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Comparison of APSIM and DNDC simulations of nitrogen transformations and N_2O emissions

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HIGHLIGHTS

► For nitrification, temperature had a larger effect in APSIM; water content in DNDC.
► For denitrification, temperature and organic carbon were more important in DNDC.
► Denitrification is triggered by rainfall in DNDC but by water content in APSIM.
► N_2O emissions increased linearly with N load in DNDC and at a lower rate in APSIM.
► Increased rainfall intensity decreased APSIM emissions but increased those of DNDC.

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ABSTRACT

Various models have been developed to better understand nitrogen (N) cycling in soils, which is governed by a complex interaction of physical, chemical and biological factors. Two process-based models, the Agricultural Production Systems sIMulator (APSIM) and DeNitrification DeComposition (DNDC), were used to simulate nitrification, denitrification and nitrous oxide (N_2O) emissions from soils following N input from either fertiliser or excreta deposition. The effect of environmental conditions on N transformations as simulated by the two different models was compared. Temperature had a larger effect in APSIM on nitrification, whereas in DNDC, water content produced a larger response. In contrast, simulated denitrification showed a larger response to temperature and also organic carbon content in DNDC. And while denitrification in DNDC is triggered by rainfall ≥5 mm/h, in APSIM, the driving factor is soil water content, with a trigger point at water content at field capacity. The two models also showed different responses to N load, with nearly linearly increasing N_2O emission rates with N load simulated by DNDC, and a lower rate by APSIM. Increasing rainfall intensity decreased APSIM-simulated N_2O emissions but increased those simulated by DNDC.

1. Introduction

Intensification of agricultural systems has resulted in remarkable increases in productivity. However, in grazed systems, only about 10–20% of the N ingested by grazing animals is retained in animal products. The remainder is returned in excreta to the paddock in a spatially non-uniform fashion as dung and urine, and then undergoes complex N transformation processes, including microbial processes such as mineralisation, nitrification and denitrification; plant physiological processes such as N uptake and assimilation; and physicochemical processes such as leaching and volatilisation. These various processes, and thus the fate of N, are affected by environmental conditions such as soil oxygen and moisture content, temperature, mineral N content, available carbon (C) and pH. The complexity of these various interconnected processes, combined with the large spatial and temporal variation in transformation rates involved in N cycling processes and N_2O productions, bedevils quantification of N losses via leaching, volatilisation and N_2O emissions from grazed pasture systems.

Various simulation approaches, such as NGAS (Mosier et al., 1983), DAYCENT (Parton et al., 1996), DNDC (Li et al., 1992), and WNMM (Li et al., 2007) are in use or are being developed that integrate process-based knowledge of the nitrogen cycle, as well as its interaction with the carbon cycle and biophysical drivers of the ecosystem. These models vary in structure and functionality, detailed descriptions of their structures and functionality have been given elsewhere (Cannavo et al., 2008; Chen et al., 2008; Shepherd et al., 2011). Such models offer the potential to decipher the contribution of individual processes to the complex system and can help us to better understand how environmental conditions combined with management strategies interact to control N cycling and losses (Schmid et al., 2001). The models vary in the level of detail or number of the

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N pools and transformation processes considered, as well as in how the processes are described. Furthermore, most simulation models use multiplicative factors to affect the potential rate of a given N process. The formalism of these factor functions varies widely between models – including the Arrhenius function, and linear or exponential function – but can have a major effect on the simulation output regardless of the model's conceptualisation (Rodrigo et al., 1997; Cannavo et al., 2008).

Models have often been found to poorly simulate both annual totals and daily rates and patterns of N_2O emissions. While the DAYCENT model simulated seasonal pattern of N_2O emissions reasonably well, the model poorly simulated daily fluxes and soil mineral N concentrations (Dalal et al., 2003). The DNDC model could only simulate N_2O emissions from a legume pasture in Australia after model adjustment and site specific parameterisation (Wang et al., 1997). Frolking et al. (1998) compared various process based models (CENTURY, DNDC, CASA, ExpertN) to measured N_2O emissions at various sites and while the general nitrogen cycling for the models were similar, simulated N gas fluxes, especially of nitric oxide, dinitrogen, and ammonia were quite different. They concluded that further model inter-comparisons, as well as comparisons to measured data sets are required. This emphasises the need for better understanding N transformations and the refinement of process based models, as well as more generalisable model parameterisation (Frolking et al., 1998). Without this assessment of mitigation options and upscaling of field scale data to sub-regional or regional level remain a challenge.

Many simulation models consider only particular N processes (Cannavo et al., 2008). For this study, the Agricultural Production Systems sIMulator (APSIM; Keating et al., 2003) and DeNitrification DeComposition (DNDC; Li et al., 1992) were chosen, as they are conceptually different but both simulate the main N processes, including mineralisation, leaching, uptake, nitrification, denitrification, volatilisation, symbiotic N fixation and gaseous N emissions.

APSIM and DNDC are models based on process-level descriptions of N cycling based on a set of balance equations and provide daily values for N transformation rates and N losses, besides many other outputs. These two models have different strengths in scale and loss pathways. The APSIM model has mainly been developed to simulate biological and physical processes in farming systems, initially with an emphasis on cropping systems, but lately also for pasture systems, with the possibility of simulating at the urine patch level as well as at the multi-paddock scale (Li et al., 2011; Vogeler et al., 2012). The DNDC model was initially developed for simulating N_2O, CO_2 and N_2 emissions and denitrification from cultivated and grassland sites, but was later improved for simulating water flow and nitrate leaching (Li et al., 2006) and other systems such as perennial pastures and N_2O emissions from dairy-grazed pasture in New Zealand (Saggar et al., 2004). The description of N transformations in these two models is conceptually different. In APSIM, the processes of nitrification and denitrification are described as an empirical reaction, expressed via a Michaelis–Menten type equation; DNDC uses a microbial growth model. In both models, processes such as nitrification and denitrification are represented as functions of N and available C, and are modified by dimensionless factors for soil water content, temperature and pH.

The objective of this model comparison is to identify the main differences in APSIM- and DNDC-simulated N transformation rates in soils with high N loads, such as those under urine patches. Specifically, the response of these two different complex models to various environmental conditions or factors will be investigated. Given that these factors have multiple roles and often interact with others, we investigate how models respond depending on the algorithms used.

