Realistic nitrogen use efficiency goals in dairy production systems: a review and case study examples

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Abstract
Nitrogen use efficiency (NUE), the ratio between N outputs in products over N inputs, is often used to evaluate N use outcomes of an agricultural system and/or the risk of environmental N losses. In this paper we address the question what NUE goals are realistic for dairy production systems. We use the following definitions of NUE: *Crop NUE*, defined as the percentage of the total N inputs taken up by crops or pasture; *Animal NUE*, defined as the percentage of total feed N intake incorporated into milk and meat; and *Whole farm NUE*, defined as the percentage of total N inputs to the farm that is exported in animal products and/or exported feed. Nitrogen surpluses (i.e. N inputs minus N outputs) are also reviewed. Published values of Crop NUE and N surplus generally ranged between 55-90% and 25-230 kg N/ha/year, respectively, while commonly reported Animal NUE and N surplus values ranged between 15-35% and 110-450 kg N/ha/year. Whole farm NUE and N surplus values ranged between 10-65% and 40-700 kg N/ha/year. In a NZ catchment study, Whole farm NUE was affected more strongly by differences between catchments (e.g. soil and climatic conditions) than by differences in management. In contrast, N surplus values differed both between-catchment and within-catchment and were good indicators of N losses to water. Realistic goals for NUE will therefore depend on the agro-climatic context in which a dairy system operates and on the economic and environmental goals the system aims to achieve. Crop and Animal NUE values can be valuable indicators for optimising fertiliser and feed use, and minimizing N losses. However, global or even national Whole-farm NUE values appear to be of limited value if the ultimate goal for setting targets is to reduce the environmental impact of N use. Whole-farm level targets based on N surplus would be a more useful indicator for this. Regardless of the metric used all metrics are calculated based on estimates of N inputs and N outputs, so it is important to agree on which items should be included in the input and output terms, and that all inputs and outputs are measured or adequately estimated. For systems that import large amounts of purchased feeds, this should include the N inputs required to produce this feed. Any NUE goals targets should be set in the context of other agro-environmental indicators such as losses of phosphorus and faecal organisms to water, carbon footprints, and energy and water use efficiencies.

Key Words
Animal NUE, Crop NUE, Dairy systems, Nitrogen Use Efficiency (NUE), Whole farm NUE

Introduction

Nitrogen use efficiency (NUE) is commonly used to assess the relative conversion of N inputs into agricultural products and to indicate the risk of environmental N losses. NUE is expressed as a ratio of outputs over inputs and can be estimated using a range of metrics, such as plant growth per unit of N (e.g., fertiliser, manure) applied; meat or milk production per unit of animal N intake; N exported from a farm per unit of N imported; or N consumed in food per unit of N used to produce the food. Regardless of the metric used, a high NUE does not necessarily infer a low risk of N loss. For some highly intensive systems, NUE can be high, but the risk of N loss, can still be considerable. Conversely, a low NUE could indicate that production levels or yields may have been compromised. In a recent publication by the Global Partnership on Nutrient Management, Norton et al. (2015) highlighted that neither a high nor a low NUE is an implicit target, but that they are situation- and impact-dependent. Optimum targets for N metrics therefore need to aim for high utilisation of N input whilst minimising N loss risk and not compromising agricultural productivity. A European Nitrogen Expert Panel recently suggested using a NUE indicator in a two dimensional N output over N input framework that combines the different indicators (EU Nitrogen Expert Panel, 2015; Figure 1). This framework considers the minimum amount of N input required for production, the maximum N surplus that is environmentally acceptable, the minimum NUE level to avoid wasting N and the maximum NUE to avoid soil mining (e.g. Lassaletta et al 2014). Once goals are set for these parameters, the indicator framework can be easily applied to assess whether desired outcomes are achieved.

In this paper we will address the question about what realistic NUE goals are for dairy production systems. Following a definition of different NUE metrics that are commonly used, we will provide a summary of the range of NUE and N surplus values measured in different dairy farming systems. We will then use the input/output framework developed by the EU Nitrogen Expert Panel to map the NUE values of the summarised studies. We will also identify the impact of current or emerging management practices or technologies on these metrics, using examples from case study farms in five catchments in New Zealand. Finally, we will discuss the merits and challenges of setting targets for realistic NUE and N surplus metrics.

