COMPARISON OF APSIM AND NZ-DNDC MODELS WITH PLANT N UPTAKE AND WATER AND NITRATE LEACHING DATA

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Abstract

Two process-based models, APSIM and NZ-DNDC, were compared with measurements over 3 years of drainage, nitrate (NO_3^-) leaching, and plant N-uptake. The data came from experiments with urine addition (1000kgN/ha) in lysimeters under pasture in the Waikato. Two irrigation schedules were applied: low irrigation (rainfall + irrigation ~1100 mm/year), and high irrigation (rainfall + irrigation ~2200 mm/yr).

Total measured drainage ranged from 520±40 mm (2009 low irrigation) to 1580±40 mm (2010 high irrigation). Both models estimated total drainage well (r = 0.93 and 0.87 respectively), although with a slight tendency to underestimation (average relative error –1.1% and –4.3%). The NZ-DNDC model simulated the drainage and leaching to 50 cm depth while APSIM and the measured values were at 70 cm. While this could make some differences to the timing of drainage and leaching, the cumulative values over the year should be minimally affected.

APSIM overestimated pasture N-uptake from early spring to summer, while NZ-DNDC underestimated N-uptake over this period. Over the entire year this resulted in an average relative error of +16% for APSIM and (+75 kg N/ha) –33% in NZ-DNDC (–175 kgN/ha).

Both models predicted similar NO_3-leaching losses in 2008 (APSIM 573 and 689 kg N/ha; NZ-DNDC 527 and 697 kg N/ha for low and high irrigation respectively) compared with measured values of 540±70 kg N/ha (low irrigation) and 620±60 kg N/ha (high irrigation). However, both models overestimated losses in 2009 and 2010. Not accounting for soil NO_3^- adsorption in allophanic soils could be one reason for the models over-estimating NO_3^--leaching losses. Both models were modified to include NO_3^- adsorption. In addition the nitrification rate was increased in APSIM (because of the high soil C) and the plant growth component in NZ-DNDC was re-parameterised to better fit the observed growth. These modifications changed the average relative error from +32% (+150 kg N/ha) to –12% (–59 kg N/ha) for APSIM and from +41% (+190 kg N/ha) to +21% (+100 kg N/ha) in NZ-DNDC.

Although the two models had different methods for simulating soil water, both produced reasonable estimates of total drainage. However, estimation of NO_3-leaching was more challenging as it depends on appropriate representation of other aspects of the N-cycle. Modifications were made to both models that improved the NO_3^--leaching simulations, but there is still room for further improvements.

Introduction

Nitrogen is leached from agricultural soils predominantly in the form of NO_3^-. Such losses not only represent an economic loss to farmers, but can also lead to eutrophication of waterways. Urine patches represent areas of high leaching risk as a large quantity of N is deposited onto a comparatively small area. However, the actual amount of N from a urine patch that is leached from the soil will depend both on the soil properties and the quantity and timing of water applied (either as rainfall or irrigation). Being able to assess accurately the risk of NO_3^--leaching would be of use both to farmers and policy-makers.

Process-based models attempt to simulate the underlying processes of a given phenomenon, and can therefore be used as tools for testing our understanding of these processes as well as extrapolating the observations of the phenomenon. If a process-based model performs well over the range of possible circumstances, it can then be used either directly or via simplified tools to estimate effects at farm or regional scale.

In this study we compared the models APSIM (Keating et al. 2003) and NZ-DNDC (Li et al. 1992; Saggar et al. 2004, 2007) with drainage, NO_3^--leaching, plant growth and N-uptake data collected over three years as part of the Pastoral 21 Environment Programme (funded by the Ministry for Primary Industries). Both models simulate the soil and plant processes occurring in agricultural systems including hydrology, plant growth, carbon cycling and N-transformations. These models have previously been compared with respect to nitrification and denitrification rates (Vogeler et al. 2013) and with measured N_2O emissions, soil moisture, and surface soil NH_4^+ and NO_3^- concentrations (unpublished data).

Methodology

Field experiment

The measured data were obtained from lysimeter studies conducted in three consecutive years: 2008/09, 2009/10 and 2010/11. Intact soil monolith lysimeters (50 cm diameter by 70 cm deep) were collected from a Horotiu silt loam in the Waikato region. The lysimeters were extracted using the method described by Menneer et al. (2008). Four replicates were used for each treatment in each year, with the same lysimeters being used for the first and third years.

