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NITROGEN WORKSHOP SPECIAL ISSUE PAPER

Integration of measures to mitigate reactive nitrogen losses to the environment from grazed pastoral dairy systems

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SUMMARY

The need for nitrogen (N) efficiency measures for dairy systems is as great as ever if we are to meet the challenge of increasing global production of animal-based protein while reducing N losses to the environment. The present paper provides an overview of current N efficiency and mitigation options for pastoral dairy farm systems and assesses the impact of integrating a range of these options on reactive N loss to the environment from dairy farms located in five regions of New Zealand with contrasting soil, climate and farm management attributes. Specific options evaluated were: (i) eliminating winter applications of fertilizer N, (ii) optimal reuse of farm dairy effluent, (iii) improving animal performance through better feeding and using cows with higher genetic merit, (iv) lowering dietary N concentration, (v) applying the nitrification inhibitor dicyandiamide (DCD) and (vi) restricting the duration of pasture grazing during autumn and winter. The Overseer® Nutrient Budgeting model was used to estimate N losses from representative farms that were characterized based on information obtained from detailed farmer surveys conducted in 2001 and 2009. The analysis suggests that (i) milk production increases of 7–30% were associated with increased N leaching and nitrous oxide (N_2O) emission losses of 3–30 and 0–25%, respectively; and (ii) integrating a range of strategic and tactical management and mitigation options could offset these increased N losses. The modelling analysis also suggested that the restricted autumn and winter grazing strategy resulted in some degree of pollution swapping, with reductions in N leaching loss being associated with increases in N loss via ammonia volatilization and N_2O emissions from effluents captured and stored in the confinement systems. Future research efforts need to include farm systems level experimentation to validate and assess the impacts of region-specific dairy systems redesign on productivity, profit, environmental losses, practical feasibility and un-intended consequences.

INTRODUCTION

The loss of nitrogen (N) from livestock production systems to waterways and the atmosphere continues to be a major global challenge that is driven by the on-going need to increase the world's food supply and by economic forces that often encourage the intensification of land use as a route to maintaining or improving farm profitability (Steinfeld *et al*. 2006). The availability of relatively cheap N fertilizer has been an important factor that has allowed agricultural intensification to occur, particularly in developing countries where usage has increased considerably in the past four decades (Bouwman *et al*. 2005; FAOSTAT 2012). The intensification of modern dairy farming systems has the potential to decrease N use efficiency (Gourley *et al*. 2012*a*) and increase losses of N to the environment (Ledgard *et al*. 1999; Oenema *et al*. 2010; Smith *et al*. 2013). On-going concerns about the environmental consequences of these increased losses mean that today's dairy farms are coming under much greater scrutiny and reinforce the need for continual improvement in dairy production efficiency.

Considerable research over the past four to five decades has given a greater understanding of the importance of N excretion in concentrated urine patches as a key source of N loss in grazed pastoral systems (Whitehead 1995). Much of this understanding has

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Table 1. *Summary of the key 'efficiency' or 'reduced nitrogen loss risk' measures for grazed pastoral dairy systems*

Aim	Potential options
More milk per cow or per unit DM intake	• Higher genetic merit animals • Lower cow replacement rate • Better feeding to improve body condition score at the start of calving • Better quality pasture/crops/supplements (optimizing protein & metabolizable energy contents)
More DM per unit of N input	• Mop-up crop during fallow period • Improved fertilizer and manure management • Exploit spatial and temporal variability in pasture N response
Reduce N loss risk	• Nitrification and Urease Inhibitors • Restricted grazing to avoid urine deposition at high risk times • Improved irrigation efficiency to minimize over-watering • Exploit spatial and temporal variability in N losses (especially N_2O)
Edge-of-field capture	• Riparian buffers • Wetland attenuation • Denitrification walls

been captured in modelling frameworks that can also address the potential environmental effects of combinations of soil–climate–land management scenarios (Brown *et al*. 2005; Ketterings *et al*. 2006). Evaluations of nutrient use efficiencies such as nutrient recovery in saleable product, farm nutrient surplus, nutrient loss (kg/ha) and management risks associated with nutrient losses to the environment, are examples of agri-environmental indicators, which can assess the effect of management strategies or system design options on environmental losses of N (Langeveld *et al*. 2007). In New Zealand, the Overseer® Nutrient Budgeting Model (Wheeler *et al*. 2011; Cichota *et al*. 2013) is used to provide N-efficiency and environmental indicators for farms, including dairy farming systems. This model also enables an assessment of the potential benefits of integrating multiple mitigation strategies, as opposed to the implementation of single options. The present paper provides an overview of current N efficiency and mitigation options for pastoral dairy farm systems and, using the Overseer® model, assesses the impact of integrating a range of these options on reactive N loss to the environment for a number of New Zealand case study dairy farms. It should be noted that Overseer® models both direct and indirect N_2O emissions. The effect of mitigation options on N leaching or ammonia (NH_3) volatilization losses and the subsequent effect on indirect nitrous oxide (N_2O) emissions are accordingly accounted for in the total N_2O emission estimates presented.

