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Integrated analysis of the effects of agricultural management on nitrogen fluxes at landscape scale

J. Kros[a,*], K.F.A. Frumau[b], A. Hensen[b], W. de Vries[a,c]

[a] Alterra, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[b] Energy Research Centre of The Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands
[c] Environmental Systems Analysis Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

The integrated modelling system INITIATOR was applied to a landscape in the northern part of the Netherlands to assess current nitrogen fluxes to air and water and the impact of various agricultural measures on these fluxes, using spatially explicit input data on animal numbers, land use, agricultural management, meteorology and soil. Average model results on NH_3 deposition and N concentrations in surface water appear to be comparable to observations, but the deviation can be large at local scale, despite the use of high resolution data. Evaluated measures include: air scrubbers reducing NH_3 emissions from poultry and pig housing systems, low protein feeding, reduced fertilizer amounts and low-emission stables for cattle. Low protein feeding and restrictive fertilizer application had the largest effect on both N inputs and N losses, resulting in N deposition reductions on Natura 2000 sites of 10% and 12%, respectively.

1. Introduction

Farmers in the Noordelijke Friese Wouden (NFW), a landscape in the northern part of the Netherlands, have a long history in developing and exploring alternatives for intensive dairy farming, to avoid its negative environmental impacts. A large part of the 600 km^2 area has been designated as Dutch National Landscape, being a landscape that is aimed to be conserved in view of its unique combination of cultural and natural elements. The landscape status of the NFW is due to the small scale parcelling structure, a high concentration of hedge-rows bordering the individual fields and the occurrence of many pingo-remnants from the Weichsel glacial period. Farmers have lowered both nitrogen (N) and phosphorus (P) losses by changing farm and field management from the 1990's onwards. In 2003, six individual cooperatives joined together to form one big cooperative, the "Noardlike Fryske Walden", currently representing some 800 farmers in the region. In 2005 the cooperative has made an agreement with the government, the Water Board and regional environmental organisations about achieving environmental quality and emission objectives at regional level rather than at farm level. Hence, the cooperative itself will decide which measures the farmers will implement (Bouma et al., 2008; Glasbergen, 2000; Wiskerke et al., 2003).

The landscape scale is often considered as a distinct scale for decision making within environmental policies (see e.g. Cellier et al., 2011). Dalgaard et al. (2011) showed that the landscape scale is an appropriate scale to illustrate scaling issues in relation to N fluxes and greenhouse gas emissions. Furthermore, the NFW is one of the six experimental landscapes within the NitroEurope project (Sutton et al., 2007), where it is acknowledged that especially at landscape scale there is a spatial interactions between N management at farm level and nearby semi-natural areas through hydrological dispersion (Van der Velde et al., 2009) and atmospheric dispersion (Dragosits et al., 2002).

The environmental goals at the landscape scale were derived for five individual source and state indicators that have been defined in national and international agri-environmental polices (EEA, 2005). These are NH_3 emission at the landscape scale, atmospheric N deposition at plot scale, N and P in surface waters at the scale of water bodies and NO_3^- concentration in the upper groundwater (Sonneveld et al., 2010a,b). The use of those environmental objectives at a landscape level implies the need for tools that explore environmental impacts of various options and scenarios for future agricultural developments. To gain insight in the environmental impacts of manure and mineral fertilizer applications in the NFW area, the integrated model system INITIATOR (Integrated Nutrient

* Corresponding author.
E-mail address: hans.kros@wur.nl (J. Kros).

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ImpacT Assessment Tool On a Regional scale) (De Vries et al., 2003b) was applied for predicting: (i) emissions of NH_3 and N_2O from animal housing systems and agricultural soils, (ii) N deposition on nearby Natura 2000 areas and (iii) N leaching and runoff from agricultural soils to ground water and surface water.

