Agriculture, Ecosystems and Environment 134 (2009) 218–233

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Modelling the fate of nitrogen following pig slurry application on a tropical cropped acid soil on the island of Réunion (France)

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ARTICLE INFO

Article history:
Received 25 November 2008
Received in revised form 19 May 2009
Accepted 7 July 2009
Available online 11 August 2009

Keywords:
Pig slurry
Maize
Andic soil
Field experiment
WAVE model

ABSTRACT

A comprehensive field study was conducted to determine the fate of nitrogen in pig (*Sus scrofa*) slurry applied to an acid tropical andic soil of Réunion with the aim of estimating drainage and nitrogen leaching below the root zone. Water movement and nitrate dynamics were monitored during two successive cropping seasons on a plot (PSP) treated with liquid manure, with an input of 264 kg N ha^{-1} the first year and 185 kg N ha^{-1} the second year, in comparison to levels recorded in a unfertilized control plot (CP). The field was cropped with rainfed maize (*Zea mays* L.) The process-based WAVE field-scale model was used to simulate water flow and nitrogen transport in the unsaturated zone and highlight the main processes controlling water and N fate. A calibration procedure was performed one year, while the prediction capability of the model was assessed during another cropping year. A sensitivity analysis was performed to address some critical parameters.

Due to the high hydraulic conductivities measured in this andic soil, the drainage risk became high when the rain intensity was above 30 mm d^{-1} and the soil humidity was close to saturation. The time between the first slurry application on PSP and the nitrate onset in the drainage water at 135 cm depth (about 15 months) was attributed to nitrate adsorption on the soil particles (the retardation factor was estimated at 2.6 in the surface layer and 1.5 in deeper layers) and to the fact that the water stored in the 0–135 cm soil layer was slowly displaced. The nitrate migrated in this andic soil at rate of about 50 mm per 100 mm of infiltrated water.

The main features of the experimental values of state variables (water content, water pressure head, NO_3^- concentration, natural mineralization and nitrification of the pig slurry ammonium at different depths and dates) as well as the water fluxes across boundaries were generally correctly reproduced by WAVE for both plots. The calibrated modelled budget error arising from net mineralization was +15 and +9 kg N ha^{-1} for CP and PSP, respectively. For the model evaluation, it was estimated at −9 and −13 kg N ha^{-1}, respectively, which was considered as very acceptable.

WAVE required refinements in some processes and parameters but was still found to be robust enough to work in conditions for which it was not primarily designed.

1. Introduction

For many years and in many regions around the world, farmers in areas with high swine and poultry production have disposed of liquid manure wastes (i.e. pig slurry, dairy effluent) by spreading them on crop fields thanks to their fertilizer function. Manures are an important source of nutrients for crops but may represent a significant environmental pollution risk. Consequently, it is essential to gain insight into manure nutrient behaviour so as to be able to efficiently manage the application practices and thus enhance the cost-effectiveness of crop production while minimizing the adverse impacts on water and soil quality.

In Réunion, pig slurry production reached 180,000 T in 2007 (DAF and CIRAD, 2007). This high amount was to be applied on limited areas (20,000 ha), but with a potential risk of contaminat-

Abbreviations: CP, control plot; DAS, day after sowing; PSP, pig slurry plot; TDR, time domain reflectometry; WAVE, Water and Agrochemicals in the Vadose Environment model.

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doi:10.1016/j.agee.2009.07.004

ing soils and water with excessive nitrogen, phosphorus or trace elements. This paper deals only with nitrogen since there is growing concern in public and regulatory agencies on possible nitrate contamination of groundwater resources and downstream lagoons on this island. In addition, the European Union Directive 91/676 obliges all Member States to assess the nitrate concentration and trophic status of their water resources in order to detect pollution and to launch Action Programmes to, for instance, optimise nitrogen fertilization efficiency in the most vulnerable zones.

A number of studies showed that adequate pig slurry applications can help to generate satisfactory crop yields, while totally or partially offsetting the need for mineral fertilizer applications (i.e. Brechin and McDonald, 1994; Cameron et al., 1995; Petersen, 1996; Zebarth et al., 1996; Jensen et al., 2000; Daudén and Quilez, 2004). On the other hand, several authors reported results which showed that there is an increased risk of nitrate leaching when liquid manure is applied to soils in large amounts or with inappropriate agronomic techniques (i.e. Nielsen and Jensen, 1990; Cameron et al., 1995; Beckwith et al., 1998, 2002; Jensen et al., 2000; Harter et al., 2002; Sanchez-Pérez et al., 2003; Thomsen, 2005; Mantovi et al., 2006). It has also been observed that in fields in which pig slurry is applied at adequate rates, there is less or equivalent nitrate leaching as compared to fields in which mineral fertilizers are applied (i.e. Beauchamp, 1986; Carey et al., 1997; Diez et al., 2001).

Extensive research on the use of pig slurry as fertilizer has been carried out in temperate (i.e. northern Europe, North America, New Zealand) and Mediterranean (i.e. Italy, Spain) regions. Studies in tropical regions are much scarcer despite the high growth of livestock production and the increased recognition that on-farm nutrient recycling is essential to avoid off-site environmental degradation.