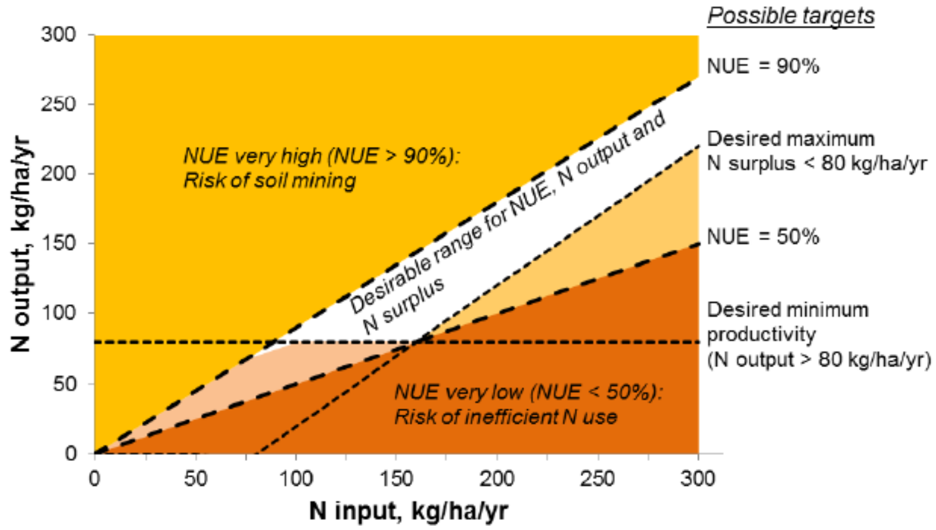

Figure 1. Conceptual framework of the Nitrogen Use Efficiency (NUE) indicator framework developed by the EU Nitrogen Expert Panel (2015). The numbers shown are illustrative of an example system and will vary according to context (soil, climate, crop). The slope of the diagonal wedge represents a range of desired NUE between 50% and 90%: lower values exacerbate N pollution and higher values risk mining of soil N stocks. The horizontal line is a desired minimum level of productivity for the example system. The additional diagonal line represents a limit related to maximum N surplus to avoid substantial pollution losses. The combined criteria serve to identify the most desirable range of outcomes.

Definition of NUE metrics

In general terms, NUE is defined as N output as a percentage of N input, whilst N surplus is the difference between N input and N output. These metrics can be expressed at a range of different scales, from microbial (e.g. Mooshammer et al. 2014), to plant or crop (e.g. Lassaletta et al. 2014), to animal (e.g. Powell and Rotz, 2015), to whole farm (e.g. Gourley et al 2012b; Powell et al., 2010), to regional (e.g. Ma et al. 2012), or even national (Oenema et al. 2009) scales. Although the definition of these metrics is generally consistent across studies, there are differences in the terminologies used. For example, the percentage fertiliser N that is taken up by a crop is sometimes referred to as fertiliser NUE (e.g. Powell et al. 2010) while in other cases it is referred to as crop NUE (e.g. Lassaletta et al. 2014). Similarly, the percentage of N intake in animal feed that is utilised in milk or meat is referred to as either feed NUE (Gourley et al. 2012a), dietary NUE (Powell & Rotz, 2015) or animal NUE (Christie et al. 2014). In this paper we will use *Crop NUE*, defined as N uptake by a crop or pasture sward, expressed as a percentage of the N input into the crop or pasture from fertiliser, manure, soil N supply and N fixation; *Animal NUE*, defined as N in animal products and expressed as a percentage of N intake by the animal from crop, pasture and/or imported feed; and *Whole farm NUE*, defined as N exported in animal products and/or exported feed, expressed as a percentage of total N inputs from fertiliser, N fixation, imported feed and/or atmospheric deposition. It is recognised that there are methodological challenges with measuring the parameters needed to calculate NUE. Some of these, such as N fixation in grazed systems, are notoriously difficult to measure.

