Environmental Pollution 159 (2011) 3183–3192

Contents lists available at ScienceDirect

Environmental Pollution

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

Effects of farm heterogeneity and methods for upscaling on modelled nitrogen losses in agricultural landscapes

T. Dalgaard [a,*], N. Hutchings [a], U. Dragosits [b], J.E. Olesen [a], C. Kjeldsen [a], J.L. Drouet [c], P. Cellier [c]

[a] Aarhus University, Department of Agroecology, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark
[b] CEH Edinburgh, Bush Estate, Penicuik, Midlothian EH26 0QB, Scotland, UK
[c] INRA, UMR Environnement et Grandes Cultures, BP 01, 78850 Thiverval-Grignon, France

ARTICLE INFO

Article history:
Received 22 February 2011
Accepted 26 February 2011

Keywords:
Agriculture
Greenhouse gas emissions
Heterogeneity
Landscape
Nitrogen losses
Upscaling

ABSTRACT

The aim of this study is to illustrate the importance of farm scale heterogeneity on nitrogen (N) losses in agricultural landscapes. Results are exemplified with a chain of N models calculating farm-N balances and distributing the N-surplus to N-losses (volatilisation, denitrification, leaching) and soil-N accumulation/release in a Danish landscape. Possible non-linearities in upscaling are assessed by comparing average model results based on (i) individual farm level calculations and (ii) averaged inputs at landscape level. Effects of the non-linearities that appear when scaling up from farm to landscape are demonstrated. Especially in relation to ammonia losses the non-linearity between livestock density and N-loss is significant ($p > 0.999$), with around 20–30% difference compared to a scaling procedure not taking this non-linearity into account. A significant effect of farm type on soil N accumulation ($p > 0.95$) was also identified and needs to be included when modelling landscape level N-fluxes and greenhouse gas emissions.

1. Introduction

Excess of nitrogen (N) is one of the main characteristics of modern, intensive agriculture, leading to severe problems with N pollution (Erisman et al., 2007) and related emissions of greenhouse gases (Johnson et al., 2007). In this context, The NitroEurope Research Project (Sutton et al., 2007; NitroEurope, 2010) studies the interactions between sources and sinks of N in order to understand its effects cascading through ecosystems in its multiple forms, represented by the more than nine different oxidation steps possible (Galloway, 1998).

In relation to agriculture, the three main types of N pollution are from ammonia (NH_3), nitrate (NO_3^-) or nitrous oxide (N_2O). Emissions of NH_3 gas are mainly related to intensive livestock production and manure management, and the environmental problems caused relate to its contribution to the formation of secondary particulate matter in the atmosphere which has an adverse impact on biodiversity when deposited in vulnerable terrestrial or aquatic ecosystems (Bobbink et al., 2010). Nitrate leaching leads to eutrophication of surface waters or pollution of groundwater (Sonneveld et al., 2010; Kronvang et al., 2008). Finally, the greenhouse gas N_2O can be emitted when ammonium is nitrified to nitrate and when nitrate is partially denitrified, processes that can occur in manure management systems (Dämmgen and Hutchings, 2008) and soils, or in groundwater or wetland areas receiving nitrates in runoff or leaching from agricultural land (Chirinda et al., 2010; Johnson et al., 2007).

Landscapes consist of a range of elements such as farmland, forestry and wetlands, that each can receive and lose a range of N compounds. The losses of N to the atmospheric or aquatic environments from these landscape elements are usually accounted separately (e.g. Hansen et al., 2000 for farmland; Gundersen et al., 1998 for forestry; Maltais-Landry et al., 2009 for wetlands), using ecosystem models that are spatially one-dimensional (vertical). This contrasts with models of the atmospheric and aquatic environments, where three-dimensional spatial models are common (e.g. Hellsten et al., 2008; Hutchings et al., 2001). In these models, interactions in the horizontal plane are acknowledged to be important. For example, it is acknowledged that the distance between an N-sensitive ecosystem and a source of NH_3 is important in determining deposition of N from the atmosphere to that ecosystem (Dragosits et al., 2006).

Agricultural systems are commonly major sources of N compounds at the landscape scale, the different types and

* Corresponding author.
E-mail address: tommy.dalgaard@agrsci.dk (T. Dalgaard).

0269-7491/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2011.02.043

quantities of N pollution being dependent on management practices (Kros et al., in this issue; Hansen et al., 2011). The fate of these N compounds and the consequences for the environment depends on the proximity of agricultural and non-agricultural landscape elements and their degree of connectivity via transport mechanisms (e.g. atmospheric or aquatic transport pathways). Gergel (2005) showed that spatial heterogeneity at the landscape level affects N pollution and greenhouse gas emissions, and that landscape level design of farming practices consequently may be an effective measure to mitigate such losses.

The importance of the geographic location of landscape elements and their interconnectivity have been investigated in the NitroEurope EU research project, where a unified landscape level NitroScape model is being constructed (Sutton et al., 2007; Duretz et al, in this issue).

In this context, the present paper is a pilot study for the further landscape scale work, in which we focus on the farming system component, and the effect of heterogeneity within this system, when scaling up from farm to landscape level. In our paper, we therefore aim to test the effects of farm heterogeneity on the modelling and upscaling of nitrogen losses and greenhouse gas emissions, exemplified in a specific Danish landscape. We especially focus on the effects of spatial heterogeneity in livestock density, the type of farming (ruminants, granivores, arable farming), and the use of N in the arable and the livestock production system. Farm N-surpluses are calculated and partitioned between the three main types of N-losses: ammonia emissions, nitrate leaching and denitrification, and the corresponding changes in N in the soil. Based on these results, we compare examples of different upscaling approaches, and identify and discuss the importance of non-linearities to be included in landscape level farm management models.

