Dynamic simulation of crop rotations to evaluate the impact of different nitrogen management strategies on water quality in Southland, New Zealand

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Abstract: Nitrogen lost from agricultural fields is one of the main causes of water pollution. In New Zealand, the National Policy Statement for Fresh Water Management authorises Regional councils to administer limits around the amount of nitrogen discharged into water systems. Enforcement of this policy requires reliable ways to quantify nitrogen losses from land uses in catchments and test future land use options for minimising those losses while maintaining farm profitability. Since measurement of nitrogen loss under field conditions can be technically challenging and costly, simulation models have often been relied on to provide this information.

The evaluation of environmental impacts from agricultural activities at a catchment scale requires integration of modelling tools designed to work at different levels. A dynamic farm systems model is needed in this context, to capture the impacts of land use changes and management decisions on water and nitrogen fluxes in the soil-plant interface. Generated information from this level can then be scaled up by hydrological models to determine the impact of farming activities at the catchment and regional scales. In this work, we used the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM), a process-based farm systems model, to evaluate the effect of fertiliser nitrogen management on crop production and nitrogen leaching from cropping rotations in the Southland region of New Zealand. For this, we developed a general simulation that can be modified with relatively simple inputs to describe a variety of farming systems typical of the region. We test and demonstrate this abstraction using simulations of three rotations (continuous wheat, pasture-wheat-grain oats, and wheat-green oats-fodder beet-peas, hereafter, Rotation 1, Rotation 2 and Rotation 3, respectively) modelled for 35 years (1980–2015). Two fertiliser management options were evaluated for each crop rotation: scheduled management where fertiliser nitrogen rates and timing of application used a prescribed schedule, and soil-test management where fertiliser nitrogen rates and timing were based on the analysis of simulated soil nitrogen levels within a specified time period.

Results indicated APSIM-estimated crop yields were within yield range for the region, and nitrogen fertiliser management had a negligible effect on crop yield. The estimated average nitrogen fertiliser applied to crops under the soil-test management was either similar or lower (by 11–12%) than nitrogen fertiliser applied under the scheduled management. The soil test management also resulted in similar or lower (17–32%) nitrogen leaching than the scheduled management (Fig. 1). These results fundamentally show that soil-test based fertiliser application has the potential to increase fertiliser nitrogen use efficiency and reduce the risk of nitrogen loss to the Southland catchment water systems. These results also demonstrate the capability of our APSIM setup to produce realistic crop production levels and account for intra- and inter-season variability in soil nitrogen and weather conditions. Using such simulation setup is a promising tool to generate valuable data to assist in assessing the productivity and environmental effects of cropping systems and alternative management options for nitrogen mitigation to improve water quality.
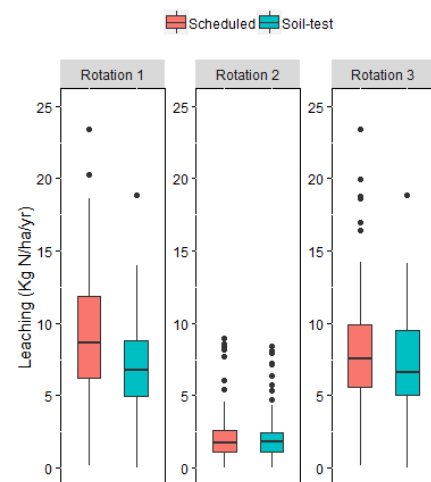

Figure 1. APSIM-estimated nitrogen leaching for two fertiliser management and three crop rotations.

