Using the 'NZ-DNDC' model to simulate the effects of changing land management on nitrous oxide and carbon dioxide emissions from New Zealand grazed pastures

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Abstract
The process-based denitrification-decomposition (DNDC) model simultaneously models agricultural trace gas emissions, soil C sequestration, and crop yield, and is ideal for mitigation-offset analyses that examine both C sequestration and nitrous oxide (N_2O) and methane (CH_4) emissions in agro-ecosystems. We have modified DNDC for estimating N_2O emissions from New Zealand's grazed pasture systems. Modifications include the addition of perennial pasture to the modelled crop list, pasture growth response to day length, and the use of a NZ-specific relationship between air and soil temperature. The soil-water balance submodel was also amended to allow the simulated soil water content to reach the same saturated conditions as were found in the field. In addition, the critical value of water-filled pore space (WFPS) for switching on denitrification was increased from 35% to field capacity (~ 60% WFPS). Excretal inputs from grazing animals were applied, based on actual grazing management. Our modified model (NZ-DNDC) simulated very well changes in WFPS for a well-drained fine sandy loam and a poorly drained silt loam soil. The modified model thus fairly reproduces the real variability in underlying processes that regulate N_2O and carbon dioxide (CO_2) emissions, suggesting it should simulate reasonably well these emissions from a range of New Zealand grazed pastures. Several simulations have been run to predict the likely results of land-use changes on soil CO_2 and N_2O emissions. These results suggest NZ-DNDC realistically simulates the effects of changes in fertiliser and grazing management on these emissions. However, further modifications may be required to more accurately simulate changes in soil C in these grazed pastures.

Key Words
NZ-DNDC model, agricultural greenhouse gases

Introduction
As a signatory to the United Nations Framework Convention on Climate Change (UNFCC), New Zealand is required to maintain and report on its inventory of greenhouse gas emissions. Recently, New Zealand also ratified the Kyoto Protocol. New Zealand is in the unusual position that 49.2% of its greenhouse gas emissions come from the agricultural sector (New Zealand Climate Change Office 2004). The agricultural greenhouse gas emissions are largely comprised of methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) emissions from agricultural soils. New Zealand is currently using the IPCC methodology for calculating N_2O emissions from agricultural soils. Emissions from animal excreta deposited during grazing are estimated using N excreted by each animal type and the national animal population statistics. The emissions factor used is 0.01 kg N_2O-N per kg excreted N. This methodology leads to large uncertainties in N_2O emission levels (~ ±65%) and cannot be used to verify attempts to mitigate N_2O emissions. There is therefore a need to account more realistically for the underlying processes when modelling agricultural N_2O emissions, to reduce uncertainties in the national N_2O inventory and verify the efficacy of mitigation strategies.

The denitrification-decomposition model (DNDC) is a process-based model initially developed to predict N_2O emissions from U.S. agricultural soils. DNDC has reasonable input requirements and simultaneously models emissions of CO_2, CH_4 and N_2O from agricultural soils as well as soil organic carbon content and crop yield. The DNDC model can be run at site or regional scale and is described in Li *et al*. (1992).

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The model was modified for New Zealand's grazed pasture systems (Saggar *et al.* 2004). Modifications included addition of a modifier for pasture growth to account for varying day length throughout the year, changes to the water-filled pore space (WFPS) threshold for denitrification from 35% to the field capacity, and changes to the air-soil temperature relationship, soil drainage and N inputs from grazing animals (Saggar *et al.* 2004). These and other recent modifications have subsequently been incorporated into the DNDC model, which now includes perennial pastures as a crop type. This New Zealand-specific model is named NZ-DNDC.

Our objectives were to test the current NZ-DNDC model for predicting changes in WFPS, soil C levels and N_2O emissions in grazed pastures, and to simulate the effects of different land management systems.

Methodology

First, the current NZ-DNDC model was tested using a series of daily N_2O emissions and WFPS measurements obtained from two dairy grazed pasture sites between April 2001 and February 2002 (Saggar *et al*. 2004). Both sites were part of Massey University's Turitea Campus, Palmerston North, were 3 km apart, and had contrasting soil types: Weathered Fluvial Recent, Karapoti fine sandy loam (well-drained) and Argillic-fragic Perch-gley Pallic, Tokomaru silt loam (poorly-drained). The experimental data were used to verify the predictions from NZ-DNDC, which include all the new features from the latest version of DNDC (DNDC 8.3G).