2. Materials and methods

In this chapter we describe the models for farm N-fluxes and the related greenhouse gas emissions (Section 2.1), the approaches for the upscaling of N-losses and greenhouse gas emissions from the farm to the landscape scale (Section 2.2), and the agricultural landscape dataset for which these models are set up and on which the upscaling approaches are tested (Section 2.3).

2.1. Nitrogen modelling

2.1.1. Farm nitrogen balances and N-surplus

The farm gate N-surplus is defined as the difference between net input (i) to the farm in the form of net feed import, net fertiliser import and N from the atmosphere; and net N output (o) from the farm in the form of milk (o1) and meat. The net meat export is calculated as N in the meat exported (o2) minus N in imported livestock (i5). The net feed import is calculated as the sum of N in imported feed (i1) and seeds (i2), minus N in cash crops and straw materials sold (o4). The net fertiliser import is calculated as the sum of N in imported synthetic fertiliser (i3) and manure (i4), minus N in manure exported (o3). Finally, the sum i6 + i7 covers N from the atmosphere in the form of N-deposition, and N fixed by legumes (equation (1), Dalgaard et al., 1998). The N-surplus is calculated as:

$$N - \text{surplus} = i1 + i2 + i3 + i4 + i5 + i6 + i7 - o1 - o2 - o3 - o4 \quad (1)$$

This nitrogen balance (N-surplus) is calculated on an annual basis for each farm by the Farm-N model (Jørgensen et al., 2005; Hutchings et al., 2006; Zander et al., 2009, http://www.fasset.dk/Upload/Fasset/Document/FARM-N_scientific_description.pdf). Within this model, the manure and synthetic fertiliser are distributed to the registered crops on each farm in accordance with the official Danish fertilisation manual, where N-fertilisation rates are determined as 10% below the economic optimum in relation to the actual fertiliser prices (The Danish Plant Directorate, 2007). This manual is also used as a reference book to determine crop yields based on the soil types registered and assumptions about crop rotations estimated by the linear programming probability model of Detlefsen and Jensen (2007). For each crop, the N-fixation from the atmosphere is calculated via the procedures of Høgh-Jensen et al. (2003, 2004), and the local N-deposition is set to 15 kg N ha^{-1} yr^{-1} (Dalgaard et al., 2002a,b). The feeding for each livestock category is based on the demand for energy and protein in terms of the production data defined (Poulsen et al., 2001), and the need for straw is derived from the housing system defined for each livestock category and each farm. Crop production surpluses are exported from the farm, while feedstuffs needed to implement the defined feed plan are imported to the farm. Finally, the Farm-N model distributes the N-surplus into farm nitrogen loss pathways in the form of ammonia emission ($N_{emission}$), nitrate leaching ($N_{leaching}$) or denitrification ($N_{denitrification}$), and estimates the soil-N accumulation ($N_{accumulation}$), defined as the accumulation of nitrogen in the soils farmed by each individual farm (equation (2), Fig. 1). This modelling is briefly described in the following sections.

$$\text{N-surplus} = N_{emission} + N_{leaching} + N_{denitrification} + N_{accumulation} \quad (2)$$

2.1.2. Ammonia emission

The ammonia emission from manure and synthetic fertilisers spread in the fields, livestock houses, and manure stores (Fig. 1) is calculated via the official Danish

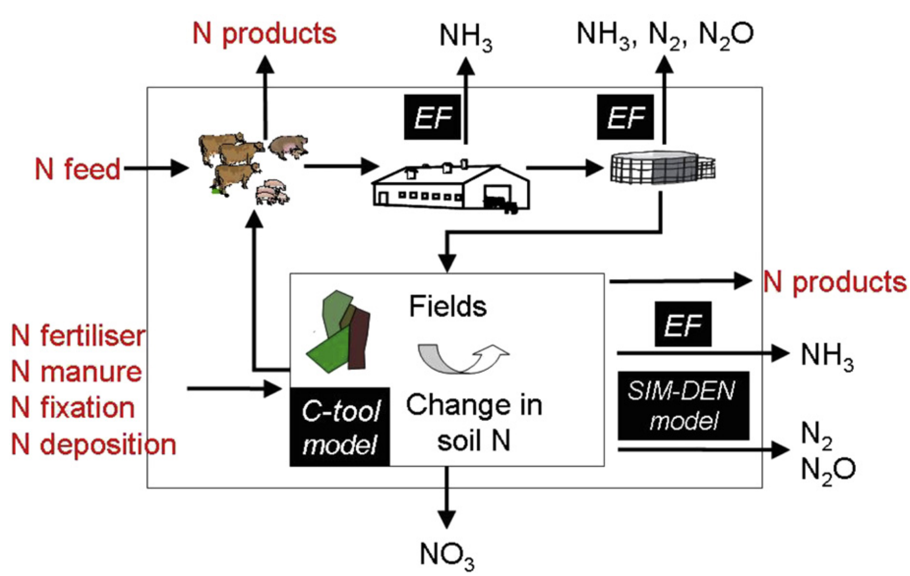

Fig. 1. Schematic presentation of the farm nitrogen balance, and the nitrogen flows included in the Farm-N model (Hutchings et al., 2006). The farm gate N-surplus is calculated as the sum of N in inputs minus N in outputs (both marked in red) and is distributed into N-losses in the form of ammonia (NH_3), nitrate (NO_3^-) or denitrification to free nitrogen (N_2) or nitrous oxide (N_2O), or changes in the soil-N pools. This modelling is based on emission factors (EF; Hutchings et al., 2001) in combination with the C-tool (Petersen, 2007) and SIM-DEN (Vinther and Hansen, 2004) component models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)