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Development and desktop-assessment of a concept to forecast and mitigate N leaching from dairy farms

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Abstract: Pastoral systems are increasingly under scrutiny for the nitrogen (N) deposited via urine, faeces and fertiliser that is subsequently transported through the soil profile into water ways. Variation in land management, fertiliser N application rates, soil type, climate and year-to-year variation in weather all affect the rate and timing of N losses via leaching. To mitigate N leaching, a better understanding of the environmental conditions and the identification of early indicators that lead to high risk of N leaching are needed. To identify early indicators for risk of N leaching from urine patches we used the APSIM (Agricultural Production Systems SIMulator) model to produce an extensive N leaching dataset for the Waikato region of New Zealand. In total 198000 simulation runs with different combinations of urine deposition date, N loading, soil type and irrigation were done. The risk forecasting indicators were chosen based on their practicality: being easy to be measured on farm (soil water content, temperature and pasture growth) or that could be centrally measured (such as weather forecasting). The thresholds of the early indicators that are likely to forecast a period for high risk of N leaching were determined via classification and regression tree (CART) analysis. This concept is illustrated in Figure 1 for a soil with a medium soil depth, with soil plant available water of 125-150 mm. The identified early indicators were then used within a N risk tool, based on a traffic light system, to trigger duration controlled grazing in a desktop evaluation to reduce N leaching on a paddock scale. Predicted reductions in N leaching ranged from 20 to 45%, depending on the number of indicators used and the risk alertness of the farmer.

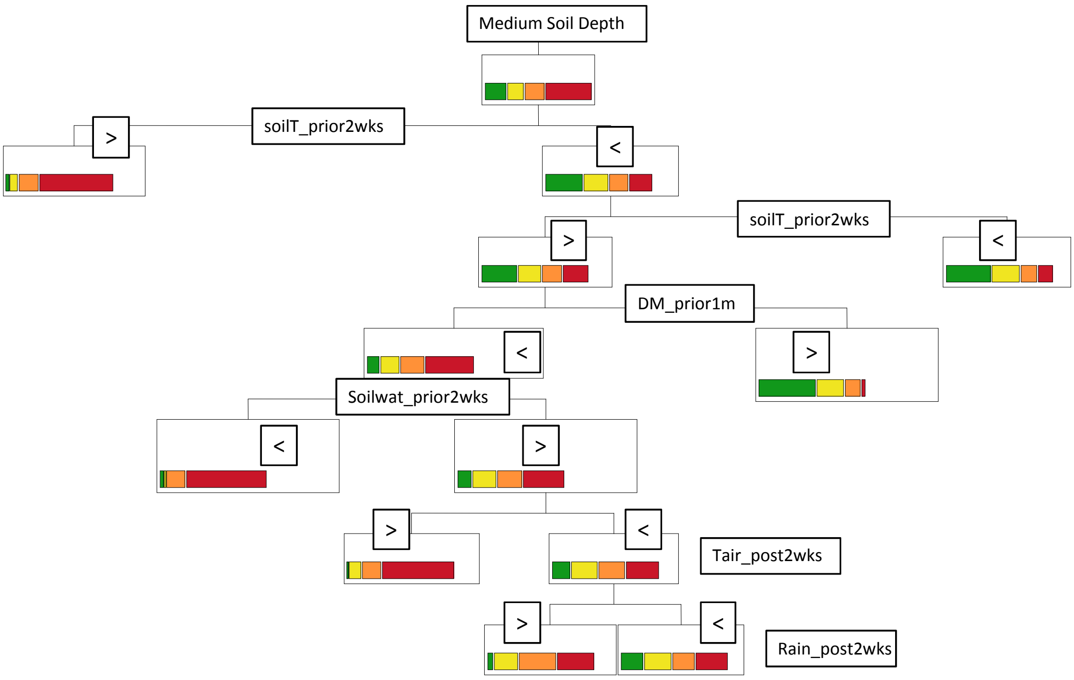

Figure 1. Classification and regression tree to predict the risk of nitrogen leaching in the Waikato region for a 750 kg N/ha deposition event. The bars indicate the percentage of simulations within the different risk categories with thresholds for N leaching of green: 0-15, yellow: 15-30, orange: 30-50, and red >50 kg/ha/yr.

