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Influence of short-term transfers on nitrogen fluxes, budgets and indirect N_2O emissions in rural landscapes

S. Duretz[1], **J.-L. Drouet**[1], **P. Durand**[2], **and P. Cellier**[1]

[1]INRA-AgroParisTech, UMR1091 Environnement et Grandes Cultures (EGC),
78850 Thiverval-Grignon, France
[2]INRA-AgroCampus, UMR1069 Sol Agro et hydrosystème Spatialisation (SAS),
35042 Rennes cedex, France

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Correspondence to: J.-L. Drouet (jean-louis.drouet@grignon.inra.fr)

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Abstract

Spatial interactions at short-term may lead to large inputs of reactive nitrogen (N_r) to oligotrophic ecosystems and induce environmental threats such as additional N_2O emissions and global warming. The paper presents a new methodology to estimate N_r fluxes, especially additional N_2O emissions, at the landscape scale by taking into account spatial interactions between landscape elements. We used the NitroScape model which integrates processes of N_r transformation and short-term transfer in a dynamic and spatially distributed way to simulate N_r fluxes and budgets at the landscape scale. Four configurations of NitroScape were implemented by taking into account or not the atmospheric, hydrological or both pathways of N_r transfer. We simulated N_r fluxes, especially direct and indirect N_2O emissions, within a test landscape including pig farms, croplands and unmanaged ecosystems. Simulation results showed the ability of NitroScape to simulate patterns of N_r losses and recapture for each landscape element and the whole landscape. They made it possible to quantify the contribution of both atmospheric and hydrological transfers in N_r fluxes and budgets. Indirect N_2O emissions were estimated at almost 25 % of the total N_2O emissions. They varied within the landscape according to land use, meteorological and soil conditions as well as topography. This first attempt has proved that the NitroScape model is a useful tool to estimate the effect of spatial interactions on N_r fluxes and budgets as well as indirect N_2O emissions within landscapes. Our approach needs to be further tested by applying NitroScape to several spatial distributions of ecosystems within the landscape and to real and larger landscapes.

1 Introduction

Nitrous oxide (N_2O) is mainly emitted by agricultural soils. Indirect N_2O emissions may occur far from zones of nitrogen application and result from a cascade of transformations and transfers of reactive species of nitrogen (N_r) through the biogeochemical, atmospheric or hydrological pathways (Galloway et al., 2003). They are estimated around 20 % of the total N_2O emissions in Europe (IPCC, 2006) and are consecutive to atmospheric deposition of ammonia (NH_3) and recapture of nitrates (NO_3^-). Indirect N_2O emissions depend on the farming system and the characteristics of the area: variations in meteorological and soil conditions, topography, spatial distribution of N_r sources and sinks which are spatially heterogeneous, in intensity and nature, at a scale of several square kilometres (Beaujouan et al., 2001; Dragosits et al., 2002). For instance, atmospheric NH_3 emitted from an animal house or a field can be redeposited to the soil and foliage of nearby ecosystems (Fowler et al., 1998). Similarly, ecosystems at the bottom of slopes can recapture groundwater NO_3^- that originates in N_r applied further up the slope in the groundwater. The relevant scale to study indirect N_2O emissions is therefore an area, namely the landscape, in which interactions occur between ecosystems and farm management, resulting from atmospheric and hydrological transfers which may be large at short-term i.e., distances of several square kilometres to several tens of square kilometres. In rural areas, the landscape 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).

Several attempts have been carried out to estimate indirect N_2O emissions from measurements (e.g., Deurer et al., 2008, Reay et al., 2009) or from the IPCC methodology (IPCC, 2006) based on emission factors (e.g., Mosier et al., 1998; Nevison, 2000; van der Gon and Bleeker, 2005). However, those estimates are highly uncertain and rarely account for both atmospheric and hydrological interactions, as well as farm management. 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. Several models have been developed to simulate N_r fluxes in rural landscapes. 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. A few studies focused on anthropogenic transfers within the terrestrial (croplands, grasslands and farm compartments) and aquatic ecosystems (e.g., Hutchings et al., 2004). Other studies focused on atmospheric transfers between terrestrial ecosystems to assess emission, transfer and deposition of NH_3 at the landscape scale (Theobald et al., 2004; Kros et al., 2011) or indirect N_2O emissions at the regional scale (van der Gon and Bleeker, 2005). However, none of those models dealt with both atmospheric and hydrological N_r transfers in a consistent way regarding temporal and spatial scales. The NitroScape model (Duretz et al., 2011) has been therefore developed to integrate processes of N_r transfer and transformation with temporal and spatial consistency between various compartments of a rural landscape: the atmosphere, several compartments of the terrestrial ecosystems (livestock buildings, croplands and grasslands) and the aquatic ecosystems (wetlands, streams and groundwater).

In this paper we describe a new approach to estimate direct and indirect N_2O emissions in relation to spatial interactions by using the NitroScape model. We also estimate the relative contribution of indirect N_2O emissions to the nitrogen budget of a test landscape and the relative contribution of both atmospheric and hydrological pathways to indirect N_2O emissions. The test landscape includes livestock buildings, croplands (maize and wheat) and unmanaged ecosystems.

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2 Materials and methods

2.1 The NitroScape model

The NitroScape model integrates in a spatially distributed and dynamic way four types of models representing processes of N_r transfers and transformations within the four corresponding compartments of a rural landscape: the atmosphere, the hydrological network, the ecosystems and the farm buildings (Duretz et al., 2011, Fig. 1). For each compartment 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 OPS-st (van Jaarsveld et al., 2004) is the short-term version of the OPS model which describes processes of dispersion, transfer and deposition of N_r pollutants over a domain where surface characteristics may vary in space. It works at various spatial scales by combining long-term (Lagrangian) and short-term (Gaussian) modelling of pollutant transfer. We used the grid-based version of OPS working at a time step of 12 h (one day- and one night-time calculation per 24 h). OPS-st was validated for NH_3 concentrations simulated on a landscape of 3 km by 3 km (van Pul et al., 2008);

- the hydrological model TNT (Beaujouan et al., 2002) represents water and NO_3^- transfer in the hydrological network of a catchment. It accounts for runoff, exfiltration, leaching, deep flows and uptake from deep soils (below 180 cm). It is mainly based on the assumptions of the hydrological model TOPMODEL (Beven, 1997). It is a distributed model that takes into account dual porosity (retention and drainage porosity). Computations are performed at a daily time step, following a mono-directional (a pixel flows into only one pixel) or multi-directional (one pixel can flow into several pixels) scheme. This scheme depends directly on the surface topography and is calculated from a digital elevation model at the beginning of the simulation;

