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MODELLING OF MITIGATION STRATEGIES TO REDUCE NUTRIENT LOADS TO WATERWAYS UNDER CHANGING CLIMATE AND LAND USE

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ABSTRACT

We have modelled the effectiveness of mitigation strategies to reduce soil nutrient leaching associated with selected agricultural land uses, particularly those associated with dairy farming. We used APSIM, a dynamic, mechanistic and stochastic platform for modelling biophysical processes in agricultural systems, to generate temporally and spatially explicit nitrate fluxes through soil profiles representative of paddocks under differing land use and management regimes. APSIM operates at a daily time step and allows the incorporation of actual and stochastic climate series, enabling assessment of leaching following discrete events; seasonal or decadal trends, or prediction of climate change impacts.

The modular, scriptable framework allows nutrient leaching associated with seasonal management regimes, or historical land use change, to be evaluated. In the same manner, mitigation strategies to reduce leaching can be assessed, examining dynamic trends in N leach, long term annual leach rates, and in respect to other soil properties or production targets affecting farm viability. Soil and climate parameters can be adjusted to represent the spatial variability of different paddocks, and paddock-scale results can be integrated across sub-catchments, providing sub-catchment scale outputs from farm and enterprise modelling that can be input to spatially constrained and temporally precise catchment models.

We will provide examples of where APSIM has been used to inform management decisions for dairy enterprises in New Zealand and also discuss the role of nitrate attenuation through denitrification via oxygen-poor groundwaters and riparian zones. We will outline the multiple lines of evidence that are required to evaluate the efficacy of denitrification impacts at any given site.

Keywords: APSIM, nitrogen leaching, land-use change impacts, denitrification, mechanistic models, nitrate attenuation.

1. INTRODUCTION

The agricultural nitrogen cycle (**Figure 1**) is a complex interplay of nitrogen inputs and outputs and phase transitions mediated by microbial activity and is highly dependent on the physical and chemical state of soils and water and farm management practices across different land uses. Inputs of N to soil in pastoral dairy systems are dominated by fertiliser application (up to 300 kg N/ha/year; e.g. NZFMRA, 2007) and excreta from grazing animals. Of the ingested nitrogen, 60-90% is excreted as urine (70-80%) or egested as dung (20-30%), resulting in average loading rates that could exceed 1500 kg N/ha/year (Snow, et al., 2016), though with considerable seasonal and climatic variability (Romera, et al., 2012). Cattle urine contains about 16 g urea/L and about 13 g/L amino acids and peptides (Bristow, et al., 1992) resulting in nitrogen concentrations of about 4 g/L, though with a daily variability that ranges from 1-13 g N/L (Hoogendoorn, et al., 2009).

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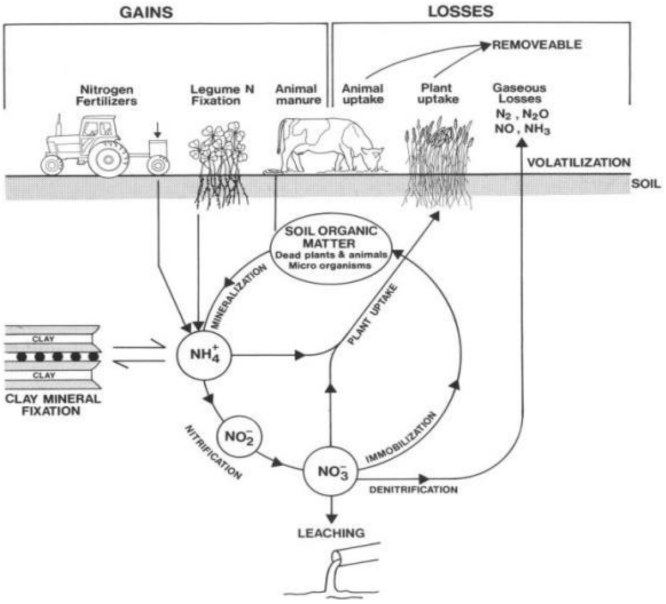