Second, the model was then used to simulate the likely effects of grazing and fertiliser management changes on emissions of N_2O and CO_2 from both dairy- and sheep- grazed pastures. Impacts of the amount, frequency and time of N inputs on emissions were assessed. Soil data for the well-drained soil were used with climate data from 2001 for all simulations. The results of these simulations are not intended to be generalised across all soil types and climate conditions. However, they can demonstrate that NZ-DNDC has the potential to account for changes in soil emissions of N_2O and CO_2 due to changes in land management. The land management changes considered were:

(A) Stocking Rates

In New Zealand, sheep stocking rates vary with pasture productivity from low (5 sheep/ha) to high (20+ sheep/ha). To examine the effect of increasing stocking rates we ran a series of simulations using the soil and climate data for a well-drained pasture site with 5, 10, 15, 20 and 25 sheep/ha. The sheep were set-stocked and grazed for the whole year. No fertiliser was added.

(B) Fertiliser N additions

Fertiliser addition is now common in New Zealand dairy farms, with fertiliser applications of up to 200 kg N/ha/yr. Both the total amount of fertiliser N and the number of split applications can affect soil N_2O emissions. We performed two series of simulations on a one-hectare pasture assumed to be grazed by 75 dairy cattle according to the schedule in Table 1 (giving an average stocking rate of ~3.3 cattle/ha).

Table 1. Grazing dates used in model simulations.

Grazing Dates	
1 Jan	4 Jul
24 Jan	27 Jul
16 Feb	19 Aug
11 Mar	11 Sep
3 Apr	4 Oct
26 Apr	27 Oct
19 May	19 Nov
11 Jun	12 Dec

(i) Fertiliser was applied in three equal applications on May 7, July 11 and Aug 26. The amount of fertiliser N added varied between 0 and 200 kg/ha.
(ii) Total fertiliser N applied was kept constant at 150 kg N/ha but was split between one to five applications throughout the year (Table 2).

Table 2. Fertiliser application dates used in model simulations. The amount of fertiliser applied (in kg N/ha) at each application date is given in parentheses.

Fertiliser Dates				
1 Application	**2 Applications**	**3 Applications**	**4 Applications**	**5 Applications**
7 May (150 kg/ha)	7 May (75 kg/ha) 11 Jul (75 kg/ha)	7 May (50 kg/ha) 11 Jul (50 kg/ha) 26 Aug (50 kg/ha)	7 May (37.5 kg/ha) 11 Jul (37.5 kg/ha) 26 Aug (37.5 kg/ha) 15 Sep (37.5 kg/ha)	7 May (30 kg/ha) 11 Jul (30 kg/ha) 26 Aug (30 kg/ha) 15 Sep (30 kg/ha) 15 Oct (30 kg/ha)

(C) Grazing regime

There are two main sheep grazing regimes in New Zealand: set-stocking and rotational grazing. In set-stocking, the animals remain in the same paddock throughout the year, whereas in rotational grazing, the animals are moved between a number of paddocks over the year. Rotational grazing tends to be associated with more intensive farming. New Zealand dairy farms are also rotationally grazed. To determine the effect of the grazing regime on soil emissions we ran two simulations of a sheep-grazed farm under set-stocking and rotational grazing management with an average stocking rate of 25 sheep/ha. Table 3 shows the grazing dates used for the rotational grazing simulation.

Table 3. Grazing dates used in rotational grazing simulation.

Grazing Dates				
14 Jan	28 Jan	11 Feb	25 Feb	11 Mar
25 Mar	8 Apr	22 Apr	6 May	20 May
3 Jun	17 Jun	1 Jul	15 Jul	29 Jul
12 Aug	26 Aug	9 Sep	23 Sep	7 Oct
21 Oct	4 Nov	18 Nov	2 Dec	16 Dec