OVERVIEW OF STRATEGIES FOR REDUCING NITROGEN LOSSES

The best way of achieving the dual and generally conflicting goals of increased productivity and reducing N losses to the environment is to ensure that 'more for less' is achieved, i.e. more milk per animal or per unit of dry matter (DM) intake, or more DM per unit of N input. Reactive N losses to the environment can be further reduced through the adoption of practices that minimize N loss risk, or capture N before it enters waterways. Table 1 provides an overview of some available options.

Improving farm system and management efficiencies: more milk per unit of DM intake or more DM per unit of N input.

Studies have shown that the relatively simple farm system and management adjustments, such as using cows with higher genetic merit while reducing stock numbers, having fewer replacement stock and growing maize and oat crops on a small proportion of the farm, increased milk production per cow or per unit of DM intake, and, as a result, reduced potential and/or actual

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N losses from intensively managed New Zealand dairy farms (Beukes *et al.* 2011). Similarly, Aarts *et al.* (2000) and Oenema *et al.* (2010, 2012) showed how higher milk yields per cow, fewer replacement stock, judicious feeding, better utilization of farm manures and balancing areas of grassland and maize production improved nitrogen use efficiency (NUE) and reduced potential N losses from Dutch dairy farms. Gourley *et al.* (2012*a*, *b*) suggested that on Australian dairy farms, improved farm nutrient balances that consider feed N intake, more precise use of N fertilizer inputs and reutilization of effluents and manures generated on-farm could deliver more feed per unit of N input (Table 1). These options are particularly relevant to intensively managed dairy systems with relatively large inputs of N via feed, fertilizer and/or effluents and manures and subsequently large N surpluses at a farm, block or paddock level.

Reducing nitrogen loss risk

Strategies that show promise for reducing N loss risk from grazed dairy farms include the use of nitrification or urease inhibitors (UIs) and manipulating the timing and/or duration of pasture grazing. The nitrification inhibitor dicyandiamide (DCD) can reduce both nitrate leaching losses (Di *et al.* 2009; Monaghan *et al.* 2009) and N_2O emissions (Di & Cameron 2003; Smith *et al.* 2008) considerably, although its effectiveness appears to be influenced strongly by rainfall, temperature (Kelliher *et al.* 2008) and the frequency and timing of DCD application (Menneer *et al.* 2008). Recent research on the effectiveness of using UIs also shows some promises for minimizing the risks of N loss via NH_3 volatilization from applied fertilizer (Saggar *et al.* 2013); although further research is required under a wider range of climatic conditions to more fully evaluate the potential of this technology for reducing N losses within a grazed system context.

In fully or partially grazed systems, 'restricted grazing' strategies that remove the animals from pasture at certain times or extend the existing housing period can reduce N leaching and N_2O emission losses by avoiding urine deposition during periods of high N loss risk (de Klein *et al.* 2006; Ledgard *et al.* 2006; Cardenas *et al.* 2011). Disproportionately greater benefits were observed if grazing was restricted shortly preceding or during periods when drainage was occurring or conditions were favourable for denitrification and N_2O emissions. However, as restricted grazing increases the amount of effluent or manure collected off-paddock, there is a risk of 'pollution swapping' by increasing NH_3 or N_2O emissions from the collected effluent or manure (del Prado *et al.* 2010) if the cow confinement systems and storage and application of effluents are not well-designed or managed.

Edge-of-field capture

The main examples of mitigation options that capture or reuse N are attenuation options that (permanently or temporarily) remove nitrate-N during the transport process between where it is generated (i.e. in the paddock) and where it impacts on water quality. The main N attenuation tools currently available are riparian buffer strips, natural and constructed wetlands, and denitrification walls. Riparian buffer strips and wetlands capture and remove nitrate-N through both enhanced plant uptake and denitrification, while denitrification walls are solely targeted at reducing nitrate into gaseous N forms (Long *et al.* 2011). The effectiveness of these attenuation options for removing N depends in large part on their ability to intercept and modify flow pathways (Schipper *et al.* 2004; Mayer *et al.* 2007; Knox *et al.* 2008) and is thus strongly site-specific.

