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DESCRIBING NITROGEN LEACHING FROM FARM EFFLUENT IRRIGATED ON ARTIFICIALLY DRAINED SOILS

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Abstract

Dairy farming generates a considerable amount of effluent which has to be stored and managed, incurring in both labour and cost requirements. Application of farm effluent to land via spray irrigation is the preferred management option in New Zealand. This practice enables better utilisation of nutrients in the effluent, but can have an adverse impact on the environment if poorly managed. Managing the application of farm effluent can be a major challenge for farms with poorly drained soil, as it can generate surface runoff in undrained soils and leaching losses in artificially drained soils. Because of this, irrigation of effluent over the winter months is not permitted in most regions. The increasing practice of off-paddock wintering systems for dairy cows, especially in South Island, results in the collection of larger volumes of effluent that need storage and disposal, representing more costs to farmers. The potential for applying effluent over winter months, reducing the need for large storage ponds, is thus appealing to farmers, but the risks of nutrient losses need to be better understood before this practice can be implemented.

In this study the Agricultural Production Systems Simulator (APSIM) was setup to describe the fate of nitrogen (N) applied as effluent irrigated on artificially drained soils. The system described consisted of a dairy farm where the cows were wintered on an off-paddock system where effluent was captured and returned to land during winter. Effluent was applied daily using a low rate, low depth system unless large rainfall (>4.0 mm) occured. This minimised the requirement for effluent storage. The modelling setup was refined and evaluated using data collected in field trials at Lincoln University's Telford Farm, near Balclutha. The simulation setup and the major model parameters related to the artificial drainage system were tested to allow extrapolation of the trial results to different soils and climates of the South Island. Implications on the practicality of applying effluent irrigation over winter and the potential risks for N leaching losses are discussed.

Introduction

Typical management of dairy farms in New Zealand involves cows grazing on paddocks all year around. Farm yard effluent collected from holding areas and the milking shed is stored in ponds and has to be eventually returned to land. This represents both increased labour and cost to the farmer. In spite of the limited time that the animals are kept off-paddock, the volume of effluent can be considerable, as it typically is quite diluted as it is mixed with rainfall and water from the milking shed (Longhurst et al. 2000; Houlbrooke et al. 2004a). Concerns regarding soil damage and animal welfare of traditional crop grazing practices are driving an increase in the usage of housing and stand-off pads over winter, especially in the

South Island. This practice results in considerably large volumes of effluent that need to be stored and spread. The application of farm effluent to land via spray irrigation is the preferred treatment option for most regional councils in New Zealand (Houlbrooke et al. 2004a). This practice avoids the discharge of effluent direct to waterways and enables nutrients to be recycled within the farm. However, if poorly managed, the risk for adverse impacts on the environment can still be high. Because of this, irrigation of effluent over winter months is not permitted in most regions. Managing the application of farm effluent can be a major challenge, particularly for farms with poorly drained soils. Surface runoff can be generated in undrained soils, while in artificially drained soils there is a high risk of leaching losses, especially through soil cracks created by the mole-plough (Houlbrooke et al. 2008). Several management options have been put forward to minimise the risk of nutrient losses from effluent irrigation. These involve improving irrigation (by reducing irrigation depth and/or intensity as well as improving uniformity) and avoiding application to saturated soils (e.g. Houlbrooke et al. 2004b; Monaghan & Smith 2004). Avoiding applications over winter corroborates the above; however, large storage ponds are needed to hold the effluent generated during this time and this requires substantial capital investment. Applying effluent over winter months using appropriate management is potentially feasible and could be appealing to farmers due to its associated lower cost. Nonetheless, the risks of nutrient losses, especially from vulnerable soils, need to be better understood before this practice can be recommended.

Considerable research on the effects of effluent application to land has been conducted in New Zealand over the last 20 years (e.g. Di et al. 2002; Houlbrooke et al. 2004b; Monaghan & Smith 2004; Houlbrooke et al. 2008; Monaghan et al. 2010). This research has been the basis for recommendations on good management and the development of regulations. New practices, such as winter housing, as well as the expansion and intensification of dairy farming bring new challenges that need to be addressed. Studying new approaches covering different soil types and climates is too costly for conventional experimentation, hence the need to combine this with computer simulation models. Process-based models are better suited for extrapolation as they are developed to describe basic processes, which are more independent of the data initially used to develop them. However, verification against actual data is still an important step to develop confidence in the model's results.

