The Effect of Temporal Aggregation on Modelling Pasture Growth and Nitrate Leaching From Urine Patches

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EXTENDED ABSTRACT

In pastoral agricultural systems ruminants harvest nutrients from a paddock through grazing and return a large proportion of the nutrients to a small proportion of the soil. Urine patches have nitrogen (N) concentrations of 500-1000 kg N /ha, far in excess of the plant's requirements. While N uptake from, and pasture growth over, urine patches is normally accelerated, the excess N remaining under the patches is thought to be the primary source of leaching from pastoral farms. Simulation models of pastoral systems that include nitrogen cycling tend to simplify the description of excretal return. Most models assume uniform return of nutrients to the soils and while there have been some studies investigating the variability and distribution of urine patches only two simulation models were found in the literature that explicitly included urine patches.

Given the importance of urine patches to the leaching process it might seem questionable that they are not routinely explicitly included in models. However, the inclusion of explicit urine patches in a model is not trivial. Consider for example a system set-stocked for 3 months over lambing. If all urine patches created within a day were considered identical in size and N content then over 100 categories of patches would be needed for each simulation year arising from those three months alone. This has consequences for simulation model complexity and runtime. One approach to simplify this would be to reduce the number of categories by aggregating the urine patches in time.

Here we use a structured simulation approach to examine the potential error of aggregating urine patches in time. What might the error be if all the urine patches created in September, for example, were mimicked by applying the nitrogen to the soil on the last day of the month rather than on each day that the pasture was grazed?

The LUCI framework model with a perennial ryegrass–white clover pasture module was used to investigate the sensitivity of predicted N leaching and pasture growth to the day, within a month, that urine was applied to the pasture. All the simulations were done with daily weather data from Lincoln, Canterbury, New Zealand for the period from 1960 to 1999. Two soil types (Deep and Shallow) and two irrigation regimes (Dryland and Irrigated) were used in the simulations. Only days 1 to 28 and application months of Mar, Jun, Sep, and Dec were considered.

The temporal aggregation of the urine so that it was all applied on the last day of the month resulted in very little error in the simulation of pasture growth. Greater error was observed in the simulation of N leaching. Of the soil-management scenarios, the lowest errors were in the Shallow-Dryland scenario and the greatest error was the Deep-Irrigated scenario. For those scenarios while there was significant error (up to 18%) from some individual events once averaged over years and months the error caused by the temporal aggregation dropped to below 1%. This suggests that a temporal aggregation scheme might not be suitable for short-term simulations but might produce accurate and unbiased results in long-term simulations.

The temporal aggregation of urine patches shows promise but needs to be tested over longer time frames and in a wider range of soils and climates. The advantage of the scheme is that it may allow explicit description of urine patches in a paddock, and therefore greater realism in the simulation model while maintaining reasonable model runtime.

1. INTRODUCTION

In pastoral agricultural systems a large proportion (60-90%) of ingested nutrients are returned to the soil as excreta in the form of dung or urine (Haynes and Williams 1993). Excretions are not evenly distributed, covering only 10-30% of the pasture surface area and result in high concentrations of nitrogen (N) in the areas of the paddock receiving urine in particular. Concentrations of 500-1000 kg N /ha in the urine patch area can be considered typical (Haynes and Williams 1993). Such high instantaneous applications of N are beyond the capacity of the pasture to utilise and are the primary source of nitrogen leaching from pastoral farms (Decau *et al.* 2004; Silva *et al.* 2005).

Models describing N leaching from pastoral fields tend to simplify considerably the description of urine patches. Most models assume uniform return of nutrients to the soils (e.g. Green *et al.* 2003; Moore *et al.* 2007). While there have been some studies investigating aspects of the variability and distribution of urine patches (Pleasants *et al.* 2007), that have taken account of urine distribution in a modelling study (McGechan and Topp 2004), or that have included urine patches in an empirical model (Di and Cameron 2000; Wheeler *et al.* 2003) only two simulation models were found in the literature that explicitly included urine patches (Hutchings *et al.* 2007; Vellinga *et al.* 2001).

