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Predictions of nitrogen leaching from a well-drained soil under dryland and irrigated dairy farming using APSIM and OVERSEER

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Abstract: As urine patches from grazing livestock are the single largest source of leached N, biophysical models that incorporate the effect of N leaching from urine patches are required to assess the impact of changes in farm management on N leaching. The objective of this study was to compare predictions of N leaching from a dairy farm as made by two contrasting tools; APSIM (Agricultural Production Systems Simulator) and the OVERSEER Nutrient Budget Model. Typically, these models are used for different purposes, require different input data, and produce outputs that are not readily comparable. APSIM is a process-based model that works on a fine scale and daily time-step whereas OVERSEER calculates N leaching on a monthly time-step and reports annual averages of N leaching for relatively large areas. As OVERSEER has been calibrated for New Zealand's farming systems and uses inputs that are readily accessible by farmers, it is the favoured tool for assessing compliance of dairy farms to proposed new regulations. However, APSIM is increasingly being used to analyse existing and proposed farming scenarios in greater detail.

The dairy system modelled in this study is located on a well-drained Manawatu silt loam soil at Massey No. 1 Dairy Farm, Palmerston North, New Zealand. Dryland and irrigated scenarios were defined to cover a range of possible management options. Results from simulations over 25 years using APSIM were analysed to obtain long-term estimates of N leaching to compare with OVERSEER predictions. Although the model inputs were set such that both models were under similar weather and management conditions, there were differences between the models regarding the effect of irrigation on N leaching (Table 1). These differences were attributed to a) differences in how the two models describe irrigation and its effect on drainage, b) uncertainties in the calculations of urinary N load, and c) differences in simulations of other components of the N cycle. Our modelling exercise revealed those N transformation processes that behave similarly from those that differ between the two models, highlighting potential knowledge gaps. The exercise also highlighted the difficulties of comparing models, and great care should be taken when comparing outputs from different sources.

Table 1. Annual N balance (kg/ha) and drainage (mm) estimates for Block 4, Massey University No.1 Dairy Farm. [1]Rainfall + irrigation.
[2]Net transfer (kg N/ha) = [(supplements produced + supplements imported + transfer to block) – (removed as supplement + transfer from block)].
[3]N in milk.

Item	Block 4 – Dryland		Block 4 – Irrigated	
	OVERSEER	APSIM	OVERSEER	APSIM
Inputs (kg N/ha)	193	181	240	184
Fertiliser	69	69	69	69
Rain[1]/fixation	110	131	143	167
Net transfer[2]	14	-18	28	-52
Outputs (kg N/ha)	131	124	173	137
Product[3]	66	66	84	84
Volatilisation	40	11	51	10
Denitrification	3	15	4	16
Leaching	*22*	*32*	*34*	*32*
Soil changes (kg N/ha)				
Organic pool	62	58	65	37
Drainage (mm)	351	338	420	368
Pasture yield (t DM/ha)	12.1	9.6	14.8	13.2

Keywords: *Dairy farming, irrigation, Nitrogen leaching losses, APSIM, OVERSEER*

1. INTRODUCTION

Dairy production in New Zealand has increased in the last two decades; during the 2013/2014 season, milk production surpassed the 20 billion litre mark for the first time (New Zealand Dairy Statistics, 2014). Furthermore, the dairy sector continues to be the country's top export earner, and it accounts for 12% of the world's dairy exports. These sustained increases in production have occurred in synchrony with growing concerns about the impact of dairy farming on the aquatic environment. In the future, nutrient losses from dairy farms to surface and ground waters will be strictly regulated. Intensive pastoral dairy farming will need to identify and adopt the systems and technologies required to meet these regulations and reduce environmental impacts. This process remains a major challenge for the sector (Monaghan et al., 2007). Dairy farms are often characterized by a higher stocking rate and more intensive management relative to other pastoral farming systems in New Zealand (Monaghan et al., 2007). Intensification, generally, increases the potential for adverse impacts on the environment, including leaching losses of nitrogen (N) to water (Abraham and Hanson, 2010). Water quality of lowland streams in New Zealand dairy farming catchments has been found to be negatively impacted. For example, nitrate concentrations exceeded the health-based maximum acceptable value (11.3 mg NO_3-N/L; set by the Ministry of Health) in 8% of the wells sampled in Canterbury in the spring of 2009 (Abraham and Hanson, 2010).