In this work we describe the procedure used to set up the Agricultural Production Systems Simulator (APSIM) to simulate effluent irrigation to artificially drained soils in order to investigate management options that minimise the need for effluent storage while maintaining a low risk of N leaching. We used an experiment on low depth/low rate irrigation conducted on the Telford farm, near Balclutha, as the basis for our validation. We further investigate, using sensitivity analysis, the biggest uncertainties that need to be addressed in order to increase confidence in the model results.

Material and methods

Experimental setup

Data from an experiment on the use of low depth and low irrigation rates for effluent application conducted at Telford dairy farm in winter/spring 2012 were used in this work. The study was performed on 2×10 m plots with Tokomairiro Silt loam soil (Mottled Fragic Pallic, Hewitt 2010) under a ryegrass/white clover sward. Each plot was hydraulically isolated with plastic sheeting down to one meter around all sides, and contained a drainage pipe (5cm in diameter) installed at a depth of 0.70 m in the middle of the plot. All drains and plot edges were dug by a chain trencher which created a neat 10-12 cm wide slot, with minimal disturbance of the surrounding soil. Gravel was added to the trench containing the drainage pipe up to a depth of 0.30 m below the surface. Drainage from each plot was collected at regular intervals and the leachate was analysed for ammonium (NH_4^+) and nitrate (NO_3^-) concentrations. The effluent was sourced from the Telford dairy farm effluent system and had an average concentration of 54 mg N/L of ammoniacal nitrogen and 40 mg N/L of organic N. The irrigation consisted of mini-sprinklers with an instantaneous application rate of 35 mm/h. The irrigation covered approximately 50% of each plot's area. Irrigation was applied daily at 10:00am (or 1pm for a period of 3 weeks in mid-June when the frost risk was high), except when rainfall exceeded 4 mm over the previous 24 hours. Irrigation depths applied were set to 1.0, 2.0, 3.0 or 5.0 mm of effluent per day. There were three replicates for these treatments plus a control, where no irrigation was applied. The experiment started on the 13th June and effluent application lasted until 10th September. No grass was harvested during this period as there was no significant growth.

Table 1: Key properties of the Tokomairiro Silt Loam soil used in the APSIM simulations. Abbreviations used are: organic carbon (OC); volumetric water content at permanent wilting point (θ_{PWP}); field capacity (θ_{FC}); and saturation (θ_S); bulk density (ρ); and saturated hydraulic conductivity (K_{SAT}). Water content and bulk density values were adjusted for gravel content.

Soil depth (m)	Sand (%)	Clay (%)	Gravel (%)	OC (%)	θ_{PWP} (%)	θ_{FC} (%)	θ_S (%)	ρ (Mg/m^3)	K_{SAT} (cm/h)
0.00-0.10	15	25	0	4.0	26	45	56	1.06	63.8
0.10-0.30	15	25	0	2.0	24	41	52	1.19	63.4
0.30-0.45	10	30	25	0.2	18	29	37	0.98	185.4
0.45-0.60	95	1	75	0.1	3	5	15	0.39	415.6
0.60-1.50	15	35	0	0.1	29	38	43	1.41	0.005

Modelling setup

The Agricultural Production System Simulator (APSIM, Holzworth et al. 2014), version 7.7, was used to simulate the fate of effluent N applied via irrigation to artificially drained soils under pasture. APSIM is a modular, process-based, farm systems model that was developed to simulate soil, crop, pasture and livestock processes with various level of complexity (a comprehensive list of publications and documentation can be found at www.apsim.info). Of specific relevance to this study, we employed AgPasture (Li et al. 2010) to simulate ryegrass/white clover pastures and the combination of SoilN, SurfaceOM, SoilTemp2 and SWIM2 to simulate soil C, N and water processes (Verburg et al. 1996; Probert et al. 1998). SWIM2 uses a Richards' equation approach to describe water movement in the soil and enables simulating subsurface drainage from mole-tile systems using the Hooghoudt equation (Malone et al. 2007). SurfaceOM and SoilN describe the cycling of residues and organic matter in the soil, allowing for the dynamic addition of organic material as well as mineral N, which can then be used to simulate the addition of effluent to the soil surface via irrigation.