This article provides an assessment of the present environmental status (year 2007, i.e., the most recent year for which farm data was available) of the NFW area and impacts of farm measures on this status, using spatially explicit input data on animal numbers, land use, agricultural management, meteorology and soil. A validation was performed by a comparison with observation based NH_3 emission estimates and measured N concentrations in surface water. The evaluated agricultural management measures focus on the reduction of NH_3 emissions and include the emission reduction from poultry and pig housing systems by using air scrubbers, low protein feeding for cattle, more restrictive animal manure application and mineral fertilizer use and low-emission stables for cattle.

2. Material and methods

2.1. Modelling approach

Methodology: Calculations for the emission of NH_3, deposition of N, emission of N_2O and N leaching to the groundwater in the NFW were performed for the year 2007 with the integrated nutrient model INITIATOR (De Vries et al., 2003b) in combination with the atmospheric OPS transport model (Van Jaarsveld, 2004). The modelling philosophy of INITIATOR is to use a relatively simple approach to be able to calculate all main N fluxes at a regional scale, while using available detailed spatial data. In this study, we linked INITIATOR with a CBS/GIAB dataset (Naeff, 2003) with animal numbers for each farm in the Netherlands to assess the N excretion and housing N emissions and a manure and mineral fertilizer distribution model (De Vries et al., 2005) to assess N manure and fertilizer inputs at a high spatial resolution (see Fig. 1).

Excretion and housing emissions: The N excretion in manure is calculated by a multiplication of the animal numbers for each farm with the excretion per animal head. The emissions of NH_3, NO_x and N_2O from housing and manure storage systems are described by a multiplication of N excretion with element specific emission fractions (NH_3, NO_x, N_2O) for different animal categories, depending on the type of emission (a maximum of 65 categories in case of N excretion and NH_3 emission, see Oenema et al. (2000)). The N excretion, minus volatilisation from housing and storage systems, is input for a manure and mineral fertilizer application module that predicts the inputs of N to the soil.

Manure and mineral fertilizer distribution: The manure and mineral fertilizer distribution model distributes the produced manure over the available arable land and grassland, while distinguishing cattle, pig and poultry manure. Within

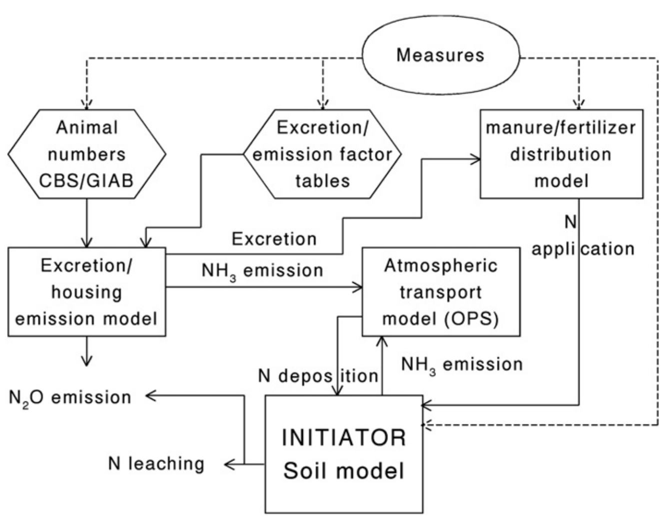

Fig. 1. Coupling of modules and model outputs in the nitrogen part of the INITIATOR model for agriculture.

a municipality, the manure is distributed according to the Dutch/EU legislation, i.e., a maximum N application rate of 170 kg N of animal manure for arable land and of 250 kg N for grassland. For each municipality a comparison is made between the maximum acceptable N input and the manure produced by grazing cattle (applied to grassland) and in housing systems. This leads to excess municipalities, where the available amount of N in manure exceeds the N application limits and shortage municipalities with a capacity to accept animal manure. The excess is uniformly distributed over the shortage municipalities. No manure is assumed to be transported in or out this region. If it is not possible to distribute the excess manure over the shortage municipalities, the excess manure is applied in the municipality were it was produced, causing an exceedance of the maximum application rate. The distribution of the amount of mineral N fertilizer is calculated according to the national fertilizer advice.