Environmental conditions that were varied included temperature, soil water content, soil organic C (SOC), pH, and initial NH_4 and NO_3 concentrations. First, however, we give a short description of the main processes relevant to N transformations by the two models, APSIM and DNDC. To eliminate the effect of water flow on these transformation processes, simulations were first done under static conditions. In the second comparison, rainfall and drainage were included. Finally, the effects of the N load under urine patches and the effect of rainfall intensity on N transformations and N_2O emissions, as simulated by APSIM and DNDC, were compared.

2. Model description

2.1. APSIM

APSIM is a framework of biophysical modules that simulate biological and physical processes in farming systems (Keating et al., 2003). The APSIM-SoilN and SurfaceOM modules simulate the dynamics of N and C on a daily time-step in soil layers, with N mineralisation, N immobilisation and nitrification, denitrification, and nitrate and ammonium adsorption and movement being explicitly described in each layer.

SoilN was set up with a uniform total carbon content over the entire soil depth (either of 3 or 6%), the soil biomass was set in each simulation layer to decline exponentially from a maximum of 8% of the active soil carbon at the soil surface to 0.8% at 200 mm deep. For the remaining carbon pool, representing the humic fraction, 20% was set as inert. A value of 12.0, typical for NZ soils was assumed for the C:N ratio of the soil organic matter.

These N processes are controlled by soil water content and flow, which are simulated within the APSIM-SoilWat model (Probert et al., 1998) or by APSWIM (Verburg et al., 1996), which was used for the study described here, and is based on Richards' equation. AgPasture (Li et al., 2011) was used as the pasture module with a ryegrass–clover mixture. For all simulations, APSIM version 7.4 was used (www.apsim.info).

A brief description of the N processes relevant to the model comparison undertaken in this study is given below.

2.1.1. Nitrification

Nitrification in the APSIM-SoilN model follows the Michaelis–Menten response to available soil ammonium, with the rate of nitrification (R_{nit}) given by:

$$R_{nit} = k_{max} \frac{[NH_4]}{[NH_4] + K_{NH4}} f(T) f(\theta) f(pH), \quad (1)$$

where $[NH_4]$ is the ammonium concentration in the soil (mg/kg), k_{max} is the maximum nitrification rate (default setting of 40 mg/kg/day), K_{NH4} is the NH_4 concentration for half the maximum response to $[NH_4]$ (default setting of 90 mg/kg), and $f(T)$, $f(\theta)$ and $f(pH)$ are functions accounting for the limitations imposed by temperature, soil water content and pH, and scaled from 0 to 1. Both $f(\theta)$ and $f(pH)$ decrease on either side of an optimum level, in drier soil or in excessively wet soil, and $f(T)$ increases exponentially up to an optimum temperature of 32 °C (see Fig. 1).

2.1.2. Denitrification

The denitrification rate (R_{denit}) in APSIM-SoilN is calculated by:

$$R_{denit} = k_{denit} [NO_3] C_A f(T) f(\theta) f(pH), \quad (2)$$

where k_{denit} is the denitrification coefficient, with a default value of 0.0006, $[NO_3]$ is the amount of NO_3 in the soil (mg/kg) and C_A is the active carbon (mg/kg) defined by Rolston et al. (1984) as:

$$C_{A,i} = 0.0031 SOC_i + 24.5, \quad (3)$$

where SOC is the sum of the soil organic C (mg/kg) of the fresh organic matter's soil carbon pools. The functions of temperature and soil water content for denitrification are illustrated in Fig. 1.

2.1.3. Nitrous oxide emissions

To account for nitrous oxide emission during denitrification (N_2O_{denit}) Thorburn et al. (2010) incorporated the approach of Del Grosso et al. (2000) into APSIM, based on an N_2 to N_2O ratio:

$$\frac{N_2}{N_2O_{denit}} = \text{Max}\left[(0.16k_1), \left(k_1 \exp\left(\frac{-0.8NO_3}{CO_2}\right)\right)\right] \text{Max}\left[0.1, \left(\left(1.5\frac{\theta}{TP}\right) - 0.32\right)\right], \tag{4}$$

where k_1 is related to the gas diffusivity in the soil at field capacity, NO_3 (mg/kg) is the nitrate concentration of the soil on a dry weight basis, CO_2 is the heterotrophic CO_2 respiration (mg C per g soil per day) and TP is the total porosity.

Nitrous oxide emissions during nitrification (N_2O_{nit}) are calculated as a proportion (k_2) of nitrified N (Parton et al., 2001):

$$N_2O_{nit} = k_2 R_{nit}. \tag{5}$$

As for the other model parameters the default value of 0.002 for k_2 was used here; Thorburn et al. (2010), however, suggest that this value might be soil-specific.

Also included was a module accounting for volatilisation based on the approach by Génermont and Cellier (1997), which was dependent on the equilibrium between NH_4 and NH_3, pH, the aqueous–gaseous equilibrium of NH_3 and the gradient between the gaseous concentration in the soil and atmosphere.

2.2. DNDC

The DNDC model consists of four primary submodules: soil climate, crop/vegetation, decomposition and denitrification. The model usually operates on a daily time-step, except following a rainfall or irrigation event, where denitrification is calculated on an hourly time-step. To allow nitrification and denitrification to occur simultaneously in aerobic or anaerobic microsites, a dynamic 'anaerobic balloon' is used (Li et al., 2000). Substrates such as C, NH_4 and NO_3 are split into aerobic and anaerobic soil microsites. The volume fraction of the anaerobic balloon (f_{anvol}) is calculated using a simplified linear correlation with oxygen partial pressure (p_{O_2}):

$$f_{anvol} = a\left(1 - b\frac{p_{O_{2,layer}}}{p_{O_{2,air}}}\right), \tag{6}$$

where a and b are constant coefficients.

For all simulations, the New Zealand-specific NZ-DNDC was used. NZ-DNDC is based on DNDC version 8.6K and has been modified for New Zealand grazed pasture conditions (Saggar et al., 2007). It should be noted that some of these equations differ in other versions of DNDC.

