicates that the IPCC value is probably, nevertheless, too high for the study region.

Methane fluxes ranged from −0.55 (±0.52) kg CH₄-C ha⁻¹ to −1.53 (±1.30) kg CH₄-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 CH₄ uptake for Baden-Württemberg was 1.39 (±0.19) kg CH₄-C ha⁻¹. Freibauer (2003) reported an uptake of only 0.5 (±0.5) kg CH₄-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)
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$_2$O 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$_2$O, 40% from CH$_4$, and 22% from CO$_2$ (Table 4). According to the official statistics (SLBW, 2003), agricultural N$_2$O 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 crop drying. Methane only had share of 1–2% of total GHGs. The results are comparable with those presented by Løthe (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 recalculating 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$_2$O 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$_2$O 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 Løthe (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).

<table>
<thead>
<tr>
<th>Management systems</th>
<th>Fruit/grapes</th>
<th>Cash crops</th>
<th>Cash crops/poultry</th>
<th>Cattle/sheep</th>
<th>Pigs</th>
<th>Baden-Württemberg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O soil direct$^a$</td>
<td>783 (30)</td>
<td>1016 (35)</td>
<td>1269 (38)</td>
<td>789 (15)</td>
<td>1284 (24)</td>
<td>918 (20)</td>
</tr>
<tr>
<td>N$_2$O soil indirect$^b$</td>
<td>307 (12)</td>
<td>395 (13)</td>
<td>442 (13)</td>
<td>449 (9)</td>
<td>703 (13)</td>
<td>458 (10)</td>
</tr>
<tr>
<td>N$_2$O others$^c$</td>
<td>420 (16)</td>
<td>531 (18)</td>
<td>590 (18)</td>
<td>236 (5)</td>
<td>401 (8)</td>
<td>345 (8)</td>
</tr>
<tr>
<td>CH$_4$ ruminants</td>
<td>31 (1)</td>
<td>16 (1)</td>
<td>29 (1)</td>
<td>2452 (47)</td>
<td>150 (3)</td>
<td>1433 (32)</td>
</tr>
<tr>
<td>CH$_4$ manure management</td>
<td>9 (0)</td>
<td>40 (1)</td>
<td>73 (2)</td>
<td>623 (12)</td>
<td>368 (7)</td>
<td>411 (9)</td>
</tr>
<tr>
<td>CH$_4$ soil</td>
<td>$-39$ (2)</td>
<td>$-37$ (1)</td>
<td>$-37$ (1)</td>
<td>$-41$ (1)</td>
<td>$-36$ (1)</td>
<td>$-39$ (1)</td>
</tr>
<tr>
<td>CO$_2$ plant production$^d$</td>
<td>1059 (41)</td>
<td>953 (32)</td>
<td>956 (28)</td>
<td>403 (8)</td>
<td>940 (18)</td>
<td>640 (14)</td>
</tr>
<tr>
<td>CO$_2$ animal husbandry$^e$</td>
<td>10 (0)</td>
<td>17 (1)</td>
<td>38 (1)</td>
<td>277 (5)</td>
<td>1488 (32)</td>
<td>4494 (100)</td>
</tr>
<tr>
<td>Total</td>
<td>2581 (100)</td>
<td>2932 (100)</td>
<td>3359 (100)</td>
<td>5186 (100)</td>
<td>5299 (100)</td>
<td>4494 (100)</td>
</tr>
</tbody>
</table>

Values in parenthesis are percent of total emissions within the production systems.

$^a$ Includes emissions from atmospheric deposition because the direct soil N$_2$O 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.
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\textsubscript{2} eq ha\textsuperscript{−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 × LU ha\textsuperscript{−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\textsubscript{2}O is responsible for most soil GHG emissions, and is highly correlated to N fertilization. Due to the significance of soil factors for N\textsubscript{2}O 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.

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