Urination events, and to a lesser extent agricultural N fertilizers and livestock manure, are the major drivers of diffuse N losses from New Zealand dairy farms (Cichota et al., 2013). Direct measurements of deep drainage and N leaching are labour-intensive, costly and site-specific. Given the spatial and temporal variation of N leaching, the use of dynamic and mechanistic biophysical models that capture the heterogeneity of this process is rapidly increasing (Vogeler et al., 2013). Biophysical models that incorporate the effect of N leaching from urine patches are required to assess the impact of farm management on N leaching (Snow et al., 2009). Models such as the Agricultural Production Systems Simulator (APSIM) (Holzworth et al., 2014) and OVERSEER® (Wheeler et al., 2006) are biophysical models that incorporate these effects. APSIM is a process-based model that works on a fine scale and daily time-step whereas OVERSEER calculates N leaching on a monthly time-step and reports annual averages of N leaching for relatively large areas. As OVERSEER has been calibrated for New Zealand's farming systems and uses inputs that are readily accessible by farmers, it is the favoured tool for assessing compliance of dairy farms to proposed new regulations (Doole, 2012). The two models have been designed for quite distinct purposes and may not be readily comparable. The objectives of this study were to examine the comparability of two contrasting simulation tools, APSIM and OVERSEER, particularly their estimates of N leaching from Massey University's No.1 Dairy Farm in the Manawatu region of New Zealand, and the relevant strengths and weaknesses of both models.

2. MATERIALS AND METHODS

2.1. Farm System, Weather and Soil Descriptions

The Massey University No.1 Dairy Farm (40.4° S, 175.6° E) is located adjacent to the Massey University and AgResearch Grasslands campuses; it is also adjacent to the Manawatu River (north and west boundaries; inner margin of low terrace on Manawatu river flats) on the outskirts of Palmerston North. The farm is 35 metres above sea level and long-term (1987-2011) mean rainfall is 1011 mm (± SD 129 mm), with monthly minimum and maximum soil temperatures of 7ºC (July) and 18.5ºC (January), respectively. The total farm area is 138.6 ha (effective area = 119.6 ha). The farm can be divided into 7 blocks (for setting up OVERSEER): Lower terrace, dryland (31.0 ha); Lower terrace irrigated (12.9 ha); Upper terrace irrigated (13.6 ha); Lower and upper terrace dryland (52.7 ha), Lucerne cut and carry (9.4 ha); Houses (16.3 ha); Trees (2.7 ha). The first four blocks constitute the grazing area (110.2 ha). Imported silage (plus on-farm produced lucerne) is offered to cows on a feed pad. Grass silage and hay made on-farm is fed directly in the paddocks. Farm dairy effluent is exported from the farm. The soils on the farm are a complex association of alluvial soils including; Rangitikei loamy sand, Manawatu fine sandy loam, Manawatu sandy loam/gravelly phase, Manawatu mottled silt loam, and Karapoti brown sandy loam. These soils types are well to excessively-well drained and prone to summer drought. For the model simulation and comparison, Block 4 (with Manawatu silt loam soil) was up-scaled to represent the whole farm with a single grazing block in OVERSEER (110.2 ha). The Manawatu silt loam is a weathered fluvial recent soil, a medium-textured, well-drained and highly productive soil. The basic soil description and soil parameters were obtained from the New Zealand soil database (www.nzsoils.org.nz) and from Landcare Research (www.landcareresearch.co.nz), respectively.