Keywords: *Integrated modelling, nitrogen management, water quality*

1. INTRODUCTION

Nitrogen loss from intensive agriculture is one of the main causes of surface and groundwater systems (Beman et al. 2005; Dymond et al. 2013; Giles 2005; Heisler et al. 2008), and many central and local governments have formulated environmental policies to protect water systems from nitrogen contamination. In New Zealand, for example, the Ministry for the Environment published the National Policy Statement for Fresh Water Management (Freshwater NPS 2014) which requires regional councils to administer a policy around limits of nitrogen discharge into water systems. Enforcement of this policy requires reliable ways to quantify nitrogen losses from land uses in catchments and test future land use options for mitigating those losses. Simulation models have often been relied on to provide this information because of the high costs and challenges associated with measuring nitrogen loss under field conditions (Cichota et al. 2010; Monaghan and de Klein 2014; Langeveld et al. 2007).

There is typically a strong physical connection between surface and ground water in a catchment. Therefore, integrated analyses of nitrogen and water flows through the landscape and between the surface and ground water systems are crucial in the assessment of effective measures to improve water quality (Elliott et al. 2016; Peckham et al. 2013). One way to facilitate such analyses is to integrate complementary modelling tools through an infrastructure (framework) that enables various models of water quality to interoperate. A dynamic farm systems model is needed in this context, to capture the effects of land use changes and management decisions on water and nitrogen fluxes among the soil, vegetation and atmosphere. Generated information can then be passed to hydrological models to integrate the effects and scale-up the impact of land use changes on water quality at the catchment level. Given the complexity and variability of farming systems and their management, simplifications are often required when simulating whole catchments and future scenarios. To ensure the robustness of predictions, these simplifications have to be well grounded and tested.

This study used farm systems modelling to evaluate crop rotations for a catchment located in the south western Southland region of New Zealand. A baseline simulation was set up with a variety of crops and management options based on local statistics and good practice recommendations. This simulation can be modified with relatively simple inputs, enabling the model to describe a variety of farming systems typical of the region. The objectives for this work were to (i) verify the model performance for predicting production levels, and (ii) use the model to estimate nitrogen losses from different land uses, and evaluate mitigation options to minimise those losses.

2. MATERIALS AND METHODS

2.1. Description of the study area

The Aparima catchment is located in south western Southland region and covers an area of 1375 km^2 (Environment Southland 2017). The catchment is predominantly cultivated land mainly in pasture to support sheep, dairy and beef cattle, with arable and forage crops grown on a small-scale (Journeaux and Wilson 2014). Crops are important for dairy feeding, and farmers often utilise 12–20% of their productive land to grow forage crops in the region (Chakwizira and de Ruiter 2009; Monaghan et al. 2010). Crops sown in the catchment include wheat, barley, oats and fodder beet (Legard 2015; StatsNZ 2018). The catchment was selected for this study because it has previously undergone economic and environmental analysis of land use change (Journeaux and Wilson 2014). Water quality information from five sites in the catchment showed algal growths and a progressive decline in macroinvertebrate health indices (LAWA 2019).

The work conducted in this study aims to contribute to on-going initiatives, such as the Aparima Freshwater Management (Aparima Community and Environment) project, a community-led multi-agency venture formed to promote good land use across the catchment as well as improve water quality and other environmental outcomes for the community.

2.2. Modelling tool and simulation setup

The model used in this study is the next generation **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM). APSIM is a dynamic model containing daily time-scale nutrient and soil water modules that allow continuous simulation of changes in nitrogen and water status in response to weather, management and crop uptake (Holzworth et al.