To allow comparison with measured data, APSIM manager scripts were used to schedule the application of effluent irrigation. The drainage system was set up to mimic the experiment described above. The soil was parameterised following procedures described elsewhere

(Vogeler et al. 2011; Cichota et al. 2013a; Cichota et al. 2013b) based on measured data (Table **1**) and supported by data from the NZ National Soils Database (Wilde 2003). Rainfall and soil moisture values were collected on site. These were complemented with weather data from nearby Telford weather station, obtained from Cliflo (NIWA 2015).

Sensitivity analysis

The basic model setup used for the comparison against experimental data was employed as the basis for the sensitivity analyses. The base simulation was modified by changing the parameters of interest (Table **2**), one at a time. Each parameter, except year, was varied 10 times over a range considered reasonable for the soil and conditions of the experiment. The sensitivity measure was defined as the ratio between the normalised deviation of a given output and the deviation in the parameter value (Campolongo et al. 2007). The effect of each parameter was determined for different outputs separately: the amount of drainage collected by the drainage system, the amounts of NH_4^+ and NO_3^- leaching (as total or those collected by the drainage system). Note that year is not formally part of the sensitivity analysis, but complements it by providing variations in weather conditions. It also allowed checking for how much variation occurred in APSIM simulated temporal trends and comparing with measured responses.

Table 2: Parameters and variation range used in the sensitivity analysis.

Parameter	Range
Drains spacing, L_D	500-2750 mm
Drains radius, R_D	10-100 mm
Lateral soil conductivity, K_{LAT}	100-2500 mm/day
Depth to impeding layer, Z_{IMP}	300-1500 mm
NH_4^+ adsorption potential, Exco	0.1-40.0 kg/L
NH_4^+ adsorption rate, Fip	0.30-0.975
Maximum nitrification rate, M_{NIT}	10-100 mg N/kg.day
NH_4^+ concentration for 50% M_{NIT}, k_{NIT50}	30-160 mg N/kg
Year	2000-2014

Results and Discussion

Experimental results and model verification

Soil moisture content in the top layer varied considerably during 2012 (Figure **1**). Values dropped to approximately wilting point following a dry weather spell during April, the moisture then increased to reach near saturation in early June, when effluent applications started. This general variation pattern was described by the APSIM model reasonably well (Figure **1**), with a mean absolute error of 8%.

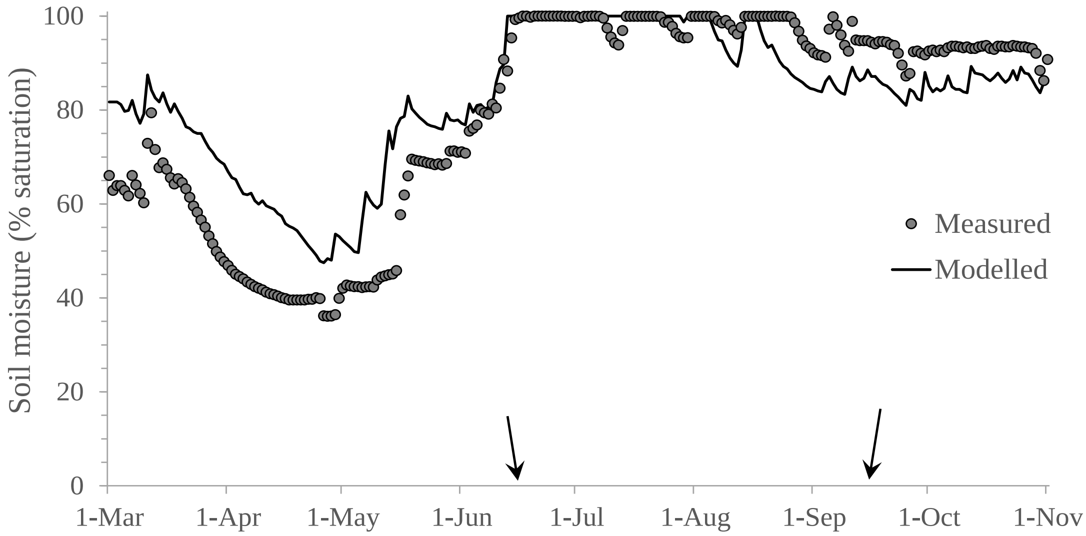

Figure 1. Measured and modelled values of soil moisture content in the 0-10 cm layer. Arrows mark the start and end of effluent applications

As expected, the volumes of drainage collected from the drainage pipes increased with increasing depth of irrigation, they also varied considerably within each treatment (Figure **2**). The leachate volumes collected in the experiment did not account for the drainage predicted by a simple soil water balance (Scotter et al. 1979), estimates suggested that approximately 40% (±8%) of total drainage was intercepted by the drainage system. The predictions of drainage volume from the APSIM model agreed well in general with the field measurements, but showed a stronger effect from irrigation depth. The simulated drainage collected by the artificial drainage system varied between 30% and 70% of total drainage, increasing as a function of irrigation depth (Figure **2**).