- the agro-ecosystem model CERES-EGC (Gabrielle et al., 2006) is a process-based model which simulates water, C and N cycles in agro-ecosystems at a daily time step and at the field scale. It models vegetation growth and development, energy balance, evapotranspiration, heat and water transfer in soil above 180 cm. It accounts for mineral and organic N inputs from the farmer and simulates NO_3^- leaching and gaseous emissions of NH_3, NO_x and N_2O. N_r transformation in soil is simulated by using the semi-empirical model NOE (Hénault et al., 2005);

- the farm model FASSET (Berntsen et al., 2003) simulates N_r species in a dynamic way and accounts for N_r transfer at the farm scale and exchanges with the outside of the landscape. It was adapted by (i) including production of animal manure either in the livestock housing or in the field and manure storage and (ii) removing the ecosystem component of FASSET. The updated version of FASSET, namely FASSET-farm, runs at a daily time step and deals with a range of livestock systems, livestock housing types and manure store types. NH_3 losses from manure in animal housing and manure storage are modelled according to Hutchings et al. (1996).

Since all those processes occur simultaneously, the four models were integrated into a common modelling framework using the PALM dynamic coupler (Buis et al., 2006). They are called modules hereafter. An additional module, namely the linker, was developed and integrated into PALM to specify the exchange of data between the other four modules. It receives and sorts fluxes and enables the calculation of N_r budgets.

For simulating the spatial interactions, a raster approach was used in NitroScape, in which the landscape is divided into pixels. TNT and OPS-st, which perform simulations on a grid, were directly integrated in this framework, using a one-to-one relationship between pixels. Individual runs of CERES-EGC and FASSET-farm were performed as many times as there were pixels occupied by an ecosystem or a livestock building. Exchange of data between modules was performed at the pixel scale: each ecosystem pixel receives and sends data which are different from those of its neighbouring pixels.

The modules of NitroScape exchange data in a dynamic way on a daily time step (i.e., the shortest time-step common to all modules) during the simulation. Each module provides information to the other modules for the next daily time step.

2.2 The methodology to estimate indirect emissions

The relative contribution of short-term transfers of N_r on N_r fluxes and budgets was estimated by implementing four configurations of NitroScape in which atmospheric or hydrological or both pathways of N_r transfer were cut or not:

- the "all transfers" (*all*) configuration corresponds to the reference configuration in which NH_3 and NO_x are emitted, transferred and deposited through the atmospheric pathway, and NO_3^- is transferred through the hydrological pathway including runoff, throughflows and interaction with the groundwater;
- the "hydrological transfers" (*hydro*) configuration corresponds to the case in which no atmospheric short-term transfers are calculated. This was implemented by not sending the emissions of NH_3 and NO_x from ecosystems and farm buildings to the atmospheric module. NH_3 and NO_x transfers and deposition were not taken into account, but daily emissions of those gases were stored to be included in the final budget;
- the "atmospheric transfers" (*atm*) configuration corresponds to the case in which no hydrological short-term transfers are calculated. This was implemented by (i) not sending wet deposition and soil NO_3^- concentration to the hydrological module to prevent runoff, exfiltration and leaching and therefore saturated lateral transfers and (iii) not sending groundwater NO_3^- to prevent uptake by ecosystems. Daily NO_3^- leaching was stored to be taken into account in the final budget;
- the "no short-term transfer" (*not*) configuration corresponds to the case in which both atmospheric and hydrological transfers were cut in NitroScape. This was implemented by (i) not sending to the atmospheric module the emissions of NH_3

and NO_x from ecosystems and farm buildings to prevent transfers and deposition, (ii) not sending wet deposition and soil NO_3^- concentration to the hydrological module to prevent runoff, exfiltration, leaching and saturated lateral transfers and (iii) not sending groundwater NO_3^- to prevent uptake by ecosystems. Daily NH_3 and NO_x emissions as well as daily NO_3^- leaching were stored to be taken into account in the final budget.

The total indirect N_2O emissions in the *all* configuration were calculated as:

$$N_2O_{\mathrm{ind,all}} = N_2O_{\mathrm{tot,all}} - N_2O_{\mathrm{tot,not}} \tag{1}$$

where $N_2O_{\mathrm{tot,all}}$ are the total N_2O emissions in the *all* configuration and $N_2O_{\mathrm{tot,not}}$ are the total N_2O emissions in the *not* configuration.

The indirect N_2O emissions due to atmospheric transfers were calculated as:

$$N_2O_{\mathrm{ind,atm}} = N_2O_{\mathrm{tot,atm}} - N_2O_{\mathrm{tot,not}} \tag{2}$$

where $N_2O_{\mathrm{tot,atm}}$ are the total N_2O emissions in the *atm* configuration.

The indirect N_2O emissions due to hydrological transfers were calculated as:

$$N_2O_{\mathrm{ind,hydro}} = N_2O_{\mathrm{tot,hydro}} - N_2O_{\mathrm{tot,not}} \tag{3}$$

where $N_2O_{\mathrm{tot,hydro}}$ are the total N_2O emissions in the *hydro* configuration.

Indirect emission factors were calculated for croplands, unmanaged ecosystems and for the whole landscape using the following equations derived from Mosier et al. (1998):

$$EF_4 = N_2O_{\mathrm{ind,atm}}/\mathrm{capt}_{NH_3} \tag{4}$$

$$EF_{5g} = N_2O_{\mathrm{ind,hydro}}/\mathrm{capt}_{NO_3} \tag{5}$$

$$EF_{\mathrm{all}} = N_2O_{\mathrm{ind,all}}/\mathrm{capt}_{N} \tag{6}$$

where EF_4 is the emission factor due to atmospheric deposition, EF_{5g} is the emission factor due to hydrological recapture, EF_{all} is the emission factor due to both atmospheric deposition and hydrological recapture, $capt_{NH_3}$ is the total atmospheric deposition, $capt_{NO_3}$ is the total NO_3^- recapture by hydrological transfers and $capt_N$ is the total N_r recapture due to atmospheric deposition and hydrological recapture.