2.2.1. Nitrification

Nitrification in DNDC is described via a series of microbiological oxidation processes under aerobic conditions, and thus only affects the proportion of NH_4 in the "aerobic fraction":

$$R_{nit} = k_{max} NH_4 B_n f(\text{pH}), \tag{7}$$

where B_n is the microbial biomass of nitrifier and k_{max} is a function of clay content and soil moisture (k_{max} is divided by 3 when soil moisture is above field capacity). The soil moisture response function for nitrification and growth of nitrifiers is given by (Li et al., 2000):

$$\begin{aligned} f_m &= 0 && \text{for WFPS} < 0.05; \\ f_m &= 1.01 - 0.21\text{WFPS} && \text{for WFPS} \geq 0.05, \end{aligned} \tag{8}$$

where f_m is the moisture factor for nitrification and WFPS is the water-filled pore space. Note that this moisture response is different

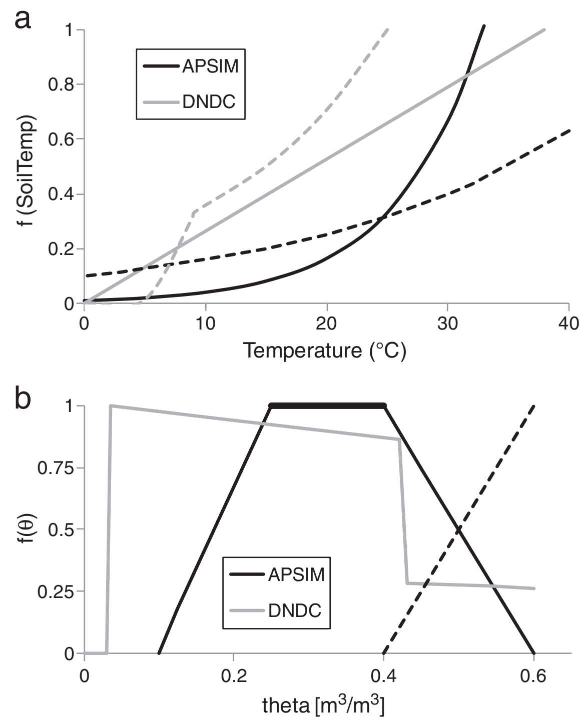

Fig. 1. Functions used for (a) temperature and (b) soil water content (θ) as used by APSIM and DNDC for nitrification (solid lines) and denitrification (broken lines).

to the one in the original DNDC version, where nitrification increased linearly to a WFPS of 90% (Li et al., 1992). Furthermore, the net growth of B_n is a function of temperature, moisture and dissolved organic C while the proportion of NH_4 in the "aerobic fraction" is also dependent on soil moisture. Thus soil moisture functions of nitrification in APSIM and DNDC cannot be directly compared.

Emissions of N_2O from nitrification are, as in APSIM, calculated as a function of the nitrification rate.

2.2.2. Denitrification and nitrous oxide emissions

Denitrification in DNDC occurs in the anaerobic fraction of the soil, which is usually small except following a rainfall event of ≥5 mm that saturates the soil. The model then simulates the reduction sequence $NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$ based on the growth of different microbial populations which compete for the available C. The consumption of species N_i (nitrate, nitrite or nitrous oxide) is given by:

$$\frac{dN_i}{dt} = \left(\frac{u_{N_i}}{Y_{N_i}} + M_{N_i}\frac{N_i}{N_{tot}}\right) \cdot B(t) \cdot \mu_{pHN_i} \cdot \mu_{T,DN}, \tag{9}$$

where u_{N_i} is the relative growth rate of N_i denitrifiers; Y_{N_i} is the maximum growth yield on N_i (kg C/kg N); M_{N_i} is the maintenance coefficient (in kg N/kg/h); N_{tot} is the sum of NO_3^-, NO_2^- and N_2O; B is the microbial biomass of denitrifier; and μ_{pHN_i} and $\mu_{T,DN}$ are the reduction factors for pH and temperature respectively. The growth term results in the transfer of mineral N to the denitrifier N pool while respiration results in the reduction of N_i to the next species in the denitrification sequence.

The growth rates of the denitrifier populations are calculated as:

$$u_{N_i} = u_{N_i,\max}\left(\frac{C}{C + K_{c,1/2}}\right)\left(\frac{N_i}{N_i + K_{N_i,1/2}}\right), \tag{10}$$

where C is the dissolved C concentration in the soil, $K_{c,1/2}$ and $K_{N_i,1/2}$ are the half-saturation values for soluble C and N_i respectively. The microbial population death rate is given by:

$$\frac{dB}{dt_{\mathrm{d}}} = M_c Y_c B(t), \tag{11}$$

where M_c is the maintenance coefficient of C (kg C per kg/h) and Y_c is the maximum growth yield on soluble C.

The rate of consumption of each species N_i ($i = NO_3^-$, NO_2^-, N_2O) is given by:

$$\frac{dN_i}{dt} \propto \left(\frac{u_{N_i}}{Y_{N_i}} + M_{N_i}\frac{N_i}{N_t}\right) B\mu_t\mu_{pH}, \tag{12}$$

where Y_{N_i} is the maximum growth yield on species N_i (kg C/kg N),M_{N_i} is the maintenance coefficient of species N_i (kg N per kg/h), and N_t is sum of the NO_3^-, NO_2^-, NO and N_2O nitrogen in the anaerobic volume fraction.