THE POTENTIAL OF INTEGRATED MEASURES FOR REDUCING NITROGEN LOSSES: CASE STUDY EXAMPLES FROM GRAZED NEW ZEALAND DAIRY FARMS

In 2001 the New Zealand dairy industry initiated a study in which regionally representative catchments that were predominantly used for dairy farming were monitored for water quality and flow, as well as changes in farm management practices that were likely to have an impact on contaminant losses (including N) to water. Some of the key trends in stream water quality are documented in Wilcock *et al.* (2013) and show how, as expected, measured N losses have increased in catchments where land use has changed from lower intensity sheep–beef farming to dairy farming. Farm scale modelling based on detailed farm surveys of farm inputs, managements and saleable outputs has also shown how N leaching losses have increased as dairy farms have intensified by, in most cases, importing more purchased feed and N fertilizer (Table 2). This link between dairy farm intensification and increased loss of N to water has also been observed in catchments in South-West Victoria, Australia by Smith *et al.* (2013), who also found some evidence to suggest that this link may have become decoupled during

Table 2. *Attributes of average farms in the catchment case study used for modelling the potential benefits of implementing a range of integrated mitigation measures on grazed New Zealand dairy farm systems*

Catchment	Toenepi		Waiokura		Waikakahi		Bog Burn		Inchbonnie	
Survey year	2001	2009	2001	2009	2001	2009	2001	2009	2004*	2010
Rainfall (mm/year)	1132		1400		540		921		5000	
Total area (ha)	70	85	75	75	249	254	218	218	210	210
Pasture	70	85	73	73	213	213	258	258	210	206
Effluent-treated†	6	17	9	14	40	56	37	65	20	32
Winter or **summer** forage crops	Minor	Minor	**2**	**2**	*36*	*41*	*40*	*40*	*0#*	*4#*
Major soil type	Free-draining volcanic silt loam		Free-draining volcanic silt loam		Free-draining stony silt loam		Poorly drained silty clay loam		Free-draining stony silt loam	
Irrigation (mm/year)	0	0	0	0	810	700	0	0	0	0
Stocking rate‡ (cows/ha)	2·9	3·3	3·4	3·2	2·4	2·9	2·5	2·5	2·0	2·0
Milk production§ (kg MS/ha)	906	1147	987	1193	852	1112	899	989	630	671
(kg MS/cow)	311	355	285	373	355	390	359	410	315	336
N fertilizer†† (kg/ha/year)	72/72	144/76	88/88	151/81	172/172	172/129	72/53	97/76	179/179	205/190
P fertilizer†† (kg/ha/year)	61/61	44/25	65/65	47/26	60/60	35/20	68/48	36/26	50/50	20/15
Purchased feed (T DM/ha/year)										
Pasture silage	0·61	0·46	0	0·2	2·0	1·1	0	0·81	1·26	0·1
Maize or cereal silage	0·27	0·49	0·32	0·21	0·5	0·1	0	0·1	0	0
Concentrates and grain	0	0	0	0·3	0	0·6	0·17	0·03	0·23	0
Hay	0	0	0	0·5	0	0·1	0	0·1	0·25	0·1
Palm Kernel Expeller	0	0·70	0	1·1	0	1·0	0	0	0	0
N leached (kg N/ha/year)	22	28	78	84	55	58	30	31	86	112
(kg/T MS)	24·3	25·0	79·0	70·4	64·6	52·2	33·4	31·3	136·5	166·9
N_2O emissions (T CO_2 eq/ha/year)	2·0	2·5	2·7	3·0	2·4	2·9	1·9	2·0	12·2	12·0
(T CO_2 eq/T MS)	2·2	2·3	2·7	2·5	2·8	2·6	2·1	2·1	19·4	17·9

* Inchbonnie catchment study commenced in 2004.
† Some farms within the Toenepi and Waiokura catchments discharge effluent to waterways after treatment via a 2-pond (anaerobic then aerobic) system.
‡ Replacement stock mostly grazed off-farm for Waikakahi and Bog Burn catchments.
§ 1 kg MS (milksolids) = *c.* 12 litres milk.
\# Uncovered pads typically used for over-wintering herds.
†† Fertilization rates for non-effluent/effluent blocks.

the second half of the 20-year monitoring period due to various changes in farm management. However, Smith *et al.* (2013) could not specify which changes may have had the greatest effect.

This farm and catchment monitoring has clearly demonstrated the challenges for reducing reactive N losses against a backdrop of farm intensification and land use change from lower intensity sheep farming to dairy. Although dairy systems have become more N efficient, the rate of productivity gains has typically been greater than the rate of efficiency gains. Some important metrics that describe this intensification for the farms in the present study are (Table 2):

- Purchased feed sourced via imported supplements or N fertilizer has increased by *c.* 5 and 4% per annum on average, respectively.
- Milk production per hectare has increased by *c.* 2% per annum (ranging from 1 to 4% per annum).
- Estimated N leaching and N_2O losses per hectare have increased by *c.* 2% per annum on average; when expressed on a per unit product basis, these losses remained either constant (N leaching) or decreased by only *c.* 1% (N_2O emissions) per annum on average.