Examples of NUE and N surplus values for dairy systems

Examples of Crop NUE values for dairy systems as reported in the literature (Table 1) were 16-57% for applied manure in US dairy systems (Beegle et al. 2008), 61-71% for Chilean dairy systems (Nunez et al.

2010), 59-77% in a Dutch dairy farm (Aarts et al. 2008) and 56-91% for 16 case study dairy farms in the Netherlands (Oenema et al. 2012). Values for N surpluses in Chilean dairy systems and Dutch research and commercial farms ranged from 25-229 kg N/ha/year. Reported Animal NUE and N surplus values ranged from 13-14% and 366-446 kg N/ha/year in NZ research trials (Roche et al. 2016) to 22-24% and 275-308 kg N/ha/year for a Dutch research farm (Aarts et al. 2000). Animal NUE values on US dairy farms and Dutch case study dairy farms ranged between 18-33% and 22-27%, respectively (Chase 2004, Powell et al. 2006, Oenema et al. 2012). As expected, Crop NUE values were generally much higher than Animal NUE values, reflecting the N inefficiency inherent to livestock production.

Table 1. An overview of NUE and N surplus values across a range of dairy production systems.

	NUE (%)	N surplus (kg N/ha/yr)	Country; brief description	Reference
Crop NUE	16–57	na*	USA; NUE from manure	Beegle et al. 2008
	59–77	85–184	Netherlands; research farm	Aarts et al. 2000
	56–91	25–229	Netherlands; 16 commercial farms	Oenema et al. 2012
	61-71	112–136	Chile; 3 grazed systems	Nunez et al. 2010
Animal NUE	13–14	366–446	NZ; Intensive dairy research trials with increasing stocking rates	Roche et al. 2016
	15–35	120–320	Australia; 17 commercial grazed systems	Gourley et al. 2012a
	17–34	110–125	USA; 12 commercial grazed and confinement systems	Gourley et al. 2012a
	22–24	275–308	Netherlands; research farm	Aarts et al. 2000
	21–36	na*	USA; commercial dairy herds	Chase 2004
	22–27	na*	Netherlands; 16 commercial farms	Oenema et al. 2012
	18–33	na*	USA; 54 commercial dairy farms	Powell et al. 2006
Whole farm NUE	8–55	40–700	Australia; commercial dairy systems	Ovens et al. 2008
	14–50	47–601	Australia; 43 commercial grazed systems	Gourley et al. 2012b
	17–42	121–358	EU: high and low N dairy systems	Castillo et al. 2000
	18–20	231–277	Ireland; 21 intensive dairy farms	Treacy et al. 2008
	21–39	124–259	New Zealand; intensive dairy farms in five different catchments	Monaghan & de Klein 2014
	22–36	174–275	Ireland: intensive dairy farm	Huebsch et al. 2013
	27–35	140–198	Netherlands; research farm	Aarts et al. 2000
	24–42	116–409	New Zealand; 4 grazed systems	Ledgard et al. 1999
	25–64	140–314	USA; 8 commercial dairy farms	Hristov et al. 2006
	29–42	98–252	Netherlands; 16 commercial farms	Oenema et al. 2012
	35-56		USA; high and low stocking rates	Powell et al., 2010

* na, not available

The Whole farm NUE values and N surpluses ranged from 8-55% and 40-700 kg N/ha/year, respectively, in Australian commercial dairy systems (Ovens et al. 2008; Gourley et al. 2012b) to 29-42% and 98-252 kg N/ha/year, respectively, for Dutch case study dairy farms (Oenema et al. 2012). Scott and Gourley (2016) provided a 22-year time series of N efficiency metrics for Australian dairy systems, which highlights the impact that intensification can have on reducing NUE and increasing N surpluses. As the industry average dairy farm intensified between 1990 and 2012, with increasing milk production per ha, driven in large part by increasing N fertiliser inputs and purchased feed, Whole farm NUE values decreased from 40-50% to 26-29% and total N surplus increased from 40-55 to 140-160 kg N/ha.