The pastures was a permanent mixture of predominately perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) and had been under a regular cutting regime for at least 4 months before collection of the lysimeters to avoid the influence of excreta inputs. Before the urine application the grass was cut down to 3.5 cm height; subsequently 8–12 other cuts were made throughout the experiment, which started in May of each year and ran for one year.

Dairy cow urine was collected from dairy heifers and urea-N was added to adjust the final total N concentration to 10.0 g/l. This was then applied to the lysimeters in a single application at an equivalent rate of 1000 kg N/ha in late May to simulate a dairy cow urine deposition.

Irrigation was applied at regular intervals to supplement rainfall so that the lysimeters received enough water to avoid stress during the period of the experiment. Two precipitation regimes were imposed on the lysimeters: annual average and twice the amount for the experimental site, based on the 30-year long-term average for the site in the Waikato region. If necessary, simulated rainfall was applied regularly and in small doses to the appropriate lysimeters as spray irrigation to meet the targeted annual rainfall regime.

Leachate was collected at regular intervals, the amount of drainage was calculated and samples were analysed for ammonium and nitrate concentrations. Further experimental details are described in Shepherd (2010).

Model Descriptions

APSIM

APSIM (Agricultural Production systems SIMulator) consists of a number of biophysical modules to simulate the different biological and physical processes occurring in farming systems (Keating et al. 2003). The relevant modules used in the simulations for this work were: soilN and SurfaceOM modules (for calculating soil C and N dynamics), SWIM2 (Verburg et al. 1996) for the soil water dynamics (based on Richard's equation) and solute transport (based on the convection dispersion equation), and AgPasture (Li et al. 2011) to describe the plant growth. APSIM version 7.5 was used. The model operates on a daily time step, with weather data and management as the main inputs.

Climate data were obtained from the Virtual Climate Station database of NIWA for the Ruakura station (www.cliflo.niwa.co.nz), and the detailed management of the experiments (irrigation, fertiliser applications, and pasture cuttings) was described using the APSIM manager module. Key soil properties for the setup of the APSIM simulations are given in Table 1.

Table 1: Key properties of the Horotiu soil with bulk density (ρ), volumetric water content (100 cm) at saturation (θ_s), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}), saturated hydraulic conductivity (K_{sat}), and organic carbon (OC)

Soil Depth [m]	Sand [%]	Silt [%]	Clay [%]	ρ [Mg/m^3]	θ_s [m^3/m^3]	θ_{FC} [m^3/m^3]	θ_{PWP} [m^3/m^3]	K_{sat} [m/h]	OC [%]
0.00–0.20	47	33	20	0.88	0.59	0.42	0.22	0.129	8.0
0.20–0.40	64	17	19	0.85	0.62	0.36	0.18	1.234	1.9
0.40–0.53	76	13	11	1.03	0.56	0.33	0.18	1.638	0.9
0.53–0.67	84	10	6	1.11	0.52	0.31	0.17	2.309	0.4
0.67–0.75	87	8	5	1.11	0.52	0.21	0.08	6.225	0.1

NZ-DNDC

The DNDC (DeNitrification DeComposition) model was originally developed to simulate greenhouse gas fluxes from cropping soils (Li et al. 1992). It has since been adapted for many different systems in a large number of countries (Giltrap et al. 2010a). NZ-DNDC refers to the model specifically adapted to New Zealand's grazed pasture systems (Saggar et al. 2004, 2007). NZ-DNDC was based on DNDC version 8.6K.

NZ-DNDC simulates soil thermal-hydraulic, plant growth, decomposition, and N-transformations. The time-step is daily except immediately following a rainfall event when the model slows down to hourly time-steps to calculate denitrification. Soil moisture uses a 1-dimensional "tipping bucket" model. Nitrification and denitrification rates are calculated based on simulated nitrifier and denitrifier pools and soil anaerobic volume fraction.

Table 2 shows the soil parameter values used to initialise the NZ-DNDC model.

Table 2: Soil parameter values for NZ-DNDC

Parameter	Value
Bulk density (g/cm^3)	0.865
Clay content	17.6%
pH	6
SOC at surface (kg/kg)	0.054
Ratio Litter/Humus/Humads	0.025/0.025/0.95
Initial NO_3^- at surface (mg N/kg)	1.06
Initial NH_4^+ at surface (mg N/kg)	5.6
Field capacity WFPS	0.76
Wilting point WFPS	0.28

Input for daily weather data included maximum and minimum temperature, rainfall and solar radiation. The simulations were started on 31 March each year. Urine application was simulated as 1000 kg N/ha urea application with 10mm water. However, Giltrap et al. (2010b) found it necessary to increase the NH_3 volatilisation rate when simulating urine patches and so the higher volatilisation rate was also used here.

