Available online at www.sciencedirect.com

ScienceDirect

Agriculture, Ecosystems and Environment 121 (2007) 153–163

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Modelling spatial heterogeneity in grazed grassland and its effects on nitrogen cycling and greenhouse gas emissions

N.J. Hutchings [*], J.E. Olesen, B.M. Petersen, J. Berntsen [1]

Danish Institute of Agricultural Sciences, Department of Agroecology, Research Centre Foulum, P.O. Box 50, 8830 Tjele, Denmark

Abstract

Nitrate (NO_3) leaching and nitrous oxide (N_2O) emissions are known to be high from urine and dung patches in grazed pasture. However, the extent to which estimated total net greenhouse gas (GHG) emissions from grazed pasture are affected by the inclusion of excreta-generated spatial heterogeneity in models is not known. The net GHG emissions include changes in soil carbon (C) storage, direct N_2O emissions and indirect N_2O emissions from ammonia (NH_3) volatilisation and NO_3 leaching. The FASSET whole-farm model was used to simulate the effect of including heterogeneity on direct and indirect GHG emissions during 2 years of grazed grassland followed by 2 years of spring barley. Simulations were performed with nitrogen (N) fertiliser rates to grassland varying from 0 to 300 kg N ha^{-1} $year^{-1}$, with or without heterogeneity in the simulation model. For N fertiliser rates of 50–150 kg N ha^{-1} $year^{-1}$, the excreta inputs were about 50 kg N ha^{-1} $year^{-1}$ greater in simulations without than with heterogeneity. This resulted from a higher plant uptake in simulations without heterogeneity. The simulated N efficiency (plant N off-take in relation to external N input) was about 5% higher for simulations without than with heterogeneity. N_2O emissions from the grazed grassland were strongly affected by N rate and heterogeneity, whereas there was little effect of these factors on N_2O emissions from the following spring barley. There was a highly non-linear response of N_2O emissions to N fertiliser for simulations without heterogeneity and an almost linear response with heterogeneity. This meant that N_2O emissions were higher for simulations with heterogeneity than without at fertiliser N rates below 100 kg N ha^{-1} $year^{-1}$, whereas the situation was reversed at N rates above 150 kg N ha^{-1} $year^{-1}$. The NO_3 leaching was higher after ploughing of the grassland than during the grazing period and inclusion of heterogeneity in the simulations increased NO_3 leaching in both the grassland and the spring barley. The estimated net GHG emissions increased with increasing N rate in both the grazed pasture and in the following spring barley. The effects were largest in the grazed grassland, and for N rates above 150 kg N ha^{-1} $year^{-1}$ simulated GHG emissions were considerably higher without than with heterogeneity. However, for N rates below 150 kg N ha^{-1} $year^{-1}$ there was little effect of including heterogeneity in the simulations on net GHG emissions from either grassland or spring barley.

Keywords: Grassland; Urine; Dung; Spatial heterogeneity; Soil carbon; Nitrate leaching; Nitrous oxide; Greenhouse gases

1. Introduction

In common with other agricultural land uses, grasslands are a source of N_2O and can be a source or a sink of CO_2. In addition to the direct GHG emissions, the IPCC methodology also requires accounting for the indirect N_2O emissions from losses of N via NO_3 leaching and NH_3 volatilisation, since a proportion of these losses are assumed to lead to additional N_2O emission in other ecosystems (Mosier et al., 1998). Oenema et al. (1997) suggested that grazed grassland might account for 10% of the global N_2O emission, although on a national basis the figure may be much higher (Chadwick et al., 1999).

C and N flows within grazed grassland differ greatly from those of other agricultural land uses, including cut grassland, due to the presence of the grazing animal. In general, the removal of both C and N from the field is less than for other

---

[*] Corresponding author. Tel.: +45 8999 1733; fax: +45 8999 1200.
E-mail address: nick.hutchings@agrsci.dk (N.J. Hutchings).

[1] Present address: Unisense A/S, Brendstrupgaardsvej 21 F, DK-8200 Aarhus N, Denmark.

0167-8809/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2006.12.009

cropping systems and there is substantial recycling of both C and N to the soil in excreta. In other cropping systems, any return of nutrients via animal manure is delayed by storage of manure and modified by losses that occur in animal housing and manure storage. In contrast, within a grazed grass field, N excreted by animals at a particular time influences the growth and composition of herbage produced over a time scale of a few days or weeks, which in turn affects the diet composition and N excretion in subsequent periods. There is, therefore, a more rapid feedback between changes in field management and animal feeding practice and changes in C and N flows than occurs for other cropping systems.