Keywords: *APSIM, urine patch, early indicators, risk forecasting, N leaching*

1. INTRODUCTION

Intensive dairy farming can result in high nitrogen (N) concentrations in the soil under urine patches. This has been found to contribute to elevated groundwater nitrate concentrations in many regions of New Zealand and worldwide. Apart from farm management practices, climate and soil type are major drivers of N leaching. Timing of N depositions is also an important factor (Vogeler et al., 2010). At present, information on the risk of N leaching from urine patches is semi-quantitative because the specific combinations of management and environmental conditions that lead to high risk of N leaching are poorly understood. Better understanding of these combinations could help farmers to choose periods of time when N leaching mitigation strategies, such as the use of stand-off pads or application of nitrification inhibitors, need to be implemented.

Various models have been developed to simulate biological and physical processes in farming systems, such as the Agricultural Production Systems Simulator, (APSIM; Keating et al., 2003) Such models can simulate combinations of management and environmental conditions in numbers that cannot be attained by experimentation, and thus help to better understand how environmental conditions combined with management strategies interact to control nitrogen cycling and losses. Thus they can be used to determine early indicators of risk of N losses to waterways and used to improve farm management systems.

In this paper we present a modelling exercise performed to identify early indicators of high risk of N leaching from urine patches The analyses included site specific factors such as soil type and climate, as well as dynamic factors, such as soil water content and temperature at time of deposition, plus weather forecast.

2. APSIM MODELLING

2.1. Model Setup

All simulations were conducted using the APSIM (version 7.2) modelling framework. The main modules from the standard release include SWIM (Verburg et al., 1996) for soil water and solute movement, AgPasture (Li et al., 2010) for pasture growth and N uptake, and SoilN (Probert et al., 1998) for soil C and N transformations. Other modules, developed specific for this project, were added to the standard release to describe the urine patch applications and the volatilisation of ammonia and have been validated elsewhere (Cichota et al., 2010b; Vogeler et al., 2010).

A comprehensive N leaching dataset was created and analysed to determine early indicators of risk of nitrate leaching from urine patches. Weather data from the Ruakura Met Station (-37.8S, 175.3E) were also included. The base simulation was set to run for three years after the urine deposition, which happened on the 15th of the given month. Nitrogen fertiliser was applied at a rate of 25 kg N/ha/month from September to June. Pasture growth was simulated assuming a mix of ryegrass/white clover, with its proportion allowed to vary according to environmental and management conditions. Pasture was harvested (cut and carry) every 21 days to a residual herbage mass of 1500 kg/ha. Irrigation was included and set in line with current practices, that is irrigation started when the plant available water (PAW) fell below 40 mm, with 20 mm being applied at a return period of 4 days. Irrigation efficiency was assumed to be 85%.

The N leaching dataset comprised the results from the base simulation replacing the deposition time (year and month), the N load, the irrigation setup, and the soil type, in a full factorial combination (numbers shown in Table 1). There were 48 generic soils types for the tool development dataset and two typical soils from the Waikato area, the Punui and Otorohanga, for the test dataset. The total amount of N leached was summed over three years after the urine deposition. The average N leaching on the paddock was calculated as the total amount of N leached from the urine patches divided by four. Generally about 25% of a paddock receives a urine deposition within a year (Snow et al., 2009). Finally the paddock scale N leaching was categorized into four risk levels, in line with the proposed traffic light N risk tool (see Figure 1.).

Table **1.** Factors varied in the simulation runs.

Factor	Number of variations
Month of urine deposition	12
Year of urine deposition	33 (1973 – 2005)
N load	5 (0 250, 500, 750, and 1000 kgN/ha)
Irrigation	2 (with and without)
Soil type	50 (description below)
Total number of combinations:	198000

2.2. Soil Types

A soil database was built, SWIM2, for these simulations. The database contained two major soil types, a group of generic soil layers, based primarily on soil texture and organic matter content, and a collection of typical soil series from across New Zealand.

