Environmental Pollution 159 (2011) 3162–3170

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

NitroScape: A model to integrate nitrogen transfers and transformations in rural landscapes

S. Duretz[a], J.L. Drouet[a,*], P. Durand[b], N.J. Hutchings[c], M.R. Theobald[d,e], J. Salmon-Monviola[b], U. Dragosits[e], O. Maury[a], M.A. Sutton[e], P. Cellier[a]

[a] INRA-AgroParisTech, UMR 1091 Environnement et Grandes Cultures (EGC), 78850 Thiverval-Grignon, France
[b] INRA-AgroCampus, UMR 1069 Sol Agro et hydrosystème Spatialisation (SAS), 35042 Rennes cedex, France
[c] Department of Agroecology, Faculty of Agricultural Sciences, University of Aarhus (AU), Blichers Allé, 8830 Tjele, Denmark
[d] Department of Chemistry and Agricultural Analysis, Technical University of Madrid (UPM), 28040 Madrid, Spain
[e] Centre for Ecology and Hydrology (CEH), Bush Estate, Penicuik, Midlothian EH26 0QB, UK

ARTICLE INFO

Article history:
Received 6 April 2011
Accepted 5 May 2011

Keywords:
Reactive N fluxes
N cascade
Integrated model
Dynamic model
Spatially distributed model
Landscape scale

ABSTRACT

Modelling nitrogen transfer and transformation at the landscape scale is relevant to estimate the mobility of the reactive forms of nitrogen (N_r) and the associated threats to the environment. Here we describe the development of a spatially and temporally explicit model to integrate N_r transfer and transformation at the landscape scale. The model couples four existing models, to simulate atmospheric, farm, agro-ecosystem and hydrological N_r fluxes and transformations within a landscape. Simulations were carried out on a theoretical landscape consisting of pig-crop farms interspersed with unmanaged ecosystems. Simulation results illustrated the effect of spatial interactions between landscape elements on N_r fluxes and losses to the environment. More than 10% of the total N_2O emissions were due to indirect emissions. The nitrogen budgets and transformations of the unmanaged ecosystems varied considerably, depending on their location within the landscape. The model represents a new tool for assessing the effect of changes in landscape structure on N_r fluxes.

1. Introduction

The sharp increase in anthropogenic reactive nitrogen (N_r) creation since the mid-1900s has increased the cascade of N_r in terrestrial, aquatic and atmospheric ecosystems, which has increased environmental impact such as eutrophication, acidification, secondary atmospheric particulate formation and greenhouse gas (GHG) emissions (Galloway et al., 2003). N_r in rural landscapes mainly originates from organic manures and mineral fertilizers. Atmospheric ammonia (NH_3) emitted from an animal house or a field can be re-deposited to the nearby ecosystems (Fowler et al., 1998). Similarly, ecosystems at the bottom of slopes can re-capture groundwater nitrate (NO_3^-) that originates in N_r applied further up the slope. In both cases, this can lead to hotspots in N_r input to the receptor ecosystem that will have impact on the ecosystem and its biogeochemical cycles. This can also lead to enhanced nitrous oxide (N_2O) and nitric oxide (NO) emissions (Beaujouan et al., 2001) and further feed the N cascade (Galloway et al., 2003). Reducing the environmental effects of N_r requires studying the processes involved in N_r transfer and transformation through the biogeochemical, atmospheric or hydrological pathways. Sources and sinks of N_r are spatially heterogeneous, in intensity and nature, at a scale of several square kilometres (Beaujouan et al., 2001; Dragosits et al., 2002) depending on the farming system and the characteristics of the area, such as variations in meteorological and soil conditions, topography and spatial distribution of N_r sources. The landscape scale is here defined as an area where significant interactions occur between ecosystems and farm management i.e., from several square kilometres to several tens of square kilometres. In rural areas, that may include a river or stream catchment, several livestock buildings, agricultural fields and semi-natural ecosystems such as forests and wetlands (Cellier et al., 2011).

