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Linking a whole farm model to the APSIM suite to predict N leaching on New Zealand dairy farms

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Abstract: Nitrogen excreted directly onto pasture on New Zealand dairy farms, particularly from urine, drives most nitrogen (N) leaching. Therefore, the representation of urine patches in different paddocks is important when modelling on-farm N leaching.

This paper:

1. describes the *Grid* and *Probabilistic* methods in connection with DairyNZ's Whole Farm Model (WFM); and

2. compares N leaching predictions using the *Grid* and *Probabilistic* methods for a simulated Waikato (New Zealand) dairy farm on a Horotiu silt loam soil (Typic Orthic Allophanic soil).

The *Grid* method divides the paddock into cells and allocates the urination events randomly for each grazing event and the *Probabilistic* method calculates the probability using the Poisson distribution of the different temporal urination patterns, estimates the N leaching from each pattern and then calculates the leaching at a paddock level. Different simplifications to each method are required to make the implementation feasible.

The modelling in this study uses a new framework called the Urine Patch Framework (UPF) that post-processes the results of the WFM and runs the Agricultural Production System Simulator (APSIM) to simulate the urine patches.

The WFM extracts the urine information for each grazing event on each paddock, accounting for the partitioning of the urine between walkways, milking parlour, and the stand-off. Only the fate of urinary N directly excreted onto pastures is analyzed in this study.

The UPF breaks each paddock into either cells (*Grid* method), or areas with different urination patterns (i.e. dates of deposition and amount excreted on each date) (*Probabilistic* method) and saves the information into text files. The software reads these files and prepares input files (.xml) for APSIM model runs, which are used to invoke APSIM for each cell or pattern. Finally, the leaching data are collected to calculate N leaching for the whole paddock and subsequently the whole farm.

The main simplification used in the *Probabilistic* method is based on the assumption that the effect of one urination event can be neglected after a number of months following deposition (months to remember). This implies that the full simulation period (i.e. the WFM run) can be subdivided into periods of time (months to remember + 1 month), which stops the exponential explosion in the number of possible urination patterns. A range from 6 to 12 months to remember was explored. For one period at a time, all the patterns are created, and later on simulated in APSIM. Nitrogen leaching results are collected only in the last month of the period, whereas the previous months are used to initialize and populate the soil model with relevant historical information (urination events, fertilization, defoliations and climate).

Nitrogen leaching predictions from both methods converged when the number of months to remember in the Probabilistic method was approximately 9-10 months. Even with 10 months to remember, the *Probabilistic* method was computationally more efficient, taking less than half of the time for the 2 year runs compared to the *Grid* method. For a 2 year run, the processing time was similar for both methods with about 14 months to remember. Ten months to remember was used throughout the rest of the study.

The average annual N leaching was similar for the *Grid* and *Probabilistic* method (37.0±14.5 vs. 38.1±10.9 kg N/ha/year, respectively). However, the *Grid* method, despite the long processing time, could be used to simulate dung patches to enable predictions of soil carbon balance.

Keywords: *Dairy farm, N leaching, urine patch, modelling.*

1. INTRODUCTION

Agricultural fertilizer, stock manure and urine are the major sources of nitrogen pollution in rural New Zealand (Ministry for the Environment, 2007). Nitrogen excreted onto pastures, particularly urine, drives the environmental impact, not fertilizer inputs *per se* (Decau et al., 2004). Four elements that complicate modelling and prediction of N leaching at the farm level are:

1. Excreta is not evenly distributed but deposited in patches with high N concentration (Di and Cameron, 2002).
2. Patches that can overlap (de Klein, 2001; McGechan and Topp, 2004; Pleasants et al., 2006).
3. The fate of the nitrogen from excreta strongly depends on the time of deposition (Haynes and Williams, 1993; Snow et al., 2007), as well as climate conditions at, and following deposition.
4. The effect of an urination event on the soil can last for several months after deposition.

Two different methods (Grid and Probabilistic) are presented that represent the complexity of N leaching at the paddock and subsequently at the farm level. This study describes a new Urine Patch simulation Framework (UPF) and compares N leaching predictions from both methods for a simulated Waikato (New Zealand) dairy farm.