The generic soils used were developed based on three layers, with Layer 1 ranging from 0 to 300 mm, Layer 2 from 300 to 750 mm and Layer 3 from 750 to 1500 mm. For Layer 1, eight key generic soil horizons (Allophanic Silt Clay Loam, Clay Loam, Silt, Silt Loam, Sandy Loam, Loamy Sand, Sand and Gravelly Sandy) were used, whereas for Layer 2 only three horizons (Allophanic Silt Clay Loam, Silt, and Sand), and for Layer 3 only two selected horizons (Clay Loam and Gravelly Sandy) were used. As previous simulations have indicated (Cichota et al., 2010a) that the risk of N leaching is highly dependent on the plant available water within the rootzone (PAW) we categorized the soils into five different soil class depths: PAW < 100 mm very shallow, PAW of 100-125 shallow, PAW 125-150 medium, PAW 150-175 deep, and PAW > 175 very deep.
For the evaluation of the N risk tool independent data was required. These simulations were conducted using the two typical soils from the Waikato area, namely the Punui and the Otorohanga soils. According to our PAW depth classification, these are classified as medium and deep soils.

2.3. Statistical analysis

To identify the most relevant variables related to N leaching, classical ANOVA and correlation analyses were performed on the full factorial dataset. Candidates for early indicators of N leaching risk were then selected to be included in the tool, taking into account their explanatory power and how robust and accessible their measurements would be. The final screening and the definition of thresholds used classification and regression tree (CART) analysis within the JMP statistical package (www.JMP.com).

3. N RISK TOOL DESIGN

The design of the N risk tool is based on a traffic light-type system with four colours corresponding to risk levels for N leaching: green =very low risk (leaching 0-15 kgN/ha/yr), yellow =low to medium risk (15-30 kgN/ha/yr), orange = medium to high risk (30-50 kgN/ha/yr), and red =high risk (leaching>50kgN/ha/yr). . These risk levels are based on the typical N leaching losses for pastoral farms calculated with OVERSEER® which typically range from 30-50 kg N/ha. The tool requires a series of input values for the factors identified as early indicators from the APSIM modelling, such as soil water content and soil temperature at the time of urine deposition. The values of the indicators are likely to be region and soil class specific.

4. APSIM MODELLING TO DETERMINE N-RISK INDICATORS

4.1. Simulation results

Simulations runs for the Waikato area using the 48 generic soils with 12 application timings, and 33 years, showed that N leaching from an N load of 750 kg/ha was highly variable, with an average amount of 47.5 kg N/ha/yr leached, about 25% of the deposited urine N. As expected the distribution was lognormal, and the standard deviation was relatively large, 19.2%. The distribution of the simulated leaching within the categories of the traffic light system was strongly dependent on the soil depth class (Figure 2), with a higher risk of N leaching on shallower soils.

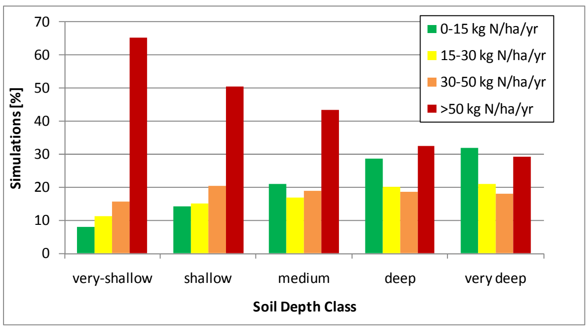

Figure 2. Effect of soil class depth on percentage of simulations in different N risk leaching classes following a urine deposition of 750 Kg N/ha averaged over all months and 33 years for the Waikato area.

For the detailed analysis of deriving early indicators for N risk leaching only the generic soils in the medium and deep soil depth classes were considered, as these were expected to more closely reflect the N leaching in the real soils within that geographical area, with the Punui and Otorohonga soil being in the medium and deep soil depth classes, respectively.

As expected from previous simulations (Vogeler et al., 2010) the month of deposition also affected significantly the distribution of N leaching risk. The number of simulations, and thus the risk of N leaching, which fell in the red category (> 50 kg N/ha/yr) was much higher from December to April or May, while from June to November the leaching risk was much lower (Figure 3). The lowest risk of leaching occurred in August and September. For February and March a 750 kg N/ha urine patch is very likely to have a high risk of N leaching, suggesting that in these months either grazing should be avoided or mitigation actions should be implemented routinely. High risk is unlikely in August and September and mitigation actions for N leaching are not needed. However, environmental damage in these months from P loss or soil structure damage due to pugging needs to be evaluated.