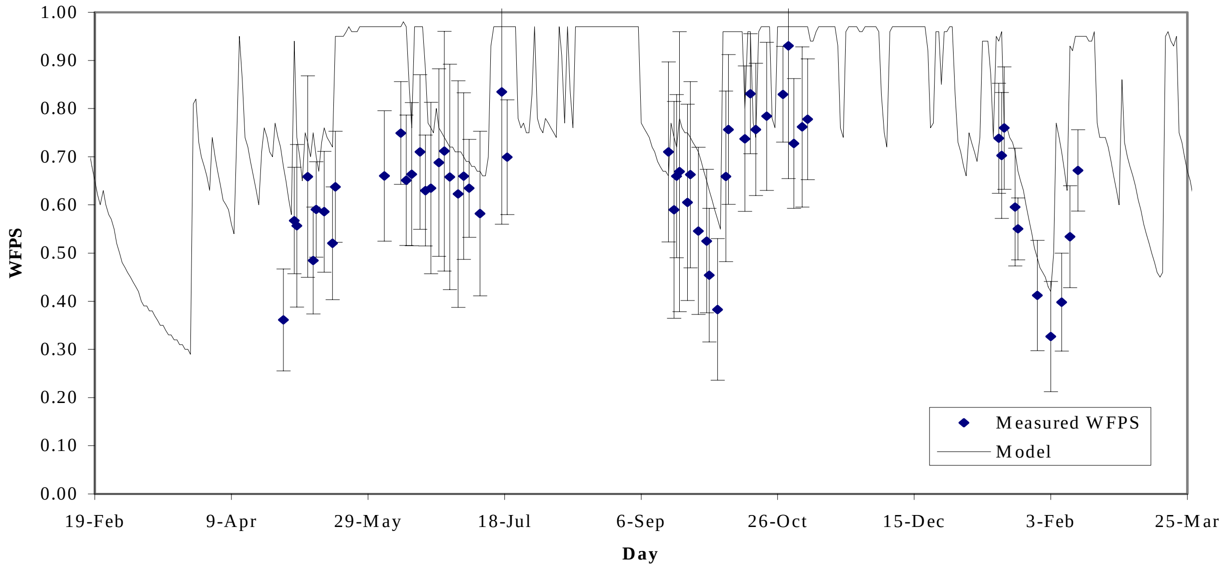
(D) Long-term changes in fertiliser N inputs

We examined the long-term impact of changes in fertiliser regimes. It is common for the rate of fertiliser application to increase as farming intensifies. We also examined what would be expected to happen to emissions when the fertiliser application rate was decreased. We ran a 100-year simulation for a 1-ha paddock grazed by a herd of 75 cattle according to the schedule given in Table 1. In Case I, no fertiliser was used for the first 50-years, then for the next 50 years 150 kg/ha of fertiliser N was added on the 1 September every year. Case II was the reverse scenario: for the initial 50-years the pasture had 150 kg fertiliser N added every year, for the following 50-years no fertiliser was added.

Results

Model Verification

(a)



(b)

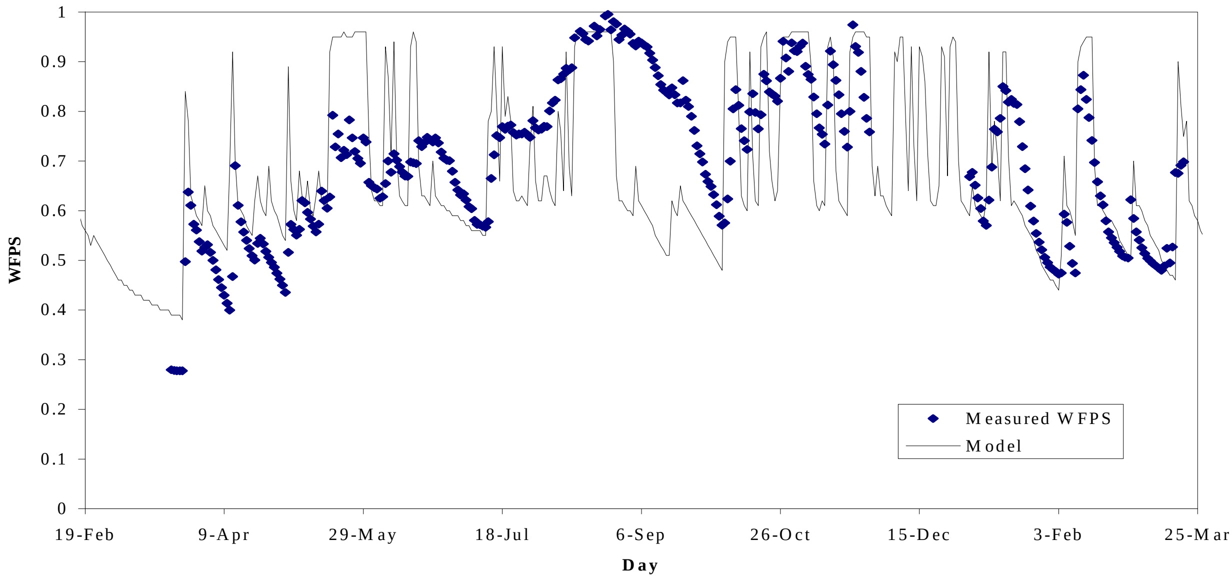


Figure 1. Measured and modelled soil water-filled pore space (WFPS) for (a) well-drained soil and (b) poorly-drained soil.

Figure 1 shows the model prediction of WFPS compared with the measured values for two sites. The model simulated very well the changes in soil WFPS during the year in both the well-drained and poorly drained soils, except that the poorly drained soil was slower to drain in September than in the model prediction.

