Modelling the effect of a nitrification inhibitor on N leaching from grazed pastures

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Abstract
The nitrification inhibitor, dicyandiamide (DCD), is a promising technology for reducing N losses from grazed pastures. However, insights as to its best usage are still required. Modelling offers a cost-effective way to determine best practice for DCD, synthesising the available knowledge. The APSIM model, with a newly developed module for nitrification inhibition, was used to investigate the role of DCD on N leaching. The model is sensitive to various environmental conditions (soil and climate) and management options (timing and application rate). The model satisfactorily described results from lysimeter experiments which showed that DCD reduced nitrate leaching by 25-50%, depending on soil and environmental conditions. The model was used to evaluate the effectiveness of DCD applications in different months and with different periods between urine and DCD applications. It is shown that DCD effectiveness in highest on winter and a lag between urine deposition and DCD application can greatly reduce the effect of DCD especially in summer. The model is a promising tool for determining DCD effectiveness under various conditions and for aiding the development of best management practices.
Keywords: model evaluation, N losses, mitigation

Introduction
The use of dicyandiamide (DCD) as a nitrification inhibitor is a promising technology for reducing N losses from grazed pastures. Applications of DCD following urea deposition, either from fertilisers or urine, have been shown to reduce N losses and also enhance pasture productivity (Di & Cameron 2007; Di *et al.* 2007; Hoogendoorn *et al.* 2008; Menneer *et al.* 2008; Smith *et al.* 2007). Despite the recent intensive research several aspects influencing DCD usage need to be better understood. Detailed understanding of the effects of environmental conditions on DCD effectiveness and on its degradation is lacking, making it difficult to define best management practices such as rates and timing of applications.

Nutrient losses are difficult and expensive to measure on a regular basis at farm scale and this makes it difficult to test the effects of changing management practices and the use of mitigation options. Modelling offers a cost-effective way to synthesise the available knowledge and thus investigate the effects of DCD applications for the whole farm and to develop best management practices. The APSIM model (Keating *et al.* 2003) is growing in popularity in New Zealand as a platform for research development and collaboration. Its modular nature also allows the development of independent modules for describing particular processes based in a common modelling protocol (Holzworth *et al.* 2010).

This paper presents a module built to simulate the effect of DCD on the nitrification process and its degradation in soils. The simulation of N cycle processes remains within the SoilN module already present in APSIM. DCD transport is also simulated independently by the water and solute transport module. Data from a lysimeter experiment are used to evaluate the module's performance. The model is then used to investigate DCD effectiveness when varying the time of application and the effects of different time lags between urine and DCD applications.

Materials and Methods
The development and simulations were done using the APSIM model framework (version 7.2 r826). The SoilN and SurfaceOM modules (Probert *et al.* 1998) were employed to describe the soil C and N cycles, while the SWIM module (Huth *et al.* 1996; Verburg *et al.* 1996) was used to account for the water and solute transport processes. The soil parameters needed were gathered from the New Zealand Soil Database (Wilde 2003) and complemented with pedo-transfer functions (Vogeler *et al.* 2010) that relate basic soil characteristics to the required parameters. Climate data were obtained from the NIWA's Virtual Climate Stations (Tait *et al.* 2006). Pasture production was simulated using the AgPasture module (Li & Snow 2010). A separated module was developed to compute the DCD effect on nitrification and its degradation.

Comparisons between the model predictions and measured data were done using results from lysimeter (50 cm diam. × 70 cm height) experiments containing undisturbed columns of the Horotiu soil (a silt loam from Ruakura Research Centre, Hamilton, New Zealand). The experiments started on 15 May 2008 and consisted of two irrigation treatments, replicated four times: low irrigation (total water inputs of 1 100 mm/yr) and high irrigation (2 200 mm/yr), both with and without DCD (10 kg/ha, applied immediately following urine deposition and repeated 70 days later). At the beginning of the experiment 1 000 kg N/ha as urine was applied. Afterwards grass was cut regularly with urea being applied as fertiliser at 25 kg/ha every month from August till May. Details are presented in Shepherd *et al.* (2009).