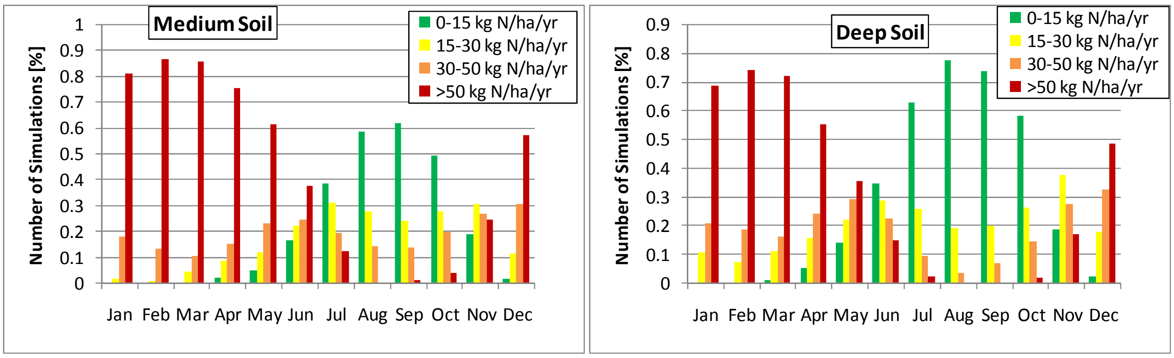

Figure 3. Effect of month of urine deposition on the distribution of N leaching risk following a urine deposition of 750 Kg N/ha to medium and deep soils over 33 years for the Ruakura case study.

4.2 Determination of a decision tree for the risk of N leaching

To determine the final set and the thresholds of the indicators for high risk of N leaching, the simulation dataset was analysed using classification and regression tree (CART). As N leaching was previously found to be dependent on the soil depth class, separate CART analyses were performed for each class, here we concentrate on the medium and deep soils. As early indicators, we selected from a list of candidates only those easily measurable on farm or obtainable from centralised forecast, namely:

- volumetric soil water content in the root zone averaged over the 2 weeks before urine deposition (soilwat_prior2wks)
- soil temperature in the root zone averaged over the 2 weeks before urine deposition (soilT_prior2wks)
- harvested dry matter in the month before deposition (DM_prior1m)
- average air temperature in the 2 weeks following urine deposition (Tair_post2wks)
- cumulative rainfall in the 2 weeks following urine deposition (Rain_post2wks)

CART analyses are made in several steps, in each step the data is split in two subsets using the criterion of maximum statistical difference. The splits in the CART analysis started on the generally most informative of the five chosen factors, shown in Figure 1 for the medium soils. For clarity only one split for each branch is shown and the actual threshold values for the splits are omitted as they vary for each soil class. The thresholds were used to trigger mitigation management for reducing N leaching as discussed below.

For both the medium and deep soil classes, the average soil temperature in the root zone in the 2 weeks prior to the urine deposition event was a good indicator of N leaching risk. Larger N leaching is more likely in warmer conditions, which probably reflects higher nitrification rates and thus larger proportion in the soil of easily leachable nitrate. Lower pasture dry matter production in the month before deposition and lower soil water content in the root zone within 2 weeks before the urine deposition event also lead to a higher risk of N leaching. These are associated with the lack of N uptake due to low plant growth. Finally, the environmental conditions in the 2 weeks following urine deposition, mainly average air temperature and cumulative rainfall, were positively correlated with risk of N leaching. While the other variables had a much smaller impact on explaining the N leaching risk, they allowed the fine-tuning of the tool especially for those periods with higher variability.