Of note is the improved fertilizer management that has occurred on effluent blocks, where both N and P fertilizer inputs have generally reduced as farmers and fertilizer representatives have considered the returns of these nutrients in applied effluent.

To evaluate the potential for offsetting the increases in N loss between 2001 and 2009, farms were re-modelled to identify some of the most effective mitigation options, applied singly or in combination, and explore whether any of the measures resulted in pollution swapping. The scenarios were derived based on the most recent survey (2009; Table 1) of typical farm practices and the suite of mitigation measures potentially available and relevant, as discussed above (but excluding edge-of-field attenuation options). The scenarios considered were:

1. Eliminating applications of fertilizer N to some of the catchment farms during winter.
2. Optimal reuse of farm dairy effluent to minimize direct losses during application to land and ensure that N fertilizer inputs account for N returns in the applied effluent.
3. Improving animal performance through better feeding and using cows with higher genetic merit. This was assumed to allow a slight reduction in animal replacement rates (to 18%).
4. Substituting half of the N-fertilized grass with purchased supplement that contained a higher energy-to-protein ratio.
5. Applying the nitrification inhibitor DCD to pasture areas.
6. Restricting the duration of pasture grazing to 10 h/day during autumn and the first 2 months of winter for Toenepi, Waiokura and Inchbonnie catchment farms, where cows are mostly grazing on pasture during this period. For the Bog Burn and Waikakahi farms that currently use a forage brassica crop to over-winter cows, it was instead assumed that cows would be housed in a herd shelter for 10 weeks over winter.
7. A scenario where all of the above options are assumed to be implemented.

The mitigation modelling results for farms in 2009 are shown in Figs 1 and 2 and have been normalized to losses modelled for the case study farms based on farm survey information gathered for 2001. This modelling analysis indicates that for all catchments the N leaching losses (without mitigations) have increased by 3–30% since 2001, with the highest increases observed in the Toenepi and Inchbonnie catchments. Most of the individual mitigation options would have relatively small effects on offsetting these increases in N leaching. For example, eliminating N fertilizer applications during winter was relevant to only two of the five catchment farms, and was predicted to reduce losses by *c.* 10% for these farms relative to the 2009 base farm losses, while improved effluent management was estimated to reduce losses by only 2–4% relative to 2009 base farm losses. However, neither option could offset the increase in leaching losses observed since 2001. Using fewer cows with higher genetic merit could offset the increase in losses since 2001 in two of the five catchments only. Replacing N-fertilized grass with a higher-energy supplement and applying the nitrification inhibitor DCD were slightly more effective measures, reducing N leaching losses by on average 15 and 16% relative to the 2009 base farm losses on average, respectively, and could in most cases offset any increases observed since 2001. It should be noted that the current modelling assumes that supplements were produced outside of the catchments and hence does not account for any off-farm effects on N losses. The single most effective measure for reducing N leaching losses from

