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Using a whole farm model linked to the APSIM suite to predict production, profit and N leaching for next generation dairy systems in the Canterbury region of New Zealand

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Abstract: Management options were explored using DairyNZ's Whole Farm Model (WFM) to predict farm-scale milksolids (MS = fat + protein) production and operating profit. Predictions of urinary-N excretions from individual cows were linked to the Agricultural Production System Simulator (APSIM) suite via a Urine Patch Framework (UPF) to estimate N leaching on a farm scale while accounting for urine patches and patch overlaps. The UPF provides the inputs for soil, pasture and crop models in APSIM to simulate soil water, carbon and N dynamics and leaching on an individual urine patch scale. APSIM simulation outputs are then fed back into the UPF, which aggregates the patch-scale predictions up to paddock and farm level to give a mechanistic prediction of N leaching per hectare for the modelled farm. The paper focuses on the methodologies, and demonstrates utility of the WFM-UPF-APSIM linked model by presenting the results for a Canterbury irrigated milking enterprise.

The Lincoln University Dairy Farm (LUDF) was used as the baseline farm for the region; it represents a high performing system typical of the Canterbury region. For the 2009/10 farming season, LUDF had a stocking rate of 4.15 cows/ha, with average genetic merit of the cows (Breeding Worth; BW) of NZ$92, used 200 kg fertilizer N/ha/yr, and imported 250 kg DM per cow of pasture silage. The WFM predicted production (1718 kg MS/ha) and operating profit ($4348/ha) with acceptable accuracy compared to the observed for LUDF for that season (1710 kg MS/ha and $4696/ha). From this baseline, two development pathways were investigated. The first pathway focused on intensification (More Milk = MM), whereby stocking rate increased to 5 cows/ha, average BW increased to 150, N fertilizer rate increased to 400 kg/ha, and imported grain was fed at 600-1000 kg DM/cow/yr. The second pathway (Better Efficiency = BE) was focused on reducing inputs and improving production efficiency by decreasing the stocking rate to 3.5 cows/ha, decreasing the N fertilizer rate to 150 kg/ha, and limiting purchased grain supplement to 100 kg DM/cow/yr. Simulations were conducted over 10 consecutive years from June 2000 – May 2010 using climate and economic inputs from the National Institute of Water and Atmospheric Research and the DairyNZ Economic Survey. Average MS and profit were higher in MM compared with LUDF and BE, but variability of profit ("risk") did not differ between scenarios. N leaching was substantially higher in MM, which means that it would only be a feasible option if a low cost technological solution was available, environmental regulations were lenient, or N leaching targets were set at a catchment rather than a farm scale. The models predicted that MS output per farm would decrease in BE, but operating profit could be maintained compared to LUDF. At a regional or catchment level it would still be possible to increase MS production providing extra land was available for expansion. Because of the low leaching losses in BE, approximately 30 kg N/ha/year, the total N leached on a regional basis could still be reduced.

A new piece of software that links an existing whole farm model with mechanistic soil, carbon and N models (in the APSIM suite) provides the capability to predict N leaching from complex distributions of urine patches in space and time. The combined capabilities of the models enable the user to predict key outcomes for dairy systems i.e. production, profit and N leaching. Future work should focus on representing soil variability within and between paddocks, and distributed computing facilities to spread the high computing load.

Keywords: *Urine patch, system design, environmental impact*

1. INTRODUCTION

A big challenge facing dairy farming in New Zealand is to hold or reduce the environmental footprint of dairying while increasing productivity. In the Canterbury region there are opportunities to re-design the irrigated milking platform (block of land where the lactating cows are kept) with options like improved cow genetics, changing stocking rate, increasing cow pasture intake and per cow milksolids (MS = fat + protein) production, using nitrification inhibitors (Di and Cameron, 2007), changing nitrogen (N) fertilizer rates, and manipulating the diet to reduce urinary-N excretion. The likely effects of these various options need to be determined before new management systems are compared in farm-scale experiments so that investment is focused on the combinations that have the greatest potential benefits for productivity and the environment.