Most of the studies highlighted the difficulties of striking the right balance between desired productivity, NUE and N surplus, with N surplus almost always increasing with productivity (i.e. N output; Figure 2). There was an even stronger relationship between N input and N surplus. Gourley et al (2012b) also showed a positive relationship between N surplus and milk production. However, there was no clear relationship between Whole farm NUE and milk production, which indicated that farm management practices and soil and climatic conditions, rather than simply productivity, are key drivers of Whole farm NUE. Oenema et al. (2012) showed that a low input organic dairy farm had the highest NUE and lowest N surplus, but also the lowest dry matter (DM) yield (and thus most likely also lowest milk production). However, at the other end of the intensity spectrum, a fully confined dairy farm achieved high DM yields, high NUE and a low N surplus, largely due to increased utilisation of manure N. Similarly, Ledgard et al (1999) reported Whole farm NUE and N surplus values for New Zealand grass/clover based dairy systems with a stocking rate of 3.3 cows/ha of 42% and 115 kg N/ha/year when no N fertiliser was used and 24% and 330 kg N/ha/year for a system using 400 kg fertiliser N/ha/year. However, a 400N system with a stocking rate of 4.4 cows/ha (and a higher milk production) had an N surplus of 410 kg N/ha/year, while it's NUE remained at 24%. The range of values for both Crop and Animal NUE were generally narrower than the range of Whole farm NUE values. This reflects the larger number of variables affecting the latter values, such as system size and type, geographical region, soil and climate conditions, and fertiliser and manure management practices.

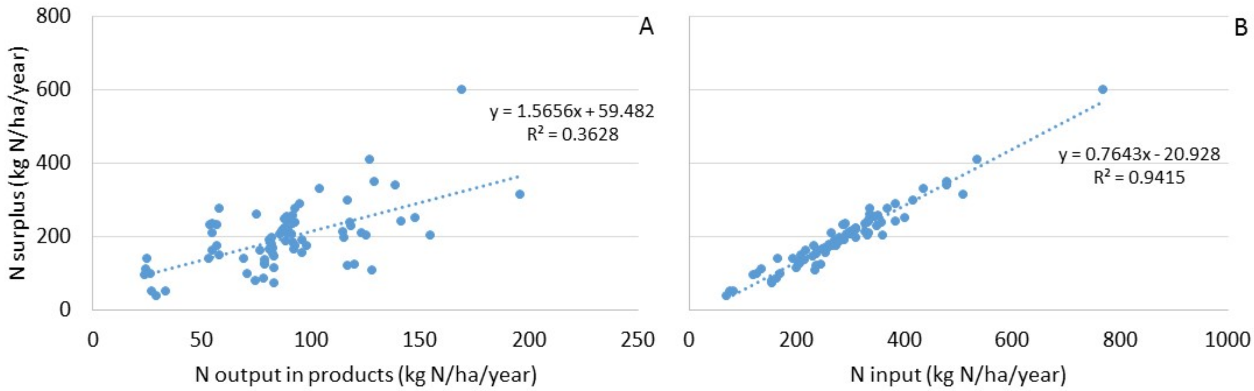

Figure 2. Relationship between N output in products (productivity; A) and total N inputs (B), with whole farm N surplus (data obtained from the studies summarized in Table 1).

Mapping results into the EU Nitrogen Expert Panel input/output framework

We used the whole farm NUE results summarised in Table 1 to populate the input/output framework proposed by the EU Nitrogen Expert panel (2015; Figure 3). This illustrated that Whole farm NUE values are generally within the 20-40% range, with a larger proportion of farms achieving NUE close to 40%, when N inputs were lower than 300 kg N/ha. In terms of productivity, 75% of the farms had N outputs exceeding 75 kg N/ha. However, the results also showed that more than half of the farms had N surpluses greater than 200 kg N/ha, while only 7% of the farms achieved an N surplus of less than 100 kg N/ha.