2.3 The test landscape

NitroScape was applied to a simplified landscape with a size of 1.75 × 1.75 km^2 corresponding to farm management in intensive rural areas with mixed crops and pig farming (Fig. 2a). From a topographical point of view, the landscape was characterized by a linear slope with a gradient of 50 m between the highest and the lowest parts of the landscape (Fig. 2c). Meteorological data used for the simulation were measured with a meteorological station located on the Kervidy-Naizin catchment (48°01′ N, 2°83′ O). This catchment was characterized by humid climatic conditions (total rainfall: 1968 mm, average relative humidity: 90 %) and little temperature contrast (average temperature: 10 °C, standard deviation: 5 °C). The prevailing wind was from the northeast and south-west, with an average speed of about 1.8 m s^{-1} (Fig. 2b). The soil type was a uniform silt loam soil. Farms were mixed crop-pig farms characterized by indoor pigs (200 sows, 2000 piglets and 2000 baconers). Pig feed was mainly based on imported feed such as wheat, soybean, barley, fishmeal and fat. Baconers were also fed with barley, pea, rye and rapeseed. Croplands cultivated on the farm were wheat and maize (Fig. 2a). Wheat received three applications of mineral fertilizer in February (60 kg N_r ha^{-1}), March (60 kg N_r ha^{-1}) and April (120 kg N_r ha^{-1}). Maize received one manure application in March (120 kg N_r ha^{-1}) and two mineral fertilizer applications in April (60 kg N_r ha^{-1}). The unmanaged ecosystems received no fertilizer or manure, but only N_r deposition.

This test landscape was represented by a matrix of 70 × 70 pixels of 25 × 25 m^2 each which corresponded to the minimal scale at which hydrological transfers occur and the maximum grid cells needed to observe atmospheric dry deposition. Within that landscape 39 fields of 49 pixels each and one field of 41 pixels were dedicated to maize crop, 39 fields of 49 pixels each and one field of 41 pixels were dedicated to wheat crop, four fields of 245 pixels each were dedicated to unmanaged ecosystems and 16 pixels were dedicated to pig buildings (Fig. 2a). One of the four unmanaged ecosystems (UM 1) was located in the north-west i.e., the highest part of the landscape; another unmanaged ecosystem was located in the centre of the landscape (UM 3), close to one of the livestock building. The other two unmanaged ecosystems were located at the bottom of the landscape: one in the north-east close to the other livestock building (UM 2) and the other in the south-east of the landscape (UM 4) (Fig. 2a).

NitroScape simulations were carried out on a whole year from 1 January to 31 December.

3 Results

3.1 Nitrogen losses, recapture and indirect emissions at the landscape scale

Total NH_3 dry deposition was around 9 kg NH_3-N ha^{-1} yr^{-1} within the whole landscape in the *all* and *atm* configurations (Table 1). Two types of N_r capture resulting from groundwater interactions with soil were taken into account: (i) capillary rise and (ii) groundwater uprising when the water table rose in soil and brought water and NO_3^- to the soil surface. The effect of groundwater uprising could be either a capture of NO_3^- if the soil NO_3^- content was lower than the groundwater NO_3^- content or a loss by dilution if the groundwater NO_3^- content was lower than the soil NO_3^- content. Total N_r inputs to ecosystems through capillary rise and groundwater uprising were around 8 kg NO_3^--N ha^{-1} yr^{-1} in the *all* and *hydro* configurations. They were zero in the *atm* and *not* configurations.

Total NO_3^- losses to the groundwater from both leaching and dilution were respectively 66, 45, 62 and 62 kg NO_3^--N ha^{-1} yr^{-1} in the *all*, *not*, *atm* and *hydro* configurations

(Table 1). Atmospheric and hydrological transfers led separately to an additional leaching of 16 kg NO_3^--N ha^{-1} yr^{-1}. Taking into account both types of transfer led to an additional leaching of 20 kg NO_3^--N ha^{-1} yr^{-1}.

Total NH_3 emissions by the landscape were around 39 kg NH_3-N ha^{-1} yr^{-1} (Table 1) in the four configurations (Table 1). Atmospheric transfers led to additional emissions of 0.7 kg NH_3-N ha^{-1} yr^{-1}. Hydrological transfers did not lead to additional NH_3 emissions. Taking into account both types of transfer led to additional emissions of 0.5 kg NH_3-N ha^{-1} yr^{-1}.

Total emissions of NO_x were around 1 kg N-NO_x ha^{-1} yr^{-1} in the four configurations (Table 1). There were no NO_x emissions due to atmospheric or hydrological or both transfers.

Total N_2O emissions were around 5 kg N_2O-N ha^{-1} yr^{-1} in the *all*, *atm* and *hydro* configurations. They were around 4 kg N_2O-N ha^{-1} yr^{-1} in the *not* configuration (Table 1). Atmospheric and hydrological transfers led to additional emissions of respectively 0.7 and 1.1 kg N_2O-N ha^{-1} yr^{-1}. Taking into account both types of transfer led to additional emissions of 1.2 kg N_2O-N ha^{-1} yr^{-1}.

3.2 Distribution of soil nitrogen capture and losses within the landscape

Average NH_3 dry deposition on soils was around 9 kg NH_3-N ha^{-1} yr^{-1}, in the *all* (Fig. 3a) and *atm* (Fig. 3b) configurations, ranging from 0 to 360 kg NH_3-N ha^{-1} yr^{-1}. The highest NH_3 deposition rates were found close to the farm buildings. The lowest NH_3 deposition rates were found in the north-west and the south-east of the landscape for pixels not located in the lee of the farm buildings. Deposition was zero in the *not* and *hydro* configurations.

Direct NH_3 emissions by soils were around 6 kg NH_3-N ha^{-1} yr^{-1} in the *not* configuration, ranging from 0 to 121 kg NH_3-N ha^{-1} yr^{-1} (Fig. 4a). The highest emissions were found for crops in the north-east of the landscape and the lowest NH_3 emissions were found for the unmanaged ecosystems. Average indirect NH_3 emissions resulting from atmospheric transfers were 0.3 kg NH_3-N ha^{-1} yr^{1}, ranging from −2 to 108 kg NH_3-N ha^{-1} yr^{-1} (Fig. 4c). Average indirect NH_3 emissions resulting from hydrological transfers were zero, ranging from −7 to 21 kg NH_3-N ha^{-1} yr^{-1} (Fig. 4d). Average indirect NH_3 emissions due to all transfers were 0.3 kg NH_3-N ha^{-1} yr^{-1}, ranging from −14 to 108 kg NH_3-N ha^{-1} yr^{-1} (Fig. 4b). In the four configurations the highest indirect NH_3 emissions were simulated close to the farm buildings located in the north-east of the landscape.