2018). Simulations were based on three representative crop rotations (Fig. 2) developed using information from a resident farmer, the Foundation for Arable Research, and New Zealand statistics data (StatsNZ 2018). Crop rotations were simulated for 35 years (1980–2015) broken into15-year runs with a 5-year offset i.e. 1980–1995, 1985–2000, 1990–2005, 1995–2010, 2000–2015. Simulations were set up using climate data for a location close to the middle of the catchment; these were obtained from the Virtual Climate Station Network (NIWA 2019; Tait and Turner 2005; Tait et al. 2006). The soil was defined as a deep silt loam (Typic Firm Brown Soil), based on data obtained from the New Zealand Soils database (Wilde 2003), complemented with pedo-transfer functions (Cichota et al. 2013). The outputs evaluated included individual crop yields, nitrogen fertiliser use, and nitrogen leaching accumulated annually from 15 March to 14 March. Two fertiliser management options were analysed for each crop rotation: (i) scheduled management (hereafter, scheduled) where fertiliser nitrogen rates and timing of application used a prescribed schedule and (ii) soil test management (hereafter, soil-test) where fertiliser nitrogen rates and timing were based on the analysis of simulated soil nitrogen levels within a specified time period. The fertiliser nitrogen rates and timing for the scheduled management were guided by information from three Canterbury farms that participated in a 6-year nitrogen leaching mitigation project (Khaembah and Horrocks 2018) and research-based recommendations (Morton et al. 2012 and 2017).
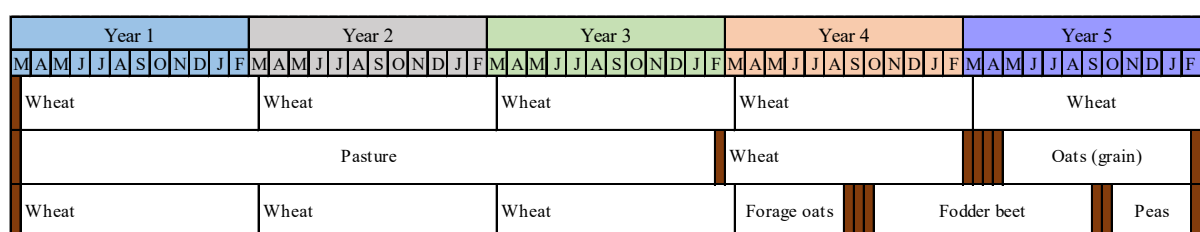
Year 1												Year 2												Year 3												Year 4												Year 5											
M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F

| Wheat | | | | | | | | | | | | Wheat | | | | | | | | | | | | Wheat | | | | | | | | | | | | Wheat | | | | | | | | | | | | Wheat | | | | | | | | | | | | |

Pasture — Wheat (Year 4) — Oats (grain) (Year 5)

Wheat (Year 1) — Wheat (Year 2) — Wheat (Year 3) — Forage oats — Fodder beet — Peas

Figure 2. Three crop rotations from the Aparima catchment. Fallow periods ranging from half to two months are indicated by brown cells. Each brown cell represents half a month.

It was assumed, for simplicity, that no nitrogen was returned as manure or urine. Pasture was managed under the cut and carry regime (with harvests triggered based on standing biomass). Forage oats were chopped and fodder beet lifted, and both were assumed to be fed off-paddock.

3.   RESULTS AND DISCUSSION

Results indicate a wide range in crop productivity (Table 1) reflecting the effect of inter-annual climate variability on crop growth. Model-estimated crop yields were within range of regional historical farm data (Millner et al. 2013; StatsNZ 2018) and research findings (Chakwizira et al. 2014; DairyNZ 2018). Apart from grain oats in rotation 2, where yield was greater under scheduled than soil-test fertiliser management, the model indicated negligible yield differences between the nitrogen fertiliser management options (Fig. 3).

Under both fertiliser managements options, green oats were used as a catch crop and received no nitrogen fertiliser, while peas received 50 kg N/ha (Table 1) at sowing. For the rest of the crops, the estimated nitrogen fertiliser inputs under the soil-test management were comparable with or lower than scheduled nitrogen inputs (Table 1). Across rotations and crops, there was wide variation in applied nitrogen under soil-test management, reflecting the dynamic in-season fertiliser application response to temporal variability in soil nitrogen supply. Substantial differences in nitrogen input were observed for wheat in rotations 1 and 3, with the model estimating, on average, 11–12% lower applied nitrogen fertiliser under soil-test than scheduled management (Table 1). For these wheat crops, dry matter production per unit of applied nitrogen (fertiliser nitrogen use efficiency) was 6% greater under soil-test than scheduled management.