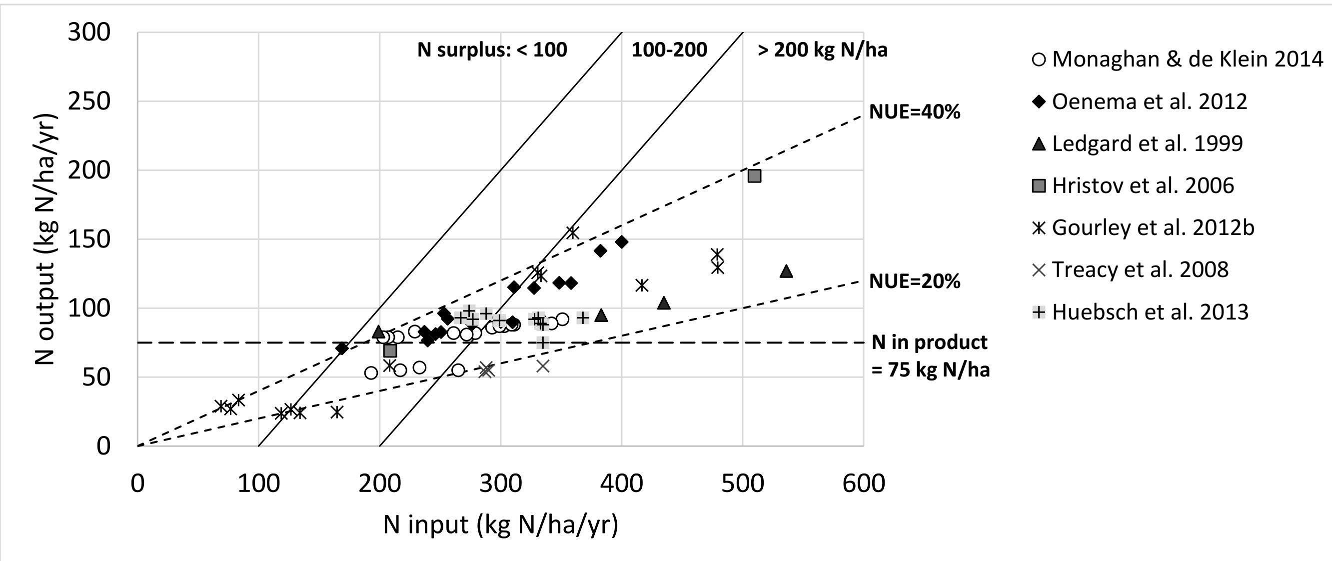

Figure 3. Examples of published annual N input and N output values of dairy systems mapped into the framework proposed by the EU Nitrogen Expert Panel (2015).

The impact of management practices on NUE – a New Zealand example

Monaghan and de Klein (2014) recently summarised key 'N efficiency' or 'reduced N loss risk' measures for grazed dairy systems (Table 2). These measures are focussed on increasing Crop or Animal NUE or targeted at reducing N losses to water. In the same study, detailed survey data of case study dairy farms in five New

Zealand catchments were used to assess the potential impacts of these measures on N losses to water using the Overseer® Nutrient Budgeting Model (Wheeler et al. 2011). The analysis was based on three different scenarios: 'efficiency', 'mitigation' and 'system changes'. These represented the progressive incorporation of N efficiency measures (2, 4 and 5 in Table 2), plus 'easy' mitigation measures (2, 4, 5, 7 and 8), plus infrastructure measures (2, 4, 5, 7, 8 and 9), respectively. Here we use the modelling data (plus unpublished data) to assess the effect of these measures on Whole farm NUE values, N surpluses and N losses to water (Table 3).

Table 2. Summary of the key 'efficiency' or 'reduced N loss risk' measures for grazed pastoral dairy systems (after Monaghan & de Klein, 2014).