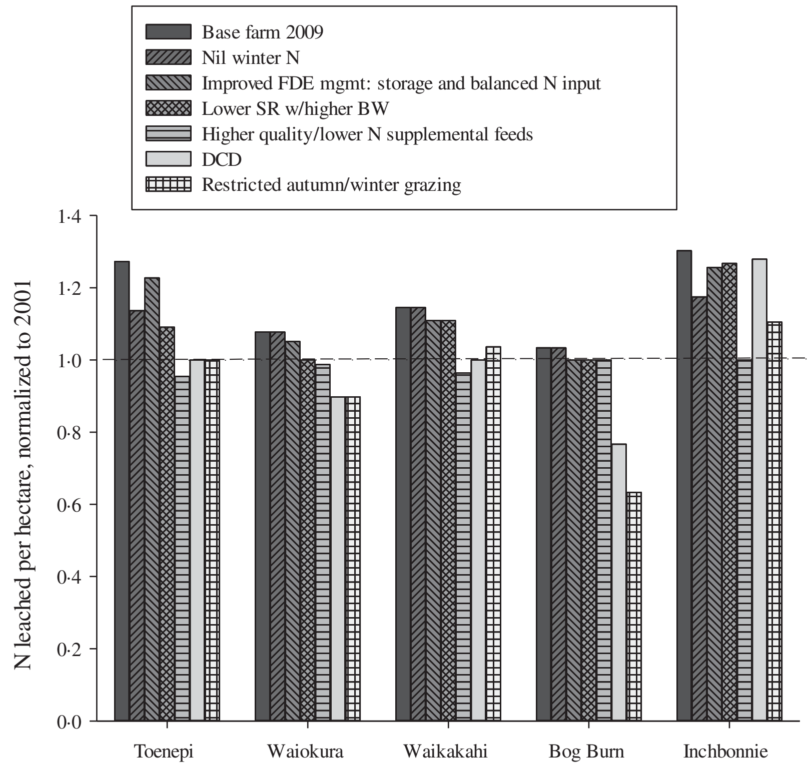

Fig. 1. Modelled nitrogen leaching losses per hectare for the catchment farms in 2009 assuming a range of individual mitigation practices have been implemented. Results have been normalized to losses estimated for each catchment Base farm in 2001. FDE, farm dairy effluent; SR, stocking rate; BW, cow breeding worth; DCD, dicyandiamide.

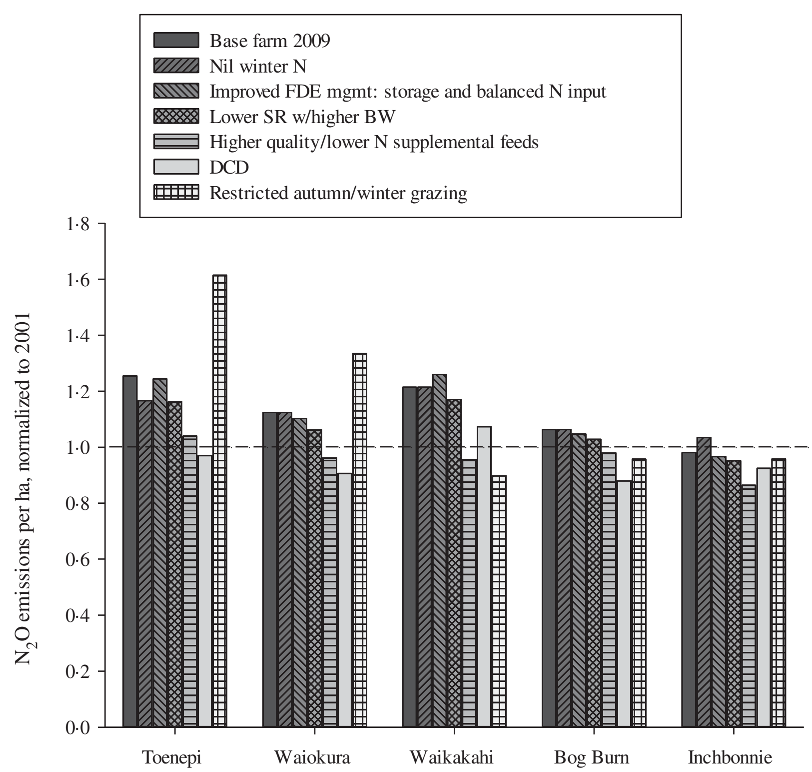

Fig. 2. Modelled nitrous oxide emissions per hectare for the catchment farms assuming a range of individual mitigation measures have been implemented. Results have been normalized to emissions estimated for each catchment Base farm during 2001. FDE, farm dairy effluent; SR, stocking rate; BW, cow breeding worth; DCD, dicyandiamide.

the farms was to limit the duration of pasture grazing during autumn and winter months. Averaged across the catchments, this was estimated to reduce N leaching losses by *c*. 20% relative to the 2009 base farm losses.

The analysis also suggested that intensification resulted in an increase in N_2O emissions (without mitigations) of 0–25% since 2001, with the highest increases observed in the Toenepi and Waikakahi catchments. As for N leaching, the implications of each mitigation measure on N_2O emissions were variable. Only three of the mitigation practices would consistently deliver reductions in per-hectare N_2O emissions relative to the 2009 base farm emissions: improving animal performance combined with a reduction in stocking rate (5% reduction on average, ranging from 3 to 7%), introducing a higher-energy supplement to the cow diet (15% reduction on average, ranging from 8 to 21%) and applying DCD to pasture (15% reduction on average, ranging from 6 to 23%). The use of a higher-energy supplement or DCD could in most cases also offset any increases in emissions since 2001. Limiting the duration of pasture grazing during autumn and winter months was estimated to lead to greater emissions of N_2O from the North Island Toenepi and Waiokura farms compared with the 2009 base farms, whereas for the South Island catchments this option resulted in reductions of 2–26% in N_2O emissions. These estimated reductions in the South Island catchments were also large enough to offset any increases observed since 2001. The increased emissions in the North Island catchments were due to the modelled increases in losses from the stored manures and effluents that were accumulated in the off-paddock herd shelter. This is an example of how some mitigation options can potentially result in pollution swapping; in the case of the Waiokura and Toenepi farms, the 17 and 21% reductions in estimated N leaching losses per hectare due to off-paddock grazing resulted in an estimated increase in total N_2O emissions per hectare of 19 and 29%, respectively, even though these estimates account for a reduction in indirect N_2O emissions due to reduced N leaching. In contrast, the restricted pasture grazing strategy was estimated to reduce both N leaching and N_2O emissions, relative to the 2009 base scenario for the three South Island model farms. The contrasting modelled responses in N_2O emissions between the North and South Island catchment farms are assumed to be attributable to the climatic factors that are influencing the N losses modelled from the stored manures (relatively large increases in emissions modelled for the warmer North Island farms) or excreta deposited to pasture and winter crops (greater benefit observed for restricting grazing duration for the cooler, wetter South Island farms).