As expected, estimated average nitrogen leaching generally was lower under soil-test management than scheduled management. This difference was evident in rotation 1 and rotation 3, with rotation 2 exhibiting minimal leaching that was similar between the two fertiliser managements (Fig. 4). On average, soil-test management reduced nitrogen leaching by 32 and 17% in rotation 1 and rotation 3, respectively.
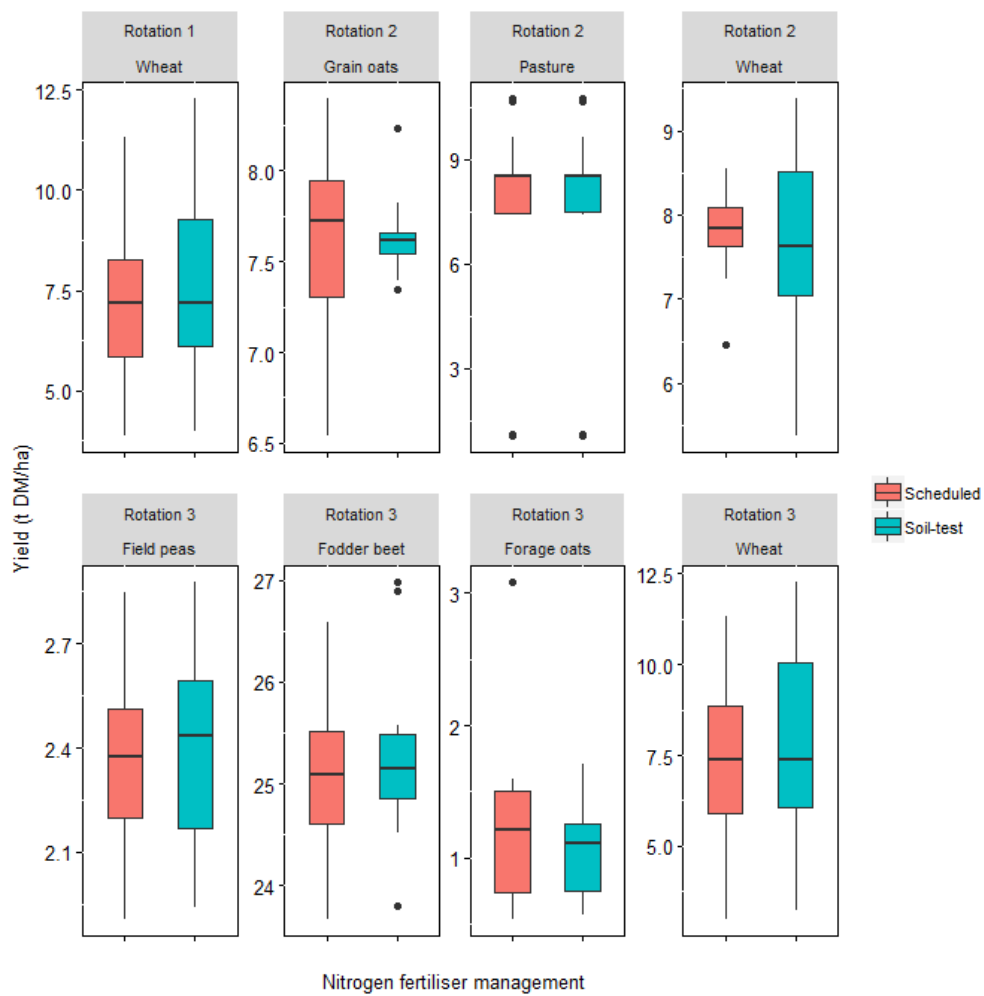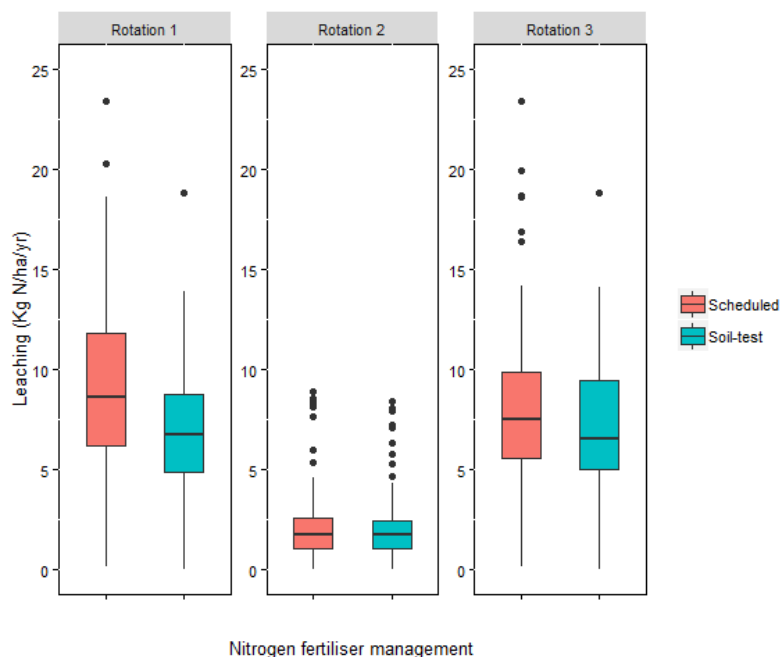
Figure 3. Dry matter (DM) yield estimated by the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM) for two fertiliser managements and three crop rotations of the Aparima catchment, Southland, New Zealand.