Most of the shallow groundwater in Canterbury has nitrate-N concentrations > 3 mg/L and 8% of wells exceed the Ministry of Health maximum acceptable value of 11.3 mg/L (Abraham and Hanson, 2010). *Escherichia coli* bacteria are also present in many of the shallow bores in Canterbury. The values of these indicators of ground water contamination will increase with the expansion and intensification of dairy farming if mitigation strategies are not implemented. Given this situation, it will be necessary for farmers to adopt a range of technologies and management practices that minimize loss of N from the dairy system.

Nitrogen intake by grazing animals far exceeds N output in products and between 75 and 90% of N ingested by dairy cows is excreted. This N is returned to the pasture in urine patches with N loadings between 500 and 1000 kg N/ha (Whitehead, 1995). Considering urine patches and patch overlaps has been shown to add high complexity and computational demand to models that predict N leaching from grazed pastures (Shorten and Pleasants, 2007). In previous models, overlap has been assumed to be unimportant (e.g. Di and Cameron, 2000), although they warned that this assumption may be an over-simplification. Pleasants et al. (2007) concluded that, at the same overall stocking rate, a grazing strategy that increases the frequency of urine patch overlaps over a short period of time (like high stocking densities in winter) would result in an increase in the expected N leaching. In assessing the importance of overlap, it is not only the probability of a point on the ground receiving urine more than once, which is low during a year, but also the proportion of the urine volume that is deposited on a previous urine patch. Shorten and Pleasants (2007) estimated that, on average, 38 and 61% of the urinary-N can be leached from single and double patches, resulting in a double urine patch leaching about 3 times more N than a single patch (Pleasants et al., 2007).

This paper describes how DairyNZ's Whole Farm Model (WFM) was used to explore combinations of management options to predict milk production and operating profit. Predictions of urinary-N excretions from individual cows were linked to the Agricultural Production System Simulator (APSIM: Keating et al., 2003) suite via a Urine Patch Framework (UPF) to predict N leaching losses on a farm scale while accounting for urine patches and patch overlaps. The UPF provides the inputs for soil, pasture and crop models in APSIM to simulate soil water, carbon, N dynamics and leaching on an individual urine patch scale. APSIM simulation outputs are then fed back into the UPF, which aggregates the patch-scale predictions up to paddock and farm level to give a mechanistic prediction of N leaching per hectare for the modelled farm. This paper focuses on the methodologies, and demonstrates utility of the WFM-UPF-APSIM linked model by presenting the results of a Canterbury irrigated milking platform.

2. METHODS

The study was conducted in two stages. The first stage involved the development of the modelling tools and the second stage the application of the models to the research task of designing a dairy system with increased production and profitability, but with reduced nutrient loss to the environment. The methodology follows these two steps by first describing the software that was coded (UPF) to post-process the results generated by the existing WFM. The UPF invokes and runs detailed soil and pasture models in the APSIM suite to simulate soil and plant processes that occur in a urine patch. The UPF

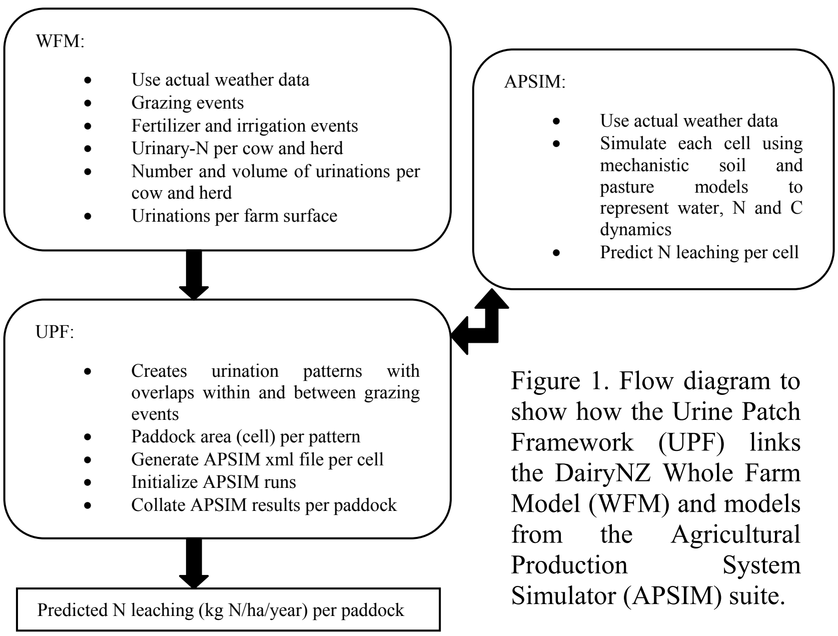

Figure 1. Flow diagram to show how the Urine Patch Framework (UPF) links the DairyNZ Whole Farm Model (WFM) and models from the Agricultural Production System Simulator (APSIM) suite.