Given the extreme variation in soil N caused by urine patches it might seem questionable that such patches are not routinely explicitly included in models. However, consider a sheep-based system set-stocked for three months over lambing. Using typical stocking densities and number of urinations per day, this would result in over 18,000 urine patches for those three months alone. If all urine patches created within one day were considered equal and spatial considerations were excluded then still more than 100 categories of patches would be needed for each year of simulation. This has obvious negative consequences for simulation model complexity and execution time.

One approach to include the effects of urine patches while still keeping the number of categories of patches reasonable might be to aggregate the urine patches in time. Specifically, here we consider the case where the pasture is continuously grazed for a month but the urine from the grazing animals is accumulated and applied, to an appropriate area of the paddock, only at the end of the month. If such a scheme introduced an acceptable error compared to returning the urine on a daily basis then only a maximum of 12 urine patch categories would be needed each year.

Here we use a structured simulation approach to examine the potential error of aggregating urine patches in time. What might the error be if we assume that all the urine patches created in September, for example, were mimicked by applying the N to the soil on the last day of the month rather than on each day that the pasture was grazed? We examine the differences caused by this assumption in simulated N leaching and pasture growth for a Deep-Irrigated, Shallow-Dryland, and Shallow-Irrigated soils, in a Canterbury climate.

2. METHODS

2.1. Model Description

The LUCI framework model is a model of a flat paddock that can be started and run for an arbitrary length of time with any sequence of crops and pastures. The model also keeps track of the state of the system and the leakage of water and N from the system (Jamieson *et al.* 2006). Many of the crop modules are based on the wheat model Sirius (Jamieson and Semenov 2000; Jamieson *et al.* 1998) connected to a soil percolation and leaching model based on the cascade model of Addiscott and Whitmore (1991). Recently a perennial ryegrass-white clover pasture module (Snow *et al.* 2007) has been added to the system to allow exploration of cropping sequences that include a pasture fallow. The pasture module is a simple crop module based on radiation-use efficiency, similar to that described by McCall & Bishop-Hurley (2003) but includes resource partitioning to roots as well as shoots similar to the routines used in Huth *et al.* (2001). LUCI-Pasture is dynamically responsive to water following McCall and Bishop-Hurley (2003) and N availability following Huth *et al.* (2001). The clover content of the pasture is fixed during any simulation run but the amount of N fixed by the legume responds to the availability of mineral N in the root zone. Soil N mineralisation was modelled using the Sirius mineralisation routines (Jamieson *et al.* 2006).

2.2. Climate, Soils, and Irrigation

All simulations were done with daily weather data obtained from Lincoln (latitude -43.79, longitude 175.61) over the period from 1960 to 1999. Three soil and management combinations were simulated: Shallow-Dryland, Deep-Irrigated, and

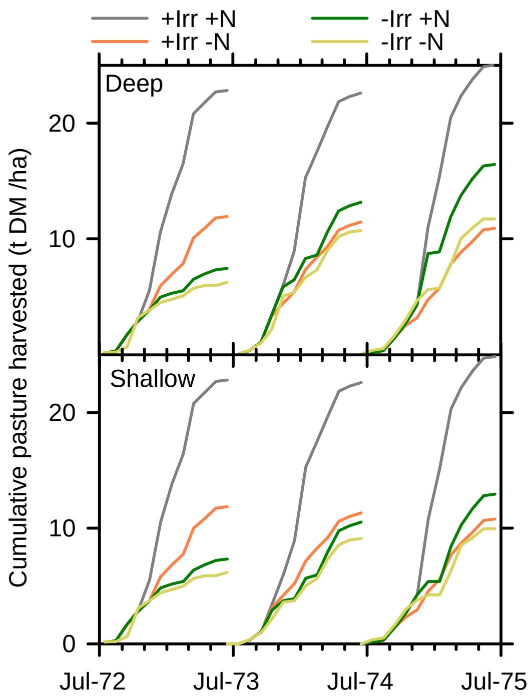

Figure 1. Response in the annual accumulations of the amount of pasture harvested to the addition of unlimited water and/or nitrogen to the Deep or Shallow soils

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Shallow-Irrigated. A Deep-Dryland combination was not included because such a system would have long transport times and was unsuitable for the short-term simulation approach used here. The Deep soil comprised 0.8 m of clay loam over a gravel subsoil to 1.5 m deep. The Shallow soil had 0.25 m of clay loam over the gravel. Such soils are typical of the Lincoln area. The physical properties of the soil layers were taken from the Temuka silt loam (New Zealand Soil Bureau 1968). Where required by the scenario, sufficient irrigation was applied to replace potential evapotranspiration every seven days between September and March inclusive.