The APSIM model with the DCD action module was then used to investigate the effect of varying application time on the effectiveness of DCD. A similar setup to the above was employed. Soil to a depth of 1.50 m was considered. Urine patches simulating the application of 750 kg N/ha were applied every 4 years (1981 to 2000). Different runs were made for depositions in January, March, May, July and September. DCD at 10 kg/ha was applied on either the day following urine deposition, one week or one month after deposition. Nitrate N leaching from these urine patches was cumulated for 4 years following deposition.

DCD action module

The module developed computes the inhibition effect on nitrification due to the presence of DCD and also evaluates DCD degradation as function of environmental conditions. The DCD inhibition effect is assumed to be proportional to its concentration in the soil. A brief description of how APSIM's SoilN module

Figure 1 Nitrification inhibition effect as a function of DCD concentration in the soil.

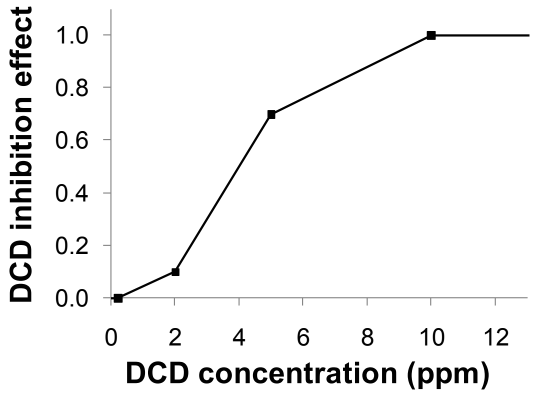


Figure 2 Environmental factors for DCD degradation.

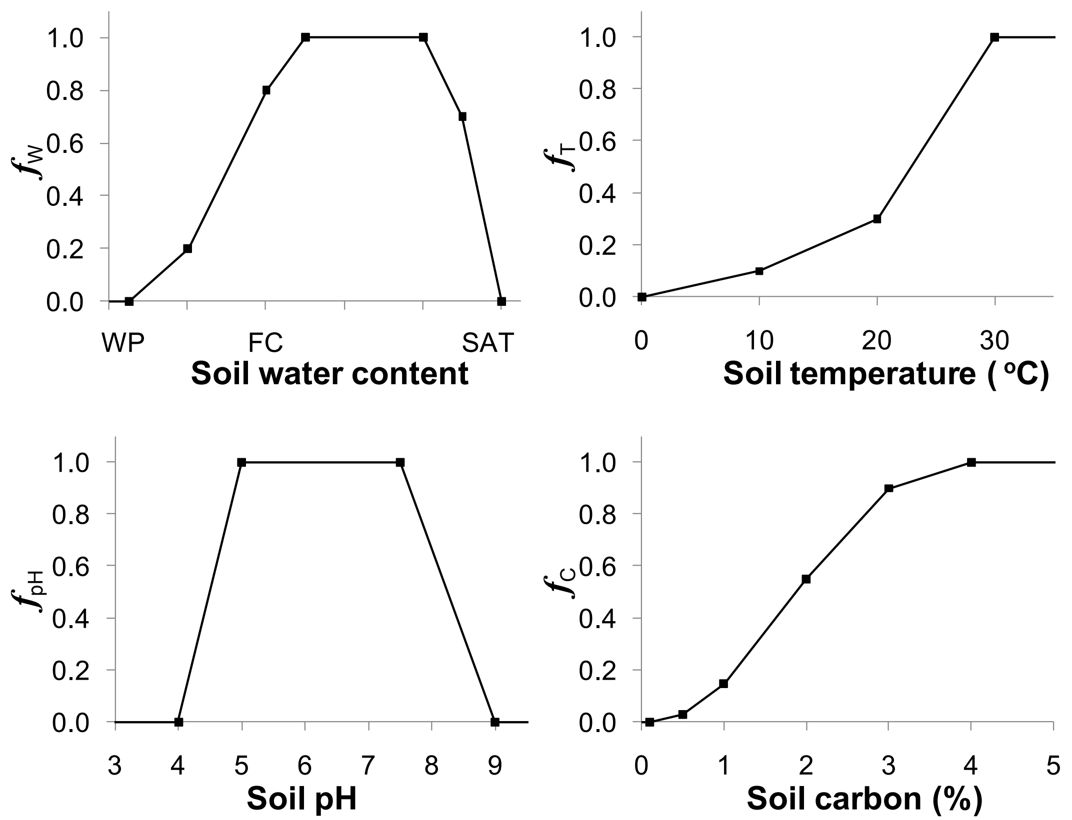
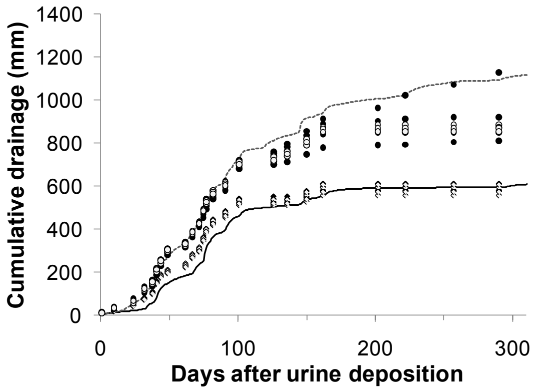