Figure 1. The soil nitrogen cycle (Di and Cameron, 2002)

Additional nitrogen inputs include: effluent application to land (typically consisting of 140-670 mg N/L (~ 10% dung + urine diluted with water) and biological N fixation (BNF) by legumes (up to 140 kg N/ha/year; Ledgard, et al., 1999). BNF has been shown to be quite variable and to decrease with increasing fertiliser application. Thus, high soil inorganic N conditions, as generated by fertiliser application results in grasses out-competing nitrogen fixing legumes and BNF can reduce to <50 kg N/ha/year (*ibid.*). Other minor N inputs may include wet and dry deposition (1-2 kg N/ha/year; Nichol, et al., 1997) and the weathering of soil parent material.

Outputs from the nitrogen cycle occur through gas emissions (N_2O and N_2 from denitrification), volatilisation (NH_3) and leaching (NO_3) loss to groundwater. Leaching losses of nitrate to ground waters has increased over the past several decades with increasing use of fertiliser and increased stocking rates across the globe. Biological denitrification helps mitigate this accumulation and occurs naturally when certain bacteria use nitrate as terminal electron acceptor in their respiratory process, in the absence of oxygen.

This paper examines the utility of the APSIM modelling platform to derive paddock and farm scale nutrient budgets that account for explicit land uses, management practices and agricultural N inputs, and spatial and temporal variability in soil processes and conditions. We provide examples of mitigation strategies for N leach that have been informed by such nutrient budgeting. We then discuss how paddock/farm scale budgeting can be incorporated into sub-catchment and catchment scale modelling and management strategies to reduce N loads to waterways.

2. NUTRIENT BUDGETS AT PADDOCK AND FARM SCALES

The use of nutrient budgets to help identify, and thereby mitigate, potential environmental impacts from the increasing use of fertilisers is now well-established (e.g. Cichota and Snow, 2009). The impacts, however, are generally impractical to measure, or are expected to be delayed due to lags in transport processes from farm to receptor (generally a waterway) and hence cannot be measured in time to undertake a mitigation strategy. Simulation models are the best alternative to predict potential impacts and a considerable number of different frameworks have been used, or are being developed, to estimate nutrient losses from paddocks and their transfer to local and regional waterways.

The spatial and temporal variation in N leaching requires the use of dynamic and mechanistic biophysical models that capture the heterogeneity of this process (e.g. Vogeler, *et al.* 2013). Models such as the Agricultural Production Systems sIMulator (APSIM) (Holzworth, *et al.* 2014) and OVERSEER® (Wheeler, *et al.* 2013) are biophysical models that incorporate these effects. APSIM is a process-based model that works on a fine scale and daily time-step whilst OVERSEER® produces annual averages across farm enterprises, with drainage and leaching calculations on a monthly time-step.

APSIM is a dynamic, mechanistic and modular modelling framework that affords potential for new modules to be added to the model from various research initiatives or for parameters of varying soil or management activities to be shared. APSIM has the ability to integrate daily climate inputs (with potential to incorporate stochastic datasets); integrate dynamic management inputs and outputs at sufficient temporal resolution to quantify farming practices (Snow, et al., 2016; Vibart, et al., 2015).

In particular, the flexibility in development of management practices and the ability to incorporate time-sensitive and transient farming scenarios (such as variable fertiliser applications; changing practice with time and climatic variability) allow realistic farming scenarios to be developed that provide a platform for future impact predictions on a daily time-step.

APSIM specifically models variables relevant to farm nitrogen (N) budgets. It takes inputs (e.g.fertiliser, effluent), pasture and stock management conditions (e.g. rotational grazing/harvesting), and crop management and generates output variables reflecting nutrient and moisture budgets at any given time or profile position.

Within APSIM, soil nutrients and moisture are modelled within the Soil Organic Matter, Soil Nitrogen, and Soil Water (SoilWat or SWIM) components, which operate in conjunction. This reflects the interdependencies between carbon, nitrogen and drainage affecting mineralisation or immobilisation of organic nitrogen, redox transformations, and losses through denitrification and leaching (Figure 2).