Modelling is helpful to study complex dynamic systems such as landscapes, where spatial interactions occur and direct measurements of N_r fluxes are time and cost consuming due to the complexity of the system. A model simulating natural and anthropogenic N_r fluxes in rural landscapes should include three main features. First, it should take into account the N_r cascade, including transfer and transformation processes in the various compartments of a rural landscape (Galloway et al., 2003) i.e., the

* Corresponding author.
E-mail address: Jean-Louis.Drouet@grignon.inra.fr (J.L. Drouet).

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doi:10.1016/j.envpol.2011.05.005

atmosphere, the terrestrial ecosystems (agro-ecosystems - including livestock buildings, croplands, and grasslands- and semi-natural areas) and the aquatic ecosystems (wetlands, streams, lakes, rivers and groundwater). Second, such a model should be spatially distributed to account for topography, spatial distribution of sources and sinks of N_r and short-term transfers between them. Third, it should be dynamic i.e., each transfer or transformation process may affect other processes during the simulation.

Several models have been developed to simulate N_r fluxes in rural landscapes but they have not fulfilled the three above conditions, since all compartments were not considered with the same spatial and temporal resolutions. Most of them focused on aquatic ecosystems to describe N_r concentrations and fluxes within and at the outlet of a catchment which may correspond to the landscape scale described above (e.g., Beven, 1997; Whitehead et al., 1998; Beaujouan et al., 2002; Vaché and McDonnell, 2006) or to larger i.e., regional scales (e.g., Arnold et al., 1998; Billen and Garnier, 2000). Recent studies have attempted to assess the effect of anthropogenic activities on aquatic and terrestrial ecosystems, especially croplands, by coupling hydrological and crop models (e.g., Beaujouan et al., 2001; Ducharne et al., 2007). Other recent modelling studies have tried to integrate all compartments of a rural landscape but focusing only on one compartment, the others being described with less detail. For instance, Hutchings et al. (2004) focused on anthropogenic transfers within the terrestrial (croplands, grasslands and farm compartments) and aquatic ecosystems to assess the effects of N_r management on drinking water boreholes. From another point of view, other studies focused on atmospheric transfers between terrestrial ecosystems to assess emissions, transfers and deposition of NH_3 at the landscape scale (Theobald et al., 2004) or indirect N_2O emissions at the regional scale (van der Gon and Bleeker, 2005). In a recent study, Kros et al. (2011) focused on atmospheric NH_3 emissions from livestock buildings and agricultural fields and transfers and deposition of NH_3 at the landscape scale. They also included the leaching of N_r compounds to groundwater and surface water, but they neglected horizontal transfers of N_r through the water system.

In this context, an integrated model, namely NitroScape, was developed to simulate N_r transfers and transformations at the landscape scale. Here, N_r includes reduced forms (NH_3, NH_4^+), inorganic oxidized forms (NO_3^- and N_2O) and organic N forms (N in manure and in crop residues or vegetation). The model includes the atmosphere and several compartments of the terrestrial ecosystems (livestock buildings, croplands and grasslands) as well as the aquatic ecosystems (wetlands, streams and groundwater). It integrates four existing models (atmospheric, farm, agro-ecosystem and hydrological models) to simulate short-term N_r transfers and transformations in a dynamic and spatially distributed way. The model was applied to a test case including livestock buildings, croplands (maize and wheat) and unmanaged ecosystems.

2. Materials and methods

2.1. Overall description of the NitroScape model

The NitroScape model integrates four types of models describing processes of N_r transfers and transformations within the four corresponding compartments of a landscape (Fig. 1):

- A farm model which manages N_r transformations in livestock, livestock housing and manure storage, and the performance of field operations (e.g., application of manure, harvesting).
- An ecosystem model, considering the different types of ecosystems, either managed or semi-natural, where N_r input is considered from different pathways: mineral and organic N_r application by the farmer, atmospheric deposition, N_r uptake, N_r transformations and losses (nitrification, denitrification, leaching, volatilization),
- An atmospheric model simulating dispersion, transport and dry deposition of NH_3 within the landscape through atmospheric pathways,
- A hydrological model simulating N_r transfer through the hydrological network, groundwater depth and soil–groundwater interaction of N_r.