Average NO_3^- inputs to soils by capillary rise and groundwater uprising were around 7 kg NO_3^--N ha^{-1} yr^{-1} in the *all* configuration, ranging from 0 to 128 kg NO_3^--N ha^{-1} yr^{-1} (Fig. 5a). Average NO_3^- inputs to soils by capillary rise and groundwater uprising were around 9 kg NO_3^--N ha^{-1} yr^{-1} in the *hydro* configuration, ranging from 0 to 135 kg NO_3^--N ha^{-1} yr^{-1} (Fig. 5b). The highest values were found for the unmanaged ecosystems in the east of the landscape.

Average NO_3^- losses to the groundwater by leaching were around 59 kg NO_3^--N ha^{-1} yr^{-1} in the *not* configuration, ranging from 0 to 191 kg NO_3-N ha^{-1} yr^{-1} (Fig. 6a). Average additional losses to the groundwater due to atmospheric transfers were −11 kg NO_3^--N ha^{-1} yr^{-1}, ranging from −55 to 149 kg NO_3-N ha^{-1} yr^{-1} (Fig. 6c). Average additional losses to the groundwater due to hydrological transfers were 23 kg NO_3^--N ha^{-1} yr^{-1}, ranging from −25 to 157 kg NO_3^--N ha^{-1} yr^{-1} (Fig. 6d). Average additional losses to the groundwater due to both atmospheric and hydrological transfers were 6 kg NO_3^--N ha^{-1} yr^{-1}, ranging from −50 to 263 kg NO_3^--N ha^{-1} yr^{-1} (Fig. 6b). In the *atm* configuration the highest additional losses were simulated close to the buildings of farm 2 and for the wheat fields. In the *hydro* configuration the highest additional transfers were simulated for the wheat fields located in the east of the landscape while the lowest additional emissions were simulated in the unmanaged ecosystems. In the *all* configuration the highest additional transfers were simulated for the wheat fields located in the east of the landscape.

Average N_2O emissions by soils were 5 kg N_2O-N ha^{-1} yr^{-1} in the *not* configuration, ranging from 0 to 72 kg N_2O-N ha^{-1} yr^{-1} (Fig. 7a). The highest values of N_2O emissions were simulated for pixels located in the north-east of the landscape which was the lowest part of the landscape. The lowest N_2O emissions were simulated for the unmanaged ecosystems. Average indirect N_2O emissions due to all transfers were around 1 kg N_2O-N ha^{-1} yr^{-1}, ranging from −37 to 29 kg N_2O-N ha^{-1} yr^{-1} (Fig. 7b). Average indirect N_2O emissions due to atmospheric transfers were around zero, ranging from −9 to 17 kg N_2O-N ha^{-1} yr^{-1} (Fig. 7c). Average indirect N_2O emissions due to hydrological transfers were 1 kg N_2O-N ha^{-1} yr^{-1}, ranging from −37 to 29 kg N_2O-N ha^{-1} yr^{-1} (Fig. 7d). The highest indirect N_2O emissions were simulated at different locations according to the type of transfer. Indirect emissions due to atmospheric transfers were located close to the farm buildings, especially those of the farm 1, while the highest indirect emissions due to hydrological transfers were located in the maize fields and the unmanaged ecosystems in the north-east of the landscape. The highest indirect emissions due to all transfers were located in the maize fields and the unmanaged ecosystems in the north-east of the landscape.

3.3 Indirect N_2O emission factor

The value of the indirect N_2O emission factor for the whole landscape was around 8, 9 and 6 % in the *atm*, *hydro* and *all* configurations respectively (Fig. 8). For croplands only, that value was around 10, 9 and 4 % in the *atm*, *hydro* and *all* configurations respectively. For the unmanaged ecosystems only, that value was around 3, 10 and 6 % in the *atm*, *hydro* and *all* configurations respectively.

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4 Discussion

4.1 Direct emissions

NH_3 emissions from soils were 11 % of the N_r inputs. This value was lower than the expected value of 37 % of fertilizers applied (ECETOC, 1994). NH_3 emissions varied within the landscape according to the N_r input patterns. The highest NH_3 emissions were simulated for crops located in the north-east of the landscape which was the lowest part of the landscape and where soil was highly saturated (*not* configuration, Fig. 4a). Nitrification was therefore limited, leading to high NH_4^+ content (Hénault et al., 2005) and therefore high NH_3 emissions (Génermont and Cellier, 1997). The lowest NH_3 emissions were found for the unmanaged ecosystems located in the north-west of the landscape where soil was not saturated.

The highest values of NO_3^- leaching were simulated for the wheat fields located in the west and the centre of the landscape (Fig. 6a, *not* configuration). The lowest values of NO_3^- leaching were simulated for the unmanaged ecosystems. The leaching rates mainly varied according to the land use and the N_r inputs.

The value of the average direct N_2O emission factor was higher than the expected value of 1 % given by the IPCC methodology (IPCC, 2006). The highest direct N_2O emissions were simulated for pixels located in the north and the east of the landscape where soil was highly saturated, leading to high denitrification rates (Hénault et al., 2005). Direct N_2O emissions also varied according to the land use and N_r inputs, with the highest N_2O emissions simulated for the wheat fields receiving more N_r inputs.

4.2 Re-capture

The simulated NH_3 deposition rates (Fig. 3) ranged within the same values as those observed by Fowler et al. (1998), with high deposition rates close to the downwind of the livestock buildings (Loubet et al., 2009). The lowest NH_3 deposition rates were found in the north-west and the south-east of the landscape for pixels located far from livestock buildings and receiving low N_r rates from them due to wind direction distribution.