The temperature response function for denitrification up to 60 °C is illustrated in Fig. 1. DNDC uses different pH response functions for the different denitrifiers:

$$\begin{aligned} \mu_{pHNO_3} &= 2 - \frac{2}{1+\exp\left(\frac{pH-4.25}{0.5}\right)}; \\ \mu_{pHNO_2} &= 2 - \frac{2}{1+\exp\left(\frac{pH-5.25}{1}\right)}; \\ \mu_{pHN_2O} &= 2 - \frac{2}{1+\exp\left(\frac{pH-6.25}{1.5}\right)}. \end{aligned} \tag{13}$$

3. Simulation setup

3.1. N transformations — simulations in uniform soil

To compare N transformations from the two different simulation approaches, APSIM and DNDC simulations were set up with uniform soil under a range of static environmental conditions. The soil was a bare sandy loam with a depth of 200 mm, which was for the APSIM simulations divided into 10 layers, and for the DNDC treated as a single layer for the static water regime and 12 layers for the dynamic water regime. Soil properties for a typical sandy loam for NZ were used with a bulk density of 1 Mg/m^3, a total porosity of 59%, θ_{FC} at field capacity and θ_{PWP} at permanent wilting point of 0.43 and 0.23 m^3/m^3. Factors that were changed included water flow regime (either static or dynamic); the initial concentration of NH_4 (100 or 500 kg/ha — which are typical concentrations in soils following fertiliser applications or urine depositions) with 10 kg NO_3 per ha^1 or 1 kg per NH_4 ha^{-1} with 100 kg NO_3 (uniform within the soil); soil water contents (θ) of 0.3, 0.45 and 0.55 m^3/m^3; soil temperature of 10, 15 and 30 °C; soil organic carbon content (SOC) of 3 and 6%; pH of 6 and 8; and rainfall of 20 mm on day 1 or at 5 mm/day over the duration of the simulation run. The simulations were run for 10 days and simulation output included cumulative and daily values of nitrification, denitrification, and N_2O and N_2 emissions.

3.2. N_2O emissions from two soils as affected by N load and rainfall intensity

To investigate the effect of N load on N transformations and N_2O emissions from urine patches, APSIM and DNDC simulations were set up with two contrasting soils and climates from New Zealand. One was a typical soil from the Waikato region, the Horotiu soil, a free-draining silt loam with an OC of 6.7%. The other was from the Canterbury region, the Templeton soil, an imperfectly draining silt loam with an SOC of 2.9%. For the APSIM simulations, the soil was 1 m deep, and divided into 25 layers. Climate data from the NIWA Virtual Climate Station network (Tait and Turner, 2005) were used. Waikato has an annual rainfall of 1240 mm and an annual mean temperature of 14 °C, and Canterbury has an annual rainfall of 680 mm and an annual mean temperature of 11.5 °C. The simulations were run for 30 years, from 1980 to 2009, for four different N deposition times (spring, summer, autumn and winter) and with four different N deposition loads (250, 500, 750 and 1000 kg N/ha). An equivalent of 6 mm of water was added to the soil to account for urine deposition, and it was assumed that the initial infiltration depth was 300 mm (Li et al., 2012). To look at the effect of rainfall, intensity simulations were set up with the same soils and climates as above, but setting the rainfall intensity to either 1, 3 or 5 mm/h, whereas in the default model setup, daily rainfall is evenly distributed over 24 h. In all cases, simulations were run for 3 months and model outputs included cumulative and daily values of nitrification, denitrification, volatilisation and N_2O emissions.

4. Results and discussions

4.1. N transformations simulations in uniform soil

4.1.1. Nitrification

Nitrification of the initial NH_4 (NH_{4ini}) in the soil as simulated by APSIM and DNDC was quite different with a high initial nitrification rate and a steep decline in NH_4 simulated by DNDC and a relatively constant nitrification rate over the 10-day simulation run for APSIM. This is shown in Fig. 2a for a simulation run under dynamic conditions, a temperature of 10 °C and NH_{4ini} of 500 kg/ha. In general, the agreement improved with increasing temperature (Fig. 2b) and decreasing NH_{4ini} (not shown). The total amounts of nitrified N over the 10 days for the simulation shown in Fig. 2 are 56 kg/ha for APSIM and 300 kg N/ha for DNDC, for the case shown in Fig. 2b these are 415 and 280 kg/ha for APSIM and DNDC. Better agreement due to a greater response of APSIM to temperature can also be seen from the simulated nitrification of NH_4 of 30 kg/ha over a period of 10 days (Fig. 3a) with the 12 combinations of factors (pH, SOC and θ). In contrast, DNDC reacted more strongly to θ, showing a decreasing nitrification at θ above field capacity (Fig. 3b), mainly due to the reduced moisture factor for nitrification (Eq. (8)). Generally, the SOC had a higher influence on nitrification in DNDC compared with APSIM (Fig. 3c). DNDC also had a higher reduction in nitrification rate as pH increased from 6 to 8 (data not shown), whereas that pH range is considered to be uniformly optimal with APSIM's default settings. The total amount of NH_4 nitrified over the simulation period of 10 days is much higher for DNDC compared with APSIM at a temperature of 10 °C, but lower at 30 °C (Fig. 2). This is again mainly due to the different temperature function used for nitrification in APSIM and DNDC (Fig. 1). Under the environmental conditions and ranges simulated APSIM showed a higher variability of nitrification over 10 days compared with DNDC, with APSIM ranging from 9.9 to 61.3 and DNDC from 19.2 to 35 kg/ha N nitrified.

4.1.2. Denitrification

Denitrification from the simulations performed under dynamic conditions and with an initial NO_3 concentration of 100 kg/ha shows increasing rates with time for DNDC but decreasing rates for APSIM (Fig. 4a). The total amount of NO_3 denitrified over the simulation period of 10 days is much higher for DNDC compared with APSIM with 2.6 and 1.2 kg N/ha. This is partly due to APSIM's low factor for soil water (Fig. 1), which was close to the value at field capacity of 0.43 m^3/m^3 in this simulation. In contrast, in DNDC, denitrification is triggered by rainfall ≥5 mm. For denitrification, DNDC shows a