Note that NZ-DNDC only simulated down to 50 cm, whereas the experimental data were from 70 cm depth. This is likely to affect the timing of apparent leaching and drainage events in the NZ-DNDC model. However, this should have less effect on the cumulative totals.

Data Analysis

Cumulative plots for drainage (Figure 1), NO_3^- leached (Figure 2), and (above ground) plant N (Figure 3) were plotted for the two models and the field data. The plant N values for APSIM and the field data were based on the plant N removed at cutting events. For NZ-DNDC it was calculated based on the daily plant N growth rate allocated to the above ground components. The reason for this difference was because cutting events in NZ-DNDC specify the amount of plant C to remove rather than the amount to leave standing.

A number of metrics were used to assess the models “goodness of fit”. These metrics were applied to the total drainage, leaching, and uptake values rather than the daily data. The metrics were: root mean square error (RMSE), Pearson correlation coefficient (r), relative error (RE), and Nash-Sutcliffe Efficiency (NSE). The RMSE is a measure of the magnitude of the model error (in units of the measured value). r measures the correlation between the measured and modelled results. We defined the RE as the difference between the means of the modelled and measured results relative to the mean measured result (so RE will be negative if the model tends to underestimate), therefore RE is a measure of bias. The NSE compares the mean square error of the model with the variance of the data. For positive NSE values this can be interpreted as the fraction of the variation explained by the model. A description of NSE is given in Legates and McCabe (1999).

A good fit between model and data would have values for RMSE and RE approaching zero. For r and NSE the best possible value is one. In both cases negative values are also possible. For r a negative value implies a negative correlation. For NSE a negative value means the model produces larger errors than would be obtained by simply using the mean of the data.

Results and Discussion

Figures 1 (a)–(d) show the measured and modelled drainages for the two treatments and three years on a daily cumulative and total basis respectively. Despite having different methods for calculating the water movement through soil both models produced similar results that agreed well with the measured data.

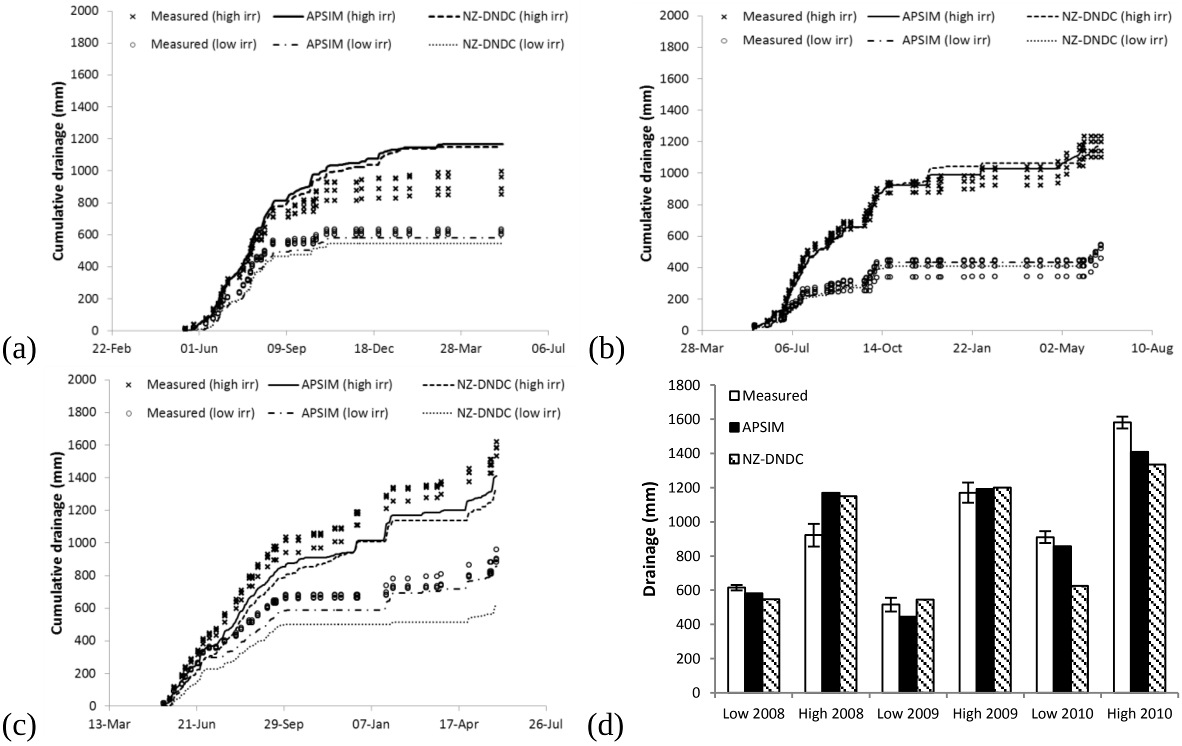

Figure 1: Measured and modelled (a) 2008 daily cumulative drainage, (b) 2009 daily cumulative drainage, (c) 2010 daily cumulative drainage, and (d) total drainage by year and irrigation treatment.