In this setting, the island of Réunion has some unique features. It has a humid tropical climate with world daily and yearly precipitation records. Soils originating from volcanic materials generally have high clay and silt contents and have an aggregated structure with high porosity and hydraulic conductivity values. Combined with high rainfall intensities, greater water and possibly leaching fluxes below the root zone than in temperate regions may be expected (Hodnett and Tomasella, 2002; Bernard et al., 2005). In addition, increased rates of nitrification, denitrification and organic matter decomposition can occur due to higher air and soil temperature, with smaller seasonal variations than in temperate areas.

Mechanistic models are powerful tools that can be used to reproduce real systems as they are based on physical, chemical and biological processes. However, most of them (Addiscott and Wagenet, 1985; Wagenet and Hutson, 1989; Brusseau and Rao, 1990; Simunek and Suarez, 1993; Vanclooster et al., 1994; Jarvis, 1994; Eckersten et al., 1996; Simunek et al., 1999 among others) were initially developed and evaluated under temperate climate conditions. According to Thorsen et al. (1998), a model generally cannot be validated, but must be tested under all conditions for which it will be used, i.e. for different climate, soil, crop and agronomic practices.

The goal of this study was threefold: (i) to gain further insight into the processes which govern the fate of nitrogen in the unsaturated zone after application of pig slurry on a tropical and andic soil cropped with maize, (ii) to model these processes in that context by comparing 2 years of field data with simulations of the mechanistic WAVE model (Vanclooster et al., 1994), and (iii) to estimate the potential risk of nitrate leaching below the root zone in conditions for which the model was not originally designed and tested.

2. Materials and methods

2.1. Field experiment

The study was conducted on the western side of the island of Réunion at the experimental site of Colimaçons (21°7′S, 55°18′E, 780 m *ASL*) during the southern summers (November to March) of 2003–2004 and 2004–2005. The climate is tropical with a hot humid season between December and April, and a dry season between May and November. The mean annual rainfall and potential evapotranspiration levels are 1600 and 800 mm, respectively, with a mean annual temperature of 19 °C with variation of 2 °C around this value. During the study period of each year, the mean daily temperature slowly increased from 19.5 °C at sowing date to 21 °C at harvest time.

The soil is in the middle of a toposequence in which Andosols (IUSS Working Group WRB, 2006) prevail. According to Feder and Findeling (2007), it is classified as a desaturated andic Cambisol, which includes: (i) a surface A horizon (0–40 cm), with a pH_{water} below 6, and (ii) an andic B horizon (40–220 cm) characterized by a pH_{water} between 6 and 6.6 and by lower organic matter content and dry bulk density than in the first horizon. At the Colimaçons site, the interface between horizons A and B was found to be at 30 cm, thus highlighting the depth of layers for subsequent measurements and modelling. The main physicochemical properties of this soil are given in Table 1. The subsoil consists of altered fissured and fractured rocks (Payet, 2005). The aquifer is located several hundreds of meters below the surface (Join and Coudray, 1993), so there is a very thick unsaturated zone.

A field that had been in fallow since 1983 was selected. An unfertilized maize–oat rotation was set up in 2002–2003 in order to reduce soil nitrogen storage prior to the experiment. In 2003, the field was split into two parts: one 620 m^2 plot (PSP) was fertilized yearly with pig (*Sus scrofa*) slurry from a nearby piggery, and another 570 m^2 control plot (CP) was left unfertilized. The field was cropped with rainfed maize (*Zea mays*, local open-pollinated variety) adapted to a tropical climate. It was sown in rows by dibbling three grains every 50 cm with interrows of 1 m. Due to losses during germination the final density corresponded to about 50,000 plants ha^{-1}. The total cycle duration (between sowing and maturity) was about 120–130 days, which is shorter than commonly encountered in colder regions. Before sowing the maize crop, pig slurry was applied on the surface of PSP at a rate of approximately 65 $m^3 ha^{-1}$ through a fire hose nozzle. It was immediately incorporated into the surface soil layer (0–10 cm) by

Table 1
Selected physicochemical properties of the investigated soil.

Soil layer (cm)	ρ_d (g cm^{-3})	pH (H_2O)	pH (KCl)	C tot. (g kg^{-1})	N tot. (g kg^{-1})	CEC ($cmol_{(+)}$ kg^{-1})	Al(ox.) + 1/2 Fe(ox.) (%)
0–10	0.9	5.1	4.4	47.7	4.91	8.71	2.3
10–30	0.8	5.7	5.2	24.9	2.68	10.9	1.8
30–100	0.85	6.2	5.8	11.3	1.25	8.7	3.7
100–200	0.8	6.5	6.2	11.4	0.91	8.7	4.1

ρ_d: Soil dry bulk density; pH (H_2O): pH of soil water extract; pH(KCl): pH of soil KCl extract; C tot. and N tot.: total carbon and total nitrogen; CEC: cation exchange capacity (acetate method); Al(ox.) and Fe(ox.): Al and Fe of oxalate extraction.