Figure 3 Measured (dots) and simulated (lines) values of drainage from the lysimeter experiment. Dots and dashed line are from high irrigation level, diamonds and continuous line are for low irrigation; full symbols are for treatments without DCD.



handles nitrification is given for clarity, followed by details of the DCD action module. Further information about SoilN as well as other APSIM models can be found on the APSIM website (www.apsim.info).

Nitrification process in SoilN and addition of DCD in APSIM

The nitrification of ammonium into nitrate in SoilN is described using a Michaelis-Menten equation, where the rate of nitrification is assumed to be a response to available soil NH_4. In addition, it also contains factors to account for the effect of environmental variables, temperature (f_T), water content (f_W), and pH (f_{pH}):

$$k = k_{\max}\left(\frac{C_{NH_4}}{C_{NH_4} + M_{NH_4}}\right) f_T\, f_w\, f_{pH} \qquad (1)$$

where C_{NH_4} is the ammonium concentration in the soil, k_{max} is the potential nitrification rate (mg N/kg/day), and M_{NH_4} is the NH_4 concentration for nitrification at half of its maximum. The factor's values all lie between 0 and 1. To account for the effect of DCD on nitrification, an inhibition factor was included to equation (1).

The SWIM module was used to describe water and solute movement. A DCD solute was created using the Solute module of APSIM and added to the simulations, SWIM was used to simulate its movement in the soil profile. DCD was assumed to have no adsorption in the soil, as some studies suggest it is highly mobile (Menneer *et al.* 2008; Vogeler *et al.* 2007).

Effect of DCD on nitrification

A function describing this effect is supplied via the APSIM user interface. Considering the nature of the process, and based on few available data, a logistic-type function was assumed, with DCD effect increasing from zero to a plateau of total inhibition when its concentration in the soil is about 10 ppm (Fig. 1).

Degradation of DCD

DCD degradation in soils has been shown to be affected by soil temperature, moisture content, pH, and organic matter content (Di & Cameron 2004; Singh *et al.* 2008). The proposed module simulates the degradation of DCD by a first-order decay process, defined by the potential daily degradation rate (%). This rate is then affected by the soil water content, temperature, pH, and carbon content as shown in Fig. 2.

Results and Discussion

Comparison with measured data

Comparisons with experimental data showed good model performance as drainage predictions were within the range of the observed values, especially for the low irrigation treatment (Fig. 3). Differences in drainage between DCD treatments were small for the

Figure 4 Measured (dots) and simulated (lines) values of nitrate leaching from the lysimeter experiment. Hollow symbols and dashed lines are from treatments with DCD; full symbols and continuous line are for treatments without DCD.