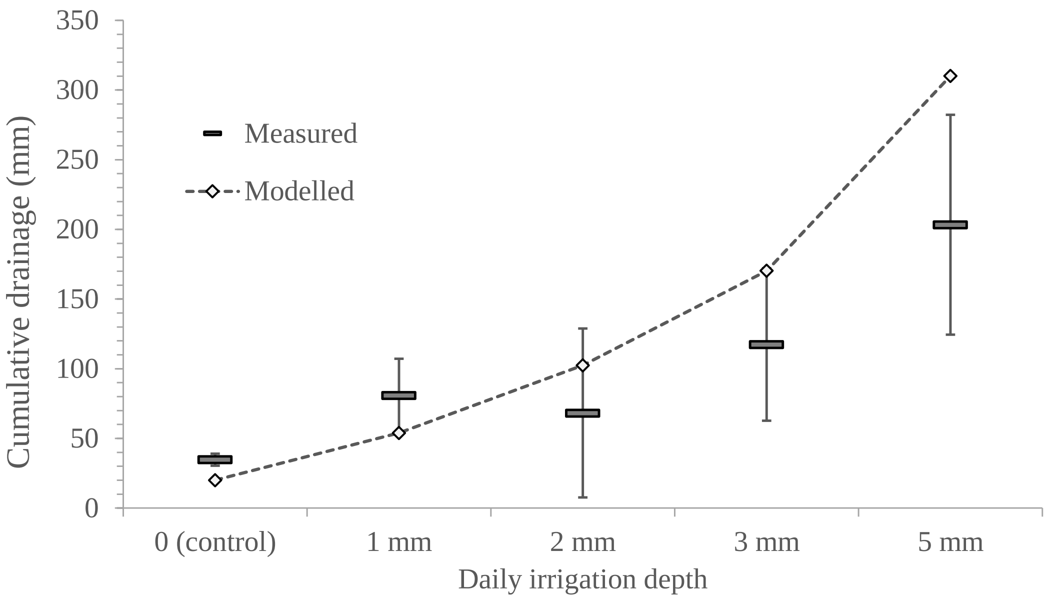

Figure 2. Measured and modelled cumulative drainage collected from artificial drains for different depths of effluent irrigation. Error bars represent one standard deviation

Analyses of leachate collected on 16 different dates between June and September showed an increase in NH_4^+ concentration as a function of irrigation depth, but concentrations did not vary significantly over time (Figure **3**). Whereas NO_3^- concentrations increased both due to greater irrigation depth and over time (Figure **4**). The concentrations of NH_4^+ were almost as high as those of NO_3^-, especially for the larger irrigation depths. These large NH_4^+ concentrations seen from the onset of the effluent application suggest the presence of preferential flow in this soil. Simulated results were not in good agreement with NH_4^+ data when typical parameters for adsorption were used; nearly no leaching of NH_4^+ was estimated for lower irrigation depths (data not shown). Lowering the adsorption parameters produced better agreement (Figure **3**), although with a trend over time that was not clearly evident in the measured data. The adjustments made to the adsorption parameters were quite drastic, for instance the distribution coefficient (called *exco* in APSIM) of the surface soil was reduced from 40.0, estimated using pedo-transfer functions described in Vogeler et al. (2011), to 0.5 L kg^{-1}. This was necessary because APSIM does not have the capability to simulate preferential flow. It is important to note that the actual adsorption parameters were not available for the soil used here, so there is considerable uncertainty about which process was preponderant. In spite of the issues with the description of NH_4^+ losses, the values for NO_3^- concentration simulated by APSIM were in good agreement with measurements (Figure **4**). This agreement was better when the adsorption parameters of NH_4^+ were adjusted as described above.

