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Simulation of regional nitrous oxide emissions from German agricultural mineral soils: A linkage between an agro-economic model and an empirical emission model

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ABSTRACT

Nitrous oxide (N_2O) emissions from agricultural land use account for 56% of German agricultural green house gas (GHG) emissions. It is assumed that this share will increase up to 60% by 2020. The realistic estimation of N_2O emissions for GHG inventory and policy scenarios requires a model approach which considers the regional drivers for both the N_2O originating processes and agricultural production.

The nitrous oxide emissions from agricultural mineral soils have been simulated for Germany at regional scale for the base year 2007, the baseline year 2020 and a scenario assuming a nitrogen tax as a mitigation instrument. For the simulation the agro-economic model RAUMIS was applied with the standard IPCC emission factor approach together with the emission model MODE, which provides emission factors considering the regional impacts of climate, soil and crop system.

The emission levels computed with the RAUMIS-MODE approach are in general smaller, and indicate a different regional distribution of the highly emitting regions (e.g., in southern Germany). For all of Germany the simulations result in an increase of 16% in the year 2020 computed with the IPCC approach and of 9% computed with the RAUMIS-MODE approach.

The simulation of a nitrogen tax of 150% on the price of purchased mineral nitrogen fertilizer results in an emission decrease of 12–13% compared to the baseline. While the impact of the nitrogen tax on agriculture production is highest in regions with low livestock density or low productivity, the mitigation effect in less productive regions is low, and vice versa. The results indicate that a nitrogen tax on mineral fertilizer does not seem to be a suitable instrument to address regional N_2O mitigation targets.

1. Introduction

1.1. Nitrous oxide emissions from German agricultural production

Nitrous oxide (N_2O) emissions from agriculture originate from nitrification and denitrification, two microbially driven processes occurring in soils, water bodies and livestock effluents (Li et al., 2012; Seitzinger and Kroeze, 1998). Microorganisms nitrify ammonium to nitrate to gain energy for growth and maintenance. This process is positively impacted by aerobic conditions, high temperatures and the amount of parent material (ammonium). In contrast, denitrification is a reduction of nitrate to atmospheric nitrogen used by microorganisms as an oxygen substitute to mineralize organic compounds. Nitrous oxide is an intermediate of denitrification under anaerobic conditions. Both processes nitrification and denitrification, are embedded in a system of interactive biogeochemical processes that vary in space and time.

By managing agricultural nitrogen cycles and applying mineral nitrogen fertilizers, agriculture causes an increase of reactive nitrogen in agricultural systems (arable and grassland soils, manure) and natural ecosystems (e.g., water bodies, forests, etc.) that are contaminated via atmospheric and hydrologic fluxes.

Germany is one of the top three agricultural producers within the European Union (EU-27) and, after France and Spain, has the third largest amount of agriculturally used land area. The comparably favorable natural production conditions and a low availability of land provoke livestock and crop farming at a very intensive level, which results in a significant share of total green house gas (GHG) emissions.

Nitrous oxide emissions from agricultural land use contribute, with 3.7%, significantly to the national GHG budget (UBA, 2011). In Germany, agricultural production is the biggest source of nitrous oxide (68%) among others (e.g., industry, fossil fuel burning). About 63% of agriculturally-induced N_2O emissions are direct N_2O

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emissions from used soils. Indirect emissions, made up of emissions from nitrogen depositions and emissions from leaching and runoff, amount to 5% and 27%, respectively (UBA, 2011). The remaining 5% come from manure management.

According to the Kyoto protocol the German government committed to an annual reporting and a significant reduction of GHG emissions. GHG emissions from German agriculture are reported in the annual National Inventory Report (NIR), the accounting methods of which are documented in Haenel et al. (2012). The German government declared a reduction of total GHG emissions by 40% by 2020 as a target (NABU, 2010; BMU, 2010). However, national agricultural stakeholders and the European Commission request a reduction of agriculturally originated CH_4 and N_2O of 25% by 2020, of 30% by 2030 (DBV, 2010) and of 42–49% by 2050 (EC, 2011). National environmental organizations even demand a reduction of total agricultural GHG emissions of 40% by 2020 (NABU, 2010) and the prescriptions of obligatory climate protection programs with corresponding measures for agriculture (Klima-Allianz, 2010).

Coupled agro-economic and biophysical models are applied to evaluate mitigation strategies with respect to their effectiveness and their impacts on agricultural production and economy.

1.2. N_2O emissions modeling – state of the art

Although it is well understood how environmental conditions control the evolution of nitrous oxide (N_2O) via nitrification and denitrification, regional annual N_2O emissions or phenomena like N_2O emission peaks after rewetting or freeze–thaw events in soils (Flessa et al., 1995) could until now not be described sufficiently on regional to global scales (Groffmann et al., 2009) and direct measurements are not possible.

In order to estimate N_2O emissions, different model approaches have been developed, which link agro-economic models with emission models, where the agro-economic models provide the activity data representing the nitrogen sources, while the emission models provide the calculation of N_2O emissions.