2.2. Simulation Tools Compared

2.2.1. APSIM Model and Parameterisation

APSIM (v. 7.7; www.apsim.info/) was used to simulate the soil-plant-animal processes occurring on the dairy farm. Briefly, APSIM is a process-based model that simulates physical and biological processes in agricultural systems (Holzworth et al., 2014). The model is a modular framework developed and maintained by the APSIM Initiative and its predecessor the Agricultural Production Systems Research Unit (APSRU, Australia). In New Zealand, the model has been tested for a wide range of leaching conditions from pastoral systems (Cichota et al., 2013). The AgPasture module (Li et al., 2011) describes a multi-species sward which interacts with other APSIM modules to produce estimates of water and N uptake and pasture production. The soil setup follows the basic procedure described by Cichota et al. (2012). The soil parameters used to parameterise the SWIM3 module in APSIM are shown in Table 2.

Table 2. Manawatu silt loam soil parameters used in the APSIM simulation.

Depth (cm)	Bulk density (cm^3/cm^3)	Air dry[1] (cm^3/cm^3)	LL15[2] (cm^3/cm^3)	DUL[3] (cm^3/cm^3)	SAT[4] (cm^3/cm^3)	KS[5] (mm/day)
0-10	1.171	0.05	0.11	0.30	0.43	2015
10-20	1.248	0.12	0.15	0.30	0.47	900
20-30	1.306	0.16	0.16	0.32	0.47	299
30-40	1.344	0.17	0.17	0.31	0.46	267
40-70	1.433	0.07	0.07	0.17	0.38	1312
70-97	1.411	0.06	0.06	0.21	0.38	1609
97-117	1.439	0.08	0.08	0.25	0.37	335
117-131	1.362	0.11	0.11	0.29	0.39	156
131-150	1.375	0.08	0.08	0.24	0.40	408

[1]Soil water content following air drying; [2]Soil water content at 15 bars; [3]Drained upper limit (i.e. field capacity); [4]Saturated water content; [5]Saturated hydraulic conductivity.

The pasture, a ryegrass/white clover mixture, was grazed rotationally from a target pre-grazing herbage mass set at 2500 kg DM to a varying residual herbage mass that ranged from 1300 (in winter) to 1600 kg DM/ha (in summer). The farm-scale model Farmax® Dairy Pro (v. 6.6.0.0) was used to ensure that the upscaling of Block 4 to the whole farm scale (as well as changes due to the addition of irrigation) was physically feasible. Farmax was also used to estimate daily dry matter (DM) intake, N intake and N removed in saleable product (milk protein/6.38) by lactating cows (Table 3). The difference between the amounts of N intake and N removed as product was assumed to be excreted, with deposition on different paddocks proportional to the time spent in each area. The N in urine was estimated from N intake values using relationships similar to those employed in OVERSEER (Ledgard et al. 2003):

$$f_{Nurine} = 31.8 + 11p_{Ndiet} \tag{1}$$

where, f_{Nurine} is the proportion of N excreted in urine (% of excreta N) and p_{Ndiet} is the N concentration in the diet (%). The urinary N loading rate (N_{Load}, kg N/ha) was calculated according to the following equation:

$$N_{Load} = \frac{(N_{Excreta} f_{Nurine}) t_{paddocks}}{a_{Urine}} \tag{2}$$

where $N_{Excreta}$ is the amount of N deposited as excreta (kg N/ha, on a paddock area basis), $t_{paddocks}$ is the fraction of time expended in the grazing paddocks, and a_{Urine} is the fraction of the paddock affected by urinations. The fractional area affected by urination events was computed using the following equation (Pleasants et al., 2007):

$$a_{Urine} = S_{density} R_{deposition} A_{patch} \tag{3}$$

where $S_{density}$ is the stock density (cows/ha per grazing day), $R_{deposition}$ is the urinary deposition rate (assumed to be 10 events per day), and A_{patch} is the average urine patch area (assumed to be 0.5 m^2). The time spent on the grazing block varied over the year, with a mean estimate of 20.6 hours per day. The urine patch applied in APSIM was simulated as an application of urea with the addition of 5 mm of water.