Soil N fluxes: The INITIATOR soil model calculates the soil emissions of NH_3, NO_x and N_2O, N uptake, N mineralisation/immobilisation, N leaching and N runoff with a consistent set of simple linear equations (De Vries et al., 2003b). First the total N input to the soil is calculated as the sum of inputs by animal manure, mineral fertilizer, atmospheric deposition and biological N fixation. Biological N fixation is estimated as a function of land use, i.e., 25 kg ha^{-1} yr^{-1} for grassland, 15 kg ha^{-1} yr^{-1} for arable land and 8 kg ha^{-1} yr^{-1} for maize land. The fate of N in soils is calculated as a sequence of occurrences and/or process rate in the order NH_3 emission, followed by N uptake, N mineralisation/immobilisation, nitrification and denitrification in the soil. We thus assumed that N uptake is a faster process than nitrification and denitrification (see e.g., Kirk and Kronzucker, 2005). All N transformation processes are described as a linear function of the inflow of N (see De Vries et al., 2003b):

- NH_3 emission depends linearly on the N input to the soil.
- N uptake (N removal from the field) depends linearly on the (effective) N input minus the NH_3 emission.
- Net N immobilisation depends linearly on the net N input (N input minus NH_3 emission minus N uptake).
- Nitrification depends linearly on the net N input minus N mineralisation/immobilisation.
- Denitrification depends linearly on the nitrification flux.

The NH_3 emissions from soils are calculated by a multiplication of the N inputs by manure and mineral fertilizer application and grazing cattle with specific N emission fractions for these inputs. Maximum N uptake rates (uptake at optimal N supply) are given as a function of land use (grass, maize and arable land using a mixture of wheat, other cereals, potatoes, sugar beet and other crops), soil type (sand, loess, clay and peat) and ground water table (dry, moist and wet) in terms of a maximum yield and related N contents. The uptake and soil N transformation parameters are given as a function of land use, soil type and/or ground water table. The flux of N leaving the top layer (0–0.5 m) is calculated by subtracting all N outputs from the soil system (emission, uptake and denitrification) from the N inputs to the soil, while accounting for the soil N pool changes due to either net N mineralisation or N immobilisation. The leaching loss from the top layer is partitioned to surface water and to groundwater (0.5–13 m) by multiplying the leaching loss with a runoff fraction (including all pathways for N moving to surface waters) and a leaching fraction (1 − runoff fraction), respectively. The runoff fraction is given as a function of soil type and groundwater table. The N_2O and NO_x emission from soils are calculated as the multiplication of specific N_2O and NO_x emissions fractions with the nitrification flux and denitrification flux. The N_2 emissions are calculated as the (total) denitrification flux minus the N_2O and NO_x emissions. INITIATOR also calculates N immobilisation/mineralisation in surface water and nitrification and denitrification in ground water, ditches and surface water and the related N_2O emissions. The considered N_2O fluxes are thus the emissions occurring in housing systems, soils (both agricultural and semi-natural), ground water and ditches. This paper does not include the emissions from surface water.

N deposition assessment: The NH_3 emissions from housing and storage systems and from the field form the input of the detailed atmospheric transport model OPS (Van Jaarsveld, 2004), to assess the N deposition on agricultural and non-agricultural systems. With the combination of INITIATOR and OPS, the NH_3 deposition due to agricultural NH_3 emissions was calculated. To enable a comparison with the critical N deposition, the total N deposition on the Natura 2000 sites (see Fig. 2c) was calculated by a combination of the thus derived NH_3 deposition with deposition patterns for the NO_x deposition and the background NH_3 deposition from sources outside the NFW, including the contribution from non-agricultural sources. These deposition fluxes from other sources of N were delivered by the Netherlands Environmental Assessment Agency (pers. comm. Hans van Jaarsveld) at a resolution of 5×5 km^2, based on national OPS model calculations and using emission data for the year 2006.

2.2. Input data

Available GIS datasets for the Netherlands as a whole were used for most of the inputs for the INITIATOR model, including the 1: 50,000 scale soil and hydrology map (De Vries et al., 2003a), the LGN land use map (De Wit, 2001; Hazeu, 2005), the