The highest NO_3^- inputs to soils by runoff and throughflow were simulated in the north-east of the landscape where water accumulated (Fig. 5). The highest NO_3^- re-capture by capillary rise and groundwater uprising were simulated for the unmanaged ecosystems in the east of the landscape. The highest values of NO_3^- inputs by capillary rise were simulated for the maize fields located in the west of the landscape (around 5 kg NO_3^--N ha^{-1} yr^{-1}). Soil water content was lower in the west than in the east of the landscape resulting in a higher capillary rise. That might be explained by the fact that the east of the landscape received water by rainfall, runoff and throughflow from the upper part of the landscape, while the west of the landscape received water by rainfall only. The highest re-capture by groundwater uprising was simulated for the unmanaged ecosystems in the east of the landscape (around 60 kg NO_3^--N ha^{-1} yr^{-1}). That means that groundwater reached the soil surface in the east of the landscape with a higher NO_3^- content than the soil NO_3^- content of the unmanaged ecosystems.

4.3 Indirect emissions

Both atmospheric and hydrological transfers and recapture led to additional NH_3 emissions up to 108 kg NH_3-N ha^{-1} yr^{-1}, additional NO_3^- losses up to 263 kg NO_3^--N ha^{-1} yr^{-1} and additional N_2O emissions up to 29 kg N_2O-N ha^{-1} yr^{-1}.

Atmospheric transfers and deposition led to additional NH_3 emissions up to 108 kg NH_3-N ha^{-1} yr^{-1} in the north-east of the landscape (Fig. 4). NH_3 deposition was approximately the same within the whole landscape, excepted in the north-east of the landscape where indirect emissions were higher due to soil saturation leading to low nitrification. Atmospheric transfers led to additional NO_3^- losses to the groundwater up to 149 kg NO_3^--N ha^{-1} yr^{-1}. The highest leaching rate was simulated close to the farm buildings located in the centre of the landscape where high N_r inputs from deposition and favourable conditions to nitrification led to higher soil NO_3^- content and consequently higher NO_3^- leaching. The highest indirect N_2O emissions due to atmospheric transfers were located close to the farm buildings especially farm 1. NH_3

deposition led to higher soil NO_3^- content leading to higher N_2O emissions, especially in the north-east of the landscape where conditions of soil saturation were favourable to denitrification. NH_3 deposition in the east of the landscape led to lower N_2O emissions. That might be explained by the fact that NH_3 deposition led to an increase of NO_3^- uptake by plants.

Hydrological transfers and recapture did not lead to additional NH_3 emissions. Hydrological transfers and recapture led to additional NO_3^- losses to the groundwater up to 157 kg NO_3^--N ha^{-1} yr^{-1}. The highest losses were simulated in the east of the landscape where high soil saturation led to high interaction with the groundwater and potentially high dilution by the groundwater. Hydrological transfers and recapture led to additional N_2O emissions up to 29 kg N_2O-N ha^{-1} yr^{-1}. The highest losses were simulated in the east of the landscape where the highly saturated soil conditions led to high interaction with the groundwater and potentially to high dilution by the groundwater. The highest indirect N_2O emissions due to hydrological transfers were simulated for the maize fields and the unmanaged ecosystems in the north-east of the landscape. Those fields and ecosystems received higher N_r from recapture and were characterized by conditions of soil saturation favourable to denitrification. Negative indirect N_2O emissions due to hydrological transfers were simulated in the wheat fields located in the north-east of the landscape, affected by dilution in the groundwater leading to NO_3^- losses to the groundwater.

The response to N_r recapture varied according to the land use. The unmanaged ecosystems had a higher value of the indirect N_2O emission factor than crops. They emitted more N_2O than crops for the same recapture of N_2O. That may be explained by competition for NO_3^- between plant uptake and denitrification with higher NO_3^- uptake by crops than by unmanaged ecosystems. Moreover, the high productivity of crops might be also linked to high water uptake by crops, leading to reducing soil saturation, then reducing denitrification and consequently reducing indirect N_2O emissions by crops in comparison with unmanaged ecosystems. Another hypothesis to explain patterns of indirect N_2O emissions is that atmospheric NH_3 deposition is more limiting than hydrological NO_3^- recapture: deposited NH_3 needs to be first nitrified before being captured by crops or denitrified, while NO_3^- may be directly denitrified. This result supports the idea of the land-use receptor approach proposed by van der Gon and Bleeker (2005) to estimate atmospheric indirect emissions. The response of N_r recapture also varied according to its location within the landscape: indirect emissions were generally higher in the north-east of the landscape where water and nitrogen accumulation led to higher denitrification rates.

The values of the indirect N_2O emission factor due to hydrological transfers may be compared with the ones of the EF5g emission factor derived from the IPCC methodology (Mosier et al., 1998; Nevison, 2000). They were higher than the maximum value of 2 % proposed by Mosier et al. (1998) and lower than the maximum value of 10 % proposed by Nevison (2000). The values of the indirect N_2O emission factor due to atmospheric transfers were higher than the ones of the EF4 emission factor derived from the IPCC methodology (Mosier et al., 1998; van der Gon and Bleeker, 2005). Moreover, the values of EF4 proposed by those authors include both short-term and long-term transfers. The high values of EF4 simulated with NitroScape might result from high denitrification rates leading to both high direct and indirect N_2O emissions.

5 Conclusions

The NitroScape model integrates processes of N_r transformation and short-term transfer in a dynamic and spatially distributed way to simulate N_r fluxes and budgets at the landscape scale. By using four configurations of NitroScape taking into account or not the atmospheric, hydrological or both pathways of N_r transfers, we showed the ability of this model to simulate patterns of N_r losses and recapture for each landscape element (i.e. pixel with a size of 25 m × 25 m) within a test landscape. Moreover, NitroScape made it possible to estimate the relative contribution of indirect N_2O emissions to the nitrogen budget of a test landscape and the relative contribution of the atmospheric and hydrological pathways to indirect N_2O emissions. The need of an integrated, spatially distributed and dynamic model is emphasized by the high variability of N_r losses and gains which were simulated within the landscape, and the effect of landscape topography and short-term processes on N_r fluxes. We also showed that N_2O emissions by unmanaged ecosystems were affected by both atmospheric deposition of NH_3 and hydrological recapture of NO_3^-, which emphasized the need to model dynamically both atmospheric and hydrological transfers of N_r. Taking into account both pathways of N_r transfers led to simulate high values of indirect N_2O emissions (almost 25 % of the total N_2O emissions). Indirect N_2O emissions were affected by both the position of recapture within the landscape and the land use of receptors. That result indicates that the spatial distribution of ecosystems and especially the ecosystems located in the zones of N_r recapture may affect N_2O emissions. This hypothesis needs to be further tested by applying NitroScape to several spatial distributions of ecosystems within the landscape and to real and larger landscapes.