Figure 2 shows a comparison of the N_2O emissions predicted by NZ-DNDC with the measured N_2O emissions. NZ-DNDC gave reasonable predictions of the N_2O emissions, although it missed the very high emission peak in January observed immediately after a summer rainfall event.

Figure 3 shows the soil organic carbon (C) predicted over a 100-year time period using the 2001 climate and farm management data from the N_2O and WFPS trials. Unfortunately there is a lack of soil C data on long-term changes of soil C in New Zealand pastoral soils to compare with the model simulations. A recent review of the New Zealand published data and results from recent research, however, suggest that soil C levels under established pastures in New Zealand may have reached a near steady state (Tate *et al.* 2003). In established dairy farms, therefore, soil C content is not expected to vary significantly from year to year. The simulated data indicated an increase in soil C for the poorly drained soil due to its relatively heavier soil texture that limits decomposition processes.

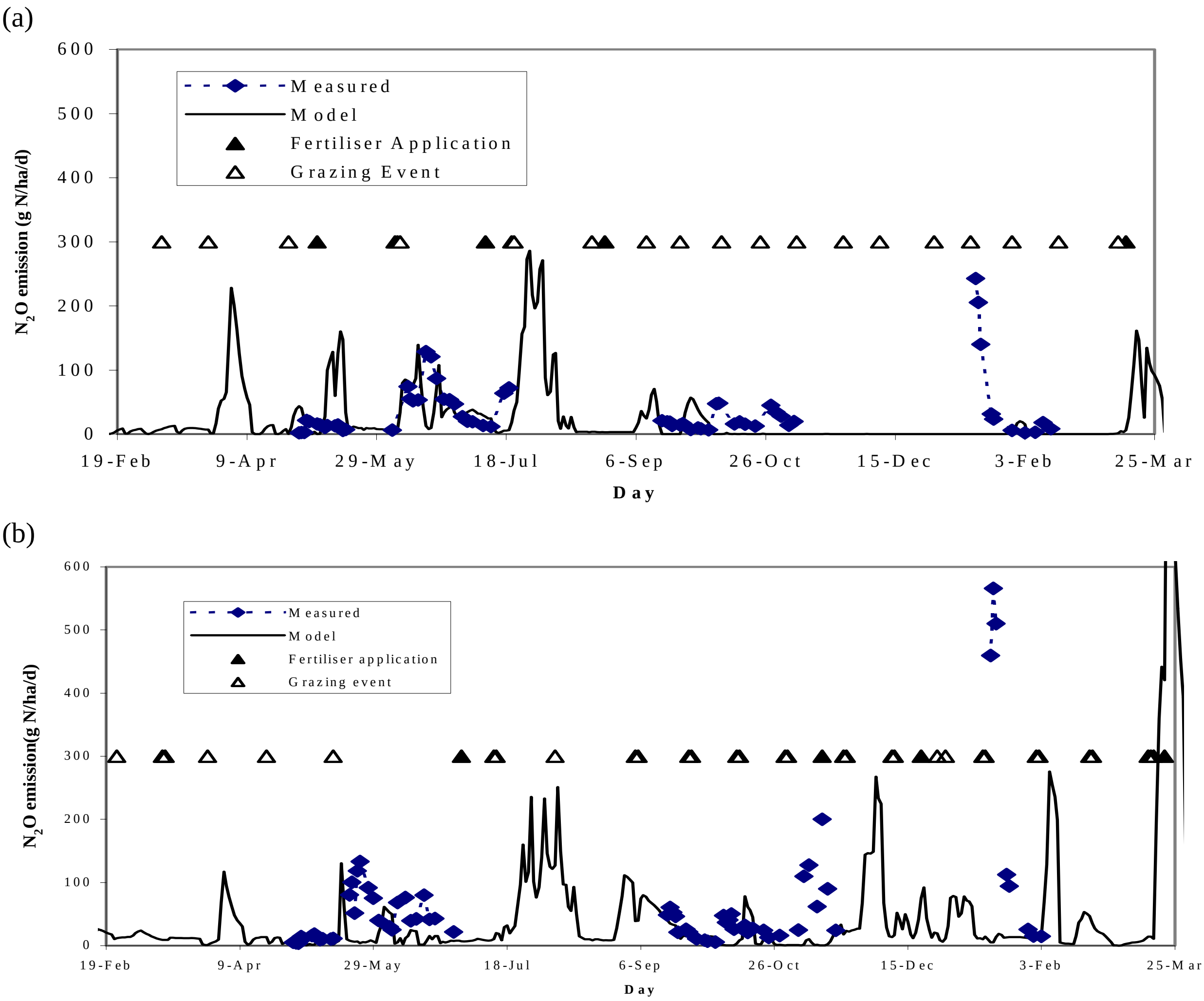


Figure 2. Measured and modelled soil N_2O emissions for cattle-grazed (a) well-drained and (b) poorly drained soil.