Figures 2(a)–(d) show the measured and modelled NO_3^- leaching for the two treatments and three years on a daily cumulative and total basis respectively. Although the models simulate the NO_3^- leaching in 2008 reasonably well, both models overestimate the leaching in 2009 and 2010. The models estimated the drainage well in 2009 and underestimated it in 2010, so the overestimation of NO_3^- leaching does not seem to be due to the water transport in the models. Instead the N-transformations and transport are more likely to be the cause.

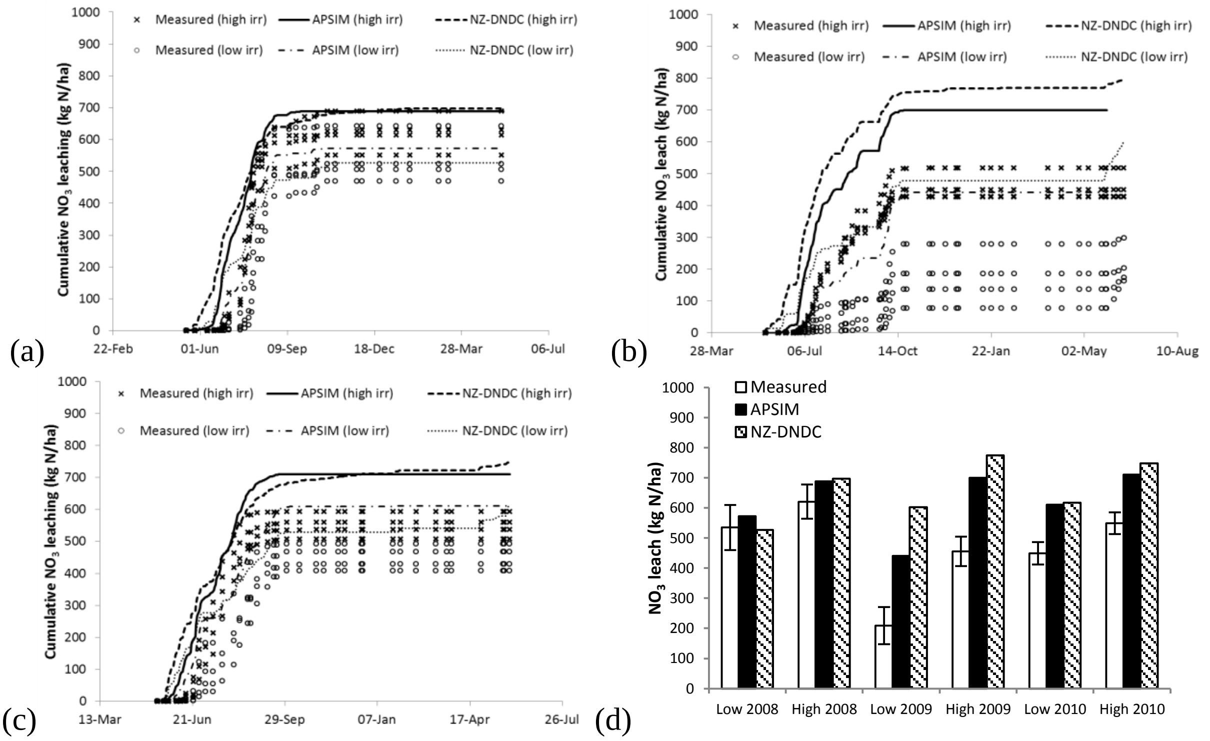

Figure 2: Measured and modelled (a) 2008 daily cumulative NO_3^- leaching, (b) 2009 daily cumulative NO_3^- leaching, (c) 2010 daily cumulative NO_3^- leaching, and (d) total NO_3^- leaching by year and irrigation treatment.