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Table 1. Nitrogen losses and recapture in the test landscape.

Configuration	NH_3 dry deposition ($kg\,NH_3\text{-}N\,ha^{-1}\,yr^{-1}$)	Capillary rise and groundwater uprising ($kg\,NO_3\text{-}N\,ha^{-1}\,yr^{-1}$)	NH_3 emissions ($kg\,NH_3\text{-}N\,ha^{-1}\,yr^{-1}$)	NO_x emissions ($kg\,NO_x\text{-}N\,ha^{-1}\,yr^{-1}$)	N_2O emissions* ($kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$)	NO_3^- leaching ($kg\,NO_3\text{-}N\,ha^{-1}\,yr^{-1}$)
all	9.0	7.5	39.2	0.9	5.6	65.6
not	0.0	0.0	38.7	0.9	4.4	45.3
atm	9.1	0.0	39.4	0.9	5.1	61.5
hydro	0.0	8.3	38.7	0.9	5.5	61.5

* means that N_2O emissions by the farms were calculated using the IPCC methodology.

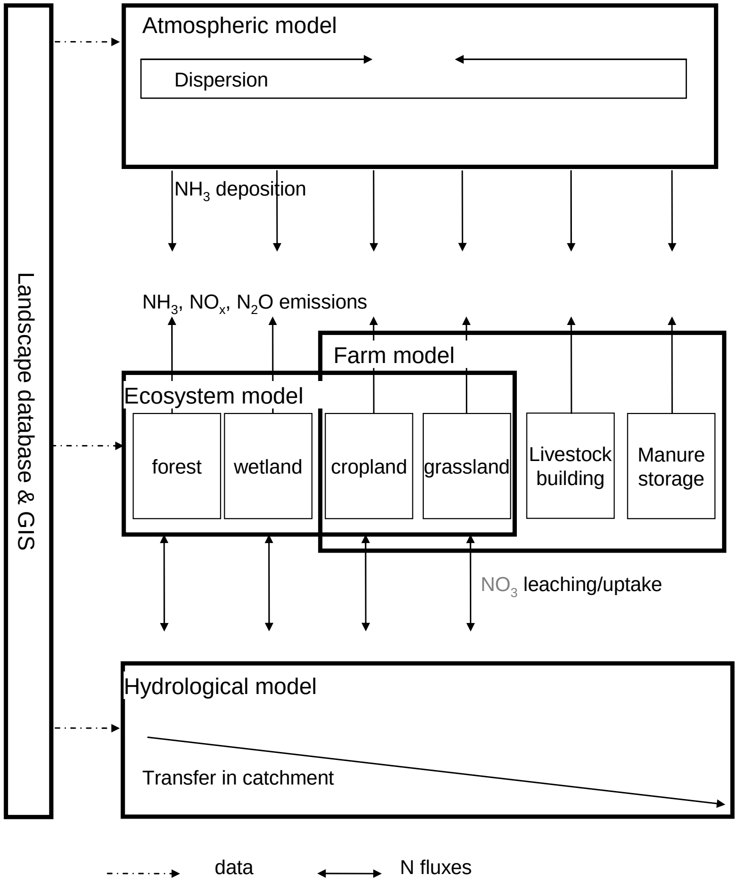

Fig. 1. The NitroScape model scheme.

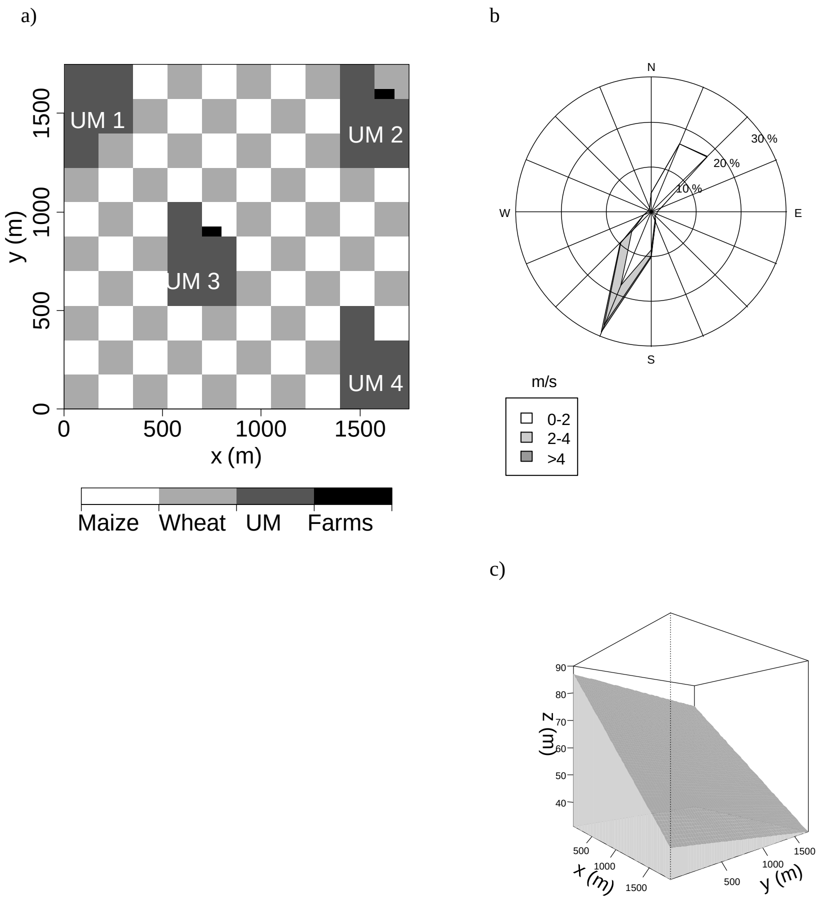

Fig. 2. **(a)** Land use in the test landscape (wheat fields received 240 kg N ha^{-1} yr^{-1} and maize fields received 260 kg N ha^{-1} yr^{-1}, UM: unmanaged ecosystem), **(b)** wind direction and speed and **(c)** topography of the landscape. x and y axes in **(c)** correspond to the ones in **(a)**.