The Soil N module is essentially a model of soil carbon dynamics, which permits the simulation of nitrogen because of the close association of carbon and nitrogen (Norton and Veselý, 2003). The module considers the dynamics in terms of four main soil organic matter pools (as well as surface residues) for each soil layer and uses the same soil structure as that used to model water transport. The four carbon pools include: Inert (not decomposing) organic carbon; fresh organic matter (crop residues, dead roots – FOM); labile soil microbial biomass (BIOM) and soil organic matter (HUM).

Transformations (mineralisation, immobilisation, nitrification and denitrification) are considered at each time step for each soil layer. Thus, mineralization (of N) is the release of mineral N from the breakdown of organic matter whilst immobilization is the tying up of mineral N by soil microbes as they endeavour to use substrates as an energy source. Decomposition and immobilisation/ mineralisation rates of organic pools are dependent on the C:N ratio, temperature and moisture content.

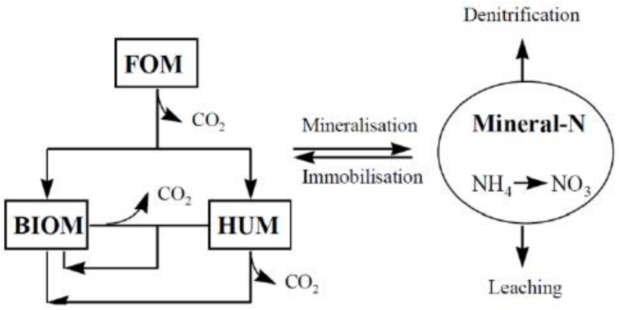

Figure 2. The soil organic matter pools in APSIM Soil N module and the transformations occurring in each layer

Leaching is determined through the water balance module, modelling solute flow assuming conservative transport of nitrate through each layer and using the Advective- Dispersive Equation (Verburg, ed. 1996). The module thus represents a simplification of the nitrogen cycle (Figure 3).

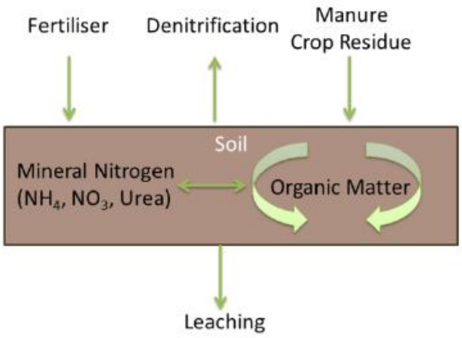

Figure 3. APSIM considers the nitrogen cycle as five interacting processes

Using APSIM, we can thus compare N leach from paddocks under differing land use, with particular reference to the accumulation or shortage of N within the soil profile. Expected and historical deficits or surpluses then inform the need for nitrate augmentation. APSIM simulates fertilizer application to the prescribed soils, as well as the cycling of N associated with crop uptake and the consumption of pasture or fodder by stock, and for specific crop and stock rotations. Theoretical nitrate profiles are generated that evolve with time depending on rainfall, soil factors and soil saturation. The results can be compared to field measurements and can provide a spatially and temporally explicit dataset of nutrient leaching across the landscape for input to deep drainage and subsequent transport modelling using surface and groundwater modelling packages.

APSIM can be used as a pre-experimental tool to explore the potential response from different conditions imposed on a farm and hence constrain experimental parameters (e.g. Buck thought, et al., 2011). This allows exploration of management strategies, such as fertiliser application rates, the timing of irrigation or effluent application, stocking rates and seasonal changes, and hence to development of mitigation and management strategies.

Rainfall has a direct correlation with leaching, as shown in Figure 4, though higher annual rainfall does not necessarily invoke higher leaching, as is evidenced by the saw-tooth pattern of the trends in Figure 4. Catchment location is critical as well as seasonality, with lower relative leach occurring in catchments closer to catchment divides or where spring rainfall is relatively low.