2. MATERIALS AND METHODS

The method used in this study consists of running an existing dairy whole farm model (WFM, Beukes et al., 2010), and then the UPF automatically post-processes the outputs of the WFM to simulate urine patches using a mechanistic soil model (APSIM, Keating et al., 2003). The WFM models pasture-based dairy farm systems on a daily time step. The WFM model simulates individual paddocks (Romera et al., 2009) and is built around a mechanistic cow model called Molly (Baldwin, 1995; Hanigan et al., 2009). Paddocks are grazed rotationally and supplements fed according to policies created by the user. Table 1 lists main symbols in the UPF model.

In the WFM, partitioning of excreted N is based on the proportion of the daily active (not resting) time cows spend on each surface (soft: pasture, standoff pad; hard: milking shed; walkways and concrete pad).

The user can select among two different methods to represent the distribution of urine load in space and time (Grid or Probabilistic, described in sections 2.2 and 2.3, respectively) by changing one parameter in an initialization file. The whole process, which is fully automated, involves the following main steps:

- The user runs the WFM for at least 2 years, collecting urine deposition information, plus other management events at a paddock level. The WFM extracts the urine information for each grazing event on each paddock [Number of urinations, amount of N excreted (kg N), urine volume (L) and paddock area (ha)]. The WFM also creates event schedules for all the walkways, the shed, and the stand-off pad to account for the partitioning of urine and faeces onto these areas. Only the fate of urinary N excreted onto pastures is analyzed here.
- The UPF divides each paddock into cells: ¼ of the area of the urine patch (Grid method) or areas with different urination patterns (i.e. dates of deposition and amount excreted on each date, Probabilistic method).
- The UPF prepares an xml simulation file (.apsim) for each cell or pattern.
- The UPF invokes APSIM to run the simulation files; and
- The UPF collects leaching data from the APSIM runs and collates the results per paddock.

General assumptions necessary for both methods were:

- A uniform probability of urinations across the paddock (no camping, no water trough effect, etc. Moir et al., 2010), but this could be improved in future versions.
- A paddock grazing event occurred over one day. In reality paddocks are frequently subdivided into strips (with temporary electric fences) which can be grazed over several consecutive days.
- Fecal N input was ignored, which should have had a minor effect in N leaching (Vellinga et al., 2001). This simplification could be relaxed in the future, which would be easier with the Grid method.
- The effect of urinary N on pasture growth on a urine patch and consequently its effect on animal response was not represented; and
- The impact of urine deposition on selective grazing behaviour was ignored.

The total urine volume deposited during a grazing event (TUV) was calculated in the WFM as the sum of the urine volume of each single cow in the mob (UV, L/cow/day) during the time in the paddock. The latter was calculated using the equation 8.2 from Bates (2009) for each instance of Molly.

2.1. Urine patch in APSIM

For each cell or pattern, APSIM receives all the necessary information from the xml files. The files include the soil description, the urine applications, nitrogen fertilizer applications and the defoliation events. Defoliation events are simulated as pasture cuts according to the residual herbage mass reported by the WFM.

In the following examples, the APSIM soil was parameterized to describe a Horotiu silt loam soil (Typic Orthic Allophanic soil; Singleton, 1991) with 8 layers (0-6, 6-17, 17-31, 31-37, 37-55, 55-73, 73-91 and 91-107 cm). A constant (urineColumn, mm), representing the amount of water in the urine, equivalent to irrigation or rainfall of 5mm was assumed. Nitrogen was applied in depth (uniformly distributed among the first four soil layers) to represent preferential flow of urine through soil macropores. This was a simplification that will be reviewed in future versions, as the initial wetting pattern (area and depth) and volume of soil affected depend on the volume of the urination event, soil type and soil moisture. Nitrogen flowing below layer 55 cm was considered as leaching (Shepherd et al, 2010).

Table **1**. Main symbols in the model

Symbols	Description	Units
General		
TUN	Total amount urinary N excretion by the whole herd. Calculated from the variable Nur in Molly.	kg N/day
TUV	total urine volume deposited during a grazing event	m^3/day
UV	daily urine volume of each cow in the mob	L/cow/day
10000	Unit conversion	m^2/ha
1000	Unit conversion	mm/m
Grid		
pdkA	area of the paddock (pdk)	ha
nOfCells	total number of cells in the grid	cells/pdk
AperuG	constant representing the area covered by one urination (u): default 0.5 m^2	m^2/u
TnOfuG	total number of urinations per grazing event	
TUA	total area of all the patches at one grazing event	m^2
UNrG	N deposition rate on the single urine patch	kg N/ha
Probabilistic		
nu	total number of urinations from one cow in a day	u/cow/day
Vperu	volume of a single urination from one cow	L/u
µVperu	average volume per urination for all the cows in the mob on a particular day	L/u
AperuP	area covered by one urine patch	m^2/u
TnOfuP	total number of urinations during a grazing event	
UNrU	N deposition rate on the single urine patch	kg N /ha
UNrO	N deposition rate on overlapped urine patches	kg N /ha