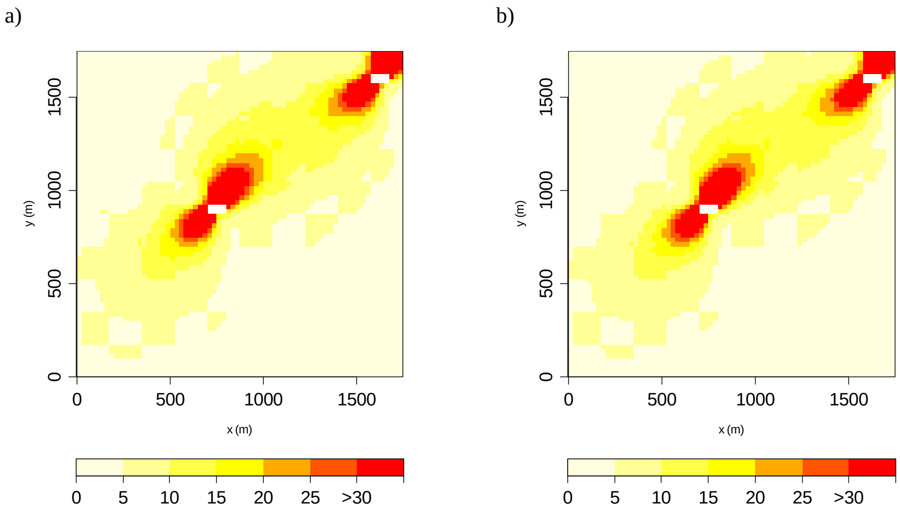

Fig. 3. NH_3 deposition in the **(a)** *all* and **(b)** *atm* configurations (kg NH_3-N ha^{-1} yr^{-1}).

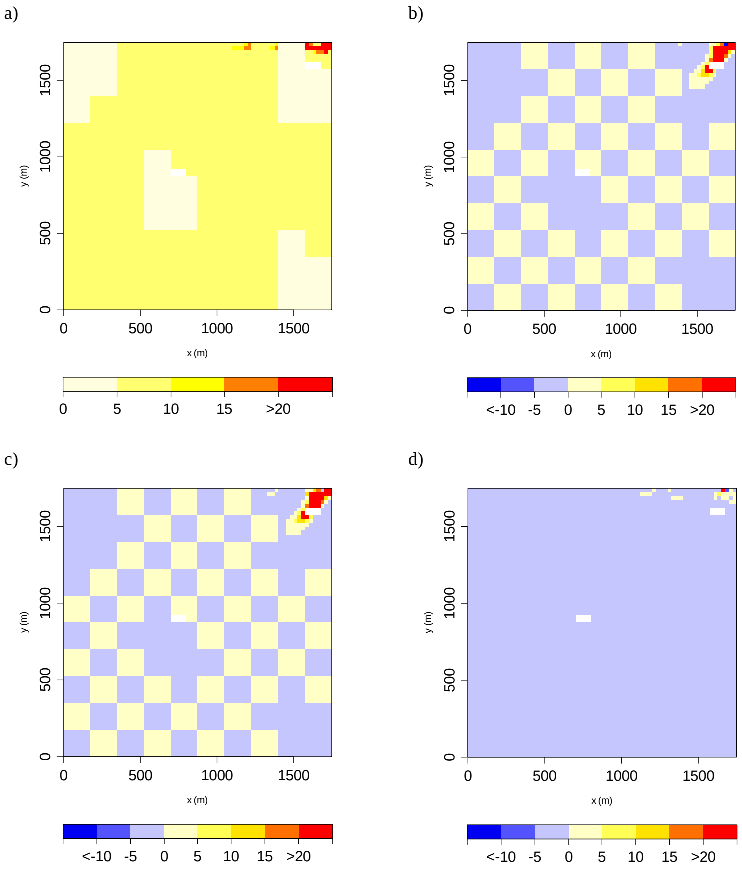

Fig. 4. (a) Direct NH_3 emissions by soils in the *not* configuration ($kg\,NH_3\text{-}N\,ha^{-1}\,yr^{-1}$). Indirect NH_3 emissions in the **(b)** *all*, **(c)** *atm* and **(d)** *hydro* configurations ($kg\,NH_3\text{-}N\,ha^{-1}\,yr^{-1}$). Negative (resp. positive) values in **(b)**, **(c)** and **(d)** means that NH_3 emissions are lower (resp. higher) in each of the *all*, *atm* and *hydro* configurations than in the not configuration.

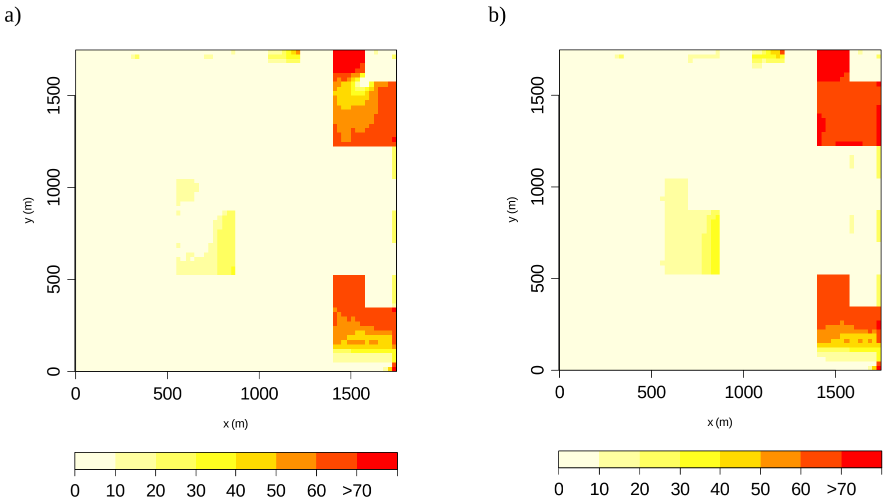

Fig. 5. NO_3^- uptake by capillary rise and groundwater uprising in the **(a)** *all* and **(b)** *hydro* configurations (kg NO_3^--N ha^{-1} yr^{-1}).