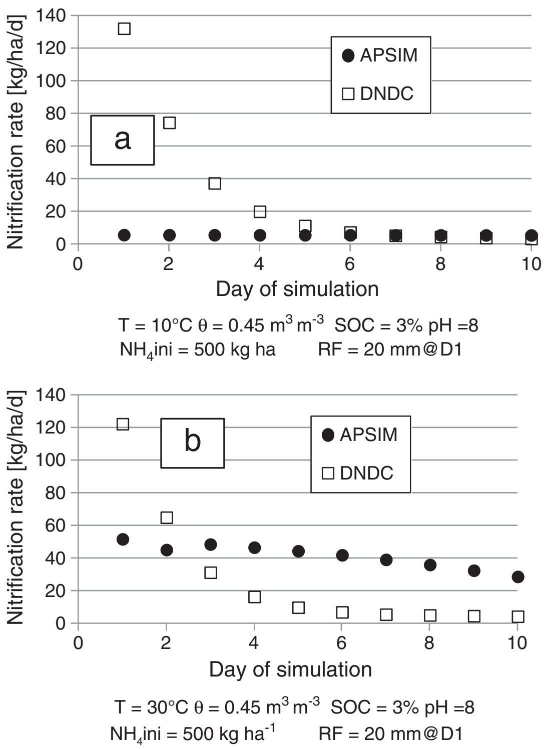

Fig. 2. Nitrification rate simulated by APSIM and DNDC over 10 days in a silt loam under (a) static conditions and (b) a rainfall event of 20 mm on day 1. The total nitrification over 10 days is also shown on the right-hand axis. T, temperature; θ, soil water content; SOC, soil organic carbon; NH_{4ini}, initial NH_4; RF, rainfall.

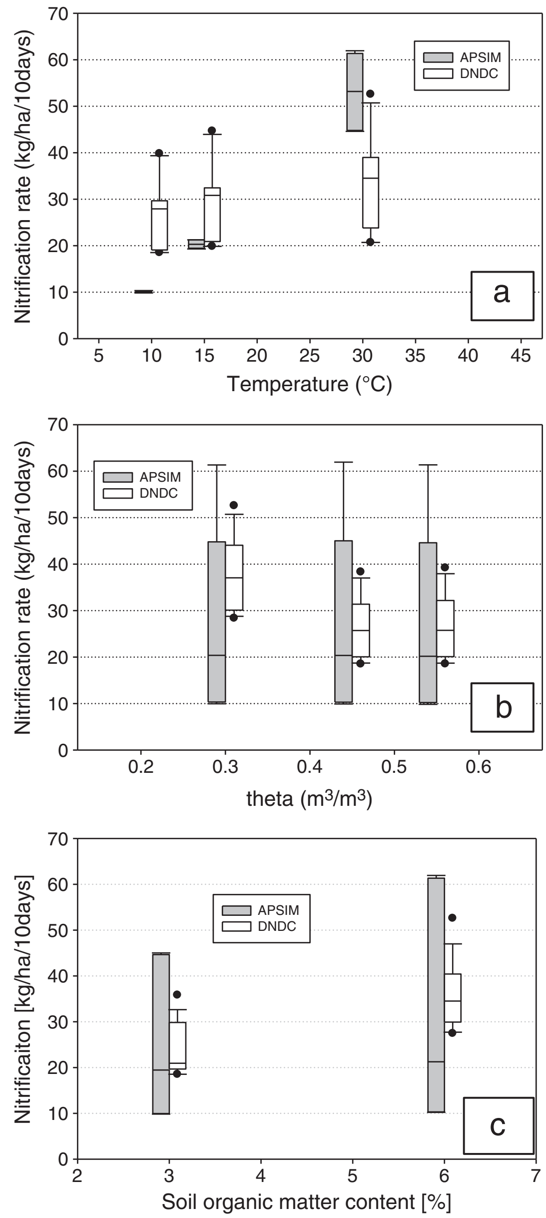

Fig. 3. Nitrification over 10 days as simulated by APSIM and DNDC for a sandy loam with an initial NH_4 of 30 kg/ha under dynamic conditions as influenced by (a) temperature (T), (b) soil water content (θ) and (c) soil organic carbon (SOC). The boxes show the 25th, 50th and 75th percentiles, and the whiskers show the 5th and 95th percentile model outputs from 12 different combinations of (a) pH, SOC and θ; (b) pH, SOC and T; and (c) T, pH and θ.

stronger influence of temperature and SOC than does APSIM (Fig. 5a and c). In APSIM, denitrification only occurs at or above field capacity, and thus equals zero in the simulations performed at a θ of 0.3 (Fig. 5b).

4.1.3. Nitrous oxide emissions

As discussed in the model description (Section 2), N_2O emissions occur during both nitrification and denitrification processes. As such, they are influenced by the same environmental conditions as nitrification and denitrification. Experimental results suggest that nitrification is the dominant source of N_2O at WFPS <0.6 (equivalent to a soil water content of 0.345 m^3/m^3 in the silt loam) and that at higher water contents, denitrification is the dominant source (Davidson, 1991). In both models, N_2O emissions from nitrification are assumed as a simple ratio (Li et al., 2000), as observed in several studies. Thus only emissions from denitrification, occurring from an initial NO_3 level (NO_{3ini}) of 100 kg/ha and an NH_{4ini} of 1 kg/ha are discussed here. As expected, the trend of N_2O emissions is similar to that of denitrification, with an increasing rate for DNDC and a slightly decreasing rate for APSIM over the 10 days (Fig. 4b). Similar to the results for denitrification, DNDC shows a larger response to temperature and organic carbon content (Fig. 6). The total amount of N_2O emissions over the 10 days is also higher in DNDC compared with APSIM with 0.9 and 0.27 kg/ha.

4.1.4. Effect of N load on N_2O emissions and denitrification

Simulated N_2O emissions by both models show higher emissions for the Horotiu silt loam in the Waikato compared to the Templeton silt loam in the Canterbury area (Figs. 7 and 8). These higher simulated emissions at the Waikato site with the higher rainfall compared with the Canterbury site are in agreement with the experimental data by De Klein et al. (2003) which showed higher emissions at higher rainfall sites.

DNDC shows little seasonal effect on N_2O emissions, whereas APSIM predicts much higher emissions from N depositions in autumn compared to other seasons. Similar seasonal trends in N_2O emissions have been found in other studies. For example, Allen et al. (1996) found higher N_2O emission rates during the autumn/winter season than during the spring/summer season in a grazed grassland in the UK, and Yamulki et al. (1998) found generally higher emissions from excreta deposited during autumn than from those deposited during summer on a poorly drained silt clay loam in the UK. Similarly, DNDC shows little seasonal effect on denitrification, whereas APSIM predicts much higher denitrification in autumn compared to in summer and spring. This model difference is partly due to the higher sensitivity of denitrification in APSIM to soil water content, and the higher sensitivity of DNDC to soil temperature.