Figures 1 and 2 indicate that mitigation practices will need to be collectively implemented to achieve reductions in N losses large enough to offset any future increases due to on-going intensification on the catchment farms. If the options above are categorized into 'efficiency' (1–3), 'mitigation' (4 and 5) and 'system changes' (6), and progressively implemented and modelled in that order, the magnitude of (technically) achievable reductions in N loss becomes more apparent. The system change was implemented last because it was assumed that the restricted grazing system (measure 6) would be the least favoured N leaching mitigation measure due to the cost and management complexity introduced by this measure and the potential pollution swapping that could occur in some areas. Model estimates of leaching, N_2O emissions, NH_3 volatilization, denitrification and total N losses were included to more fully consider any implications of pollution-swapping that may potentially arise from these sets of collective measures (Fig. 3). Loss estimates have been normalized to 2001 for each catchment farm to remove the effects of skewing that would otherwise be apparent if actual losses per hectare were plotted on individual axes.

Although there is variability between the catchment farms, this modelling of the introduction of collective measures for an average farm suggests that 'efficiency' measures (scenarios 1–3) could reduce N leaching losses from the 2009 Base farms by 7–21% (mean of 13%). A co-benefit of introducing these would be a reduction in N_2O emissions of *c*. 7%. Although these N leaching reductions are significant, they are only estimated to reduce losses, on average, to levels calculated for the 2001 Base farms (Fig. 3). Implementation of both 'efficiency' and 'mitigation' measures (scenarios 1–5) would reduce total N leaching and N_2O emissions from the 2009 Base farms by *c*. 30%, or by *c*. 22% if compared against the 2001 Base farms. Finally, implementation of all the strategies, including 'system change' (scenario 6), is predicted to reduce N leaching and N_2O emissions from the 2009 Base farms by 44% (range 33–61%) and 22% (range 11–32%) on average, respectively; or by 34 and 12% relative to the 2001 Base farms, respectively. At a technical level, these potential reductions are substantial, although they do require progressively greater

