SOIL NITROGEN AND SOIL WATER DYNAMICS IN CROP ROTATIONS: ESTIMATION WITH THE MULTIPLE CROP SINGLE PURPOSE MODEL

Edith N. Khaembah, Hamish Brown, Joanna Sharp and Rob Zyskowski

The New Zealand Institute for Plant & Food Research Ltd
Private Bag 4704, Christchurch, 8140, New Zealand
Email: Edith.Khaembah@plantandfood.co.nz

Abstract
The objective of this study was to evaluate the Multiple Crop Single Purpose model (MCSP) in the Agricultural Production Systems sIMulator (APSIM) for its dynamic estimation of soil water, soil mineral nitrogen (N) and nitrate leaching of crop rotations. MCSP is an APSIM crop module that allows the simulation of multiple crop types. It is based on the mechanisms and coefficients of the OVERSEER® crop model and is intended for the single purpose of estimating the water and N uptake of crops grown in rotations in New Zealand.

Independent data for evaluation were from a 2004–07 field trial involving two crop sequences; (i) potatoes → winter fallow → peas → potatoes and (ii) potatoes → autumn wheat → potatoes. The trial also included two irrigation and three N treatments. Measurements of soil water, soil mineral N and nitrate leaching were made at specified times during the trial. Nitrate leachate solutions were sampled at a depth 60 cm under the first potato crop and at 150 cm depth for the rest of the trial period. The output variables used for model evaluation were soil water and soil mineral N concentration in the whole 150 cm profile, and nitrate leached out of the top 60 cm of the soil profile (for the first potato crop) and the whole 150 cm profile for the rest of the trial period.

Prediction of total soil water content was accurate, as indicated by the low relative root mean square error (RMSE) of 9% and nil bias in the estimation. The model explained 57 and 67% of the variation in the measured data for soil mineral N and nitrate leaching, respectively. These results indicate that, overall, there was good agreement between simulated and measured data. This demonstrates that MCSP, in the APSIM framework, can be used to simulate nitrate leaching in crops grown in rotations in New Zealand.

Key words: Multiple Crop Single Purpose model**,** APSIM, nitrate leaching, crop rotation

Introduction
Present intensive agricultural practices are associated with high inputs of inorganic nitrogen (N) fertiliser, often in excess of the crop's N requirements. Unused N is subject to loss, mostly as nitrate-N which easily leaches out of the soil profile and into groundwater. Nitrate leaching is a major environmental issue, and many central and local governments have formulated environmental policies to protect water systems from nitrate contamination. In August 2014, the New Zealand government released the National Policy Statement for Fresh Water Management (Anon, 2014) which requires regional authorities to control loads of contaminants discharged into water systems. To enforce this policy, regional authorities require reliable monitoring of nitrate flow through farm systems and estimation of the risk of

its loss via leaching. One approach is to measure leaching under field conditions, but this can be challenging, prohibitively time-consuming and costly. An alternative approach is to estimate nitrate leaching using computer simulation models.

The Agricultural Production Systems sIMulator (APSIM) is one of the dynamic simulation models frequently used to assess the environmental impacts of of agricultural activities (Stewart et al, 2006, Stone & Heinemann 2012, Biggs et al, 2013, Vogeler et al, 2013). A key feature of APSIM is its daily time-step nutrient and soil water modules which allow continuous simulation of changes in the N and water status of the soil in response to weather, management and crop uptake (Holzworth et al, 2014; Probert et al, 1998). The most recent generic crop template, the Plant Modelling Framework (PMF), enables crop models to be established at different levels of complexity (Brown et al, 2014). This paper briefly describes a new generic crop model, the Multiple Crop Single Purpose model (MCSP) implemented in PMF and assesses its predictive quality using experimental data.

Methods

Multiple Crop Single Purpose model

The Multiple Crop Single Purpose (MCSP) model is an implementation of the mechanisms and coefficients of the OVERSEER® cropping model (Chicota et al, 2010) in the PMF. MCSP in APSIM (MCSP-APSIM) maintains the user-specified yield function of OVERSEER® but includes modifications to the tissue N concentration so the crop can respond to N and water stress. MCSP-APSIM is intended for the single purpose of estimating the water and N uptake of crops grown in rotation in New Zealand.