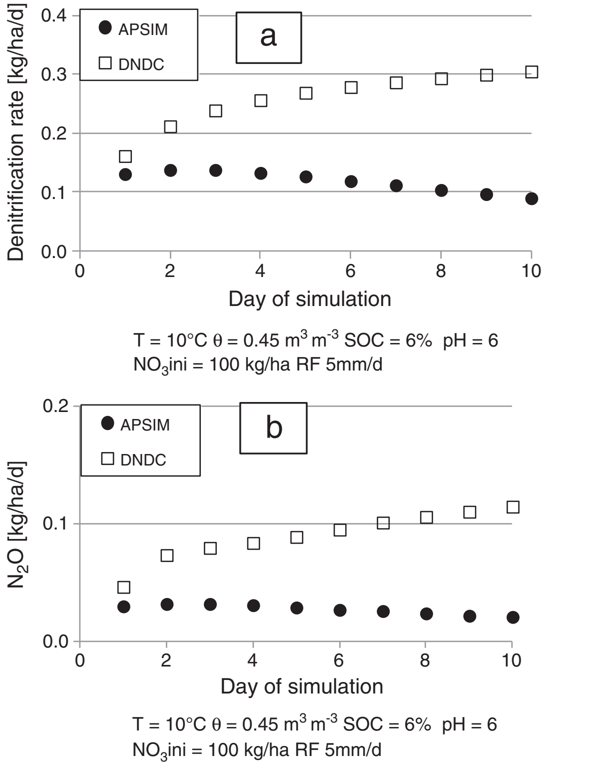

Fig. 4. (a) Denitrification rate and (b) N_2O emissions simulated by APSIM and DNDC over 10 days in a silt loam with a rainfall of 5 mm/day. *T*, temperature; *θ*, soil water content; NO_{3ini}, initial NO_3.

Furthermore, N_2O emissions as a function of N load show a slightly plateaued response in APSIM, whereas emissions increase almost linearly in DNDC. Information on the effect of N load on N_2O emissions is limited. Breitenbeck and Bremner (1986), studying N_2O emissions from ammonia fertiliser, found emissions decreasing from 1.6% to 0.9% of applied N with increasing fertiliser rates from 75 to 450 kg N/ha, supporting the response simulated by APSIM.

For both soils, DNDC simulates higher emissions than APSIM (Figs. 7 and 8).

Xing et al. (2011) found, by comparing APSIM simulations to experimental data from incubation experiments, that N_2O emissions simulated by APSIM were too low. They suggested that this might be due to an underestimation of the denitrification rate, which, in turn, might be due to the temperature and soil moisture response functions. Their experiment was performed at a temperature of 25 °C, where the difference between the temperature factors of APSIM and DNDC is higher than for our two simulated sites, with mean annual temperatures of 14 °C and 11.5 °C (Fig. 1). Furthermore, the APSIM-simulated denitrification as dependent on N load is much higher compared to that simulated by DNDC. Thus an underestimation of denitrification by APSIM is not the reason for the lower simulated N_2O emissions by APSIM compared to DNDC, at least at the higher N loads. APSIM-simulated denitrification increases nearly linearly with increasing N load, whereas denitrification simulated by DNDC reaches a plateau at an N load of 250 kg/ha and remains almost constant thereafter. This might be caused by the soil not being under anaerobic conditions for very long in both the Waikato and the Canterbury climates. This limits denitrifier population growth and thus denitrification, which is, as expected, more pronounced in the drier Canterbury climate and in summer. While these different responses of N load to denitrification are not explicitly shown, they can be inferred from Fig. 9, which shows simulated N_2O emissions as a function of denitrified N for the

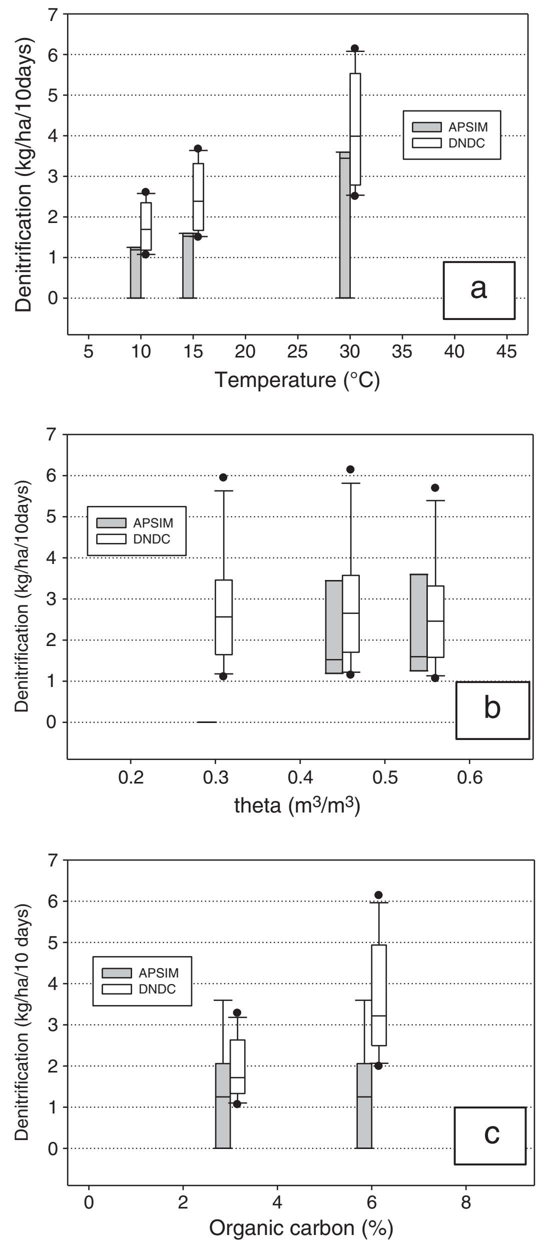

Fig. 5. Denitrification over 10 days as simulated by APSIM and DNDC for a sandy loam under dynamic conditions as influenced by (a) temperature (*T*), (b) soil water content (*θ*) and (c) soil organic carbon content (SOC). The boxes show the 25th, 50th and 75th percentiles, and the whiskers show the 5th and 95th percentile model outputs from 12 different combinations of (a) pH, SOC and *θ*; (b) pH, SOC and *T*; and (c) *T*, pH and *θ*.