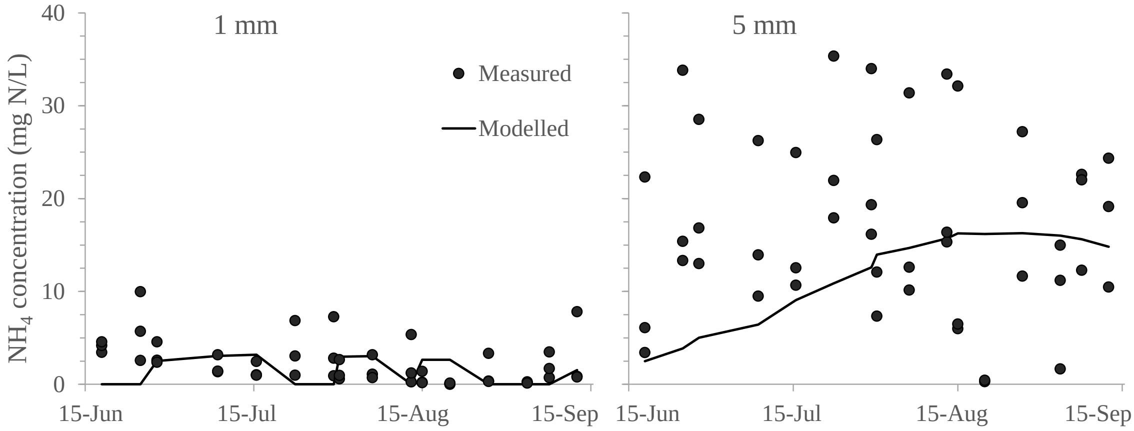

Figure 3. Measured and modelled values of NH_4^+ concentrations in the leachate collected from artificial drains for two different depths of effluent irrigation (1 mm or 5 mm).

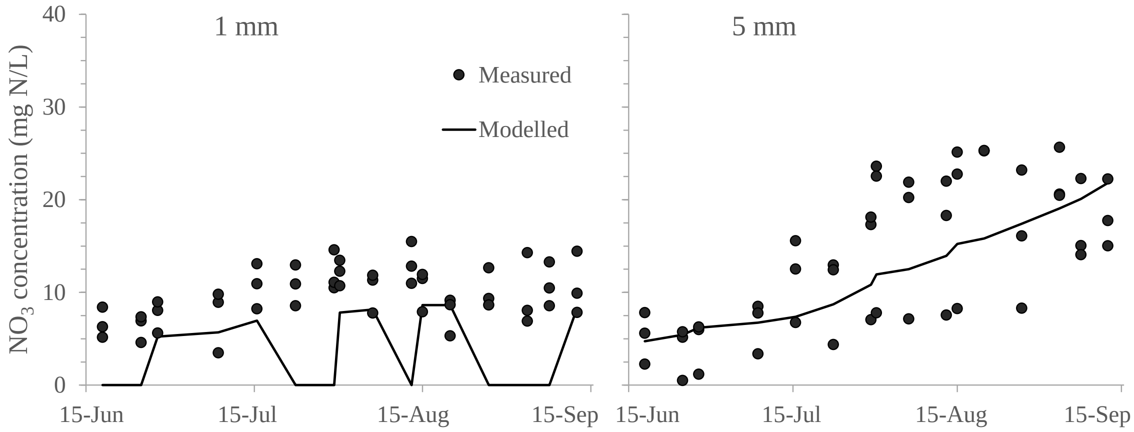

Figure 4. Measured and modelled values of NO_3^- concentrations in the leachate collected from artificial drains for two different depths of effluent irrigation (1 mm or 5 mm).

Sensitivity analysis

The analyses of the parameters controlling the simulation of artificial drainage (spacing and diameter of drains, K_{LAT}, and depth to impermeable layer) showed that the model outputs of interest here were not particularly sensitive to them (Table **3**). Total drainage was nearly insensitive (indexes close to zero) to the parameters in the range considered. Variations in the pattern of soil moisture and total drainage collected by the artificial drainage system were also only slightly affected by changes in these parameters, with the exception of the depth to the impermeable layer, which showed some considerable effect. The remaining parameters were related to N balance and did not have any noticeable effect on drainage.