To simulate N leaching from urine patches (in contrast to areas that did not receive urine), a parsimonious approach was used. For each treatment and each replicate year, 13 paddocks were simulated: one represented the area without urine while the remaining represented a urine deposition in each month of the year. This procedure approximately mimics the approach used by OVERSEER (Selbie et al., 2013). Urinary N load varied over the year following equation (2) and whole paddock estimates of N leaching were obtained from weighted averages (based on area urinated) of the leaching from each of the 13 paddocks. To account for the full effect of urine deposition, the simulations were followed for two years (without adding urine in the second year). A more detailed description of a similar approach can be found in Vogeler et al. (2013). To estimate long-term averages, APSIM simulations were run over 25 years and the annual results were averaged.

2.2.2. OVERSEER Model and Parameterisation

OVERSEER (v. 6.2.0; www.overseer.org.nz) is a farm-scale nutrient budget model developed to aid in designing soil nutrient balances and soil nutrient budgets for the main soil nutrients (N, P, K, S, Ca, Mg and Na) applicable to most New Zealand farming enterprises (Wheeler et al., 2006). Leached N accounts for the N moving below the root zone, which is calculated on a monthly basis (Shepherd and Wheeler 2012). The model has become the standard framework used for estimating nutrient emissions from New Zealand agricultural industries (Doole, 2012). Of particular interest to this study is the model's ability to estimate on-farm nitrate-N (NO_3-N) leaching losses below the root zone.

An OVERSEER simulation file, initially produced by a fertiliser consultant describing the Massey No.1 Dairy Farm and its management as of 2011/2012, was used as the base for this study. The characteristics and basic management of Block 4 were up-scaled to represent the whole farm (110.2 ha effective area). Changes in management and stock density were checked for feasibility using Farmax. To produce comparable simulations to APSIM, the weather parameters of OVERSEER were manually set to represent the long-term averages of the same period used in APSIM (1987 - 2011). These were mean annual rainfall of 1011 mm, mean annual temperature of 13.1°C and annual potential evapotranspiration (PET) of 836 mm. Following current farm management, all dairy effluent was exported from the system, and the solid effluents from the feed pad were applied to the lucerne cut-and-carry block.

2.3. Farm Management and Scenarios Tested

Massey's No.1 Dairy Farm management has changed in recent years; it currently holds a spring-calving Friesian herd with some crossbreds (240 cows) under once-a-day milking. The herd is kept on the farm year-round (lactating and dry cows) while replacement cows are bred and reared elsewhere. To reduce the number of variables to reproduce in the two models, the farm was simplified by making the whole farm to have the same characteristics and basic management of Block 4. The grazing block was fertilised with a blend of ammonium sulphate and urea (37 kg N/ha) in August and urea (32 kg N/ha) was applied in November. In addition to the basic dryland setup of Block 4, the effect of irrigation on N leaching was analysed. Irrigation needs were simulated in APSIM based on a centre pivot setup (applying 20 mm each day, with a return period of 5 days between December and March). The monthly average irrigation depths identified in APSIM were used as inputs in OVERSEER, namely 45, 55, 55 and 35 mm during Dec, Jan, Feb and Mar, respectively. The farm-scale model Farmax Dairy Pro was used to examine the carrying capacity of the farm scenarios based on home-grown and imported feed, adjusting livestock numbers when necessary, and to examine the biological feasibility (i.e. matching feed supply with feed demand) of the farms modelled (Table 3).

3. RESULTS AND DISCUSSION

3.1. Limitations of Model Comparison

Validation of models with experimental data is an integral part of the model development process. In our study, however, models were solely compared against each other as appropriate measured data was not available. Model comparison plays a vital role in understanding the strengths and weaknesses of the models at capturing temporal and spatial variations of processes, how these processes interact, and how the different modules (e.g. pasture growth and soil N dynamics) inter-relate. When comparing models it is important to ensure that appropriate data was used to parameterise the models (Giltrap et al., 2013). Cichota and Snow (2009) point out that when comparing long-term average models with single-point average models, the former tend to present considerably less variation than single point, daily models. It is thus important that the setup of both models is such that the differences in scale are taken into account when comparing their outputs. In the present work, the more detailed model (APSIM) ran for 25 years to mimic the long-term average approach of OVERSEER. Concomitantly, the weather and irrigation parameters of OVERSEER were set up to reflect the averages of the same period simulated by APSIM. Without these precautions, the two models can produce outputs that diverge considerably.