Horotiu silt loam in the Waikato. The results for the Templeton silt loam in the Canterbury area are similar and not shown here. Although emissions increase nearly linearly with denitrification in APSIM, in DNDC, emissions increase at a much higher rate with N load compared to denitrification. This suggests that in DNDC, at high N loads, nitrification may become a major source of N_2O emissions.

4.1.5. Effect of rainfall intensity on N_2O emissions

APSIM and DNDC show quite different responses to rainfall intensity on N_2O emissions, as shown for a deposition of 750 kg N/ha in either spring or autumn (Fig. 10). APSIM shows the highest emissions with lower rainfall intensities, whereas DNDC simulates higher emissions at higher rainfall intensities. The default setting of APSIM

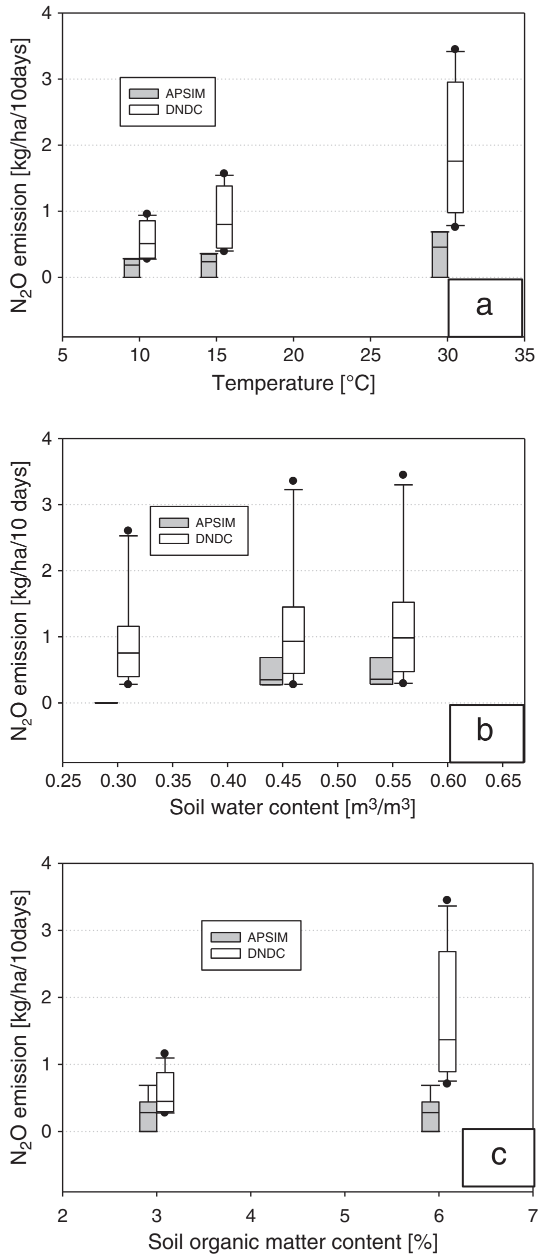

Fig. 6. N_2O emissions over 10 days as simulated by APSIM and DNDC for a sandy loam under dynamic conditions as influenced by (a) temperature (*T*), (b) soil water content (θ) and (c) soil organic carbon content (SOC). The boxes show the 25th, 50th and 75th percentiles, and the whiskers show the 5th and 95th percentile model outputs from 12 different combinations of (a) pH, SOC and θ; (b) pH, SOC and *T*; and (c) *T*, pH and θ.

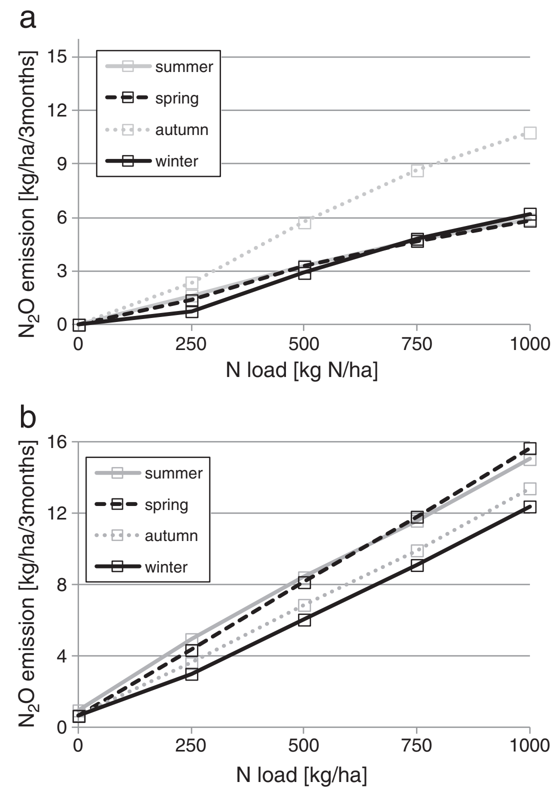

Fig. 7. N_2O emissions simulated by (a) APSIM and (b) DNDC as dependent on N load and time of deposition in a Horotiu silt loam in the Waikato region of New Zealand. The average of 30 years of simulation (1980–2009) is shown.