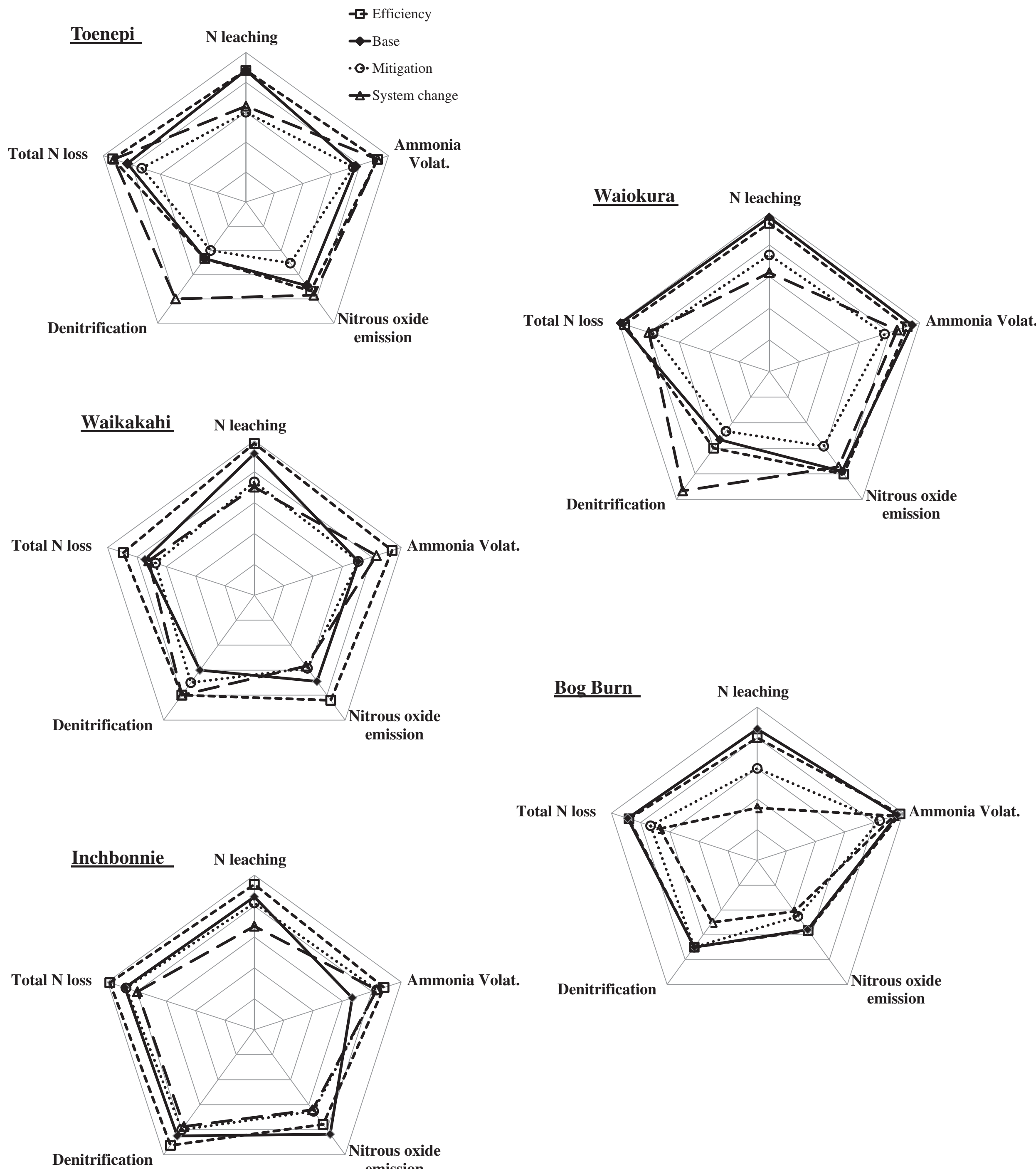

Fig. 3. Model estimates of leaching, nitrous oxide emissions, ammonia volatilization, denitrification and total N losses from the catchment farms for scenarios where efficiency (□; scenarios 1–3), mitigation (○; scenarios 4 and 5) or system change (Δ; scenario 6) measures are assumed to be collectively and progressively implemented. Base farm losses for 2001 are shown as solid black lines (⧫). Lowest losses are at the centre and increase with distance outwards.

management expertise and, in some cases, may incur significant cost. However, the 'efficiency' measures (scenarios1–3) are likely to result in no cost or even a cost saving, as they represent increases in total farm efficiency (i.e. more milk per cow or per unit of DM). The 'mitigation' measures, in particular the restricted grazing option, are likely to incur cost and may require incentives (e.g. carbon trading) or regulations (e.g. nutrient loss capping to protect water quality) to support their implementation. Fortunately, in most

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cases the combined strategies do not result in pollution swapping or greater total N losses to the environment (Fig. 3). Exceptions to this general finding are the greater denitrification losses modelled for the Toenepi, Waiokura and Waikakahi farm scenarios. As observed for N_2O losses, denitrification losses increased on the Toenepi and Waiokura farms when all practices were collectively implemented due to the effects of storing effluent captured on the off-paddock confinement facility. Reasons for the greater denitrification losses modelled for the Waikakahi farm are unclear, although they are very small in absolute terms at only 1 or 2 kg N/ha/year.

IMPLICATIONS FOR CATCHMENT FARMS

These modelling assessments suggest that integrating a range of strategic and tactical management and mitigation options can reduce N losses to the environment, while maintaining milk productivity. It is apparent from this analysis, however, that there is no 'one size fits all' approach to the challenge of reducing N losses from these dairy systems and that the ability to reduce losses will vary between individual farms depending on their existing management practices and level of farm inputs. While most of the 'efficiency' options evaluated are in principle equally relevant to all the catchment farms, some of the mitigation practices are inappropriate due to the considerable variability evident in soil and climate factors for the catchment farms. The most obvious example of this is the low effectiveness of DCD in the Inchbonnie catchment, where the extremely high rainfall (4·5 m per annum) was the cause of the low predicted reductions in N leaching and N_2O emissions of only 2 and 6%, respectively. In contrast, in the drier Bog Burn catchment estimates of N leaching and N_2O emissions were reduced by 26 and 17% due to DCD application, respectively. Another example is the use of a restricted grazing strategy during autumn and winter to reduce urinary N returns to pasture ahead of winter rainfall and drainage. Although this is modelled to deliver N leaching reductions of 17–21% for the warmer North Island catchments of Toenepi and Waiokura, the unintended consequences of implementing this measure are the modelled increases in N loss via NH_3 volatilization and N_2O emissions from the herd shelter and stored effluents (Fig. 3). This is the only scenario where an individual measure is predicted to actually result in an increase in total N losses, in this case by 12 and 1% for the Toenepi and Waiokura catchment farms, respectively. Although increases in NH_3 volatilization are also modelled for the restricted autumn–winter grazing management scenario when applied to the cooler South Island catchment farms, these increases are relatively small, and total N losses are still 6–10% lower than modelled for the equivalent Base farms.