receives output from APSIM for all the individual urine patch simulations, which is then collated and scaled to paddock and farm level (Figure 1). The second step involved the initialization of the baseline dairy farm in WFM, and the re-design of this baseline farm along two pathways in an attempt to lift productivity and profitability while reducing N loss to the environment. The baseline and re-designed systems were simulated with the WFM-UPF-APSIM linked models for 10 consecutive climate years to predict milk production, profitability and N leaching.

2.1. Linking WFM to APSIM via the UPF

DairyNZ Whole Farm Model (WFM)

The WFM (Beukes et al., 2008) represents a pasture-based dairy farm with individual paddocks and cows simulated on a daily time step. Molly is a mechanistic and dynamic model that simulates cow metabolism in the WFM (Hanigan et al., 2009). Molly represents the critical elements of digestion and metabolism of a dairy cow. The cow's production is influenced by the quantity and quality of feed and by her metabolic capacity to absorb and convert nutrients into milk (i.e. genetic merit). Molly's feed intake is driven by metabolic demand. Feed quality is described in a feed composition table in the WFM where the user defines feed fractions for all feeds used in the farm system. The feed fractions are processed through Molly's digestive system and nutrients absorbed into the bloodstream. The metabolic energy content of the feed is, therefore, not an input, but a product of digestion and absorption. Molly predicts enteric methane (CH_4), urinary-N, faecal-N, milksolids (MS = fat + protein) and milk urea-N.

The pasture model in WFM (Romera et al., 2009) is climate-driven using weather data as provided by the National Institute of Water and Atmospheric Research (NIWA) from the nearest weather station, or using interpolations from the nearest weather stations (virtual climate) for a particular location. Pasture growth responds to N applied as either mineral fertilizer or irrigated effluent N. Some or all paddocks can be irrigated according to a user-defined irrigation policy. Pasture response to irrigation water is determined by soil moisture levels at the time of irrigation. Paddocks are grazed rotationally. Post-grazing herbage mass influences pasture re-growth. Paddocks can be eliminated from the grazing rotation for all or part of the year as part of a cropping policy e.g. maize, cereal or brassica crops. Supplements (home-grown or bought) can be fed to cows according to policies created by the user. Other user-defined policies related to cow management include breeding, grazing off the farm, drying off, culling and replacement.

In the WFM, the deposition of the excreted N (urinary- and faecal-N) from each cow is based on the proportion of the daily active time spent on different surfaces (pasture, bark-covered standoff pad, milking shed, races and concrete feed pad). The following rules were used:

- Cows rest 8 hours a day (i.e. total active time = 16 hours);
- Cows excrete only when they are active (i.e. not resting);
- Cows never rest on hard surfaces (i.e. milking shed, races, concrete feed pad);
- Active time on hard surfaces is user-defined and is determined by farm set up and management. Default settings are 4 h/day in the milking shed, 1 h/day on the races for twice-a-day milking. The user sets the time on the concrete feed pad (h/day) in the supplement feeding policy;
- The resting time on pastures is determined as a function of the time spent on pastures and the total time on soft surfaces;
- The resting time on the standoff pad is the difference between 8 h and the resting time on pastures;
- The number of urinations is proportional to active time on each surface [i.e. urination proportion on surface = active hours on surface / (total active time)];
- Only the fate of urinary-N directly excreted onto pastures was analyzed in this study; and
- Faecal-N was ignored because of the relatively slow release of NH_4^+ from the organic N in dung, and therefore the minor importance of this source to N leaching losses (de Klein and Eckard, 2008).