The modelled estimates for N leaching were more sensitive to the two parameters related to NH_4^+ adsorption (Exco, especially, and Fip), although only NH_4^+ leaching was affected to a considerable extent. Both NH_4^+ and NO_3^- leaching estimates were sensitive to the parameters controlling the nitrification rate (M_{NIT} and k_{NIT50}). Reducing NH_4^+ adsorption or nitrification rate were necessary for the APSIM model to simulate any leaching of NH_4^+ at low irrigation rates. However, changes in the nitrification rate parameters created a strong temporal trend (NH_4^+ leaching increase with time) that was not observed in the field measurements, and also exacerbated the trend in NO_3^- leaching. Therefore, adjusting the adoption parameter *Exco* appears to be the best way to reproduce the trends on the observed data. It should be noted that a reduction in NH_4^+ adsorption could be explained by this soil being of low ion retention or that retention sites were not available to the NH_4^+ applied with effluent. The later could be expected by the occurrence of preferential flow, which was likely to occur (e.g. Monaghan & Smith 2004). The exact process cannot not be identified with the current data and future work is needed to better understand this. Preferential flow routines also need to be implemented in the APSIM soil model.

Table 3: Sensitivity indexes of drainage and N leaching to selected model parameters. Values for drainage and N leaching are considered as total or the amount collected from the artificial drainage system only.

	Drainage		NH_4^+ leaching		NO_3^- leaching	
Parameter	total	drains	total	drains	total	drains
Drains spacing	0.006	0.078	0.013	0.057	0.016	0.089
Drains radius	0.001	0.013	0.003	0.009	0.003	0.015
Lateral soil conductivity	0.008	0.094	0.015	0.07	0.02	0.106
Depth to impeding layer	0.013	0.184	0.027	0.144	0.036	0.205
NH_4^+ adsorption potential	0.000	0.005	1.087	1.081	0.078	0.098
NH_4^+ adsorption rate	0.001	0.017	0.36	0.395	0.068	0.079
Maximum nitrification rate	0.001	0.011	0.989	1.136	0.416	0.439
NH_4^+ conc. for 50% nitrif.	0.001	0.013	1.082	1.174	0.353	0.341

Running the simulation over 15 different years provided insights to whether the experimental results were representative or not of average conditions. Both drainage and leaching were quite variable between different years (e.g. total N leaching on Figure **5**). It can be seen that 2012, the year the experiment was conducted, was close to the mean pattern over the years.

The results suggest that conclusions based on the experimental data are representative of an average year, but the temporal variability is quite large. Risk analyses would be advised before any recommendation on the applicability of the effluent management could be made to real situations.

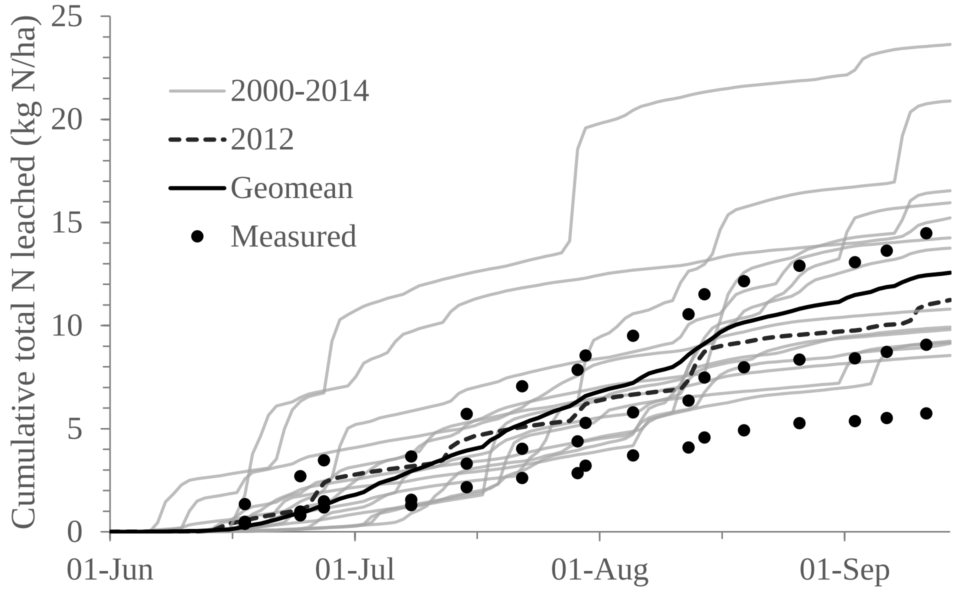

Figure 5. Measured and modelled values of cumulative total N leaching collected by an artificial drainage system on a Tokomairiro soil under effluent irrigation at 1.0 mm/day. The experimental year (2012) and the geometric mean of the 15 simulated years are highlighted as bold lines.