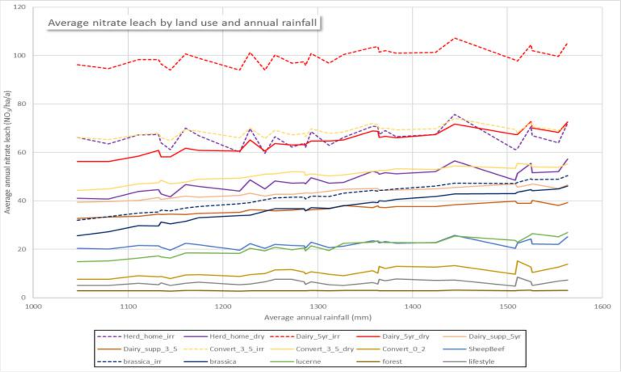

Figure 4. Modelled long-term nitrate leach by land use for 31 virtual climate stations across central North Island, New Zealand, ranked by average annual rainfall

2.1 Nitrate Leaching Across Land Use and Time

Nitrate leaching time series (using the period 2008-2012 for illustration) for well-drained soils without irrigation (Figure 5), for well drained soils with irrigation (Figure **6**), and for poorly-drained soils (Figure 7) indicate that, in general, for similar land uses leaching was higher for well drained soils and scenarios that incorporated irrigation.

Returns from APSIM modelling successfully captured monthly and seasonal variation associated with both rainfall events and species growth curves with annual spikes in nitrate leaching observed during the winter months. This likely corresponds with high rainfall events occurring concurrently with higher nitrogen availability in the soil due to April fertiliser application and decreased water and nitrogen demand during the winter months. Analysis of nitrogen demand and pasture growth support these assertions.

Conditions associated with Year 2 of the conversion process, from plantation to pasture, resulted in the highest rate of nitrate leaching, likely due to decreased uptake of nitrogen from soil and/ or return of fixed nitrogen during the winter dormancy of the re-growth. The lucerne scenario exhibited one of the lowest rates of nitrate leaching, likely due to the high nitrogen demand due to continual growth and nitrogen replenishment needed following regular grazing. In other scenarios, increased leaching was associated with higher feed consumption (i.e. stocking rate), decreased loss of

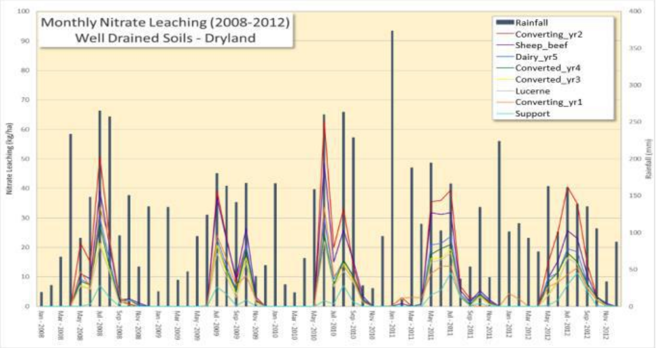

Figure 5. Modelled time series (2008-2012) of nitrate leaching for dryland land uses on well drained soils

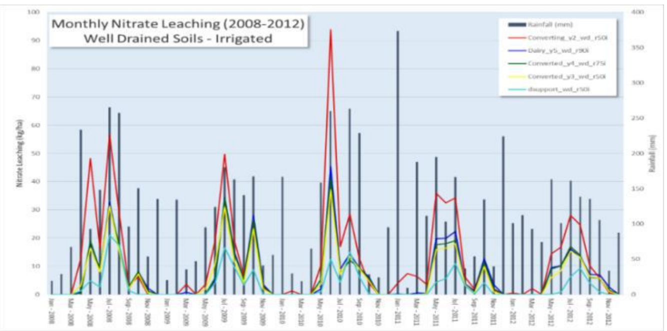

Figure 6. Modelled time series (2008-2012) of nitrate leaching for irrigated land uses on well drained soils