Agricultural Production System Simulator suite (APSIM)

APSIM is a suite of models that provides a flexible structure for the simulation of climatic and soil management effects on growth of crops and pastures in farming systems (Probert et al., 1998). SoilWat, the default soil water model in APSIM, is a cascading layer model (Probert et al., 1998). For this exercise, SoilWat was parameterized to describe a Templeton fine sandy loam (Immature Pallic Soil) with 6 layers (0-18, 18-33, 33-55, 55-73, 73-100 and 100-150 cm).

SoilN and SurfaceOM are the APSIM modules simulating nitrogen turnover in the soil, and decomposition of surface organic matter, respectively. SoilN provides a balance of both carbon and nitrogen in the soil and includes a labile soil organic matter pool that decomposes more rapidly than the bulk of the soil organic matter. SurfaceOM is a mechanistic model of surface residue decomposition that is able to maintain the correct carbon and nitrogen balances (Probert et al., 1998). The combination of SoilWat, SoilN and SurfaceOM simulate the dynamics of water, carbon and N in the soil. For this exercise, each urine deposition was simulated as the appropriate amount of N applied as fertilizer plus 5 mm of water as irrigation. The N was applied in depth by uniformly distributing it amongst the first four soil layers to represent preferential flow of urine through soil macropores. This was a simplification as the initial wetting pattern (area and depth) and volume of soil affected depends on the volume of the urination event, soil type and soil moisture (Stout, 2003). Nitrate-N flowing below 100 cm (layer 5) was considered as leaching.

Pasture growth in APSIM was simulated using a version of the pasture model described by Romera et al. (2009) adapted for APSIM. The adaptation included the use of the root module part of the Plant2 (generic plant model in the APSIM suite), which enables N and water uptake by the pasture. Also, the senescent tissue from the aerial parts of the pasture contributes to SurfaceOM. The same weather files used in the WFM simulation were used to drive the weather-dependent models in APSIM.

Urine Patch Framework (UPF)

The UPF was coded in Smalltalk (©Instantiations Inc 1994, 2010) to extract the necessary output from a WFM simulation, to organize the input for the APSIM simulation for each urine patch, to collect the output from each APSIM simulation and to collate and scale the results to paddock and farm level. The role of the UPF is to generate the xml files for the APSIM simulations that include the soil description, the urine applications, nitrogen fertilizer applications, and irrigation and defoliation events. WFM output is used to generate the urine, fertilizer and irrigation applications and defoliation dates. Cow grazing is not simulated in APSIM, so defoliation events are simulated as pasture cuts according to the dates and post-grazing herbage masses reported by the WFM. The feedback from the urine patch soil to animals via pasture differential responses was not represented.

The process involves the following main steps:

- The WFM runs for at least 2 years. The data from the first year of the WFM run are necessary to stabilize water and nutrient pools in APSIM. Data from the second year are used to generate N leaching predictions from APSIM;
- The WFM generates urine deposition information, plus other management events at a paddock level. This includes the number of urinations, amount of N excreted (kg N), urine volume (Litres) and paddock area (ha) for each grazing event;
- Using the WFM information, the UPF generates cells (m^2) for each paddock with different urination patterns according to dates of deposition and amount excreted on each date;
- The UPF generates an input file (.xml) for each cell for APSIM to run; and
- The UPF collects leaching results from each APSIM run, and collates it per paddock per day.

The generation of the cells with different urination patterns per paddock is a major component of the UPF and is described in detail by Romera et al. (2011). Romera et al. (2011) also present validation results for the WFM-UPF-APSIM linked model.

2.2. Development of the baseline and future farm scenarios

The Lincoln University Dairy Farm (LUDF) was used as a baseline to compare two future farm scenarios. LUDF represents a well-documented commercial-scale farm with excellent production and economic performance (van Bysterveldt and Christie, 2007). The first scenario - More Milk (MM) - represents further intensification along the current pathway and assumes cows with increased genetic merit (Breeding Worth; BW), greater use of N fertilizer, higher stocking rate and the option of using large amounts of supplementary grain feeding. This scenario aims to deliver more milk and profit per farm but will come with a greater environmental footprint, and so could operate only if new technologies can reduce this footprint or lenient regulations exist. The second scenario - Better Efficiency (BE) - represents an alternative pathway with cows of even higher genetic merit, reduced N fertilizer, lower stocking rate and lower grain input than MM. The Better Efficiency option aims to equal current LUDF milk production (although it represents an increase of

35% from current Canterbury average MS per ha) and profit, but with a reduced environmental footprint. Some key characteristics of LUDF and the future scenarios are given in Table 1.