Table 1. Nitrogen fertiliser applied to crops in rotation. The scheduled rates were fixed model inputs while soil-test rates were estimated by the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM) model based on daily soil testing. Values in the parentheses represent the range.

Rotation	Crop	Nitrogen fertiliser management	
		Scheduled	Soil-test
1	Wheat	250	220 (120–330)
2	Wheat	250	242 (150–300)
	Grain oats	180	180 (150–210)
	Pasture	150	150
3	Wheat	250	223 (90–330)
	Forage oats	0	0
	Fodder beet	160	158 (142–182)
	Field peas	50	50

Figure 4. Nitrogen leaching estimated by the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM) for two fertiliser managements and three crop rotations of the Aparima catchment, Southland, New Zealand.

These model-estimated outputs largely show that soil-test-based fertiliser application has the potential to increase fertiliser nitrogen use and reduce the risk of nitrogen loss to the water systems in the Aparima catchment. Testing the soil to determine the amount of nitrogen fertiliser needed by a crop over the season is recommended and information is readily available for New Zealand farmers (e.g. Morton et al. 2012 and 2017). However, the regularity of soil testing and the splits of nitrogen fertiliser application differ from farmer to farmer. In general, soil tests are performed 1–3 times over spring and small amounts of nitrogen applied pre- or at-sowing followed by 2–3 large top-dressings during vigorous crop growth (Auld R, pers comm.). Depending on soil type and climate, application of nitrogen in large amounts can increase the risk of nitrogen leaching.

The continuous testing of the soil and fertiliser application depicted under the soil-test management in this study is potentially a better method than the traditional soil-test method where results from representative paddocks are extrapolated to similar areas of the farm, e.g. paddocks with similar soil type (Morton et al. 2012 and 2017). The APSIM model is capable of simulating individual paddocks (or sections of those paddocks) and can therefore, account for field and temporal variability in soil nitrogen status. As demonstrated by this study, generic crop rotations abstracted from actual farming system can produce realistic estimates of average production levels and include inter-annual variability. The effects of different fertiliser management and the estimated nitrogen inputs for the two scenarios tested were also in line with expectations. Thus, the use of such simulation setup is a promising tool to generate valuable data to help assess productivity and environmental effects of cropping systems and nitrogen mitigation options to improve water quality. Future work will focus on expanding the tests and integrating APSIM simulations with hydrology modelling via an inter-operable modelling framework to simulate water quality at the catchment level.

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