4.2. Using the N risk tool for mitigating N leaching

To demonstrate the use and the effectiveness of the N risk tool, we tested it using the results of the simulations using descriptions of real soils, the Otohoranga and Punui. We tested the tool's performance for triggering duration-controlled grazing (DCG) using indicators and trigger values identified using the simulations from the generic soils. DCG was defined as leaving the cows on the paddock for only 8 hours/day as compared to the 20 hours/day of the typical management (Christensen et al., 2010). This was done for the period between 1973 and 2005, considering one grazing event per month. Estimated average N leaching and reduction in N leaching when using DCG triggered by the N risk tool was compared to typical grazing management, and DCG fixed throughout the year with cows on the paddock for 12, 8 or 4 hrs. Figure 4 shows the average annual N leaching from a paddock for both the Otorohonga and Punui soils, with clear reduction on N leaching when using DCG as compared to typical management. The effectiveness of DCG when triggered by the N risk tool always varied between these two limits.

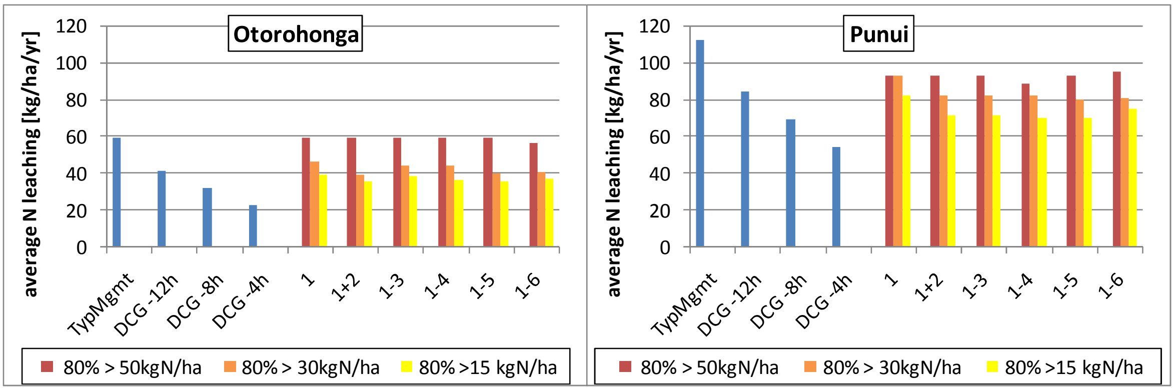

Figure 4. Average annual N leaching for typical management and duration controlled grazing of either 12, 8 or 4 hrs, and (DCG) fixed throughout the year or triggered by the N risk tool. Tool trigger set at different risk levels and with varying number of indicators: 1 = soilwat_prior2wks; 2 = soilT_prior2wks; 3 = DM_prior1m, 4 = Tair_post2wks; 5 = RF_post2wks, 6 = Tair_post2wks and RF_post2wks.

As expected average annual N leaching in the Otorohanga soil was lower than in the Punui soil, and the extent to which DCG reduces N leaching is also smaller than for the Punui soil. It also depends on the length of time the cows spent on the paddock. Using the early indicators identified from the generic soils to trigger DCG for 8 hrs grazing only when the probability is ≥80% for N leaching above 50 kg/yr (red risk class) does not significantly reduce N leaching for the Otorohonga soil, even if all five indicators are used. In contrast for the Punui soil the use of only one indicator (soil temperature) substantially reduces N leaching, and the use of more factors had not much further influence. Triggering DCG using lower N leaching levels (orange or yellow risk class) reduces N leaching in both soils.