Conclusion

Simulating effluent irrigation in artificially drained soil represents quite a challenge. In this work we were able to use the APSIM model to describe an experiment that aimed to assess the possibility and potential impacts of effluent irrigation over winter months. The APSIM model results were in reasonable agreement with experimental data, but the parameters controlling NH_4^+ adsorption had to be considerably reduced for the model to estimate NH_4^+ leaching at level similar to that of measurements. The sensitivity analyses showed that further work is needed to clarify the process responsible for the leaching of NH_4^+, but the model can be used to extrapolate the experimental results to other conditions. The analyses also suggested that the experiment adequately represented an average year and highlighted large temporal variability. A risk analysis is recommended before any recommendation regarding the management of winter effluent can be made to the wider community.

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References

Campolongo F, Cariboni J, Saltelli A 2007. An effective screening design for sensitivity analysis of large models. Environmental Modelling & Software 22(10): 1509-1518.

Cichota R, Snow VO, Vogeler I 2013a. Modelling nitrogen leaching from overlapping urine patches. Environmental Modelling & Software 41: 15-26.

Cichota R, Vogeler I, Snow VO, Webb TH 2013b. Ensemble pedotransfer functions to derive hydraulic properties for New Zealand soils. Soil Research 51(2): 94-111.

Di HJ, Cameron KC, Silva RG, Russell JM, Barnett JW 2002. A lysimeter study of the fate of N-15-labelled nitrogen in cow urine with or without farm dairy effluent in a grazed dairy pasture soil under flood irrigation. New Zealand Journal of Agricultural Research 45(4): 235-244.

Hewitt AE 2010. New Zealand Soil Classification. 3rd ed. Landcare Research Science Series No.1. Lincoln, New Zealand, Manaaki Whenua Press. 136 p.

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C and others 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software 62: 327-350.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO 2004a. A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality. New Zealand Journal of Agricultural Research 47(4): 499-511.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA 2008. Land application of farm dairy effluent to a mole and pipe drained soil: Implications for nutrient enrichment of winter-spring drainage. Australian Journal of Soil Research 46(1): 45-52.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO 2004b. Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. New Zealand Journal of Agricultural Research 47: 405-415.

Li FY, Snow VO, Holzworth D, Johnson IR 2010. Integration of a pasture model into APSIM. In: Dove H, Culvenor RA ed. 15th Australian Agronomy Conference. Pp. 6.

Longhurst RD, Roberts AHC, O'Connor MB 2000. Farm dairy effluent: A review of published data on chemical and physical characteristics in New Zealand. New Zealand Journal of Agricultural Research 43(1): 7-14.

Malone RW, Huth N, Carberry PS, Ma L, Kaspar TC, Karlen DL, Meade T, Kanwar RS, Heilman P 2007. Evaluating and predicting agricultural management effects under tile drainage using modified APSIM. Geoderma 140(3): 310-322.

Monaghan RM, Smith LC 2004. Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. New Zealand Journal of Agricultural Research 47(4): 417-428.

Monaghan RM, Houlbrooke DJ, Smith LC 2010. The use of low-rate sprinkler application systems for applying farm dairy effluent to land to reduce contaminant transfers. New Zealand Journal of Agricultural Research 53(4): 389-402.

NIWA 2015. CliFlo: NIWA's National Climate Database on the Web. Retrieved 15-Sep-2015 2014, from http://cliflo.niwa.co.nz

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): 1-28.

Scotter DR, Clothier BE, Turner MA 1979. The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. Australian Journal of Soil Research 17(3): 455-465.

Verburg K, Ross PJ, Bristow KL 1996. SWIMv2.1 user manual. Melbourne. 109 p.

Vogeler I, Cichota R, Snow VO, Dutton T, Daly B 2011. Pedotransfer functions for estimating ammonium adsorption in soils. Soil Science Society of America Journal 75(1): 324-331.

Wilde RH 2003. Manual for National Soils Database. Palmerston North. 53 p.