Aim	Potential options
Increase Crop NUE (*More DM per unit of N input*)	1. Catch crop during fallow period 2. Improved fertilizer and manure management 3. Exploit spatial and temporal variability in pasture N response
Increase Animal NUE (*More milk per unit DM intake*)	4. Higher genetic merit animals 5. Lower cow replacement rate 6. Better feeding to improve body condition score at the start of calving 7. Better quality feed (optimizing protein & metabolizable energy contents)
Reduce N losses	8. Nitrification and urease inhibitors 9. Restricted grazing to avoid urine deposition at high risk times 10. Improved irrigation efficiency to minimise over-watering 11. Exploit spatial and temporal variability in N losses

Table 3. The effect of progressive implementation of 'efficiency', 'mitigation' or 'system change' measures on annual Whole farm NUE values, N surpluses and N losses for dairy farms in five New Zealand catchments. See text for explanation of the scenarios (Monaghan & de Klein 2014 and unpublished data).

Catchment	Scenarios	N input kg N/ha/yr	N output kg N/ha/yr	Whole farm NUE %	N surplus kg N/ha/yr	N loss water kg N/ha/yr
Toenepi	Base farm	303	87	29	216	33
	+Efficiency	279	82	29	197	28
	+Mitigation	261	82	31	179	20
	+System change	272	81	30	191	19
Waiokura	Base farm	333	91	27	242	53
	+Efficiency	311	88	28	223	46
	+Mitigation	309	88	28	221	35
	+System change	293	86	29	207	31
Waikakahi	Base farm	351	92	26	259	90
	+Efficiency	342	89	26	253	87
	+Mitigation	299	89	30	210	71
	+System change	299	87	29	212	38
Inchbonnie	Base farm	233	57	24	176	126
	+Efficiency	217	55	25	162	109
	+Mitigation	265	55	21	120	100
	+System change	193	53	27	140	75
Bog Burn	Base farm	229	83	36	146	43
	+Efficiency	215	79	37	136	40
	+Mitigation	207	79	38	128	32
	+System change	203	79	39	124	16

The results showed that Whole farm NUE values for the base farms varied between catchments (24-36% NUE), but that the different N mitigation scenarios had a relatively small effect on NUE values within a catchment. There was also a large *between*-catchment variability in estimated N surpluses and N leaching losses. However, in contrast to the NUE values there was also a significant *within*-catchment variability in N surplus and N leaching losses. This is further illustrated in Figure 4 for two of the five catchments.

The large between-catchment variability in NUE is not surprising, and reflects the *inherent* attributes and conditions that affect the NUE values, especially differences in potential production due to soil and climatic conditions. This inherent variability in NUE values between catchments, regions and even countries does highlight the difficulties of setting 'standard' or 'global' NUE goals. The within-catchment variability in NUE is affected by the *management* attributes of the farms, such as fertiliser use and management, purchased feed, stocking rate and grazing management. In our case study examples, the different N mitigation scenarios resulted in a slight increase in within-catchment NUE values due a larger reduction in N inputs compared to the reduction in N outputs. The mitigation measures also resulted in a progressive reduction in both N surplus and N leaching losses, and in some cases also N losses to air (Figure 4).