The milk payout was assumed to be NZ$6.10/kg MS and prices for 2008-09 (DairyNZ, 2009) were used in the simulation. For all scenarios, replacement cows were produced on farm but grazed off together with all dry cows. Variable costs were a driver of differences in operating profit because the three scenarios differed quite markedly in cow numbers. No allowance was made in the scenarios for differences that may arise in labour skills required, extra milking time because of milk yield and herd size differences, or differences in animal health or reproductive performance. The calculation of economic parameters followed DairyNZ Economic Survey guidelines (DairyNZ, 2009).

Table **1**. Key features of Lincoln University Dairy Farm (LUDF) and two future farm scenarios, More Milk (MM) and Better Efficiency (BE)

	LUDF	MM	BE
Stocking rate (cows/ha)	4.15	5.0	3.5
Cow genetic merit (BW, $)	92	150	180
N fertilizer (kg N/ha/year)	200	400	150
Grain (kg/cow/year)	none	600-1000	100

2.3. Simulations and measurements

The WFM was first used to simulate the actual production (kg MS/ha) and operating profit ($/ha) from known starting conditions and management decisions for LUDF for a single farming season, June 2009 to May 2010. Actual weather data from the Lincoln weather station were used. Since Economic Survey data for 2009/10 were not available at the time of the exercise, economic input data for the 2008/09 season were used but the milk payout was increased to NZ$6.10/kg MS to reflect the actual payout for the 2009/10 season. Using the same weather and economic input, the WFM was used to simulate production and profit from the MM and BE scenarios for a single year. N leaching (kg N/ha/yr) from the three scenarios was predicted using the WFM-UPF-APSIM linked model. No account was taken of the effects of winter grazing off or forage or grain crop production off farm on environmental outcomes. Although it was an acceptable simplification for this exploratory study with the new linked model, these activities will have to be accounted for in the future since it has become increasingly accepted that a full Life Cycle Assessment (LCA) of any agricultural enterprise must take account of the environmental effects of all factors associated with food production.

In an attempt to evaluate the variability in production, profit and N leaching (mean, STDEV) as affected by weather and economic inputs each of the three scenarios was simulated with WFM-UPF-APSIM over 10 consecutive climate years from the Lincoln weather station, June 2000 – May 2010. It should be noted that simulations over consecutive years incorporate the carry-over effects of pasture covers, feed stores, cow condition, and breeding performance from year to year, which confounds the effects of weather and economics of a particular year on the performance measures of that year. WFM has a database with historic economic input data, and in these multiple-year simulations WFM automatically changes the economic input, including milk payout, according to the simulated year.

Table **2**. Farm physical, economic, and N leaching predictions from WFM-UPF-APSIM for the Lincoln University Dairy Farm (LUDF), More Milk (MM) and Better Efficiency (BE) farms for the 2009/10 season

	LUDF	MM	BE
Physical			
MS produced (kg/cow)	414	437	453
MS produced (kg/ha)	1,718	2,184	1,588
Pasture harvested (grazed plus cut for silage, kg DM/ha)	16,814	18,105	16,025
Purchased feed (kg DM/cow)	305[1]	800[2]	100[3]
Peak cows milked (cows/ha)	4.15	5.0	3.5
Mean lactation length (days)	266	280	277
Economic			
Operating profit ($/ha)	4,348	4,810	4,334
Leaching			
N leached (kg N/ha/yr)	25	38	24

[1]= pasture silage [2]= barley grain [3] = maize grain

3. RESULTS

The WFM was able to simulate the actual total production for LUDF for the 2009/10 season very well, predicting production (1718 kg MS/ha) and operating profit ($4348/ha) with acceptable accuracy compared to the observed for LUDF for that season (1710 kg MS/ha and $4696/ha). This lends confidence to the model predictions for the two future scenarios (Table 2). A summary of the results of the multiple-year simulations are presented in Table 3.