The presence of grazing animals contributes to an increase in spatial heterogeneity in the cycling of C and N. This is primarily due to the deposition of excreta in patches rather than evenly over the field. Within cattle urine and dung patches, the N deposited in a single event is typically equivalent to over 200 and 2000 kg N ha^{-1}, respectively, which contrasts with a limit for the DM growth response of intensive temperate grassland of about 400 kg N ha^{-1} for the whole growing season (ten Berge et al., 2002). There is therefore good reason to expect that C and N cycling, and the associated losses of greenhouse gasses, will display high spatial variability in grazed grassland. This spatial heterogeneity creates technical and logistical problems that make the field investigation of C and N dynamics difficult (Velthof and Oenema, 1995a; Anger, 2002), so modelling is a natural alternative for the study of C and N cycling in grazed pasture.

A number of modelling studies have analysed N dynamics in grazed pasture. Combining relatively simple empirical relationships within the context of a systems model can quantify the major N flows, even without an explicit description of spatial heterogeneity (Scholefield et al., 1991). However, separating the dung and urine areas from the rest of the pasture in the model allows the impact of excretal returns to be estimated more explicitly and has been used to investigate the losses of nitrate via leaching (van de Ven, 1992). Since the timing of excretal returns has been shown empirically to be important (Hack-ten Broeke et al., 1996), increasing both the spatial and temporal resolution enables the consequences of more fine-scale pasture management to be studied. McGechan and Topp (2004) used a combination of existing models to assess the significance of spatial heterogeneity on nitrate leaching from grazed pasture. However, this assessment was based on a static analysis of the interaction between animal and grassland, whereas in practice, this interaction is dynamic (Hutchings and Kristensen, 1995). For example, at the field scale, N excreted by animals at a particular time influences the growth and composition of herbage produced, which in turn affects the diet composition and N excretion in subsequent periods.

Assessing the emissions of GHGs from pasture poses some particular challenges. In addition to the spatial heterogeneity, the emissions of NH_3 and N_2O are relatively small fractions of the total amount of N flowing within the system. The changes in C sequestered in the soil also demand that soil processes must be modelled in detail. In this paper, modelling is used to investigate the potential effect of including spatial heterogeneity from urine and dung patches on the estimated emission of greenhouse gases from grazed grassland.

2. Materials and methods

2.1. FASSET farm model

The FASSET farm model (Berntsen et al., 2003, http://www.fasset.dk) was extended to describe the dynamics of spatial heterogeneity in grassland and the management of grazed and cut fields within the rotation. In FASSET, grass dry matter (DM) growth and herbage N concentrations are simulated using a dynamic crop model (Olesen et al., 2002; Berntsen et al., 2005). The soil is modelled as a series of layers, each layer containing water, several organic matter pools and both ammonium and nitrate N. The transformations of soil C and N were modelled according to Petersen et al. (2005a,b) and Chatskikh et al. (2005), and the soil water transport was simulated using the approach of Addiscott and Whitmore (1991). The time step of the model is 1 day.

2.1.1. Spatial heterogeneity

Spatial heterogeneity is modelled by simulating the creation of dung and urine patches at specified time intervals. The time intervals are constant for a particular simulation and were here set to 21 days, a value that was found by trial and error to produce stable output within a reasonable simulation time. FASSET is implemented using object-oriented techniques, with each field consisting of one or more aggregate areas. These aggregate areas represent an aggregation of numerous, small patches that can be considered sufficiently homogenous that the dynamics of C, N and water can be modelled as if they were a single entity.

The grassland is initially assumed to be spatially homogenous and is modelled by a single (basal) area (Fig. 1). When grazing begins, dung and urine depositions create heterogeneity in the distribution of C and N. To reflect this heterogeneity, two new areas (D1 and U1) are created, corresponding to the area affected by the dung and urine, respectively. On creation, the crop and soil models within these areas are cloned from those in the basal area. The amounts of dung and urine N predicted by the cattle model (see below) are then added to the appropriate areas. The size of the basal area is decreased accordingly (Fig. 2).

In the second period, the areas newly affected by the dung and urine are again calculated. Some of this new excreta will be deposited on the existing dung and urine areas, so three