Data for testing MCSP

Independent data for testing MCSP-APSIM were from a crop rotation field experiment conducted at Lincoln, Canterbury from October 2004 to March 2007 (Francis et al, 2006 and 2007). The soil at the site is deep well-drained Templeton silt loam with available water-holding capacity of about 190 mm/m of depth (Jamieson et al, 1995). The trial evaluated two crop sequences; (i) potatoes → winter fallow → spring peas → potatoes and (ii) potatoes → autumn wheat → potatoes. Two irrigation treatments (W1 = optimum and W2 = excess) and three N fertiliser rates (N0 = nil, N1 = optimum, N2 = excess) were also evaluated (see Francis et al, 2006 for details). Measurements included soil mineral N, soil water content and leachate nitrate concentrations at different times during the trial period. Crop yield and crop N uptake were measured at harvest. Soil for mineral N analysis was sampled at 30 cm intervals from the soil surface to 150 cm depth. Time domain reflectometry (TDR) was used to measure soil water in the top layer (0–30 cm). Soil measurements in other layers were made with a neutron probe, with tubes installed to a depth of 150 cm. Leachate was sampled at 60 cm depth under the first potato crop and at 150 cm depth for the rest of the trial period. Leachate was sampled only once under the pea and wheat crops due to low rainfall during this period.

Initialisation of the soil in MCSP and assumptions

The soil water module SoilWat was used. Initial values of the bulk density for each layer were obtained from data collected at the start of the experiment. In APSIM, the water and solutes present in the soil layer and water and solutes entering that layer are assumed to be fully mixed (i.e. 100% efficiency). In this study, an efficiency factor of 0.9 was selected because it gave the best fit for nitrate leaching for most of the simulations. Concern about incomplete mixing between resident and incoming/draining soil water fractions has been raised in previous studies (Sharp et al., 2011; Van der Laan et al, 2013). To reduce uncertainty around drainage estimates, nitrate leaching was calculated using the soil solution nitrate concentration of sampled leachate and the drainage calculated by MCSP-APSIM. Using the user-defined function in MCSP-APSIM, crop yields were adjusted to ensure the N uptake in the model matched measured N uptake.

Model evaluation

The statistical evaluation of MCSP-APSIM focused on soil water, soil mineral N and nitrate leaching measured on sampling dates. The agreement between observed and predicted measurement were evaluated using three statistical criteria (Gauch et al, 2003; Kobayashi & Salam, 2000).

(i) Root mean square error (RMSE) and its proportion compared with the observed mean (RMSE %):

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}(Oi - Pi)^2\right)}; \qquad \mathrm{RMSE\%} = \left(\frac{\mathrm{RMSE}}{\bar{\mathrm{O}}}\right) \text{ x } 100$$

Where n is the number of observations, Oi is the observed value, $\bar{\mathrm{O}}$ is the mean of the observed values, and Pi is the value predicted by the model.

(ii) Squared bias (SB)

$$\mathrm{SB} = (\bar{O} - \bar{P})^2 / \frac{1}{n}\sum(Oi - Pi)^2$$

Where $\bar{O}$ and $\bar{P}$ are the means of the observed and predicted values, respectively.

Results and discussion

Soil water dynamics

Temporal changes in total soil water in the profile for four representative treatments (Fig.1) indicate that MCSP-APSIM captured the general trends and produced good estimates of total soil water in the profile during the trial period. Overall, the difference between the observed and predicted means (~0.3%) and the bias in the data (Fig. 2a) were negligible. The good fit for soil water content was also reflected by a low RMSE (8.9%), indicating that the simulated data explained the majority of the variation in the observed data. Volumetric water content over time for different layers of the profile illustrated for one treatment (Fig. 3) also showed mostly similar trends for the measured and MCSP-APSIM predicted data. The satisfactory prediction of soil water dynamics illustrated here is important for the confidence in the ability of MCSP-APSIM to simulate nitrate leaching. This is because the ability of the model to accurately predict nitrate leaching in the soil partly depends on adequate simulation soil water dynamics.