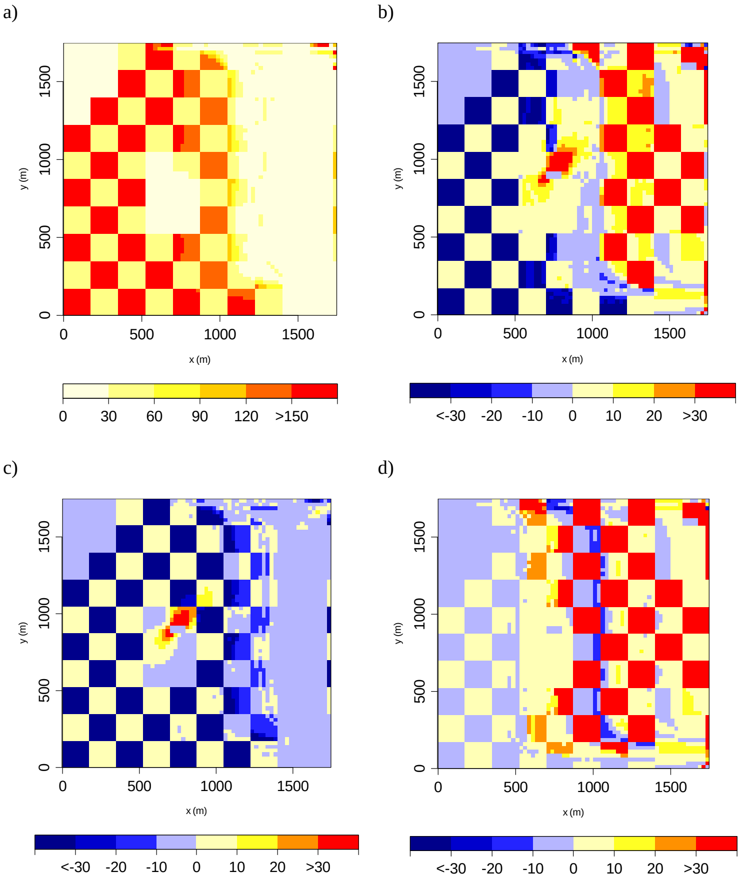

Fig. 6. **(a)** Direct NO_3^- losses to the groundwater in the *not* configuration and indirect NO_3^- losses in the **(b)** *all*, **(c)** *atm* and **(d)** *hydro* configurations (kg NO_3^--N ha^{-1} yr^{-1}). Negative (resp. positive) values in **(b)**, **(c)** and **(d)** means that NO_3^- losses are lower (resp. higher) in each of the *all*, *atm* and *hydro* configurations than in the *not* configuration.

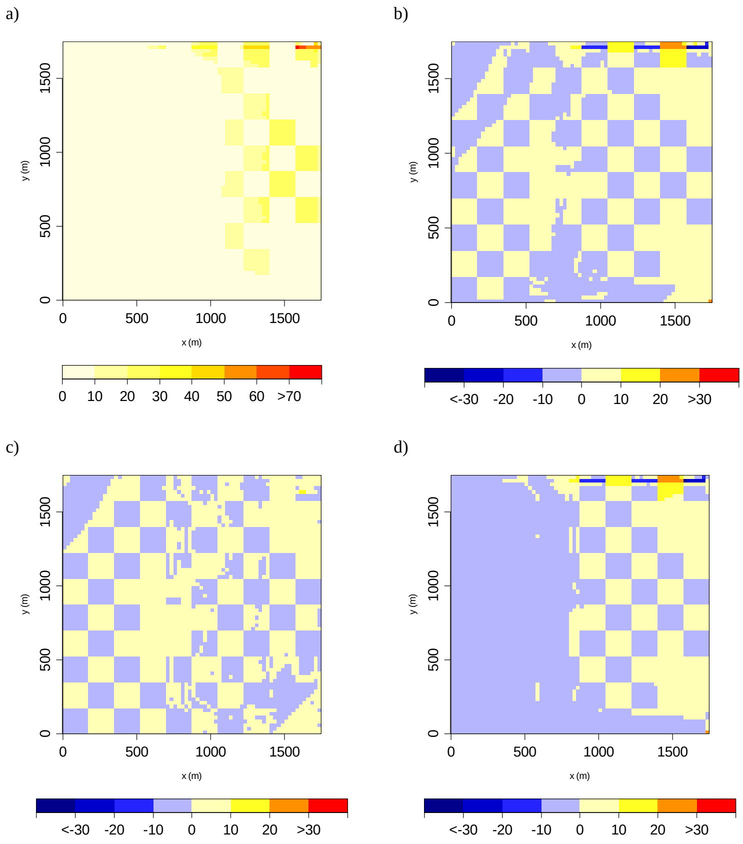

Fig. 7. **(a)** Direct N_2O emissions in the *not* configuration and indirect N_2O emissions in the **(b)** *all*, **(c)** *atm* and **(d)** *hydro* configurations (kg N_2O-N ha^{-1} yr^{-1}). Negative (resp. positive) values in **(b)**, **(c)** and **(d)** means that N_2O emissions are lower (resp. higher) in each of the *all*, *atm* and *hydro* configurations than in the not configuration

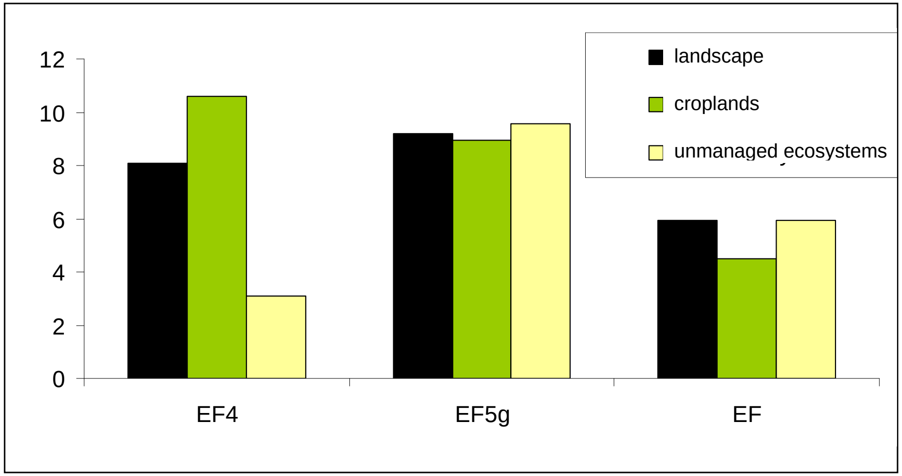

Fig. 8. Indirect N_2O emission factor in the *atm* (EF4), *hydro* (EF5g) and *all* (EF) configurations for the whole landscape, all croplands and the four unmanaged ecosystems. Values are in percentage of kg N_2O-N emitted by kg N captured.