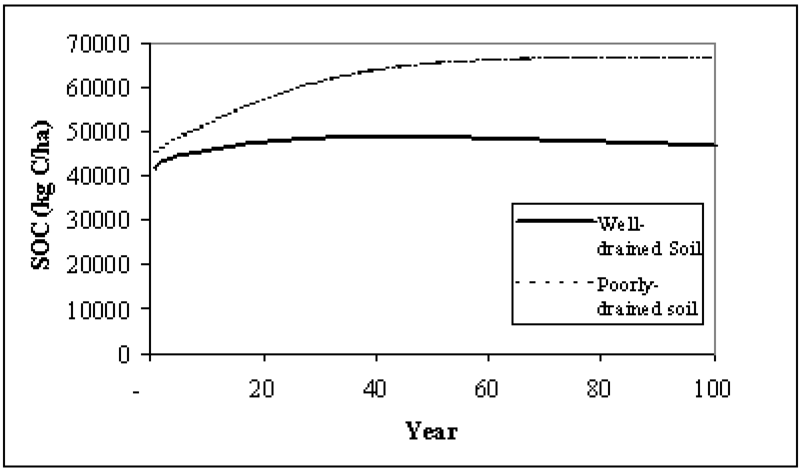


Figure 3. Soil organic carbon variation with time for cattle-grazed farms with well and poorly drained soils.

Validation tests indicated that NZ-DNDC might need further improvement to estimate the measured behaviour of soil C in grazed pastures more accurately. The model does, however, provide some insight into likely trends in N2O emissions under different management regimes.

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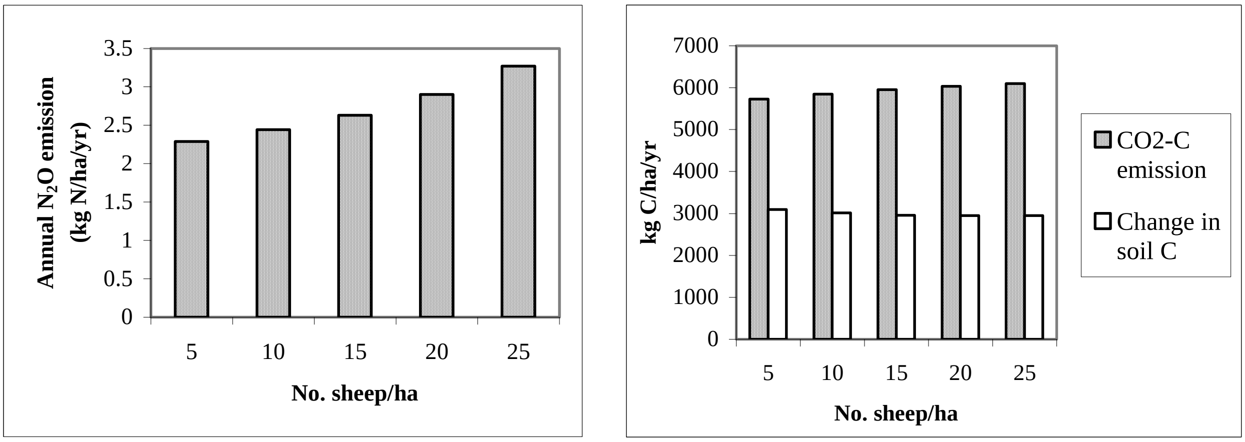
Simulating impacts on soil N_2O and CO_2 emissions of changes in land management

(A) Effect of different stocking levels

Figure 4 shows the results of these simulations. Both the soil CO_2 and N_2O emissions increased with increasing stocking rates as a result of higher excretal C and N inputs. However, the relationship between increases in N_2O emissions and stocking rate was non-linear. These simulations indicate the proportion of added N emitted as N_2O varies with amount of excretal input. Therefore a single emission factor would not predict N_2O emissions accurately over a range of stocking-rates.

While the soil CO_2 emissions increased slightly with increasing stock-numbers, soil C decreased. These results indicate the addition of excretal C and N inputs may accelerate turnover of soil organic matter. It may also indicate that increasing grazing intensity reduces plant C input to soil.