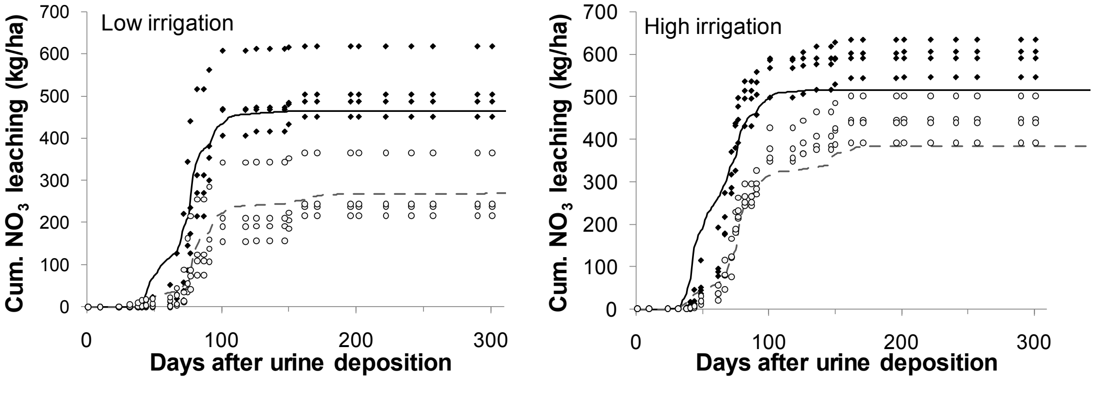
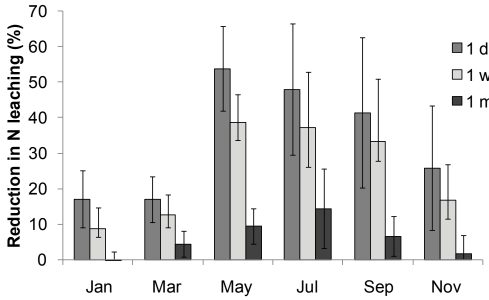


Figure 5 Reduction of N leaching over 4 years as affected by applications of DCD after one day, one week, or one month from urine deposition. Whiskers represent one standard deviation.



measured data and nearly identical for the simulations and so are not shown on Fig. 3. Nitrate leaching was also satisfactorily predicted by the model, with most of the predictions within the range of measurements (Fig. 4). Again, better agreement was found for the low irrigation treatment. Based on these comparisons the proposed DCD module can be considered suited for describing NO_3 leaching in the Horotiu soil. For a more reliable extrapolation of these results further studies with different soils and environmental conditions should be carried out.

Effect of timing of DCD application

Simulations using APSIM with the DCD module showed that the effectiveness of DCD applications following urine deposition can vary widely within the year. Reductions in N leaching due to the presence of DCD are shown in Fig. 5. Two trends are clearly demonstrated; DCD effectiveness is higher in winter and decreases with increasing lag between urine deposition and DCD application. Results also show that summer and early autumn are when DCD is less effective (Fig. 5), even though this is when leaching risk is high.

The effect of delaying DCD application after the urine has been deposited is also influenced by the month of deposition. Applying DCD a month after a January urine deposition reduces DCD effectiveness to zero as most of the nitrification has already happened. In contrast, DCD applied a week or even a month after urine deposition in May or July considerably reduced N leaching.

The nitrification process and its interaction with environmental conditions is complex, and the presence of inhibitors makes it harder to fully understand and quantify. More research is necessary to increase confidence in the modelling results as there is considerable uncertainty in the relationship between DCD concentration and the inhibition effect and in the degradation parameters. However, despite this uncertainty, and given the number of interplaying variables that can influence the DCD effectiveness in the soil, the proposed model is a promising tool with which to synthesise the existing knowledge and to define best ways to use this mitigation option.

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