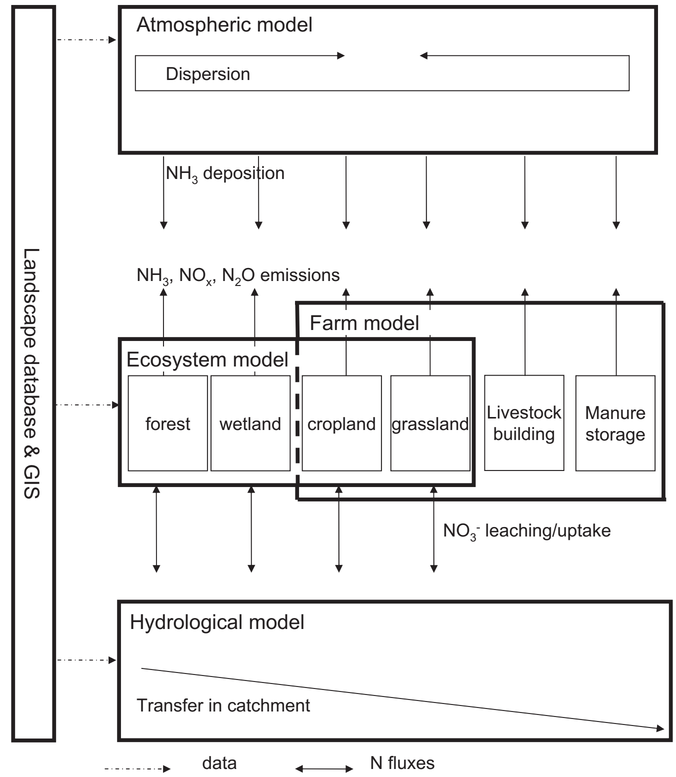

Fig. 1. The NitroScape model scheme: component models and modelled processes (full arrows: nitrogen fluxes, boxes: components of the NitroScape model, ticked arrows: data from the database e.g., parameterization, meteorological data).

Since all these processes occur simultaneously, they have been integrated into a common modelling framework providing a compromise between the level of detail in process description, the relevant temporal and spatial scales for describing the relevant processes and computing capacity.

The temporal scales in landscape processes cover a wide range: atmospheric processes are the fastest ones (from minutes to hours); hydrological and soil processes are potentially the slowest ones since they vary from several hours to several decades, and farm management is event-based. Considering this wide range of time scales, the best compromise was to run NitroScape at a daily time step. The simulation period should be at least one year, in order to capture the seasonal variations of N_r transfers and transformations.

Regarding spatial scales, the size of the landscape is relevant to describe processes in the four compartments of NitroScape: a first order catchment for hydrological processes, a small region with a mosaic of ecosystems for atmospheric processes and a set of farms including livestock buildings, fields and semi-natural areas for farm and ecosystem management. The landscape is represented by a matrix of pixels with a size resulting from a compromise between accounting for the relevant processes involved in N_r fluxes and reasonable computing time. That resulted in a pixel size of 25×25 m.

2.1.1. The component models of NitroScape

For each component of NitroScape, models were selected according to their ability to simulate N_r processes at the landscape scale and their consistency regarding temporal and spatial scales.

The atmospheric model has to account for processes of N_r transfer and deposition from sources to sinks distant from several tens of metres to a few kilometres, and their variation with meteorological and surface characteristics (Fig. 1). The basic time scale for this type of model has to distinguish between day and night because dispersion and surface processes are related to plant functioning (e.g., stomatal conductance) and micrometeorological conditions (e.g., atmospheric stability). Based on those pre-requisites, a set of candidate models was considered: ADMS