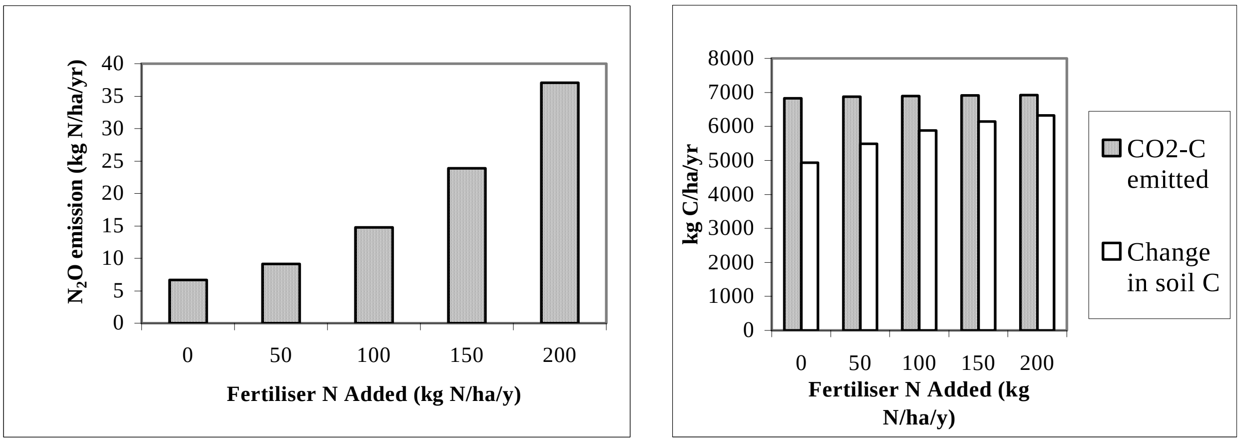


(a) **(b)**

Figure 4. Modelled annual (a) N_2O emissions and (b) change in soil C and soil CO_2 emissions for sheep-grazed farm. No added fertiliser N.

(B) Effect of different fertilizer application levels

(i) Figure 5 shows the soil N_2O and CO_2 emissions as the total amount of fertiliser-N was increased. There was an increase in the soil N_2O emissions with increasing levels of applied fertiliser.



(a) **(b)**

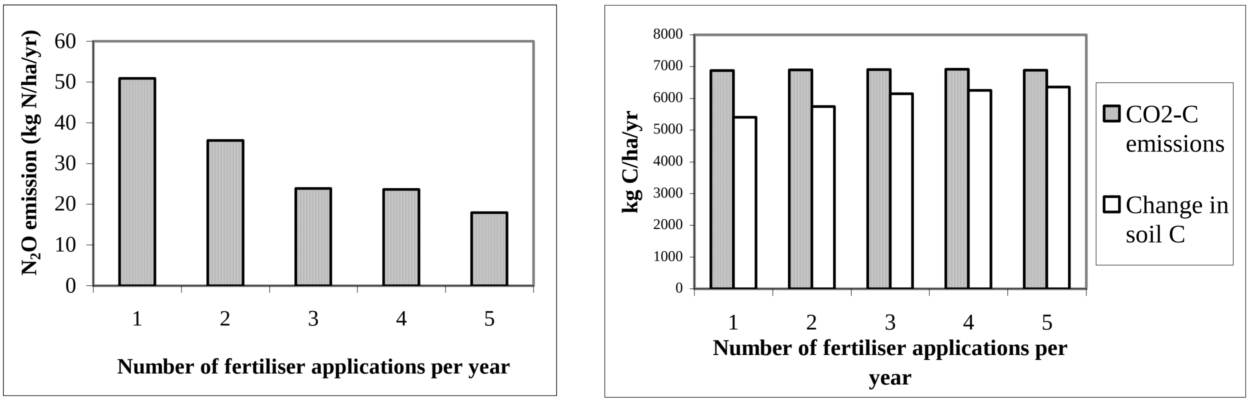
Figure 5. Modelled annual (a) N_2O emissions and (b) change in soil C and soil CO_2 emissions from cattle-grazed farm with different amounts of applied fertiliser-N. Excretal-N input was 348 kg-N/ha/year.

The soil CO_2 emitted did not significantly increase with fertiliser application, but this does not account for any changes in the input of C to soil due to enhanced plant growth. The effect of enhanced plant growth can be seen in the higher rate of increase in the soil C with higher fertiliser application. The model suggests increased fertiliser use increased the soil C.