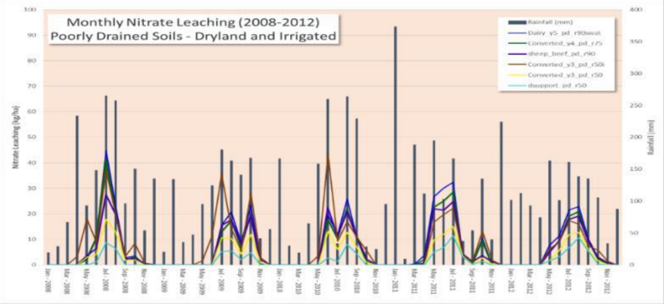

Figure 7. Modelled time series (2008-2012) of nitrate leaching for land uses on poorly drained soils

nitrogen in animal products, and a higher proportion of ryegrass relative to (nitrogen-fixing) clover in the pasture.

Combining the multiple land uses across multiple catchments allows spatial (and temporal) consideration of changes in nitrate leach.

2.2 Mitigation Modelling

APSIM provides a quick and efficient tool to investigate the potential impacts of future mitigation activities. For example, Figure 8 illustrates the consequence of reducing fertiliser application from 150 to 80 kg/ha/a on the total nitrate leach. Long-term leach is reduced, and the actual leaching distribution is changed due to the impact of varying rainfall regimes through time.

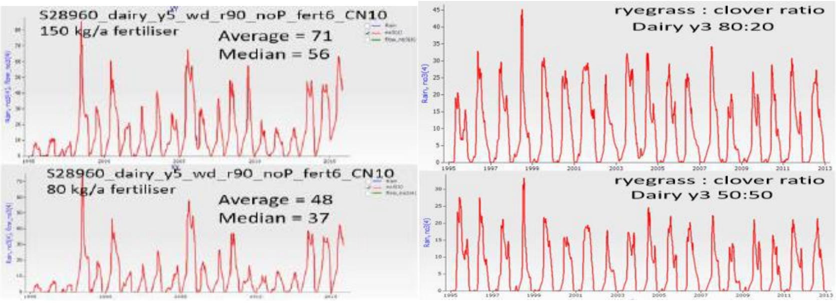

Figure 8. APSIM time series of nitrate leach under (left) differing fertiliser application regimes and (right) different ryegrass to clover ratios of the pasture

Similar operations can be carried out to determine the direct consequences of other mitigation measures if the measure can be related to specific changes in either a management or physical input to the APSIM modules. For example, maintenance of high clover to rye grass ratios in pasture, can be modelled and reveals a significantly lower nitrate leach for high clover ratios (Figure 8).

A suite of potential mitigation strategies can be modelled and compared, and the effective sensitivity of farming systems assessed recognising that not all mitigation strategies are applicable to all land uses, nor all situations for a given land use. Critical strategies include reduction in fertiliser application at critical times and the exclusion of stock from waterways as well as enhanced identification through establishment of riparian zones

Expert opinion and past experience will guide the effective choice of mitigation strategies across different land uses. APSIM will quantify indicative changes in nitrogen leach under the different strategies and inform how specific mitigation strategies can reduce total nitrogen leached from the farming enterprise. Thus, Figure 9 provides an example of the spatial consequence of low and high mitigation strategies and highlights that only those catchments that respond to the mitigations should be targeted. For most catchments, mitigation is either ineffective or adds no further value to reducing nitrate leaching.

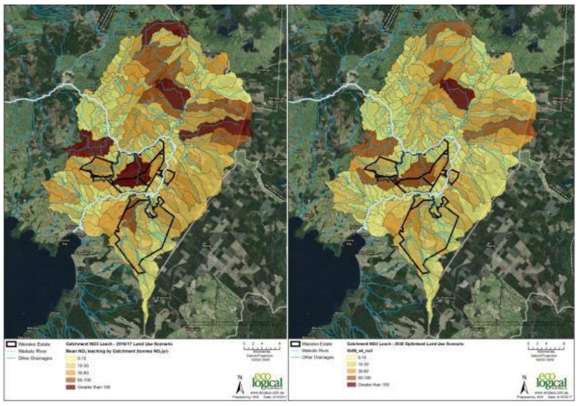

Figure 9. Example of APSIM modelling of the consequence of mitigation reductions across catchments in the Central North Island, New Zealand. Left image: no mitigation nitrate leach (2016 land use); right image: nitrate leach following mitigations actions (2016 land use with 15 years' mitigation actions)