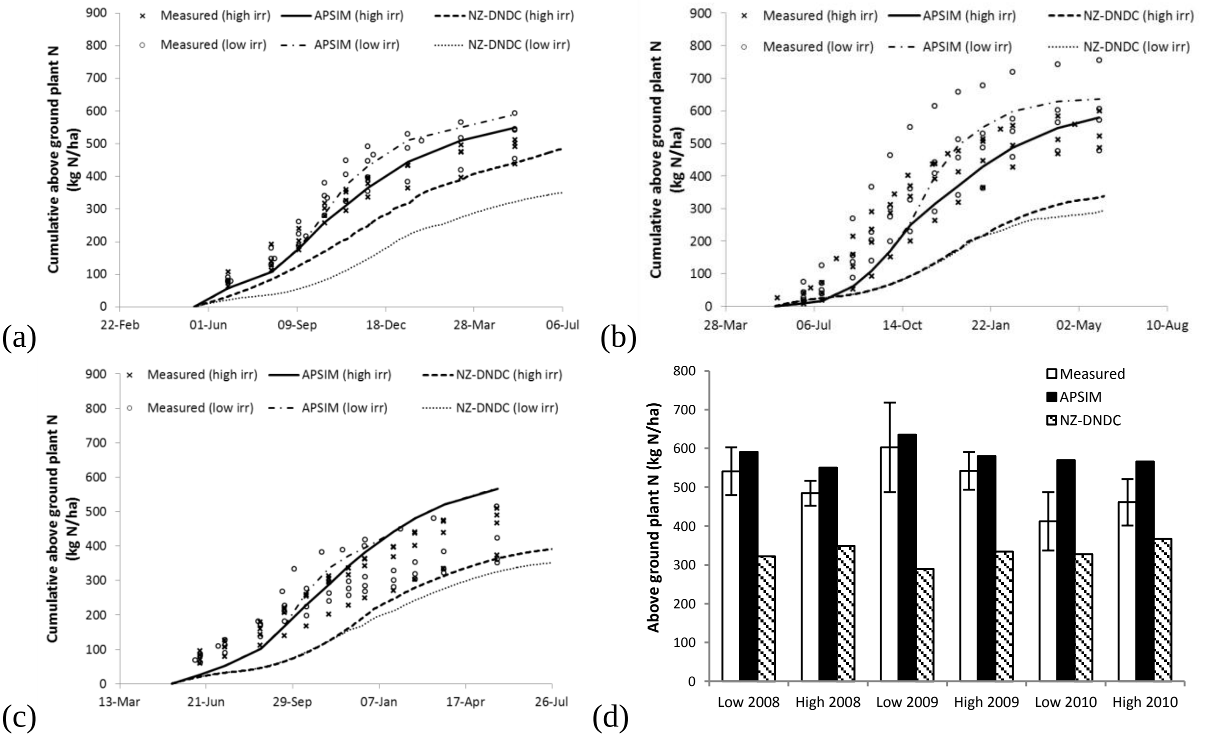

Figure 3: Measured and modelled (a) 2008 daily cumulative above ground plant N, (b) 2009 daily cumulative above ground plant N, (c) 2010 daily cumulative above ground plant N, and (d) total above ground plant N by year and irrigation treatment. Note that for NZ-DNDC the plant N is based on plant N uptake allocated to the above ground components whereas for APSIM and the measured values plant N is the N removed by cutting.

Figures 3(a)–(d) show the measured and modelled (above ground) plant N uptake for the two treatments and three years on a daily cumulative and total basis respectively. APSIM generally simulates the above ground plant N uptake well, although with a slight tendency towards over-estimation. NZ-DNDC consistently underestimated plant N uptake.

Table 2: Goodness-of-fit statistics for APSIM and NZ-DNDC simulations compared to measured annual totals

	APSIM				**NZ-DNDC**			
	RMSE	**r**	**RE (%)**	**NSE**	**RMSE**	**R**	**RE (%)**	**NSE**
Drainage	129 mm	0.93	-1.0	0.87	183 mm	0.87	-5.5	0.73
NO_3^- leach	169 kg N/ha	0.81	32	-0.68	234 kg N/ha	0.27	41	-2.24
Plant N	87 kg N/ha	0.80	15	-0.95	193 kg N/ha	-0.66	-35	-8.63

Table 2 shows the goodness-of-fit statistics for the two models based on the annual totals. These confirm the observations from Figures 1(a)–(d) that both models do a reasonably good job of estimating the total drainage.

Although both models had negative NSEs for NO_3^- leaching, due to over-estimation of leaching losses, APSIM had a reasonably high *r* value compared with NZ-DNDC. As the total drainage was generally well simulated, the problem must be related either to the estimation of the amount of NO_3^- available for leaching or to NO_3^- transport.