4. DISCUSSION AND CONCLUSIONS

Urine patches and patch overlaps cannot simply be ignored in modelling N leaching from pastoral dairy systems. This is confirmed by the results from test simulations over one year showing that up to 39% of the total urine volume was deposited on overlapping urine patches covering 8% of the paddock area. This is important when comparing dairy systems with changes in management variables, such as stocking rate and rotation length, which changes the magnitude of urine overlaps. The approach implemented here, which used probability theory for calculating areas of urination and overlaps within and between grazing events (probabilistic method, see Romera et al., 2011), showed promising results.

WFM predictions for the 2009/10 season for LUDF (baseline) and two future scenarios showed production (MS/ha) changed by 27% and -7.6% for MM and BE scenarios, respectively, compared with LUDF (Table 2). The result for the former was driven by the stocking rate of 5 cows per ha; for the latter, although MS yield per cow was high, the constraint on N fertilizer and grain use meant that a stocking rate of only 3.5 cows per ha could be supported. The results of the multiple-year simulations showed a lower climate-driven variability in MS per ha for BE (Table 3).

Nitrogen leaching changed by 23% and -17% for MM and BE, respectively, compared with LUDF (Table 3). The MM scenario showed clearly what happens to N leaching when attempts are made to achieve the full milk production potential of a system based on grazed pasture. The combination of high temperatures and solar radiation for 9 months of the year and alleviation of soil water deficit by irrigation means that pasture will respond to high levels of N fertilizer. Returning urine to pasture from 5 cows per ha for 9 months results in large N leaching losses from urine patches. This scenario would only be feasible if a low cost technological solution was available, environmental regulations were lenient, or catchment rather than individual farm targets were imposed for N leaching.

Milk cash income changed by 26.4% and -8.3% for MM and BE, respectively, compared with LUDF reflecting differences in MS produced per ha. Farm working expenses changed by 41.8% and -13.2 % for MM and BE respectively compared with LUDF reflecting the increased variable costs associated with a move to 5 cows per ha and the cost of extra N fertilizer and grain for MM; for BE a lower stocking rate reduced variable costs as did the lower inputs of N fertilizer. At the current payout (NZ$8/kg MS) and feed input prices MM is an attractive scenario. Although an intensified system, MM did not demonstrate a greater variability of profit ("risk") compared to LUDF and the de-intensified BE system (Table 3), meaning milk price and input costs were closely correlated over the time period of the multiple-year simulations (2000-2010).

Table **3**. Mean and coefficient of variation (CV) of production, profit and N leached for the Lincoln University Dairy Farm (LUDF), More Milk (MM) and Better Efficiency (BE) scenarios simulated over 10 consecutive seasons from 2000/2001 to 2009/10

	LUDF	MM	BE
MS production			
Mean (kg/ha)	1,679	2,170	1,578
CV (%)	4	4	2
Operating profit			
Mean ($/ha)	3,115	3,280	2,941
CV (%)	47	49	51
N leached			
Mean (kg N/ha/yr)	35	43	29
CV (%)	29	21	24

Scenario BE represents a situation where there are no feasible technological solutions and there are stringent regulations concerning N leaching and other pollutants at the individual farm level. In this situation, the models predicted that MS output per farm would decrease, while operating profit could be maintained. At a regional level it would still be possible to increase MS production providing extra land was available for expansion. Because of the lower leaching losses, approximately 30 kg N/ha/year, the total N leached on a regional basis could still be reduced. The requirement for support land would be substantially reduced because of the lower stocking rate and lower reliance for feed produced off-farm.

A new piece of software that links an existing whole farm model with mechanistic soil, carbon and N models (in the APSIM suite) provides the capability to predict N leaching from complex distributions of urine patches in space and time. Simplifications were required to speed up runtime, allowing the linked models to be used to explore potential farm scenarios over a number of consecutive climate years and economic inputs, within acceptable time frames. The combined capabilities of the models enable the user to predict key outcomes for dairy systems i.e. production, profit and N leaching. This utility was demonstrated for a Canterbury dairy platform. Future work should focus on representing soil variability within and between paddocks, and distributed computing facilities to spread the high computing load.

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