Within APSIM (version 7.3) the pasture crop was simulated using a version of the model described by Romera et al (2009) adapted for APSIM. The default models in APSIM, SoilN (carbon-nitrogen dynamics) and SoilWat (soil water model) were used (Probert et al., 1998) in this first version of the UPF. Future versions could use a more sophisticated soil water module (SWIM, Huth, et al., 1996) if required.

2.2. Grid method

For each paddock the UPF creates a grid with equal size cells. The size of each cell was set to ¼ of a urine patch. APSIM runs for each cell from the beginning to the end of the simulation. A necessary assumption for this method was a constant area per urination (AperuG) for all the grazing events throughout the simulation (0.5 m^2 in this study). The area of the cells and of the urine patches are input parameters that can be modified by the user.

The total number of cells (nOfCells) per paddock was calculated as:

$$\text{nOfCells} = \frac{\text{pdkA} \times 10000}{\frac{\text{AperuG}}{c}} \tag{1}$$

where: c = cells per urine patch (4 in the examples that follow), i.e. each cell has an area equivalent to ¼ of the assumed urine patch area.

For example, if the size of the urine patch is 0.5 m^2 and the size of the paddock is 1ha, then the number of cells required would be 80000 [=10000/(0.5/4)].

The number of urinations per grazing event to be applied to the Grid (TnOfuG), can be calculated as:

$$TnOfuG = \frac{TUA}{AperuG} \quad (2)$$

where: $$TUA = \frac{TUV}{\frac{urineColumn}{1000}}$$

The N deposition rate on the urine patch (UNrG, kg N/ha) was:

$$UNrG = \frac{TUN}{TUA} \times 10000 \quad (3)$$

All the urination events are randomly applied to the cells of the grid, giving different temporal urination patterns. The number of cells to run can be pruned by grouping those cells affected by the same urination pattern (urinated on the same date/s) and by collating all the non-urinated cells into one. The opportunity of pruning diminishes as the number of grazing events increases.

2.3. Probabilistic method

After a single grazing event there are areas of the paddock either not urinated upon (B), urinated upon once (U) or more than once (O) (i.e. 3 categories). After 2 grazing events, there are 9 possible combinations of categories (patterns), and after 3 grazing event, there will be 27 possible patterns ranging from BBB where an area receives no urine on each occasion, to OOO where an area receives urine more than once on each occasion, and so on.

The number of possible patterns increases exponentially with the number of grazing events. On average, for each paddock there could be around 12 grazing events in a year, which would create 3^{12} (531441) patterns. Using the APSIM model, and considering a run time of 4 sec per simulation year, it would take approximately 24 days to simulate one paddock for one year, or 480 days for a farm with 20 paddocks. Based on the processing constraints, a series of simplifications were implemented.

The main simplification used in the Probabilistic method was based on the assumption that the effect of one urination event can be neglected after certain number of months following deposition (months to remember hereafter). This implies that the full simulation period (i.e. the WFM run) can be subdivided into periods of time (months to remember + 1 month), which keeps the exponential explosion in the number of urination patterns under control. Nitrogen leaching results are collected only in the last month of the period, whereas the previous months are used to initialize and populate the soil model with relevant historical information (urination events, fertilization, defoliations and climate).

Other specific assumptions involved:

- Patch sizes vary between grazing events reflecting the variation in urine volume per urination (approximately 0.2 m^2/L), which in turn varies as calculated in equation (5). Although, the urine patches were considered to be the same size within each grazing event (AperuP).
- The amount of N in each urination was the average for that herd for that grazing event. That is, although cows are simulated individually and produce different amounts of N, all urine patches of the same grazing event will have identical N amount: total urinary N of the herd divided by total number of urinations (TnOfuP, see below).
- All overlapped (2 and more overlaps) patches were combined (weighted average N deposition rate) within each grazing session into one category (O); and
- Patterns that represent a very low proportion of the urinated area were not simulated. Patterns were sorted by probability, and those that together accounted for less than 1% of the urinated area were omitted. The urinary N in these cells was evenly distributed among the other patterns, proportional to their area.