The cost associated with implementing each of the management options evaluated above is obviously an important consideration that will govern likely rates of adoption by farmers. Although these costs are subject to the price volatility often attached to farm input costs and product returns, it is reasonable to assume that the efficiency measures evaluated in the present paper will incur little or no cost and in fact are likely to deliver a net return where superior animal performance has been assumed. The net costs associated with the mitigation practices (DCD and lowered dietary N content) will fluctuate depending on input prices and milk returns. Recent evidence presented by Gillingham *et al.* (2012) would suggest that the small to modest increases in pasture production in response to DCD application are likely to at least partly off-set the costs of applying this product in many situations. The economic consequence of modifying dietary N content is, however, subject to a number of price variables, the most important of which are the cost of the low-N feed, such as maize or cereal silage/grain, and the price of milk (Jensen *et al.* 2005). The measure that is likely to incur greatest cost is the restricted grazing strategy, which requires significant capital investment and some degrees of on-going management cost associated with the required changes in animal and effluent management practices. An unintended consequence of this strategy could be that farmers might use the housing or stand-off facility to increase stock numbers by bringing in more supplements to maximize the return on investment. As a result, reactive N cycling in the system could be intensified and total N losses potentially higher, although losses per unit of product are likely to be lower. Given these cost implications, and the pollution swapping potential discussed above, the restricted grazing strategy is likely to have more limited applicability than the other options considered here.

FUTURE OPTIONS AND RESEARCH NEEDS

The catchment case study analysis suggests that improved management and mitigation practices can partially offset increased N losses associated with recent farm intensification. However, on-going intensification will require future options to minimize or reduce reactive N losses to the environment. These future options could include genetic solutions such as continuous improvement of the genetic merit of dairy cows (Beukes *et al.* 2011) or the development of pasture species with low N concentration to minimize N excretion in predominantly grazed systems (Parsons *et al.* 2013). Other options include those that accelerate the reduction of N_2O to environmentally benign N_2 during denitrification. This reduction process is the only known sink of N_2O in pastoral systems and is catalysed by the microbial enzyme nitrous oxide reductase (N_2OR) encoded by the *nosZ* gene (Thomson *et al.* 2012). Manipulating the soil physicochemical and/or environmental factors that influence *nosZ* gene expression and/or N_2OR activity could provide scope for accelerating N_2O reduction in urine patches, thereby reducing N_2O emissions from grazing livestock systems. Such manipulations or technologies could also have a spillover benefit in that they could be used in areas where the risk of NO_3^- leaching poses an environmental threat. Using the technologies in combination with technologies or practices that enhance total denitrification (e.g. riparian areas or wetlands) would result in reduced nitrate pollution to waterways without increasing the risk of N_2O emissions from these areas. Future options could also focus on further exploiting the spatial and temporal variability in soil, environmental and climatic drivers, to further increase NUE ('more for less') or the effectiveness of mitigation options such as nitrification inhibitors ('reduced N loss risk'). For example, Shepherd *et al.* (2011) showed that 40–50% of urine deposited in late summer/early autumn (i.e. well before the start of the drainage season) could be lost through leaching. Therefore, targeting N mitigations early could substantially reduce the risk of N leaching, particularly in summer-dry areas where pasture growth rates, and thus N uptake, are limited. Similarly, the spatial and temporal variability in soil moisture, a key driver of N losses (van der Weerden *et al.* 2012), could be exploited by using real-time soil water monitoring to improve tactical decision making for fertilizer, manure and/or grazing management to reduce N leaching and N_2O emissions.

Finally, evaluation of the whole dairy system (i.e. dairy farm and associated land used for feed production) is important when assessing the effectiveness of management interventions that tighten the N cycle. This scale of analysis adds considerable complexity and places much reliance on modelling tools that attempt to simulate system responses relative to a change in land use management. Although the knowledge of biological systems and their response to farm management interventions remains surrounded by uncertainty, the challenging and pressing issues at hand require use of the modelling tools available and acknowledge the uncertainties inherent in model outputs. Recognizing these uncertainties can then guide future research needs and modelling tool development.

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