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Modelling reactive nitrogen fluxes and mitigation scenarios on a landscape in Central France

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ABSTRACT

The intensification of agriculture has been made possible by increasing the supply of synthetic mineral nitrogen to crops. That has led to increased losses of reactive nitrogen (N_r e.g. ammonia NH_3, nitrous oxide N_2O, nitrogen oxides NO_x, nitrate NO_3^-, ammonium NH_4^+) in the environment that may produce negative impacts on agroecosystems: soil, water or air pollution, greenhouse gas emission, biodiversity loss. The nitrogen losses result from a cascade of a large number of processes that interact spatially and temporally in agroecosystems. Integrated models are very useful to investigate such complex systems.

We used the NitroScape model that couples an agroecosystem model, a cattle farm model, an atmospheric model of dispersion, transport and deposition, and a hydrological model. It made it possible to simulate processes of the nitrogen cascade at the landscape scale (i.e. a domain from a few square metres to a few tens of square kilometres). The model was applied on an agricultural site of 427 ha in Central France to simulate nitrogen flows for years 2014 and 2015. It used data from measurement campaigns and farm surveys that provided soil characteristics, meteorological data and crop management for the two years of simulation. The simulation results were compared to nitrogen fluxes and concentrations measured in the air, the soil and plants.

The simulated N_r fluxes were consistent with the observed fluxes (i.e. low root mean square error, coefficients of regression significant at a 5% level). The coupled NitroScape model that integrates numerous related-nitrogen processes was therefore able to reproduce the main N_r fluxes. However, there were discrepancies between simulated and observed values for N_2O emissions resulting from denitrification and for NH_3 volatilisation. The model showed that the main N_r losses were due to NO_3^- leaching, which accounted for 11% of the nitrogen outflows (29 $kg\,N\,ha^{-1}\,yr^{-1}$). Total losses of N_r (emissions of NH_3, NO and N_2O, and NO_3^- leaching) in the environment accounted for 13% of the nitrogen outflows.

Two alternative scenarios aiming at enhancing nitrogen use efficiency and mitigating losses of N_r in the environment were built and assessed with the model. Simulations showed that changing nitrogen fertilisation and including catch crops and buffer strips led to a 18% decrease of NO_3^- losses. They also showed that including pea in crop rotation led to a 25% decrease of mineral fertilisation and a reduction of NO_3^- losses of 2 $kg\,N\,ha^{-1}\,yr^{-1}$. The NitroScape model is a valuable tool to assess the effect of nitrogen management at the landscape scale on mitigation of nitrogen losses in the environment.

1. Introduction

Since the discovery of the Haber-Bosch process, the massive use of nitrogen fertilisers in agroecosystems has widely contributed to the accumulation of reactive nitrogen (N_r) in the air, soils, water bodies and natural ecosystems through the nitrogen cascade (Galloway et al., 2003). N_r transfers and transformations result from anthropogenic activities, numerous complex biogeochemical processes in soil and vegetation, and transfers by either the hydrological or the atmospheric pathway. A part of the nitrogen supplied by fertilisation is uptaken by crops or stored in soil organic matter (Butterbach-Bahl et al., 2011). The remaining part of nitrogen is either transferred in the hydrosphere by leaching, runoff or erosion as nitrate (NO_3^-), ammonium (NH_4^+), or emitted in the atmosphere as ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x). N_r emissions in the environment from agricultural activities are a major concern for environmental policies

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(Oenema et al., 2011). It is crucial to mitigate N_r losses because of the various negative impacts of N_r forms on air, water and soil quality, ecosystem equilibrium, biodiversity and greenhouse gas balance and also to improve nitrogen use efficiency. N_r accumulation in freshwater is shown to deeply disturb ecosystems by increasing nutrient availability and water acidity. This eutrophication phenomenon leads to wide dominance of a few phytoplankton and macrophytes species. N_r input in freshwater is known to be mainly originated by NO_3^- leaching from agricultural lands (Billen et al., 2011; Durand et al., 2011). The NH_3 that is emitted into the atmosphere may fall back on soils, plants, streams and waterbodies as dry deposition, or also wet deposition after a rain event, resulting in eutrophication or acidification of ecosystems. The N_2O that is emitted in the atmosphere is a stable greenhouse gas, with a lifespan of about 150 years, and contributes to global warming. Emissions of N_2O and NO_x may cause respiratory diseases and contribute to tropospheric ozone formation (Hertel et al., 2011).

Nevertheless, in current agricultural systems, nitrogen inputs are essential to reach the production objectives required to make farm profitable and fit food demand. Mitigation plans should focus on increasing nitrogen efficiency, reducing at the same time fertilisation costs for farmers and nitrogen losses towards the environment while maintaining production.