The agro-economic model GLOBIOM (Global Biomass Optimization Model, Havlík et al., 2011; Schneider et al., 2011) accounts for the major GHG emissions and sinks related to agriculture and forestry, particularly emissions related to crop cultivation, land use, and livestock for 27 international regions. The model Agricultural Sector and Greenhouse Gas Mitigation Model (ASMGHG) simulates N_2O emissions in the United States for 63 regions (Schneider and McCarl, 2003; Schneider et al., 2007), the model European Forest and Agricultural Sector Optimization Model (EUFASOM) accounts for N_2O emissions for the European Union at country level (Schneider et al., 2008). The model Common Agricultural Policy Regionalised Impact (CAPRI) represents agricultural GHG emissions resulting from crop production, livestock and manure management at the regional NUTS2 scale for the 27 EU member states (Britz, 2008; ; Pérez Domínguez, 2005; Leip et al., 2008, 2010, Leip et al., 2011a,b). De Cara et al. (2005) calculated N_2O emissions from European agriculture by integrating IPCC methods into AROPAj (De Cara et al., 2005). In a study by Durandeau et al. (2010) AROPAj was coupled to the biophysical model CERES-EGC (Gabrielle et al., 2006) via response functions.

The model GAS-EM (GASeous EMissions) computes the N_2O emissions for the German National Inventory Report (NIR) on the NUTS1 federal state level and uses the agricultural production data which are provided the agro-economic model RAUMIS (Regional Agriculture and Environmental Information System) (Haenel et al., 2012).

Furthermore, some spatial models have been developed to represent GHG emission focused on specific German regions such as southern Germany with the model Agro-eConomic pRoduction model at rEgional level (ACRE) (Henseler et al. 2008, 2009; Henseler, 2011) or the federal state Baden-Wuerttemberg with the EFEM-DNDC (Economic Farm Emission Model) (Schäfer and Neufeld, 2006; Neufeld and Schäfer, 2008).

Three basic approaches can be differentiated for the emission accounting in the agro-economic models: the IPCC emission factor, process-oriented models and empirical models. The IPCC emission factor is published in IPCC (1996, 2006) and represents N_2O fluxes estimated from N_2O evolution as a fraction of reactive nitrogen (N) in biogeochemical systems Bouwmann (1996). The IPCC emission factor is a nitrogen amount-based approach, the ''IPCC approach'' is used in the models introduced above: CAPRI, GAS-EM, ACRE.

Process-oriented models (like EPIC or DNDS) represent the soil vegetation atmosphere systems according to the state of the art of process understanding (Leip et al., 2011a,b). These models simulate mass and energy cycles of the whole Soil–Vegetation–Atmosphere Systems in a spatio-temporal resolution that fits to the dynamics of processes inducing direct N_2O emissions. Process-oriented approaches are used in the models: GLOBIOM, ASMGHG, EU-FASOM, CAPRI-DNDC and EFEM-DNDC.

Empirical (Freibauer and Kaltschmitt, 2003; Dechow and Freibauer, 2011) and conceptual models (Jungkunst et al., 2006) were developed on plot-scale measurements across central Europe and Germany, which consider the climatic conditions as drivers of relevant emission peaks (e.g., during freeze thaw events) (Stehfest and Bouwman, 2006).

Meta models are a further development and are an abstraction of the model originally developed to describe the process. Several meta-models that simulate the input/output relationship of DNDC Europe are discussed in Villa-Vialaneix et al. (2012).

1.3. Objective of the study

Several studies present the accounting or the simulation of GHG emissions from German agriculture. However, these studies are either highly regionally differentiated, but only for parts of Germany (e.g., Schäfer and Neufeld, 2006; Neufeld and Schäfer, 2008), or they consider all of Germany and use the less differentiated IPCC approach (e.g., Haenel et al., 2012).

The objective of this study is to fill the gap of a study presenting regionally differentiated simulation of agricultural N_2O emission from mineral soils for all of Germany. The simulations are presented for the base year 2007 and projected for the year 2020 as a baseline. In a policy scenario a nitrogen tax on the price for purchased mineral nitrogen is a simulated mitigation instrument.

For the simulation the regional agro-economic model RAUMIS has been used with two different approaches: (1) the IPCC approach and (2) the linkage to the empirical emission model MODE. The study presents and compares the results for both approaches and discusses the impact of the nitrogen tax and the differences between the approaches at sector and at regional scale.

2. Linking MODE and RAUMIS

The empirical N_2O simulation model MODE and the regional agricultural supply model RAUMIS have been linked in order to provide simulations of N_2O emissions from German agriculture which consider the regional differentiation of both agricultural production and N_2O emissions. MODE provides regionally differentiated emission factors to compute the regional N_2O emissions from the activity data, while RAUMIS provides the regionally specific activity data of agricultural production.

2.1. The model MODE

The model MODE was developed to estimate direct annual N_2O emissions of agricultural mineral soils in Central Europe and was