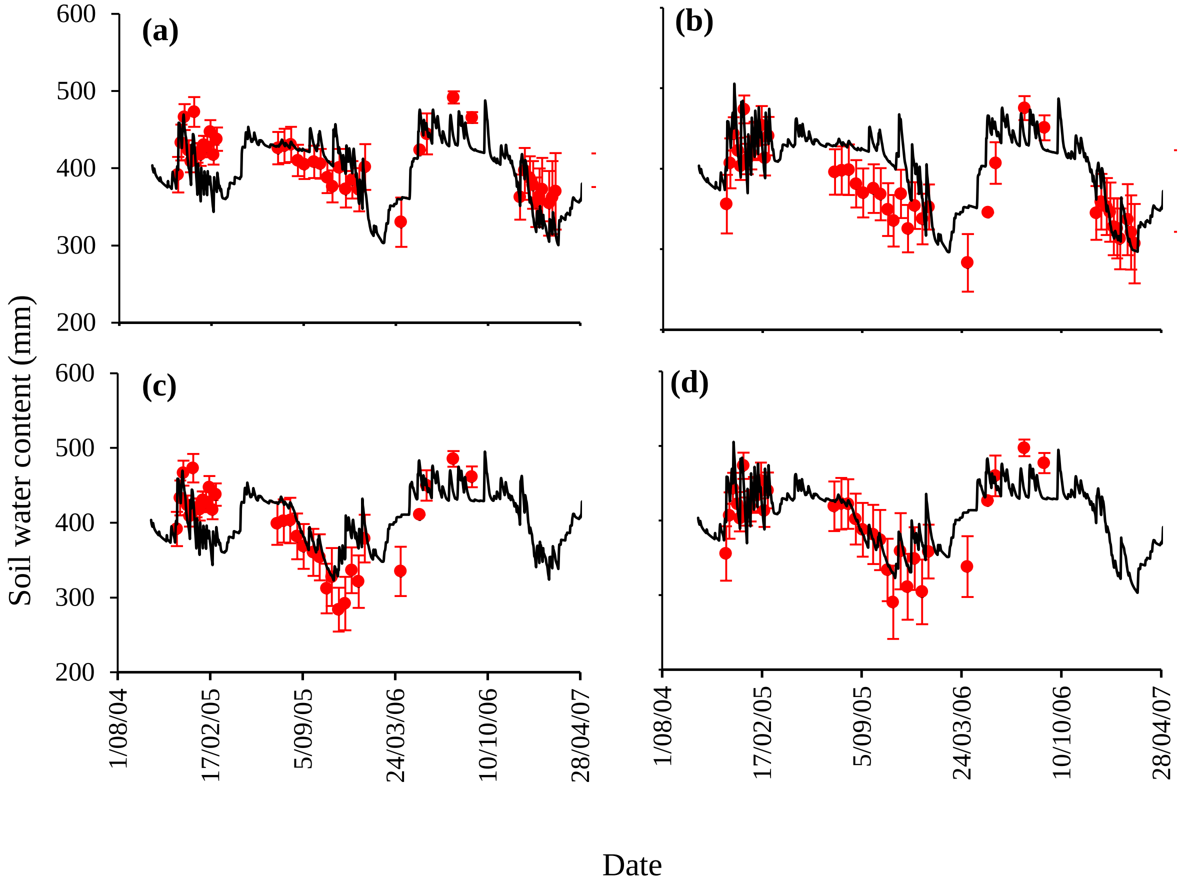

Figure 1: Measured (symbols (mean ± SD)) and predicted (lines) soil water content in the profile (0–150 cm depth) over time for four crop rotations. (a) Sequence 1: W1 N1 treatment, (b) Sequence 1: W2 N1 treatment, (c) Sequence 2: W1 N1 treatment and (d) Sequence 2: W2 N1treatment.