Volume per urination

For each cow, each day, the total number of urinations is:

$$nu = \frac{UV}{Vperu} \quad (4)$$

Vperu was preliminarily calculated by assuming that the frequently quoted figure of 2.5 L corresponds to an average New Zealand crossbred adult cow with a live weight (LW) of 486 kg. The single-urination-volume of any other adult cow was calculated as: adultVperu = 2.5 /486 × MW (MW is mature weight, kg). The Vperu for young cows was assumed to be proportional to their metabolic weight relative to mature metabolic weight:

$$Vperu = adultVPeru \times \left(\frac{LW}{MW}\right)^{0.75} \quad (5)$$

The total number of urinations (TnOfuP) is the sum of nu for all the cows grazing the paddock. The average volume per urination (µVperu) is the average for all the cows in the mob on a particular day.

Area per urination

The area covered by a single urination (AperuP, m^2/urination) was calculated assuming a urineColumn of 5 mm (McGechan and Topp, 2004) and a cylinder shape, and is described as:

$$AperuP = \frac{\mu Vperu}{urineColumn} \quad (6)$$

Area affected at paddock level

The Poisson distribution (see de Klein, 2001) was used to calculate the proportion of the area of the paddock covered by each category within a grazing event:

$$p(D, r) = \frac{e^{-D} \times D^r}{r!} \quad (7)$$

where: D = excretal density, which is the total area of all the patches on one grazing event put together as a proportion of the total paddock area, $D = \frac{TnOfuP \times AperuP}{pdkA}$; r = number of excreta on the same area (0, 1, or 2), i.e. levels of overlapping; TnOfuG = total number of urinations during a grazing event, i.e. the sum of nu (equation (4)) for all the cows in the mob.

The proportion of area not urinated is $p_{(D,r=0)}$, for the area urinated once is $p_{(D,r=1)}$ and for the area urinated more than once [i.e. $p_{(D,r>1)}$], the proportion was calculated as the remaining area: $p_{(D,r>1)} = 1 - p_{(D,r=0)} - p_{(D,r=1)}$.

When several grazing events are combined, the probability of each pattern was calculated as:

$$P(D_{1...n}, r_{1...n}) = \prod_{i=1}^{n}(D_i, r_i) \quad (8)$$

where: i = ith grazing event; n = number of grazing events being considered; D = excretal density on the ith grazing event; r = number of overlapping on the same area in the ith grazing event.

Urinary N deposition rate

Within one grazing event, the rate of urinary N applied (kg N /ha equivalent) on a single urination (UNrU) depends on the average amount of N per urination and the area covered by one urination.

$$UNrU = \frac{TUN}{TnOfuP \times AperuP} \times 10000 \quad (9)$$

Since the areas urinated more than once are to be collated, the N rate on such area (UNrO, kg N/ha) will be calculated as:

$$UNrO = \frac{TUN - UNrU \times pdkA \times p_{(r=1)}}{pdkA \times p_{(r>1)}} \quad (10)$$

2.4. Comparison between methods

A typical 'all pasture' Waikato dairy farm was set up in the WFM, with a stocking rate of 3.4 cows/ha, grazing all year round on perennial ryegrass pastures. Nitrogen fertilizer was applied at a rate of 230 kg N/ha/year, spread over five applications. Paddocks were rotationally grazed, with grazing rounds of 30-100 days in winter; 20 days in spring; 30 days in summer and 40-80 days in autumn. The calving season was July-August and the herd was milked until the 10th of May when cows were dried off. Replacement cows were purchased as 2 year olds at the end of May. First, the effect of the number of months to remember (from 6 to 12) in the Probabilistic method was analyzed for the year 2005 in one out of 15 paddocks simulated in the WFM scenario. The WFM and the UPF were run for the years 2004 and 2005, but only the second year was analyzed, i.e. after a meaningful history of urination patterns was established. Second, the N leaching results from both methods were compared. In this case the WFM and UPF were run for 8 pairs of years (2000-2001 to 2007-2008) for 2 paddocks, again taking the second year for the comparisons.