For above-ground plant N both models also had negative NSE values. However, APSIM values correlated reasonably well, but tended to overestimate emissions. NZ-DNDC consistently underestimated plant N. The NZ-DNDC plant N value was based on plant N uptake rather than removal (as was measured), which should, if anything, lead to an overestimate of plant N. In addition, it predicted the incorrect trend with respect to high and low irrigation, leading to a negative correlation coefficient. For NZ-DNDC the under-estimation of plant N uptake could partially explain the over-estimation of NO_3^- leaching, but not for APSIM.

The Horotiu soil is allophanic and has been observed to have some capacity to adsorb NO_3^- ions (Holland & During 1977). This process would reduce the amount of NO_3^- leached, but had not been included in either of the models. Therefore the models were modified to allow for some adsorption of some NO_3^- using a linear adsorption model with a coefficient of 0.1 in the top 0-15 cm, 0.25 from 15-40 cm and 0.95 from 40-60 cm. In addition, the plant growth equation in NZ-DNDC was re-parameterised to fit the observed growth data.

In APSIM, the nitrification rate was increased to account for the high SOC levels. This change was not incorporated into NZ-DNDC as Inubushi et al. (2005) found that the microbial biomass carbon as a fraction of SOC in andisols is lower than in non-andisols. As NZ-DNDC uses a fixed fraction of SOC to calculate microbial biomass carbon (which affects nitrification and denitrification rates), microbial activity is likely to be overestimated if anything.

Figures 4-6 and Table 3 show the daily cumulative and total drainage, NO_3^- leaching and above ground plant N uptake as well as the goodness-of-fit statistics using the modified models.

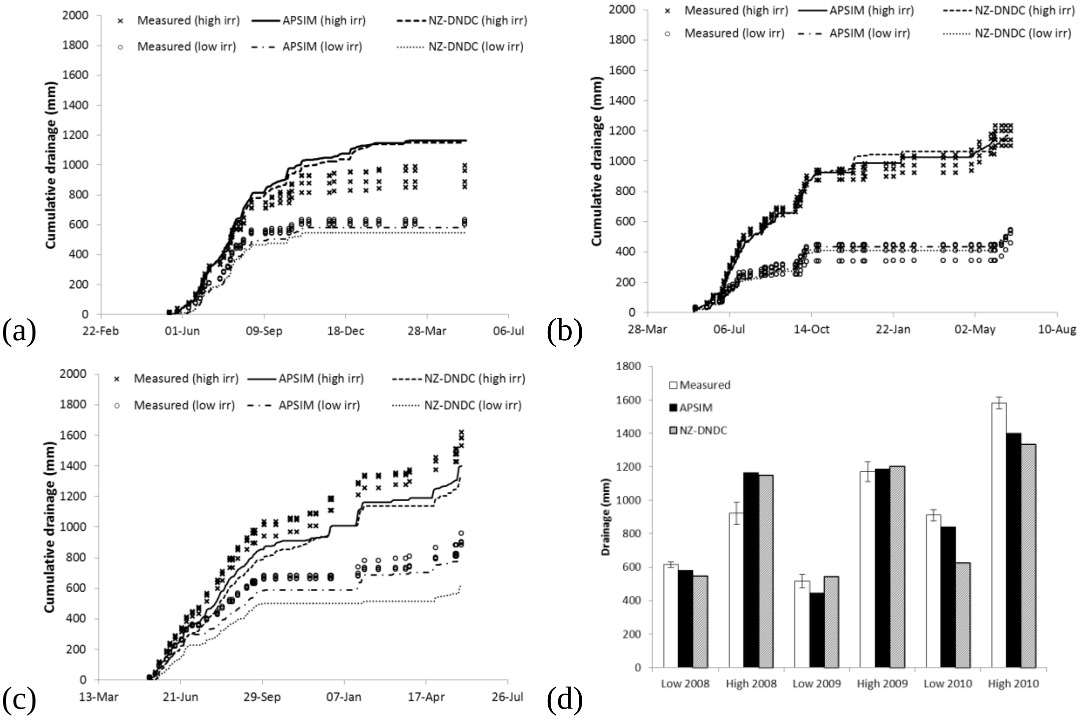

Figure 4: Measured and modelled (a) 2008 daily cumulative drainage, (b) 2009 daily cumulative drainage, (c) 2010 daily cumulative drainage, and (d) total drainage by year and irrigation treatment using modified APSIM and NZ-DNDC models.