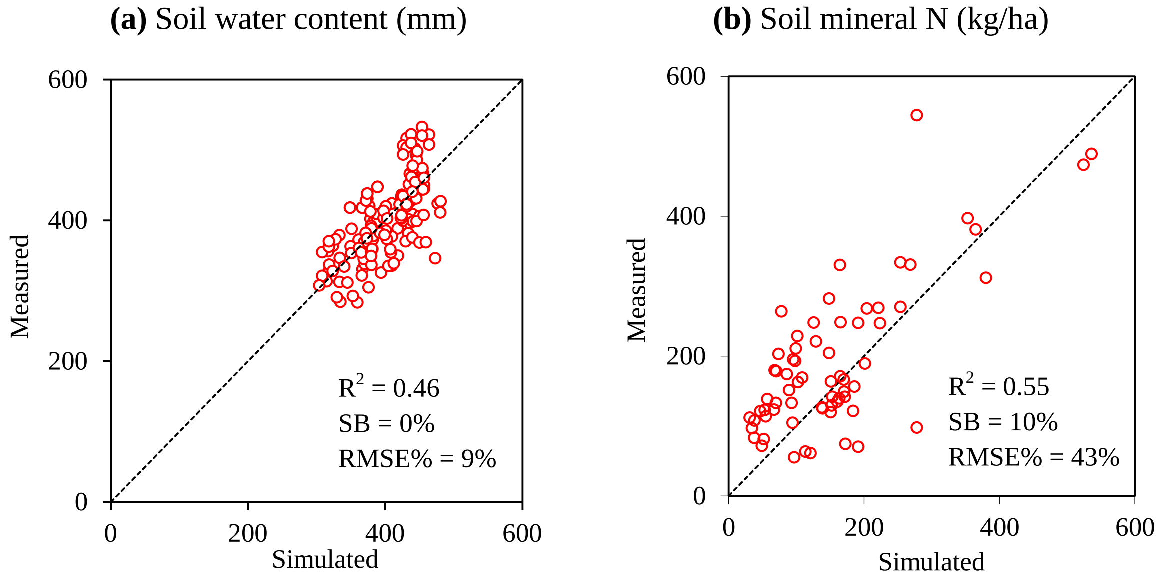

Figure 2: Measured versus simulated values of (a) soil water and (b) soil N content in the profile in relation to the 1 : 1 reference line (dotted).

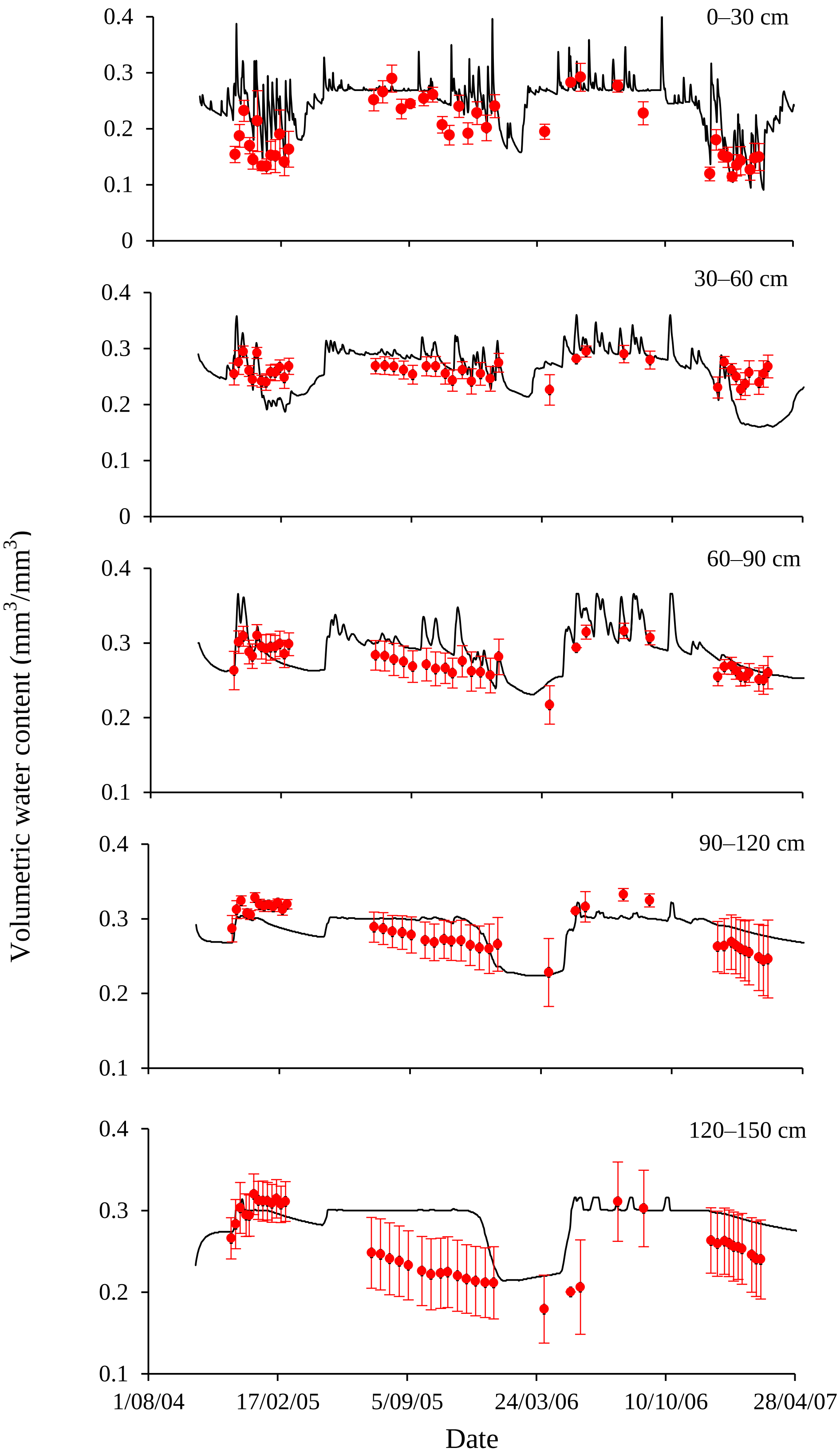

Figure 3: Temporal changes in measured (symbols (mean ± SD)) and simulated (lines) volumetric soil water at different soil depths for sequence 1 (N1 & W1) treatment.