The assessment of efficient agricultural systems for nitrogen cannot be led under a large range of climate, soil and management conditions from field measurements only. It would be too much time-consuming and could not be exhaustive. Spatial modelling is therefore very useful to quantify N_r fluxes within landscapes, especially when local field data are scarce. Models can be also used to assess the effects of measures aiming at mitigating N_r emissions in a large range of scenarios. However, field measurements are required to parameterise models and evaluate model performance. The emission processes of the different forms of N_r in agroecosystems have been described and modelled mainly at the field scale with one-dimension models such as STICS (Brisson et al., 2002), CERES-EGC (Gabrielle et al., 2006) or DNDC (Li et al., 2006). These models are able to simulate crop growth and dry biomass, N_2O, NO_x and NH_3 emissions from fields, as well as NO_3^- leaching to groundwater. The performance of the model depends, among other things, on its parameterisation from field data. The whole N_r cascade has been also described at the regional scale (e.g. the Seine catchment; Billen et al., 2013) or the European scale (Leip et al., 2007) using for instance the DNDC model. Spatial interactions in N_r processes were already considered using models such as TNT2 (Beaujouan et al., 2002) which couples the agroecosystem model STICS and the hydrological transport model TNT (Beaujouan et al., 2001). They were applied to catchments of a few square kilometres to assess the impact of cropping practices on catchment discharge, NO_3^- leaching and NO_3^- concentration in the aquatic compartment (Ferrant et al., 2011). The CASIMOD'N model couples the TNT2 model with a livestock management model (Moreau et al., 2013). Spatial interactions in atmospheric transfer were also modelled by Kros et al. (2011) using the INITIATOR model which computes soil and livestock housing emissions coupled with the atmospheric transport model OPS (van Jaarsveld and Bleeker, 2004) at the regional scale in Northern Netherlands. So far, spatial interactions in the N_r cascade at the landscape scale have been modelled for only one single or two landscape compartments taken in pairs (e.g. agrosystems and the atmosphere, agrosystems and the hydrosphere, agrosystems and farming systems). Only a few studies have attempted to fully integrate all those compartments into spatially distributed models, but only on theoretical landscapes (Duretz et al., 2011). It is necessary to take into account together the fluxes of the different forms of N_r in order to better quantify N_r fluxes and better assess the performance of different mitigation scenarios of N_r losses, especially because of the importance of spatial and temporal interactions between processes such as leaching, nitrification, denitrification, volatilisation, nitrogen uptake (Sutton et al., 2007; Drouet et al., 2012). It is also relevant to account for a larger area than the field scale, like a landscape of a several square kilometres, integrating spatial (including lateral transfer) and temporal interactions between N_r sources (e.g. fertilised crops, livestock buildings) and sinks (e.g. grasslands, protected areas) (Theobald et al., 2004; Cellier et al., 2011).

The objective of this study was to assess the performance of a complex model such as NitroScape, to simulate the main fluxes of the different forms of N_r in the actual conditions of an agricultural site located in Central France. In the context of environmental policies aiming at mitigating N_r losses, we also used the model to compare the nitrogen budget of actual practices with two scenarios for optimising agricultural practices and changing land use.

2. Materials and methods

2.1. The study site and data collection

The NitroScape model was applied on an agricultural site of 427 ha, which is a catchment and part of the "Observatoire Spatialisé Orléanais des Sols" ("OS^2") located in Central France (Gu et al., 2013). The site is characterised by cambisols, fluvisols and luvisols, overall hydromorphed, and lies on a layer of clay accumulated on a depth of about 30 cm to 100 cm (Fig. 3). These soils have high fertility. Most of these moist soils are drained and the drain outlets are piped in the small "Gouethière" stream that flows into the "Loir" river (Fig. 1; Grossel et al., 2016). The site elevation varies from 215 m at the top of the catchment to 175 m at the outlet.

The site included 63 fields from eight different mixed crop farms and one crop-livestock farm (Fig. 1). The dominant crop was winter wheat, which occupied around 50% of the site area in 2014 and 2015 (Fig. 2). There was also winter rapeseed (21% of the site area in 2014 and 15% in 2015), winter barley (13% of the site area in 2014 and 18% in 2015), and maize (around 10% of the site area). The most common crop rotations were rapeseed-wheat-wheat and rapeseed-wheat-barley. Pea crop was also present in a few crop rotations. Spring crops as maize or pea were sown in March and April while winter crops as rapeseed, barley and wheat were sown before winter (in August, September and October). Winter crops were harvested in July and maize in October. The crop-livestock farm located in the south-east of the site (Fig. 1) was an extensive farming system with a few beef suckler cows (about ten heads) grazing on three grassland fields, and with no livestock housing. It had an original crop rotation including flaxseed and alfalfa. Field management followed the local regime with fertilisation only in spring and no irrigation. All soils were tilled, except for wheat sown after rapeseed in which case farmers practiced reduced tillage. The crop-livestock farm practiced reduced tillage for all soils. The straws of cereals (wheat, barley) were incorporated, except for the crop-livestock farm where they were used for animals. Nitrogen forms for mineral fertilisation were either liquid (N39 solution) or solid (ammonitrate 33.5) (Table 3). Some farmers brought organic manure in August (poultry manure, pig slurry), but this practice was not systematic.Management data as farming practices were collected through farm surveys between 2012 and 2015. Those data included farm management (fertilisation type, date and amount, crop type, sowing, tillage and harvest date, and livestock management). Meteorological data were collected by a weather station set up on the study site. Annual rainfall was 690 mm in 2014 and 560 mm in 2015. The structure (i.e. topography, soil units, land use) of the site had already been described and spatial data had been stored in raster layers thanks to a Geographic Information System. Soil properties data were used to parametrise the NitroScape model. Data for assessing model outputs (soil water content (SWC), above ground dry biomass (DM), N content in DM, N_2O emissions, NH_3 concentrations, soil NO_3^- and NH_4^+ concentrations) were measured at several periods in 2014 and 2015. Above ground DM and N content in DM were measured at three growth stages (top of inflorescence at one cm, flowering and maturity) by sampling plants (eight rows of one metre long each per sampling point). Emissions of N_2O were measured