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A simulation modelling study of water pollution caused by outwintering of cows

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ABSTRACT

A simulation modelling study has been carried out of water pollution due to outwintering of beef and dairy cows on sacrifice field areas. Use has been made of the weather-driven MACRO model to simulate rapid transport of components of deposited excreta to field drains through macropores in saturated soil during or after rainfall. Such saturated soil conditions arise around the periphery of field areas which have become poached due to trampling by animal hooves. Simulations were set up to represent outwintering experiments carried out over two winters at two sites. Further simulations were set up as scenario tests over 10 years' weather at the same two sites. Simulated results show that outwintering is likely to lead to significant levels of water body pollution by ammonium and phosphorus. Results also show no benefit in periodically moving a feeder to a different location in the grassland field, as simulated pollution levels appeared to be similar for a moved feeder to those for a static feeder. The study demonstrates the value of a hydrological model previously calibrated and tested at sites with continuous measurements of outflows, which can be exploited in scenario tests for a field situation which differs slightly from that at the calibration sites.

1. Introduction

Weather-driven simulation models, which link contaminant transport processes with soil hydrology, have been found to be particularly valuable for the study of diffuse pollution of water bodies arising from agricultural activities. The Swedish MACRO model has been developed to simulate the hydrology of a soil with field drains and with a two-domain representation of the soil pore-space, together with processes by which contaminants are transported through the soil to the drains (Jarvis, 1994; Jarvis et al., 1999). This model has previously been calibrated and tested, using data from soil conductivity measurements, and from field sites instrumented to measure discharges via field drains of contaminants such as phosphorus, ammonium and *E. coli* micoorganisms (McGechan et al., 2002; McGechan, 2002, 2003a). These calibration simulations demonstrated the value of considering macropores as a domain of pore space separate from the soil matrix, for simulating transport of particulate contaminants such as inorganic phosphorus sorbed onto mobile faecal particles. The calibration measurements were very demanding in resources, but there are further opportunities for exploiting the model in scenario tests using long periods of weather data and for a field situation which differs slightly from that at the calibration sites. This study describes such scenario tests representing outwintering of beef and dairy cows in 'sacrifice fields', a practice which is becoming more common as a low cost alternative to providing and maintaining winter housing for livestock, but which is causing concerns about environmental pollution implications. This required some adaptations to the normal procedures where a uniform field is represented in MACRO simulations, to represent a field with a small area of severely damaged soil where animals congregate in wet winter conditions. The adapted modelling procedure, together with the previous calibrations of MACRO for a uniform field, have been used to estimate the extent of ammonium and inorganic phosphorus losses to water bodies via field drains during the winter period from a field with cows being fed silage in a feeder ring.

2. Background and modelling tools

2.1. Description of problem

Livestock systems pose a risk of water pollution by contaminants such as nitrates, ammonium, phosphorus and pathogens (Hooda et al., 2000). In general, grazing livestock tend to spend a proportion of their time congregating in certain areas of a field such as around gates, feeders, drinking troughs or where there is shelter from wind or rain.

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However, in the outwintering situation, there is a particularly marked uneven spatial distribution, with cows spending a very large proportion of their time in the vicinity of feeders, since with little grass growth there is no incentive to roam over the field to find fresh standing grass to eat. Trampling by hooves in a concentrated area leads to compaction and soil damage ('poaching'), particularly when the soil is wet. Rainwater cannot infiltrate through the compacted soil surface so puddles form in hoofprints. Also, a high proportion of the daily excretion of urine and faeces is deposited in the poached area. Hence the concentration of excreted pollutants rises to a high level in hoofprints, other puddles and ponding water. The only route by which water can move is by surface runoff to a less compacted strip at the periphery of the poached area, where the heavily contaminated water can infiltrate the soil surface. During rainfall, rapid overland flow occurs to this peripheral strip, leading to saturated soil conditions down to the level of the water table and the field drains.

In comparison with the outwintering situation where excretion takes place directly onto the soil surface at a time and under conditions conducive to high losses by leaching to the drainage system, if livestock are housed during winter manure or slurry are collected for subsequent field spreading. Such spreading should be carried out in a controlled manner, at a time of year when plants are growing rapidly so can use the nutrients they contain as a valuable asset to substitute for bought-in mineral fertilizer, potentially minimising the level of environmental pollution of waterbodies. Vinten et al. (2004) measured higher levels of contamination of field drain discharge water by *E. coli* pathogens from grazing animals depositing faeces directly onto fields, compared to that from slurry applications.

In contrast to the UK, it is normal practice in New Zealand for dairy cows to spend the winter period outdoors in 'winter runoff units', and there are major concerns about contamination of water bodies during winter from such units (Monaghan et al., 2007).