2.3. Simulations and Scenarios

The objective of the simulations was to examine the potential variation that might arise if all the urine patches created during a month of set stocking were applied to the simulated soil on the last day of the month. In these scenarios we simulate just a single urine patch area and for its lifetime (4 years). A full matrix of simulations for the following factors was run:

- application day of month: 1, 2, … 28;
- application year: 1961, 1962, … 1994;
- application month: Mar, Jun, Sep, and Dec;
- soil-management: Shallow-Dryland, Deep-Irrigated, and Shallow-Irrigated.

This resulted in over 11,000 simulations. Each simulation was initialised in April the calendar year before the target application date. The pasture was sown on 1-April with 25 kg N of starter fertiliser at sowing and again one month later. Throughout the simulation the pasture was harvested to a biomass of 1500 kg DM /ha on a 21-day cycle with no return of nutrients to the soil. The simulation was run from sowing until the target application date when 1000 kg of urea-N was applied to the soil. The simulation was then allowed to run for 4 years after the end of the month in which the urea was applied. Records of the amount of N leached at 1.5 m deep and the amount of pasture harvested were kept for each simulation.

The variation caused by accumulating the urine to the end of the month was analysed by averaging the pasture harvested and the fate of the applied N for days 1 to 27 of any month and year and comparing the average to the appropriate values from application on day 28 of the month and year. All values were from the urine patch area and life-time (nominally 4 years) only and were expressed as averages or totals over the 4 years.

Initial simulations, to test the sensitivity of pasture production to water and nitrogen, were run under conditions of no added water or nitrogen and sufficient additions that one or other was not limiting growth.

3. RESULTS AND DISCUSSION

Initial simulations, to test the sensitivity of the scenarios to irrigation and N, were done by running simulations for the two soils with and without full irrigation (+Irr and –Irr) and N (+N and –N) fertilisation. Some typical results are shown in Figure 1. The Deep soil was more N responsive (in the absence of irrigation) than the Shallow soil and the opposite ranking applied with respect to irrigation responsiveness. On average over the 34 years of simulation, the addition of both irrigation and N had the capability of increasing the amount of pasture harvested from 9 and 8 t DM /ha yr in the Deep and Shallow soils to almost 22 t DM /ha /yr/.

A selection of simulations showing the variation in pasture and N leaching response over time as affected by soil and irrigation scenario as well as timing of application is shown in Figure 2. Pasture response to N application was largely complete in one year and showed about a 30-40% increase in the amount of pasture growth when

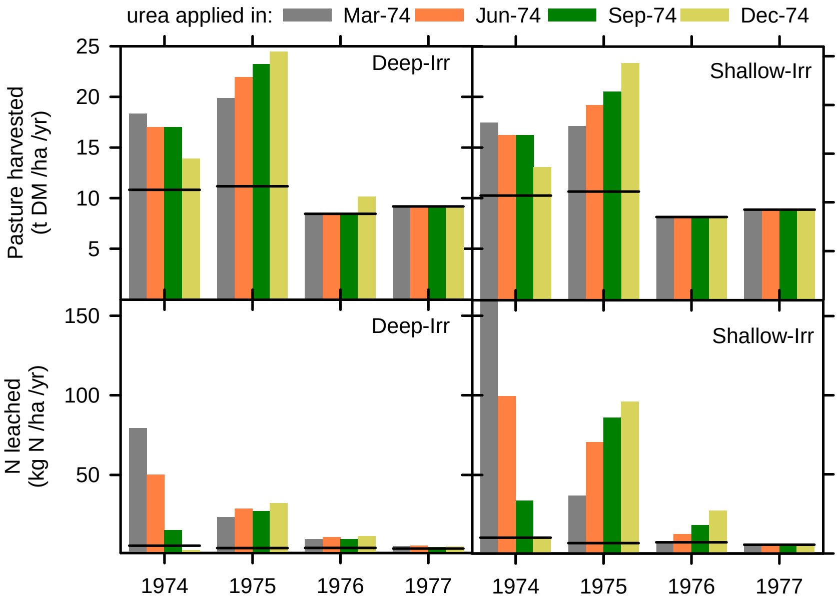

Figure 2. Annual pasture harvested or nitrogen leached following application of 1000 kg urea-N /ha on the first day of four different months to the Deep- or Shallow-Irrigated soils. The black lines show the no application case.