Table 3. Key biophysical measures of Massey University's No.1 Dairy Farm (from Farmax).

Item	Dryland	Irrigated
Grazing area (ha)	110.2	110.2
No. of cows (1st July)	240	303
Stocking rate (SR; cows/ha)	2.2	2.7
Milksolids (kg/ha)	775	979
Milksolids (kg/cow)	356	356
Supplements as a % of feed offered	35	39
Purchased feed as a % of feed offered	15	19

3.2. Background Calculations and Estimates of N Leaching Losses

Predicted urine patch N loads, as calculated on a monthly basis, ranged from 395 (June) to 841 (October) kg N/ha (mean = 571 kg N/ha) for the non-irrigated scenario and from 396 (June) to 745 (January) kg N/ha (mean = 560 kg N/ha) for the irrigated scenario. These values are within the range reported by Vogeler et al. (2013), but are smaller than the rate of 1000 kg N/ha reported by Haynes and Williams (1993). The latter value, which is one of the most frequently cited references for urinary N loading, is based on a urinary N concentration of 10 g/L, urination volumes of 2 L, and wetted patches of 0.2 m^2. The area of the urine patch reported by Haynes and Williams (1993) is considerably smaller than the area considered in the present study (0.5 m^2). The area used here is more in line with more recent measurements (Moir et al., 2011). In addition to the urinary N load to each patch at the different grazing events, the total area affected by urination events also influences N leaching at both paddock and farm scales. Given the previously described urine patch assumptions, the paddock area affected by urination on a given grazing day was, on average, 2.6% and 3.3% for dryland and irrigated scenarios, respectively. Urination events covered 31% (dryland scenario) and 39% of the grazing area on an annual basis, due primarily to the livestock numbers carried by each scenario. Similar values (areas covered by urine on a given grazing day) were reported by Vogeler et al. (2013) for a Waikato farm that was either stocked at 3 cows/ha (3.5%) or at 2.6 cows/ha (3.0%).

Pasture growth estimated by the models were in agreement with measured values at the site (available at http://www.massey.ac.nz/massey/home.cfm). Adding irrigation during the summer months increased the pasture production in OVERSEER and APSIM to 14.8 and 13.2 t DM/ha, an additional 2.7 and 3.6 t DM/ha, respectively. The increase in pasture growth is in agreement with pasture growth responses to irrigation on Manawatu farms as reported by DairyNZ (available at www.dairynz.co.nz/feed/pasture/pasture-growth-data). For comparison purposes, N leaching losses from individual urine patches and non-urine affected areas were aggregated to obtain total N leached on the grazing block for both (dryland and irrigated) scenarios (Table 1). Estimates of N leaching losses below the root zone differed between models, although the absolute values cannot be verified as there were no measurements. Notably, OVERSEER estimated a 55% increase in N leaching when irrigation was applied, whereas APSIM predicted no changes. The APSIM simulations suggest that the addition of irrigation resulted in an increased N use efficiency (greater herbage growth and therefore increased N uptake over summer, leaving less N to be leached during winter). This process may have counterbalanced the greater amounts of N deposited as urine for the irrigated treatment that carried a greater number of cows.

It is important to note that urine patch N returns in APSIM were specified according to N intakes inferred from Farmax and OVERSEER, and were quite simplified in this modelling exercise. The number of urinations per day and the area of patches were fixed and there were no overlaps. Other possible sources for the divergence in N leaching estimates between the two models relate to the description of irrigation and its effect on drainage. Both OVERSEER and APSIM produced similar amounts of drainage for the dryland treatment (Table 1). In APSIM, the addition of 190 mm/year of irrigation water resulted in less than a 9% increase in drainage, whereas this increase was almost 20% in OVERSEER. This could help explain the increase in N leaching under irrigation in OVERSEER. Additionally, differences between the magnitudes of various N transformation processes were predicted by the models, particularly volatilisation and denitrification (Table 1 and Figure 1). These differences make comparisons of the whole N balance of the two models difficult.