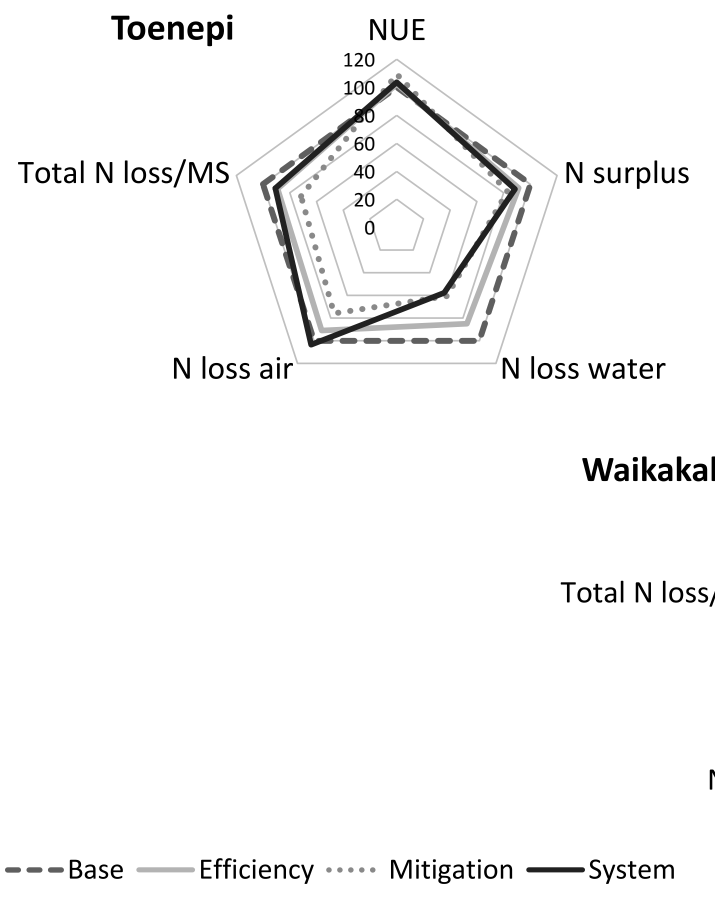

Figure 4. The effect of N management scenarios on relative changes (% change from Base) in NUE, N surplus and N losses from typical dairy farms in the Toenepi and Waikakahi catchments in New Zealand. 'Total N loss/MS' is the estimated total N losses to water and air per unit of milk solids (protein and fat) produced; 1 kg milk solids (MS) = *c.* 12 L milk. See text for explanation of scenarios (Monaghan & de Klein 2014 and unpublished data).

Discussion

The results summarised in this paper support the view that realistic goals for NUE for dairy systems will depend on the agro-climatic context in which the systems operate and the economic and environmental goals they are aiming to achieve. If we assume that efficient N fertiliser use or optimum feeding strategies will largely be driven by economic or financial impacts, then Crop and Animal NUE values will be valuable indicators for optimising fertiliser and feed use. Similarly, if the economic impact of Whole farm NUE is an important consideration then a so-called 'commercial' NUE value may be of use. Bittman et al. (2016) defined this metric as N removed in products as a percentage of all 'purchased' N. This excludes 'free' N inputs such as atmospheric deposition and N fixation. However, if we assume that the ultimate goal for setting Whole farm NUE values is to reduce the environmental impact of reactive N use, then global or even national Whole-farm NUE targets appear to be of limited value for achieving this. This was illustrated by the fact that the 'between-catchment' variability in NUE values in the New Zealand catchment study was much greater than the 'within-catchment' variability. The NUE values were largely insensitive to the adoption of mitigation options to reduce N leaching losses, but N surpluses were substantially reduced. Therefore, whole-farm level targets based on N surplus would be a more useful indicator of the risk of reactive N losses. The key thing that will result in both an increase in NUE and a reduction in N surplus is to better utilise nitrogen that is recycling within a system (i.e. animal excreta) to either allow higher N outputs for the same N input, or to lower N inputs while maintaining N outputs in products. In our dairy catchment example, the key management attributes that achieved an, albeit slight, increase in NUE and a significant reduction in N surplus were a reduction in fertiliser and feed N inputs, a reduction in the number of less productive animals, and grazing management to reduce the risk of N losses in autumn/winter and utilisation of the captured excreta N in the following spring.

Regardless of the metric used to assess the N efficiency of a system, it should be noted that all metrics are calculated based on estimates of N inputs and N outputs. It is therefore important that all inputs and outputs are measured or adequately estimated, despite the methodological challenges with estimating, for example, N fixation in clover-based systems. Additionally, agreement is required on which items should be included in the input and output terms. The EU Nitrogen Expert Panel has recently drafted a guidance document on the items that should be included in the input and output terms (EU Expert Panel, 2016). For systems that export manure off-farm, the panel suggests that manure export should be considered as "a negative input", i.e. the total N input should be corrected for manure N export. This will result in a lower NUE, than if manure export is included in the N output term. Also, for systems that import large amounts of purchased feeds, the N inputs required to produce this feed should also be accounted for as part of the N efficiency assessment.

Finally, it should be recognised that N is only one of a range of indicators that need to be considered when assessing the environmental impacts of agriculture. Any targets should be set in the context of other agro-environmental indicators such as losses of phosphorus and faecal organisms to water, carbon footprints, and energy and water use efficiencies.

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