Profile soil N

Total soil mineral N in the profile for four treatments is represented in Fig. 4. Except for the first two measurements, predicted soil mineral N concentrations followed the same trend as measured values. Analysis of all treatments collectively indicated the model under-predicted soil mineral N in the profile (SB = 10%). Simulated data explained 57% of the variation in the measured data (Fig. 2b). This is satisfactory but less accurate compared with profile soil water prediction probably because of the substantial spatial variation in the soil N measurements as displayed in Fig. 4.

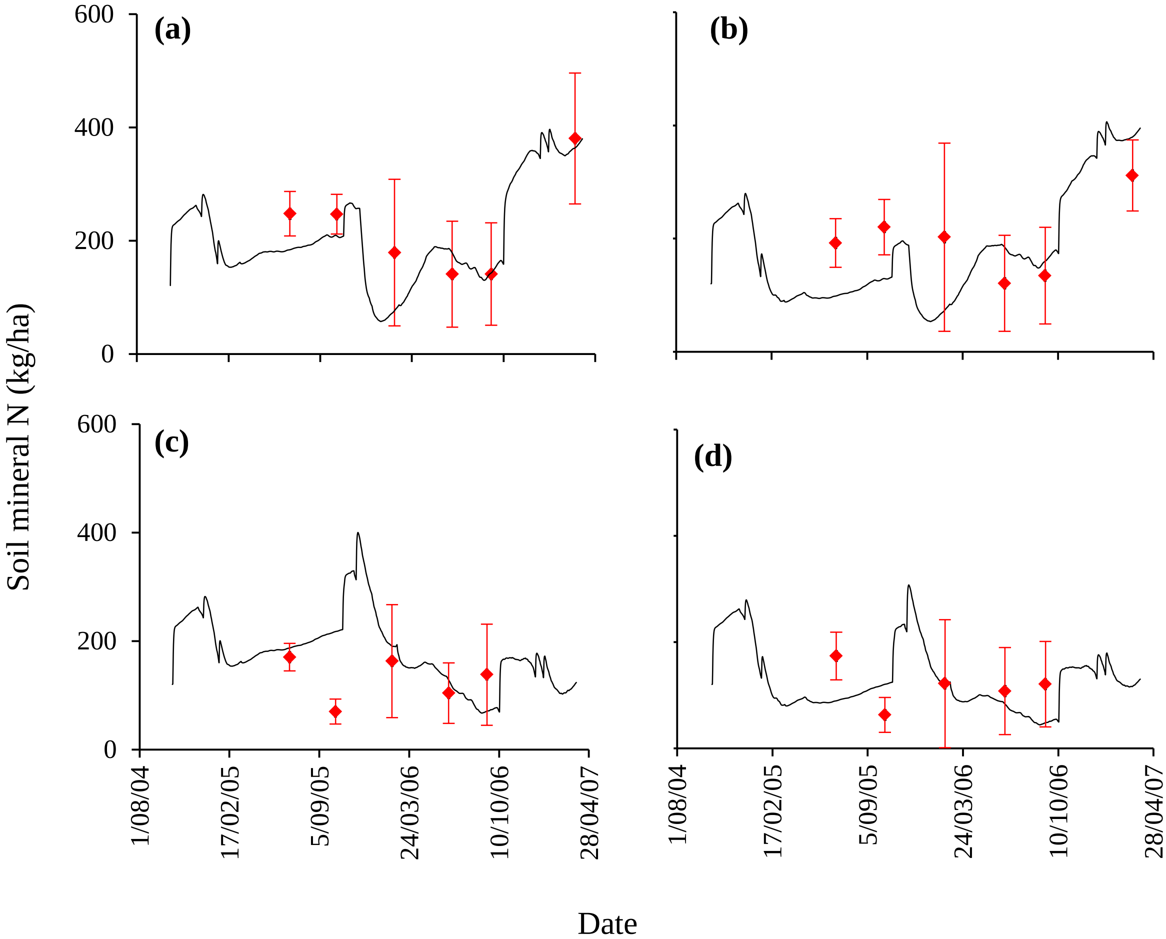

Figure 4: Observed (symbols (mean ± SD)) and predicted (lines) soil N concentrations in the profile (0–150 cm depth) over time for four crop rotation treatments. (a) Sequence 1: W1 N1 treatment, (b) Sequence 1: W2 N1 treatment, (c) Sequence 2: W1 N1 treatment and (d) Sequence 2: W2 N1treatment.