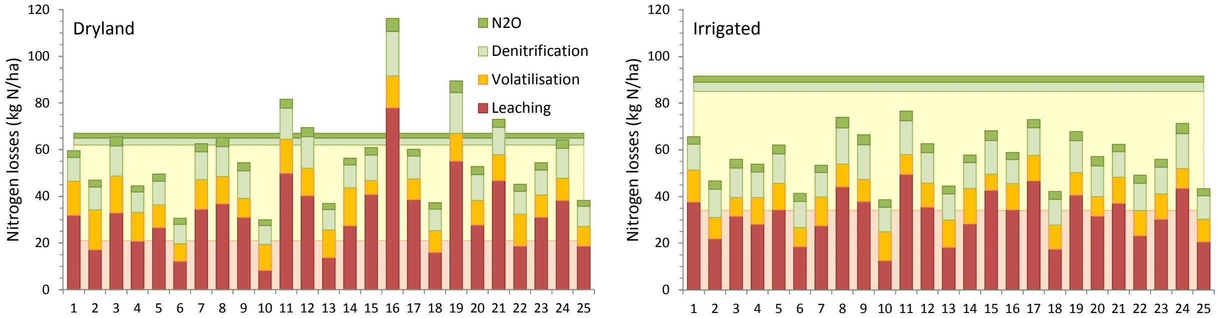

Figure 1. Annual N loss estimates from different soil N transformation processes for Block 4, Massey University's No.1 Dairy Farm. Outputs from APSIM are represented by stacked columns (year 1 = 1987, year 25 = 2011); outputs from OVERSEER are represented by stacked colours present in the background.

The timing of urine deposition throughout the year has a sizeable impact on N leaching from urine deposition (Shepherd et al., 2011). The highest risk of N leaching originates from the urine deposited in late summer and early autumn, although actual leaching commonly occurs during the following winter months (Figure 2). These findings are in agreement with those reported previously under measured (Shepherd et al., 2011) and simulated (Vogeler et al., 2013) urine patch depositions. Even in the absence of experimental data, as in our modelling exercise, model comparisons are useful for differentiating between those N transformation processes that behave similarly from those that behave differently, highlighting potential knowledge gaps. The exercise also highlights the difficulties encountered when comparing both models and the care required when comparing outputs from different sources. There are still considerable unknowns that require further research; further work should also include comparison with measured data. It has been pointed out that none of the models have been formally validated for all processes under New Zealand grazed pasture conditions (Giltrap et al., 2013).

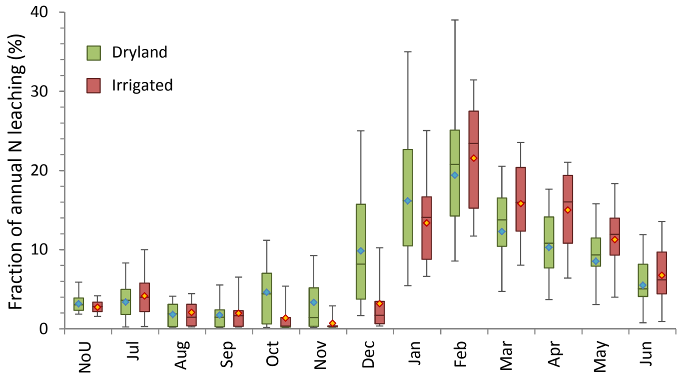

Figure 2. Monthly contribution from urinary depositions to annual N leaching, as calculated by APSIM. The boxes show the 25th, 50th and 75th percentiles, and the whiskers the 5th and 95th percentiles.

Although the inputs were set such that the models were under similar weather and management conditions, there were differences between the models regarding the effect of irrigation on N leaching; these were attributed to differences in how the two models describe irrigation and its effect on drainage, to uncertainties in the calculations of urinary N load, and to differences in simulations of other components of the N cycle. While the APSIM model is more sensitive to environmental conditions and management practices, the model requires many inputs, with many model parameters not readily available at the farm level. In contrast, the OVERSEER model is more user-friendly and has the ability to easily upscale nutrients lost from paddocks to farm level.

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