2.3 Catchment Scale Modelling and Management Incorporating Attenuation Through Denitrification

Leaching of N from paddocks or farms is rarely completely eliminated, with potential for diffuse N discharge to a receiving water body. Significant attenuation, however, may be achieved under conditions conducive to denitrification. Denitrification consists of a sequence of enzymatic reactions leading to the evolution of nitrogen gas. The process involves the formation of a number of nitrogen intermediates and can be summarized as follows:

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

Denitrifying bacteria are ubiquitous in nature; hence denitrification occurs wherever oxygen levels are low and a suitable electron donor (such as carbon, or iron sulphide) is present to promote the enzymatic reaction (e.g. Tesoriero and Puckett, 2011).

Rates are variable, however, and hard to determine (Hallberg and Keeney, 1993) and are dependent on the relative availability of oxygen and two distinct denitrification pathways can be defined:

- Shallow, vertically-controlled denitrification where shallow recharge (leaching) waters reach a de-oxygenated water-table, commonly associated with peaty soils or organic-rich clay soils where water movement is slowed. Denitrification tends to be rapid as long as sufficient organic carbon is present and oxygen levels are below 2 mg/L.
- Deeper, horizontally-controlled denitrification where reduced waters promote gradual denitrification over variable time frames dependent on oxygen and carbon concentrations.

Thus, even where conditions promote denitrification, reduction, or attenuation, of nitrate may not be significant if the source of nitrate either outstrips the denitrification rate, or the travel time from source to receptor is too short for the rate to be effective. APSIM derived nutrient budgets can include denitrification in the soil profile and be used to inform likely accumulation of N reaching anoxic water, or can identify locations within the catchment where large N inputs are added. Forward prediction can then be achieved through numerical modelling of solute transport, for example with the use of MODFLOW and MT3D/RT3D.

In this context, research carried out worldwide highlights the important role riparian buffers play in denitrifying diffuse discharges. For example, Rassam, et al. (2005) presentfield results and modelling of groundwater discharging to organic-rich, slow-flowing surface waters resulting in a high potential for denitrification in the shallow (near-surface) groundwater system. Nitrate concentrations may reduce by a factor of two for each day the nitrate-rich waters spend in this environment: Increased N leachate may be buffered by wider riparian zones.

We have shown elsewhere (Herron, et al., 2015; Cetin, et al., 2014) that reduction of nitrate concentration by a factor of two was achieved when oxic ground waters pass through an anoxic zone prior to discharge to a large inland lake in New Zealand.

In-stream denitrification can also be effective. Harvey, et al. (2013) and Roley, et al. (2012), for example, report up to 3 orders of magnitude reduction through denitrification in the hyporheic (water-sediment interface).

3. CONCLUSIONS

APSIM modelling was successfully undertaken for a range of land uses (including: livestock/dairy production, cropping, forestry, as well as the process of conversion of tree plantations to dairy farming). The use of APSIM provides the advantage over other modelling packages of higher temporal resolution (i.e. daily results) which can be used to refine management practices and the ability to undertake predictive scenarios of land-use change, including provision of temporal changes during the conversion process.

A sensitivity analysis was undertaken and demonstrated a consistent relationship between stocking rate and fertiliser changes and the associated leaching response. This has provided a means to evaluate any uncertainty in catchment leaching predictions given variability in farm system management and operation and tailor mitigation strategies to reduce nitrogen leaching from the farm system.

Nitrate leach from paddocks may also be attenuated through natural denitrification and impacts from nitrate reaching waterways can be reduced through judicious development of riparian zones and understanding of groundwater systems that discharge to surface waters.

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