Nitrate leaching

Results of the four treatments representing optimum N fertiliser rate and two irrigation treatment rates (Fig. 5) indicate that predicted nitrate leaching followed the same trend as calculated values. On average, the model over-estimated nitrate leaching by 7.2 kg/ha (9%). The bias in the data was 8% and the simulated data accounted for 67% of the variation in the data (Fig. 6). There was wide variation in the measured leaching data for the first potato crop. This was possibly influenced by the model's inability to account for variability in the soil N status as a result of moulding. Overall, predicted leaching followed the same trend as measured values and MCSP-APSIM's response to irrigation treatment was adequate.

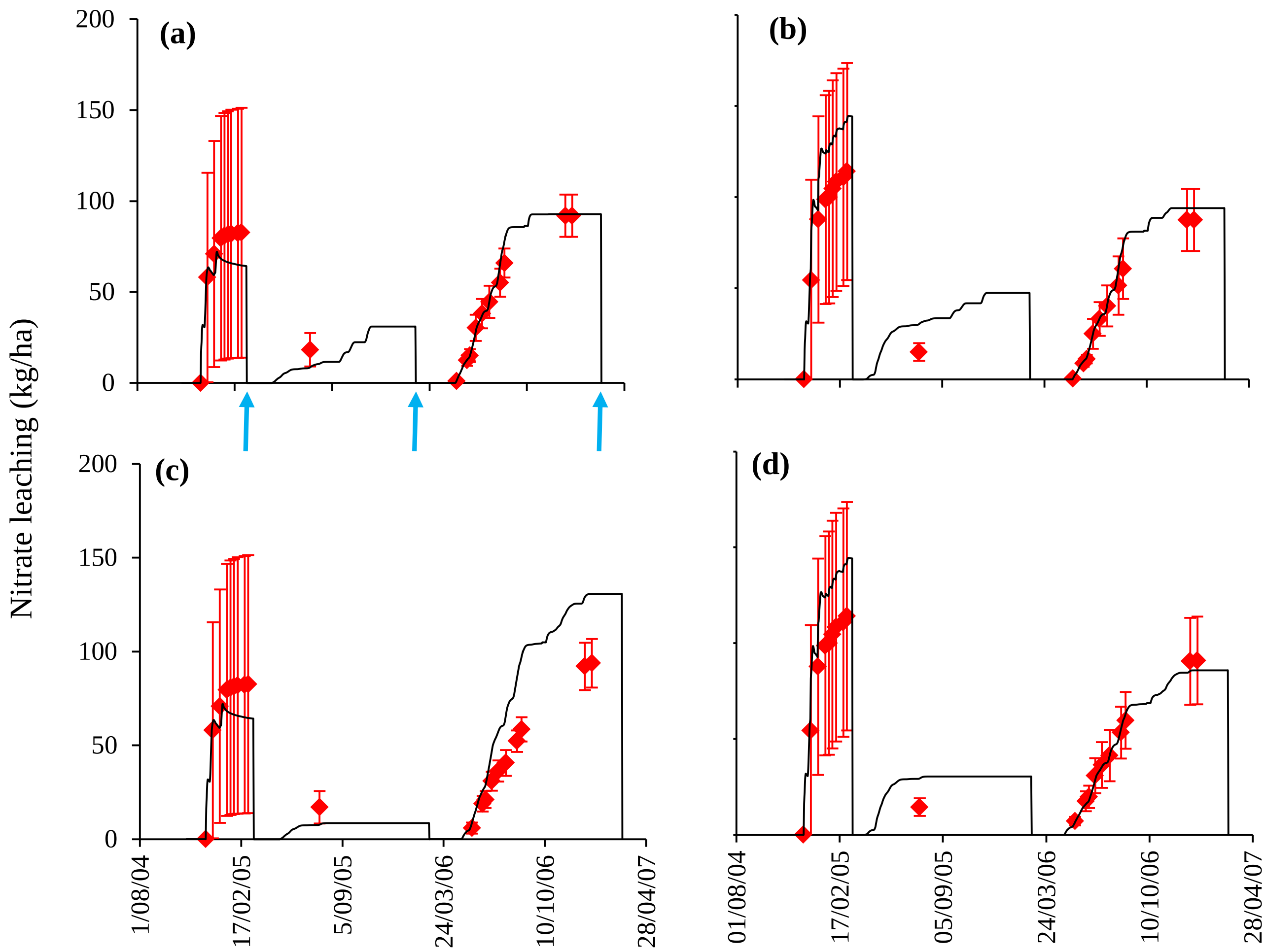

Figure 5: Cumulative nitrate leaching comparisons between calculated (symbols with associated SD bars) and simulated (lines) during the cropping season of four treatments. (a) Sequence 1: W1 N1 treatment, (b) Sequence 1: W2 N1 treatment, (c) Sequence 2: W1 N1 treatment and (d) Sequence 2: W2 N1treatment. Arrows indicate the time of crop harvest.

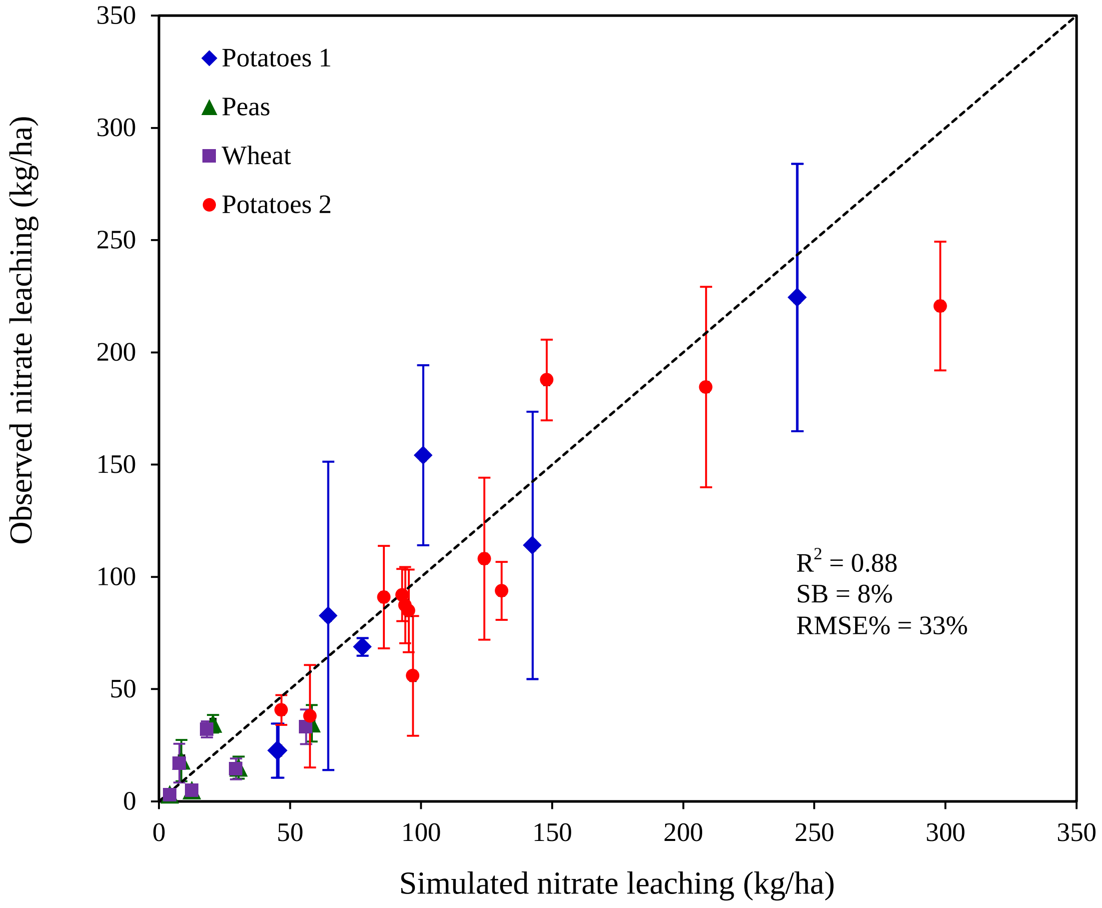

Figure 6: Observed (mean ± SD) versus predicted values of cumulative nitrate leached under different crops in two crop rotation sequences, relative to the 1 : 1 line (dotted).