In terms of N-deposition, 3.3 cattle/ha is approximately equivalent to 24 sheep/ha. The model predicted N_2O emissions from 3.3 cattle/ha (with no added fertiliser N) of 6.7 kg N/ha/y, while the N_2O emissions for 25 sheep/ha were 3.3 kg N/ha/y (Figures 4a and 5a). The major difference between the sheep-grazed and dairy-grazed simulations was that the sheep were set-stocked for the entire year, whereas the cattle were grazed on a rotational basis. As a result, the simulations indicated a large difference in N_2O emissions between sheep-grazing and dairy-grazing systems.

(ii) The modelled annual emissions of N_2O and CO_2 with increased frequency of 150 Kg N/ha/yr applications are displayed in Figure 6.

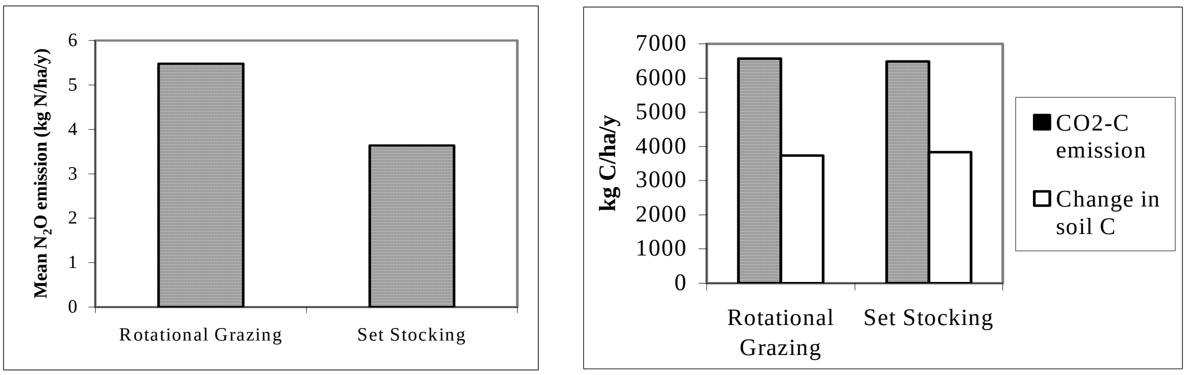
Increasing the number of fertiliser applications reduced the annual N_2O emissions. The N_2O emissions do not follow a simple linear relationship with the number of applications. The timing of the applications can also play a critical role (simulations not reported). The proportion of applied N lost as N_2O depends on soil moisture conditions at the time of application. If fertiliser is applied at a time when the soil moisture content is high (or if it becomes so shortly after the application), there will be more N_2O emitted than if the same amount of fertiliser was applied to dry soil.



(a) (b)
Figure 6. Modelled annual (a) N_2O emissions and (b) change in soil C and soil CO_2 emissions from cattle-grazed farm with 150 kg/ha/yr total fertiliser nitrogen added. The number of fertiliser applications each year was varied from one application to five applications per year. The total N-input from animal excreta was 348 kg/ha/yr.

The addition of C to the soil also increased with increasing frequency of fertiliser applications. This is related to the decrease in N_2O emissions, as less N lost to the atmosphere means more N available for plant growth, thereby increasing C inputs to the soil.

(C) Differences between set-stocking and rotational grazing

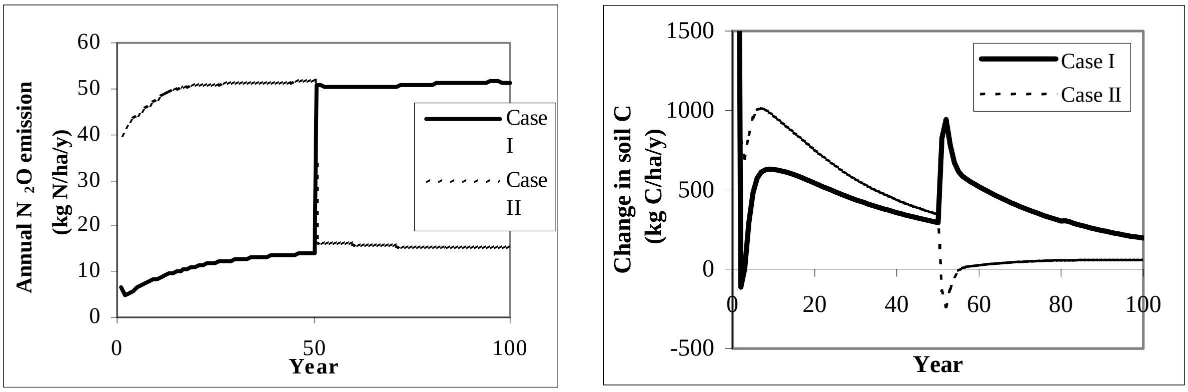


(a) (b)
Figure 7. Simulated annual (a) N_2O emissions and (b) change in soil C and soil CO_2 emissions for a sheep farm grazed at a stocking rate of 25 sheep/ha. For the set-stocking simulation, 25 sheep grazed a 1-hectare paddock for 365 days. In the rotational grazing simulation, a flock of 365 sheep grazed the paddock for 25 days spread throughout the year. Total N from excreta was 365 kg N/ha/y for both simulations.