averaged over the four years of simulation. Neither soil type-management scenario nor month of application had much effect of the magnitude of the pasture growth response. Leaching from the urine-affected soil was 600-900% higher than the soil with no N application This is consistent with the observations that most of the N leaching in grazed pasture systems arises from the urine patch areas (Haynes and Williams 1993). In contrast to pasture growth, timing of application was important in N leaching with proportionately more leaching from the autumn and winter applications than the spring and summer applications (Figure 2).

The temporal aggregation proposed was that, during a set-stocked simulation, instead of creating categories of urine patches every day, a single category of appropriate size be created on the last day of the month. Figure 3 shows the percentage error in the pasture growth and Figure 4 show the error in N leaching from the urine patch areas alone arising from this assumption. The three soil-management scenarios are shown and the month of application. The box-whisker plots show the variation arising from the 34 application years.

While there was little error in pasture growth (Figure 3) arising from the temporal aggregation there was a consistent pattern with month of application. The temporal aggregation caused an overestimate of growth from the June and September applications and an underestimate from the March and December applications. The extremes were a 1.6% underestimate in December 1978 and a 0.75% overestimate in June 1991. Neither of these has any physical significance in a grazing system.

While the error in N leaching from the temporal aggregation (Figure 4) was about an order of magnitude greater than that in pasture growth. The pattern in the error with month of application was the inverse of that observed in pasture growth with leaching underestimated in the June and September applications. This arose because application on day 28 consistently pushed the application date later into the year when the probability of the N being leached passed the root zone before it could be taken up by the pasture was decreased.

The least error was observed in the Shallow-Dryland scenario. The leaching in the simulations with temporal aggregation in 98% of the cases (133 out of 136) was within ±5% of the no-aggregation simulations. The greatest errors were seen in the Deep-Irrigated scenarios. There 65% of the temporal aggregation cases were within ±5% and 88% of the cases were within ±10% of the no-aggregation simulations. While some of the errors in particular months were relatively high, e.g. 18% underestimate in September 1994 and a 15% overestimate in December 1988 for the Deep-Irrigated, these averaged out over the years and application months. Once the median error was taken across the application years, only one

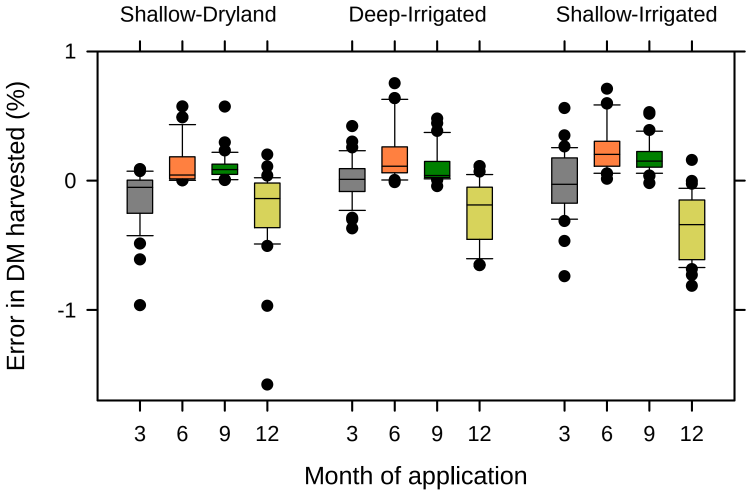

Figure 3. Percentage error in the amount of pasture grown resulting from temporal aggregation of urine patches created in March, June, September, or December for the three soil-management scenarios. The boxes show the 25th, 50th, and 75th percentiles, the whiskers show the 5th and 95th percentiles and the symbols show the outliers resulting from the 34 application years.

case (Deep-Irrigated December application) was more than ±5% error and after averaging across the application months (as would normally happen in a grazing simulation) all the errors were within ±1% of the no-aggregation case.