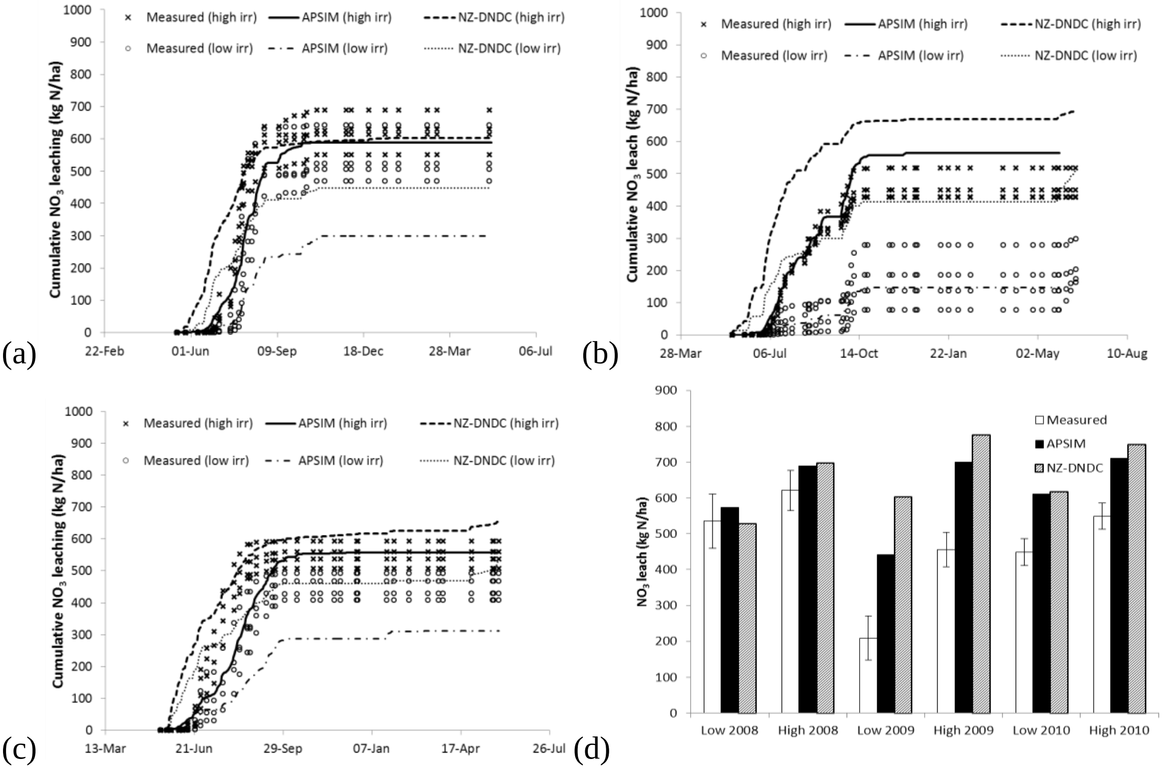

Figure 5: Measured and modelled (a) 2008 daily cumulative NO_3^- leaching, (b) 2009 daily cumulative NO_3^- leaching, (c) 2010 daily cumulative NO_3^- leaching, and (d) total NO_3^- leached by year and irrigation treatment using modified APSIM and NZ-DNDC models.