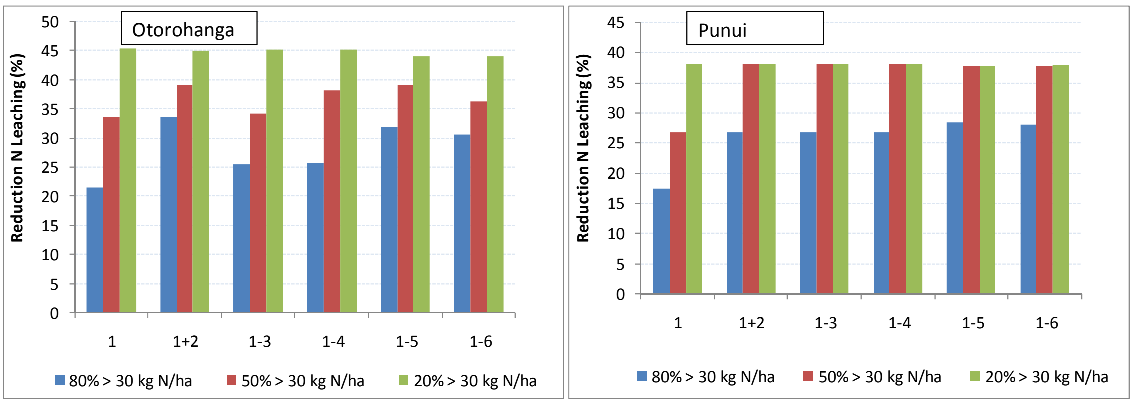

Figure 5. Reduction in average annual N leaching [%] when using DCG triggered at probabilities to exceed 30 kg N/ha/yr of 80, 50 and 20%, also with different number of indicators: 1 = soilwat_prior2wks; 2 = soilT_prior2wks; 3 = DM_prior1m, 4 = Tair_post2wks; 5 = Rain_post2wks, 6 = Tair_post2wks and RF_post2wks.

Apart from the threshold value of N leaching used (50, 30 or 15 kg N/ha/yr) the risk alertness of the farmer has an effect on the reduction in N leaching when using our N risk tool to trigger DCG. The risk alertness of the famer influences the probability level in order to trigger the DCG decision. The reduction in N leaching by using the early indicators to trigger DCG for 8 hrs when the probability of exceeding 30 kg N/ha/yr is ≤ 80, 50, and 20% is shown in Figure 5 for the two soils. A very risk sensitive farmer, taking action when the probability is > 20% can, even using only one indicator (here soil temperature) reduce the average annual N leaching from a paddock by 45% in the Otorohonga soil, and by 38% in the Punui soils. In this case, the use of more indicators does not much improve the forecasting of leaching risk. A farmer less concerned with reducing leaching and prepared to take more risk, acting only when the probability of exceeding the leaching threshold is higher than 80% can still reduce N leaching by about 21 and 18%, for these two soils, when using one indicator only. If more indicators are taken into consideration the potential reduction improves up to 32 and 28%.

Besides the reduction in N leaching by using indicator-triggered DCG, the number of days (Time of DCG) the farmer has to shift or remove the cows of the paddock is important as it adds both effort and costs. A very risk alert farmer, acting when the probability of exceeding 30 kg N/ha/yr is greater than 20% would opt for DCG for most of the time (Figure 6). The use of more indicators would reduce the time of DCG, justifying the use of the forecast factors as early indicators for triggering DCG. A more risk taking farmer would opt for DCG less frequently, but therefore also reduce N leaching by a lesser extent. The balance between N leaching reduction and time a mitigation action is required is highly dependent on the effort and cost of the action.

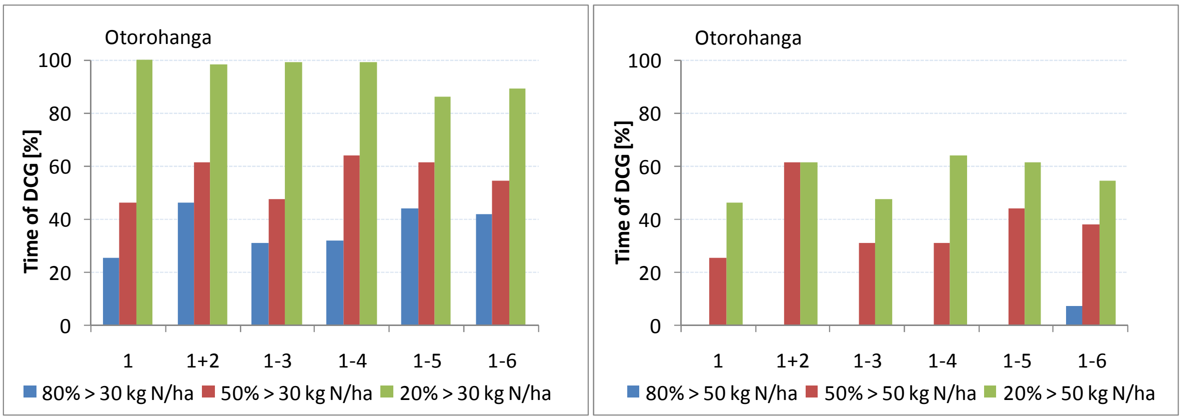

Figure 6. Average number of actions triggered by the N risk tool as a function of the risk alertness with probabilities of leaching being above 30 kg N/ha at 80, 50 and 20 %. Also varying the number of indicators used in the tool: 1 = soilwat_prior2wks; 2 = soilT_prior2wks; 3 = DM_prior1m, 4 = Tair_post2wks; 5 = RF_post2wks, 6 = Tair_post2wks and RF_post2wks.