3. RESULTS AND DISCUSSION

Both methods converged when the number of months to remember was around 9-10 months. Even with 10 months to remember, the Probabilistic method was computationally more efficient, taking less than half the time for the 2 year runs compared to the Grid method. Furthermore, it was estimated (results not shown) that the Grid method would have taken approximately 230 days for a 10 year run with the computer used for this study (Intel® Core™ CPU, 4300 @ 1.8 GHz, 1.79 GHz, 0.98 GB of RAM), whereas the Probabilistic method completed this task in less than 2 days. For a 2 year run, both methods would take more or less the same time with about 14 months to remember.

With 8 pairs of years simulated, using 10 months to remember in the Probabilistic method, both methods produced similar patterns (R^2 = 86%) in terms of annual N leaching (Figure 1a). The average annual N leaching was similar (37.0±14.5 vs. 38.1±10.9 kg N/ha/year, for Grid and Probabilistic method respectively). In most of the years, the Probabilistic method predicted slightly more N leaching than the Grid method, except for 2008. The reasons for this inversion need to be investigated further, but it could be related to the worst drought on record in the Waikato region. The average monthly distribution of N leaching was also very similar between methods (R^2=96%), with a large proportion of N leaching happening in winter (Figure 1b).

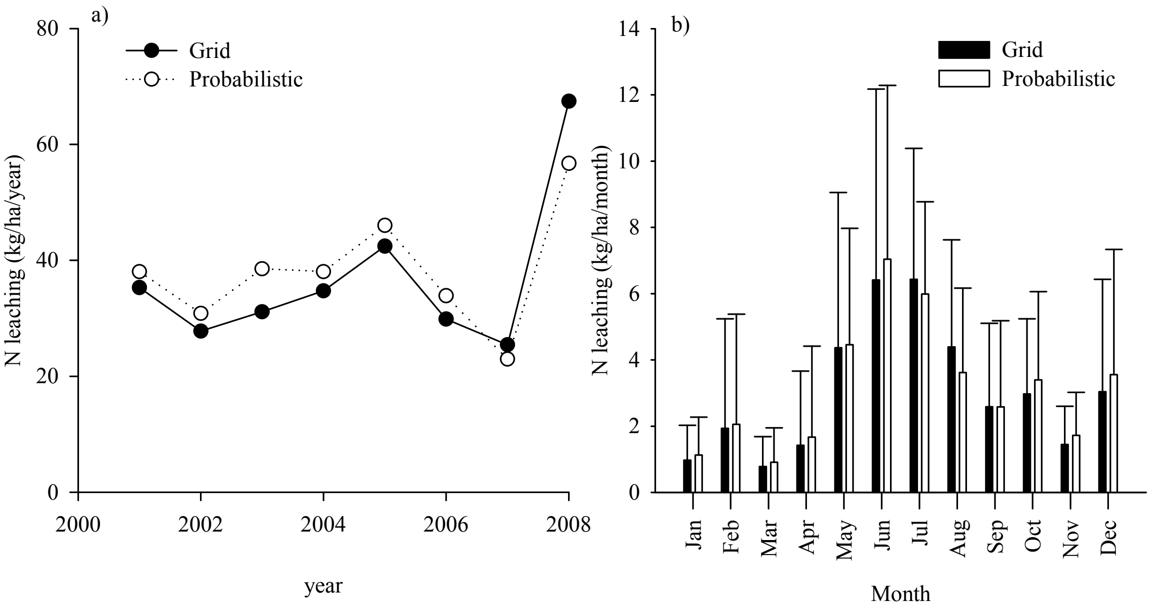

Figure 1. Comparison between the Grid and Probabilistic (10 months to remember) methods. a) annual N leaching and b) monthly distribution of N leaching and standard deviation. Average of two simulated paddocks.

The Grid method represents a spatial simplification, whereas the Probabilistic constitutes a temporal simplification. Both methods show advantages and disadvantages. The Grid method could enable the inclusion of dung patches and grazing strips in the simulation whereas the Probabilistic method could be used to study longer simulation periods, with acceptable computing times. Further model development may include the representation of uneven urine patch distribution, the inclusion of fecal N and the use of the SWIM soil water model in APSIM.

4. CONCLUSIONS

The two methods compared here are equally useful, with advantages and disadvantages that determine which one is more appropriate for different circumstances. The Grid method is more appropriate when dung patches need to be represented, for example to account for soil carbon balances. The Probabilistic method is faster and produces similar estimations of N leaching. Further work will evaluate the UPF against observed data and study the effect of urine deposition timing on N leaching.

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