Figure 7 shows that rotational grazing produced higher N_2O emissions than set-stocking, which suggests the soil system is capable of processing frequent small pulses of N inputs, but large inputs are likely to produce more N_2O. This has implications for attempts to produce regional and national estimates of N_2O emissions from stock numbers alone. Averaging stock numbers over wide areas is likely to produce an underestimate. Areas that are intensively grazed need to be accounted for in regional and national emissions estimates. There was a much smaller difference between the two methods in the CO_2 emissions and change in soil C.

The N_2O emitted by the rotationally grazed sheep was close to the N_2O emission from the cattle-grazed paddock with no fertiliser in Fig 5a when the small differences in the total N input and number of grazing events between the two simulations are accounted for.

(D) Long-term changes in fertiliser N inputs
To examine the long-term effect of changing fertiliser use we ran two 100-year simulations (Figure 8). In the first simulation the cattle-grazed paddock had no fertiliser applied for the first 50 years, then 150 kg of fertiliser N was added each year on September 1st for the next 50 years. The second simulation was the reverse: the paddock received 150 kg of fertiliser N for the first 50 years then no fertiliser applications for the next 50 years. A herd of 75 cattle were grazed according to the schedule in Table 1.



(a) **(b)**

Figure 8. Modelled annual (a) N_2O emission and (b) change in soil C for cattle-grazed farm. In Case I no fertiliser was added in the first 50 years and 150 kg/ha/yr fertiliser nitrogen was added for the following 50 years. In Case II the fertiliser was added for the first 50 years then no fertiliser was applied for the next 50 years. The fertiliser was applied as three applications of 50 kg each year. The total N-input from animal excreta was 348 kg/ha/yr.

For the N_2O emissions, the model suggests that when the fertiliser applications ceased the N_2O emissions dropped, but the level was slightly higher than the level of emission seen where no fertiliser had been applied. The net soil C gains followed a different pattern. In Case I, the rate of soil C gain peaks when the fertiliser treatments begin, then gradually decays to the level seen before the fertiliser was applied. In Case II, the soil C gain is higher while the fertiliser treatments are being received. When the fertiliser treatments stop, there is a soil C loss for about 5 years. The rate of soil C gain then increases slowly, but remains at a lower level than Case I with no fertiliser treatments.

Conclusion

While there is still much scope for fine-tuning NZ-DNDC, it already provides a useful tool for simulating the likely impacts on New Zealand's agricultural greenhouse gas emissions of changes in grazing regimes and fertiliser management. From a series of simulations NZ-DNDC predicted that increasing stock numbers and levels of fertiliser application result in increased soil emissions of N_2O from dairy and sheep grazed pastures. Soil C decreased with increasing stock numbers but increased with higher fertiliser applications.

These results indicate changes in land management can have a dramatic effect on greenhouse gas emissions. Simulated rotational grazing produced N_2O emissions several times as large as those produced using set-stocking at an equivalent level. The level of N_2O emissions also depended on the timing of fertilisation and grazing events. There was also evidence that the soil N_2O emissions and annual soil C gain were affected by historical fertiliser applications.

The NZ-DNDC model could therefore account for emission changes from a number of environmental and management factors that influence greenhouse gas emissions from agricultural soils not currently accounted for by the methodology used to estimate New Zealand's emissions inventory.

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References

Li C, Frolking S, Frolking TA (1992) A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model Structure and Sensitivity. *Journal of Geophysical Research* **97,** 9759-9776.

New Zealand Climate Change Office (2004) National Inventory Report New Zealand 2004: Greenhouse Gas Inventory 1990-2002 (including common reporting format (CRF) for 2002), April 2004.New Zealand Climate Change Office, Wellington, New Zealand. Also online: http://www.climatechange.govt.nz

Saggar S, Andrew RM, Tate KR, Hedley CB, Rodda NJ, Townsend JA (2004) Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems* **68**, 243-255

Tate KR, Scott NA, Saggar S, Giltrap DJ, Baisden WT, Newsome PF, Trotter CM, Wilde RH (2003) Land-use change alters New Zealand's terrestrial carbon budget; uncertainties associated with estimates of soil carbon change between 1990-2000. *Tellus Series B – Chemical and Physical Meteorology* **55**, 364-377