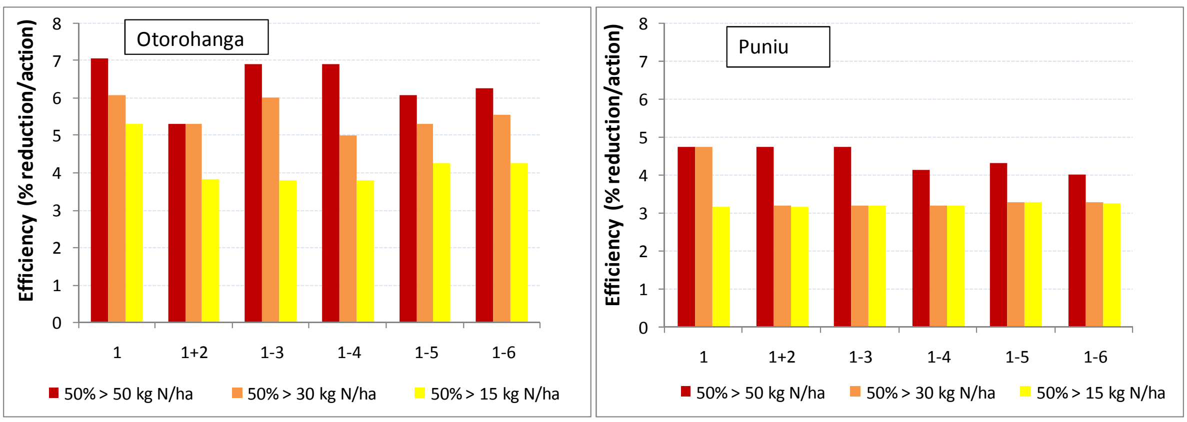

Figure 7. Efficiency of DCG triggered by early indicators when probability of exceeding 50, 30 and 15 kg N/ha is greater than 50%. Also with varying the number of indicators: 1 = soilwat_prior2wks; 2 = soilT_prior2wks; 3 = DM_prior1m, 4 = Tair_post2wks; 5 = RF_post2wks, 6 = Tair_post2wks and RF_post2wks.

The efficiency of the use of indicator triggered DCG, which we define by the ratio of reduction in average annual N leaching and the number of actions depends on the risk level and on the number of indicators that are used to trigger the actions. Based on a probability of 50% (Figure 7) the efficiency is highest when actions are triggered at high risk level (leaching >50 kg N/ha/yr), which would be expected as the actions target the peaks of N leaching. The efficiency declines with lower thresholds as lower leaching periods are also targeted. Including more than one indicator for decision making can increase the efficiency, but even sometimes reduces it.

5. CONCLUSIONS

Using APSIM simulations, a N leaching dataset was produced for the Waikato region to determine early indicators for risk of N leaching from urine patches. In order of importance, soil water content and temperature two weeks before, DM before 1 month, air temperature and rainfall after two weeks were the most important determinants of nitrogen leaching. Trigger values for the indicators were determined by CART analyses and are dependent on the soil depth class. The N risk tool was tested by triggering duration controlled grazing (DCG) to reduce N leaching on a paddock scale. Reduction in N leaching ranged from 20 to 45%, depending on the number of indicators used and the risk alertness of the farmer. The efficiency of the tool varied with the number of indicators and the soil type, suggesting that more fine–tuning of the tool is required. The choice of risk levels to trigger management actions depends highly on current and future regulations within different catchments. The risk alertness of the farmer is also an important component, and this also can affect N leaching.

Besides tuning and testing the N risk tool and the early indicators in other soils and climate, the tool needs to be tested with other mitigation technologies, such as nitrification inhibitors. The tool also needs to be further developed and up-scaled onto the farm level to help the farmer to identify best management practices that reduce the risk of N leaching in synchrony with other environmental risks.

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