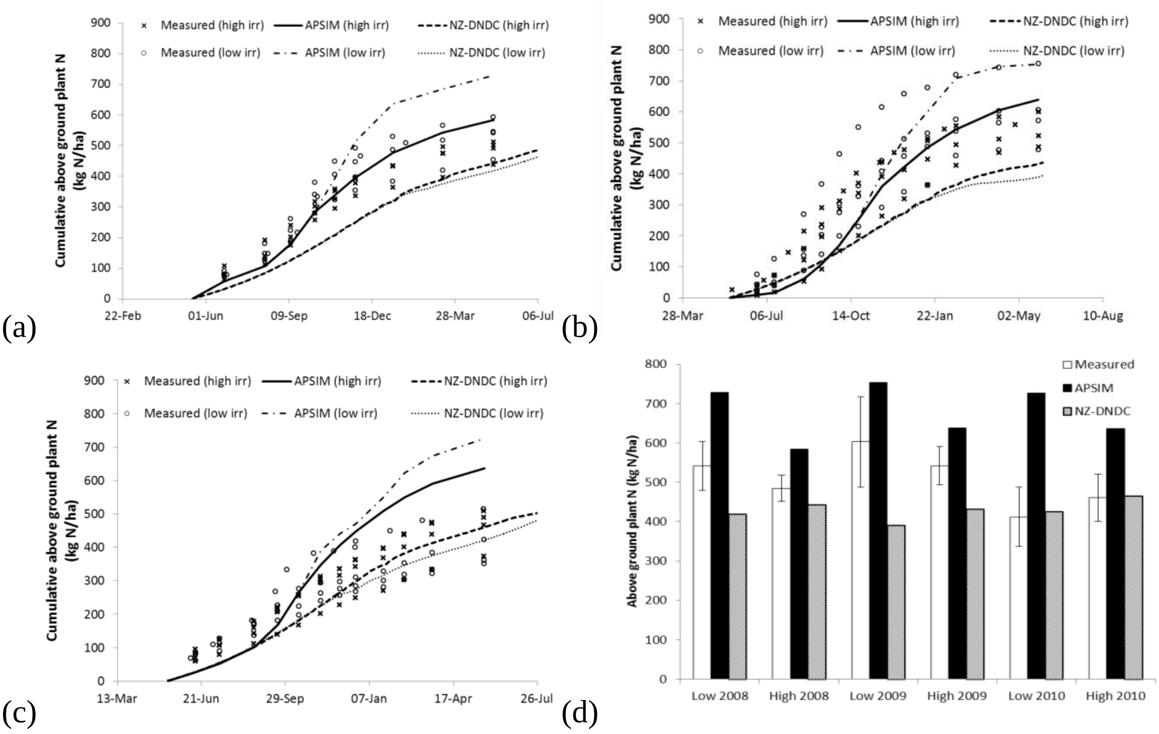

Figure 6: Measured and modelled (a) 2008 cumulative above ground plant N, (b) 2009 cumulative above ground plant N, (c) 2010 cumulative above ground plant N, and (d) total above ground plant N by year and irrigation treatment using modified APSIM and NZ-DNDC models. Note that for NZ-DNDC the plant N is based on plant N uptake allocated to the above ground components, whereas for APSIM and the measured values, plant N is the N removed by cutting.

The modifications had very little effect on the simulated drainage (Figure 4), but the overall the NO_3^- leaching simulation improved in both models (although *r* decreased slightly for APSIM) (Table 3). In 2008 and 2010, NZ-DNDC total NO_3^- leached was within the measured range for both irrigation regimes while APSIM underestimated the leaching from the low irrigation treatment. In 2009 APSIM simulated close to the total NO_3^- leaching for both irrigation treatments while NZ-DNDC overestimated both (Figure 5). The modifications improved the simulated plant uptake in NZ-DNDC although it was still underestimated in some years (Figure 6). NZ-DNDC uses a constant C/N ratio for plant biomass, rather than allowing the N content to vary as observed in the field. The poor model fit for plant N may be a consequence of this.

Table 3: Goodness-of-fit statistics for modified APSIM and NZ-DNDC simulations compared to measured annual totals

	APSIM				**NZ-DNDC**			
	RMSE	**r**	**RE (%)**	**NSE**	**RMSE**	**r**	**RE (%)**	**NSE**
Drainage	131 mm	0.93	–1.7	0.86	183 mm	0.87	-5.5	0.73
NO_3^- leach	123 kg N/ha	0.76	–12	0.11	167 kg N/ha	0.28	+22	–0.64
Plant N	186 kg N/ha	0.30	+34	–7.94	112 kg N/ha	–0.66	-15	–2.22

Both models improved NO_3^- leaching in terms of NSE and RMSE. The NSE for the modified APSIM became positive for leaching indicating that the model had some explanatory power, but the simulation of the above ground plant N got worse. NZ-DNDC improved both NO_3^- leaching and above ground plant N, although both still had negative NSE values meaning that the model did not explain the observed variability well.

Conclusions

Both models simulated the water drainage well, despite having quite different methods for calculating water transport. However, this did not translate directly into reliable estimates of NO_3^- leaching.

Simulating the N-cycle is difficult due to the large number of interacting processes involved. NO_3^- adsorption was identified as a process that could be important in allophanic soils, but is not typically accounted for in the models. Adding NO_3^- adsorption (along with increased nitrification in APSIM and re-parameterising plant growth in NZ-DNDC) resulted in better goodness of fit statistics for NO_3^- leaching simulations in both models. However, for APSIM this caused a worsening of the fit for plant N. The goodness of fit statistics for NZ-DNDC improved for both above-ground plant N uptake and NO_3^- leaching, although the negative NSE values indicated the model fit was still poor. This suggests the descriptions of some processes still need to be improved in both models. For NZ-DNDC, allowing the plant C/N ratio to vary is one possible improvement.

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