2.2. Through-soil transport in saturated soil

Some simple soil hydrological models describe water movements only in the vertical direction, from rainfall infiltrating the soil surface, to the level where it is taken up by plant roots, or by deep percolation down to groundwater. However, in northern Europe, many agricultural fields have field drains requiring a more complex representation of the hydrology with water movements in both horizontal and vertical directions. Also, for some purposes it is beneficial to split the modelled soil pore space into two 'domains', the small soil matrix pores within soil aggregates, and the 'macropore' domain of worm-holes and spaces around soil aggregates. Of particular interest is the process of 'macropore flow' or 'by-pass flow' in saturated soil where contaminants pass rapidly by the easy path around soil aggregates to field drains at a very short interval following deposition. During the winter period, this form of transport occurs when the soil water content is at or near saturation, usually with a water table rising to near the soil surface. Ponding and surface runoff are often observed in such conditions. Ammonium derived from excreted urine passes rapidly to field drains by macropore flow, but if it enters the soil matrix within aggregates it becomes sorbed and eventually converted to nitrate by nitrification. Similarly, 'particulate phosphorus', which is essentially inorganic phosphorus sorbed onto mobile faecal particles, passes rapidly by macropore flow but is trapped if it enters the soil matrix.

2.3. Basic features of MACRO model

The main features of the MACRO model, including the hydrological and contaminant transport equations in two 'domains', have been described in detail by Jarvis (1994). The hydrological routines in MACRO are similar to many other soil water models, with the tension (water release) and hydraulic conductivity relationships for specified layers in the soil profile represented by mathematical functions, enabling Richards' (1931) equation to be solved at successive timesteps. MACRO differs from other models in its treatment of processes in the larger soil pores (macropores) when capillary forces are very low, so water movements can be assumed to be driven by gravitational forces alone. The boundary between the macropore and soil matrix (micropore) domains is considered to occur at a soil water tension of 1.2 kPa (the 'break point'), with the corresponding water content and hydraulic conductivity values given by mathematical functions. In the soil matrix pore region where both capillary and gravitational forces must be considered, the hydraulic functions are as described by Brooks and Corey (1964) and Mualem (1976). The break point tension represents soil which is actively draining so it is considerably wetter than field capacity (which is commonly considered in the UK to occur at a tension of around 5–6 kPa). In MACRO, contaminant transport is treated separately with different concentrations in each of the two domains. Account can be taken of degradation of the contaminant, and also sorption of the contaminant onto soil components. A special version of MACRO to simulate colloid-facilitated transport of contaminants has also been developed (Jarvis et al., 1999). This version requires two sequential simulations: the first represents transport of the colloid taking account of trapping or other constraints to colloid movement; the second simulation represents transport of the contaminant taking account of sorption both onto colloids and onto static soil components. All simulations with MACRO require records of historic precipitation and other weather variables required to estimate evapotranspiration. While the normal interval for such variables is one day, the hydrological routines in MACRO benefit from the option of using hourly records of precipitation.

2.4. Previous studies using the MACRO model

Selection of parameter values representing the water release and hydraulic conductivity curves for calibration of the MACRO model was based on a similar calibration of another Swedish model SOIL (Jannson, 1991), as described by McGechan et al. (1997). For this earlier calibration study, field and laboratory measurements had been made for three soil types from Scottish sites. Calibrated MACRO simulations with ammonium as the contaminant (McGechan, 2003a) were tested and found to give good fits to data measured following slurry spreading at an instrumented drained plot field site at Easter Howgate (near Edinburgh) by Parkes et al. (1997). Calibrated simulations with the special colloid version of MACRO and inorganic phosphorus as the contaminant (McGechan et al., 2002; McGechan, 2002) were similarly tested against drained plot field measurements following slurry spreading at a site near Dumfries (Hooda et al., 1999). The colloid version of MACRO was also tested against phosphorus loss data at the same Dumfries site during autumn grazing (McGechan, 2003b).

3. Information and data for modelling

3.1. Field sites

The outwintering project with which this modelling study is associated involved field observations at four sites in England, plus one in Wales and one in Scotland. Observations at the sites during two winters were records of cow numbers, dates of the beginning and end of the outwintering period in the sacrifice fields (Table 1), type and location of feeders, feedstuffs in the feeders, as well as assessments of the state of ground in different parts of the grazing fields. However, the procedure for putting silage bales into the feeders differed between the sites. At the Scottish site and two of the English sites, the feeder remained in one position near the edge of the field throughout the outwintering period, and a new bale of silage was added to it every few days. At the Welsh site and the other two English sites, wrapped bales were put out in various positions over the field area at the beginning of the period, then one bale was unwrapped every two or three days during the