These analyses suggest that, for the conditions simulated here, while significant errors might be introduced by temporal aggregation for individual grazing days or months there is no bias of significance. Therefore for simulations that are run over many years and months, the temporal aggregation may be a useful step towards representing urine patches in simulation models while keeping the model complexity and runtime to reasonable levels.

Note that the simulations presented here are for the urine-patch area of the paddock only. However the pasture growth and leaching have been calculated for four years after the urine application. Because in most grazing systems (Haynes and Williams 1993) about 25-30% of the paddock is affected by urine per year, roughly, there is about a 4 year return period between applications. This does however depend on stocking rate and on how the pastures are managed but the 4-year results from the urine patch areas here are approximately equivalent to a whole-paddock average.

The simulations shown here are preliminary and test the potential variation arising from aggregating daily urine loads from set-stocked grazing to the last day in the month. This initial testing shows promise but needs to be repeated over longer time frames, in a wider range of soils and climates, and with the inclusion of volatilisation processes. Previous work (Lilburne *et al.* 2006) suggested that partitioning a paddock into urine and non-urine areas might be a useful way to scale up to simulation of whole-paddock leaching. Here we have begun investigation of how such a scheme might be implemented as explicit inclusion of all urine patches would lead to unacceptable model execution times. This scheme may provide a useful balance between explicit description of urine patches in a paddock, and therefore greater realism in the simulation model while maintaining reasonable model runtime.

4. CONCLUSION

Urine return from ruminants grazing pastoral systems effectively concentrates large amounts of N into relatively small areas of the paddock. This results in patches where the nutrients are far in excess of plant requirements and the excess N is thought to be the primary source of N leaching from pastoral farms. Most pastoral simulation models assume uniform return of nutrients to the soils, probably because of the large increase in model complexity and execution time that would be caused by explicit inclusion of patches. This study explores one approach that would allow the explicit inclusion of urine patches while still maintaining reasonable model execution time by aggregating the urine patches in time. We used a structured simulation approach to examine the

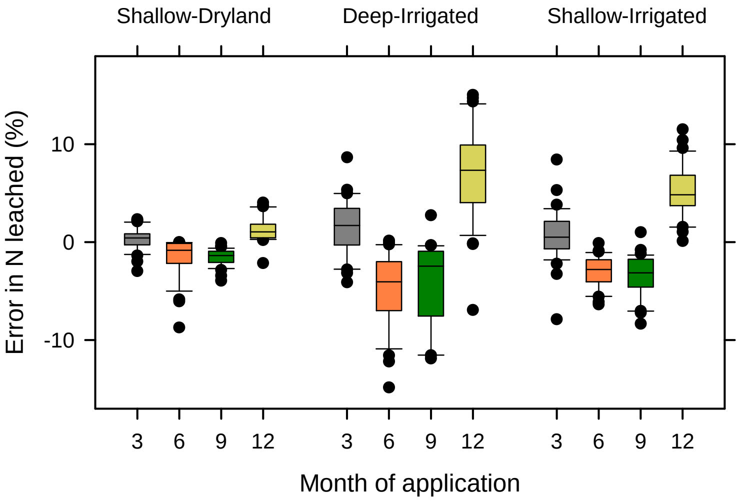

Figure 4. Percentage error in the amount of N leached resulting from temporal aggregation of urine patches created in March, June, September, or December for the three soil-management scenarios. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles, the whiskers show the 5^{th} and 95^{th} percentiles and the symbols show the outliers resulting from the 34 application years.

potential error arising from aggregating all the urine patches created within a month of set-stocked grazing into one application at the end of the month using the LUCI framework model with a perennial ryegrass–white clover pasture module.

The temporal aggregation of the urine so that it was all applied on the last day of the month resulted in very little error in the simulation of pasture growth. Greater error was observed in the simulation of N leaching. Of the soil-management scenarios, the lowest errors were in the Shallow-Dryland scenario and the greatest error was the Deep-Irrigated scenario. For those scenarios while there was significant error (up to 18%) from some individual events once averaged over years and months the error caused by the temporal aggregation dropped to below 1%. This suggests that a temporal aggregation scheme might not be suitable for short-term simulations but might produce accurate and unbiased results in long-term simulations.

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5. ACKNOWLEDGMENTS

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