Conclusions

Comparisons between simulated and measured values as well as the statistical analysis indicate that MCSP-APSIM adequately accounted for the temporal changes in soil water content, soil N concentration and nitrate leaching. Although there were cases where simulations were not completely satisfactory in terms of absolute values, MCSP-APSIM captured trends and exhibited sensitivity to irrigation and N fertiliser rates. These results provide confidence in the ability of MCSP-APSIM to simulate nitrate leaching in crops grown in rotation in New Zealand.

Acknowledgement

Research was completed under the MBIE core programme, Land Use Change and Intensification (LUCI), and the Overseer crop module testing project, funded by the Foundation for Arable Research, Horticulture New Zealand and Overseer Management Services Ltd.

References

Anon, 2014. National Policy Statement for Freshwater Management 2014 (NPF-FM 2014).

http://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2014; accessed Feb 2015.

Biggs JS, Thorburn PJ, Crimp S, Masters B, Attard SJ, 2013. Interactions between climate change and sugarcane management systems for improving water quality leaving farms in the Mackay Whitsunday region, Australia. Agriculture Ecosystems & Environment 180: 79-89.

Brown HE, Huth NI, Holzworth DP, Teixeira EI, Zyskowski RF, Hargreaves JNG, Moot DJ, 2014. Plant Modelling Framework: Software for building and running crop models on the APSIM platform. Environmental Modelling & Software 62: 385-398

Cichota R, Snow VO, Wheeler DM, Hedderley D, Zyskowski R, Thomas S, 2010. A nitrogen balance model for environmental accountability in cropping systems. New Zealand Journal of Crop and Horticultural Science 38: 189-207.

Francis GS, Thomas S, Barlow HE, Tabley FG, Gillespie RN, 2006. Fertiliser and irrigation management effects on nitrate leaching from rotations of annual crops. In: *Implementing sustainable nutrient management strategies in agriculture*. (Eds L.D. Currie and J.A. Hanly). Occasional Report No. 19, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. pp 330-333.

Francis GS, Thomas S, Barlow HE, Tabley FG, Gillespie RN, Zyskowski RF, 2007. Management strategies to minimise nitrate leaching from arable crops. In: *Designing sustainable farms: Critical aspects of soil and water management*. Occasional Report No. 20. (Eds L.D. Currie and L.J. Yates). Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. pp 443-447

Gauch HG, Gene Wang JT, Fick GW, 2003. Model evaluation by comparison of model-based predictions and measured values. Agronomy Journal 95: 1442-1446.

Holzworth D, Huth N, deVoil P, Zurcher E, Herrmann N, McLean G, Chenu K, van Oosterom E, Snow V, Murphy C, Moore A, Brown H, Whish J, Verrall S, Fainges J, Bell L, Peake A, Poulton P, Hochman Z, Thorburn P, Gaydon D, Dalgliesh N, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li F, Wang E, Hammer G, Robertson M, Dimes J, Carberry P, Hargreaves J, MacLeod N, C M, Harsdorf J, Wedgewood S, Keating B. 2014. APSIM - Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software 62: 327-350

Jamieson PD, Martin RJ, Francis GS, 1995. Drought influences on grain yield of barley, wheat, and maize. New Zealand Journal of Crop and Horticultural Science 23: 55-66.

Kobayashi K, and Salam MU, 2000. Comparing simulated and measured values using mean square deviation and components. Agronomy Journal 92: 345-352.

Probert ME, Dimes JP, Keating BA, Dalal RC, Strong WM, 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems 56: 1-28.

Sharp JM, Thomas SM, Brown HE, 2011. A validation of APSIM nitrogen balance and leaching predictions. Agronomy New Zealand 41: 67-77.

Stewart LK, Charlesworth PB, Bristow KL, Thorburn PJ. 2006. Estimating deep drainage and nitrate leaching from the root zone under sugarcane using APSIM-SWIM. Agricultural Water Management 81: 315-334.

Stone LF, Heinemann AB, 2012. Simulation of nitrogen management in upland rice with ORYZA/APSIM 2000 model. Revista Brasileira De Engenharia Agricola E Ambiental 16: 611-617.

Van der Laan M, Annandale JG, Bristow KL, Stirzaker RJ, du Preez CC, Thorburn PJ, 2013. Modelling nitrogen leaching: are we getting the right answer for the right reason? Agricultural Water Management 133: 74–80.

Vogeler I, Cichota R, Snow V, 2013. Identification and testing of early indicators for N leaching from urine patches. Journal of Environmental Management 130: 55-63.