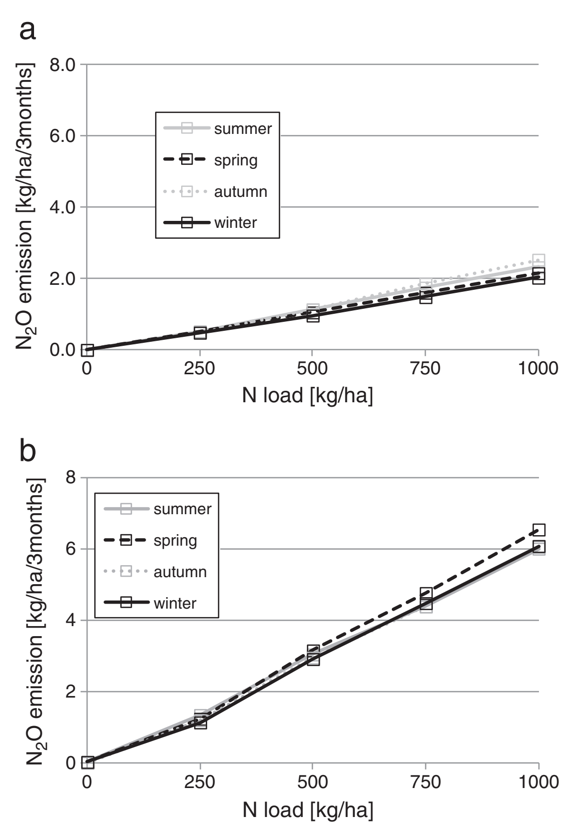

Fig. 8. N_2O emissions simulated by (a) APSIM and (b) DNDC as dependent on N load and time of deposition in a Templeton silt loam in the Canterbury region of New Zealand. The average of 30 years of simulation (1980–2009) is shown.

assumes that daily rainfall is evenly distributed over the day, while DNDC assumes that rain falls at a fixed rate for the required number of hours. Ideally, any modelling of N_2O emissions should consider subdaily rainfall intensities, as this has a large effect on total emissions.

5. Conclusions

This paper presents a comparison of the two different models, APSIM and DNDC, to simulate nitrogen transformation rates, including nitrification, denitrification and N_2O emissions in soils. The comparison included simulations in uniform soils under static and dynamic

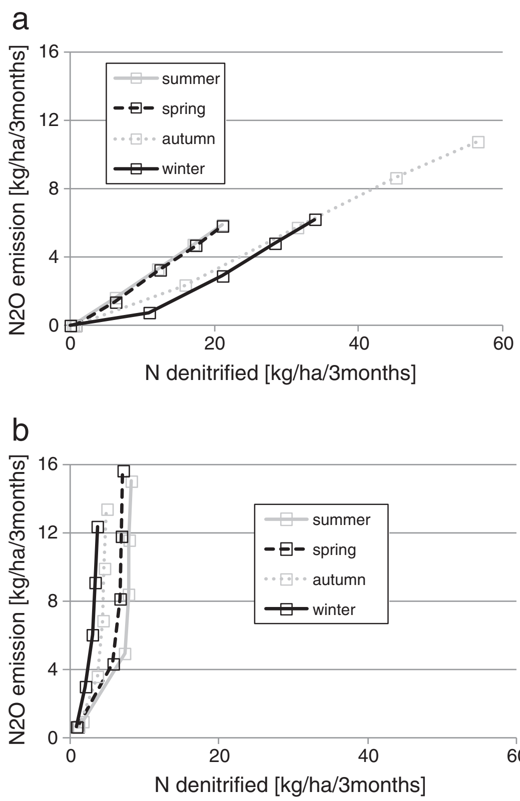

Fig. 9. N_2O emissions simulated by (a) APSIM and (b) DNDC as a function of denitrified NO_3 following an N application ranging from 0 to 1000 kg/ha at different times in a Horotiu silt loam in the Waikato region of New Zealand. The average of 30 years of simulation (1980–2009) is shown.

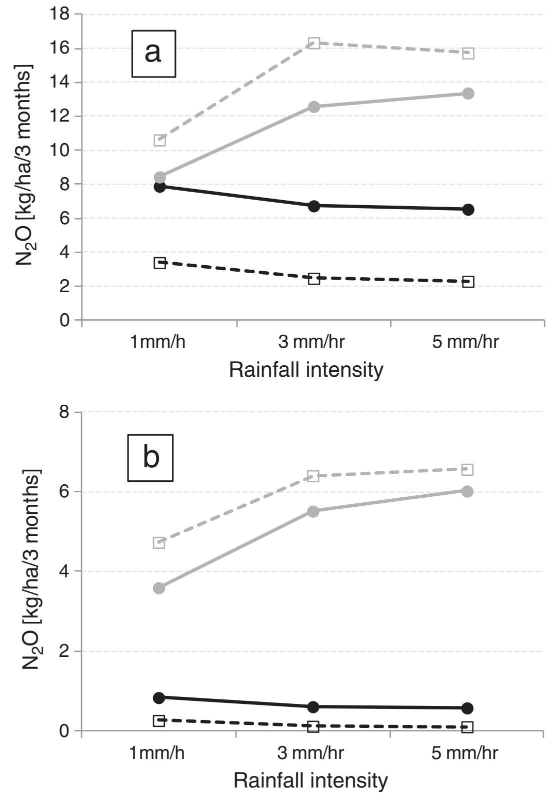

Fig. 10. N_2O emissions simulated by APSIM (black lines and symbols) and DNDC (grey lines and symbols) from a load of 750 kg N/ha deposited in either spring (broken lines) or autumn (solid lines) on either (a) a Horotiu silt loam in the Waikato region or (b) a Templeton silt loam in the Canterbury area of New Zealand. The average of 30 years of simulation (1980–2009) is shown.

conditions, with initially either high NH_4 or NO_3 soil concentrations. APSIM- and DNDC-simulated nitrification and denitrification rates over 10 days were quite different. In APSIM, temperature had a larger effect on nitrification, but in DNDC, the soil water content had more effect. Regarding denitrification, DNDC showed a stronger influence of temperature and SOC than did APSIM, and was triggered by rainfall in DNDC but by soil water content in APSIM. APSIM and DNDC also showed quite different responses to N load on N_2O emissions, with a plateaued response in APSIM and a linear response in DNDC to N load. Increasing rainfall intensity showed decreased N_2O emissions in APSIM but increased emissions in DNDC.

As the next step, APSIM and DNDC model outputs will be compared to data sets from various regions of NZ, including measurements of soil water content, soil NH_4 and NO_3 concentrations, and N_2O emissions following urine application. The model/data inter-comparison, with the differences in model responses to environmental factors highlighted in the current study, will help to illuminate model strengths and weaknesses, and to identify response functions that might need to be modified for better model performance and perhaps even a response function that can be varied according to site-specific conditions to account for microbial adaptation, as suggested by (Farquharson and Baldock, 2008).

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