Eco-efficient pasture based dairy farm systems: a comparison of New Zealand, The Netherlands and Ireland

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Abstract

European and New Zealand dairy farmers pursue high productivity, while meeting the requirements of environmental legislation. Due to market constraints, New Zealand dairy farming has traditionally relied on low-input grazed perennial ryegrass (*Lolium perenne* L.) – white clover (*Trifolium repens* L.) pastures and on grazed forage crops in seasons with low pasture production. However, in the past three decades the use of synthetic nitrogen (N) increased, allowing higher stocking rates and more milk production per hectare, but increasing N surplus per hectare and therefore potential N loss to the environment. The use of supplements has also increased, with an increasing number of farmers investing in infrastructure to feed cows off-pasture during the winter. This is seen to benefit the animal as well as the environment because supplements provide the opportunity to reduce surplus N intake, and collected urine and faeces can be applied efficiently on pastures or crops. In Europe, indoor systems, use of supplements and efficient manure application methods are common. There is interest in improving production and utilisation of home-grown pastures and crops to reduce costs and overall environmental footprint. This is where the challenge for European and New Zealand dairy systems meet: there is a common need to examine how crops and forages can be used to improve N efficiency in the soil-plant-dairy cow system. Combining best practices and recent advances in European and New Zealand research provides scope for cost- and nutrient-efficient and highly productive dairy farm systems.

Keywords: milk production systems, nitrogen surplus, eco-efficiency, grazing management, multispecies swards, forage crop, farm dairy effluent

Introduction

Despite different market circumstances and farming systems, European and New Zealand dairy farmers pursue high production, while meeting environmental goals of their respective communities. In Europe, intensification was propelled after the Second World War by production targets and subsidies, and side-effects became apparent in the 1970s and 1980s (e.g. Cartwright *et al.*, 1991; Henkens and Van Keulen, 2001). Many EU countries developed policies to reduce the impact of agriculture on the environment. For example, the Netherlands implemented legislation to reduce nutrient losses from manure in 1984, and the European Union introduced the Nitrate Directive in 1991 (European Community, 1991). By contrast, New Zealand is only just embarking on the route to legislation aimed at maintaining or improving freshwater quality. Deterioration in water quality of main rivers (nutrient enrichment and reduced visual clarity) was observed (McColl and Hughes, 1981) and shown to be correlated with pastoral, plantation and urban land cover (Ballantine and Davies-Colley, 2013; Larned *et al.*, 2004). To protect New Zealand lakes, rivers, aquifers and wetlands, the National Policy Statement for Freshwater Management was published by the New Zealand Government in 2011 (Ministry for the Environment, 2011). This requires the New Zealand Regional Councils to develop and implement water quality standards and accompanying regulation to achieve or maintain these by 2030. Risks to water quality include the potential for erosion (sediment deposition), nutrient loss and microbial contamination, e.g. *Escherichia coli*. Causes of erosion and microbial contamination are clear, and measures to reduce these risks have been defined and in some cases implemented via voluntary agreements, e.g. the Dairying and Clean Streams Accord in 2003 (Fonterra *et al.,* 2003), followed by the Sustainable Dairying: Water Accord in 2013 (DairyNZ *et al.,* 2013). Nutrient loss, however, specifically nitrate leaching, is a more difficult issue to target. At present, Regional Councils are developing limits for nutrient loss to water for different land uses. Dairy farming has been identified as a sector with relatively high nitrate leaching levels, compared with low-input summer-dry sheep and beef farming (the dominant land use systems in New Zealand), and is likely to face substantial regulation limiting farm-scale estimated nitrate leaching or nitrogen (N) surplus.

The New Zealand dairy industry relies heavily on exports: 95% of the milk produced is exported, mainly as whole-milk powder (Statistics New Zealand, 2014). This makes the industry vulnerable to fluctuating global prices and income. For example, 2013-2014 was a record season with a listed milk solids (MS; fat plus protein) price of €5.34 kg MS^{-1} (at €0.63 per NZ$; LIC and DairyNZ, 2014). By December 2014, the country's largest milk processor announced a forecast milk price for 2014-2015 of €2.96 kg MS^{-1} (Fonterra, 2015). Due to these market fluctuations, and the absence of subsidies, New Zealand dairy farming has traditionally relied on low-input year-round grazed perennial ryegrass-white clover pastures, complemented by forage crops (mainly brassicas) in seasons with low pasture production. When urea manufacture began in New Zealand in the 1980s, synthetic N fertiliser use increased, and consequently, New Zealand dairy farming intensified rapidly (PCE, 2004). At the same time the use of supplements on New Zealand dairy farms increased. Both increased feed production from N fertiliser, and the use of bought-in supplements support higher stocking rates and more milk production per hectare. However, using more inputs to produce more milk increases the N surplus per hectare and therefore potential and actual N loss to the environment (e.g. Basset-Mens *et al.*, 2009; De Klein *et al.*, 2010; Oenema *et al.*, 2011).

In most European countries over the past 25 years there has been a shift away from pasture-based systems to greater use of conserved forage-based systems, especially forage maize. It is common to keep dairy cows off-pasture: restricted-duration grazing is often implemented during the growing season, and during late autumn and winter cows are kept indoors. Milk prices for European dairy farmers have been relatively stable and high, due to a system of intervention purchasing and exports refunds. Hence higher production costs have been accepted. However, milk production within the EU is now entering a new phase. The milk quota system will be abolished on the 1st of April 2015, and the intervention price support for butter and skim milk powder will be significantly reduced. This will result in much greater volatility in EU milk prices because of fluctuating world supply/demand. This volatility in prices is likely to become a continuing feature of EU dairy markets, requiring systems of milk production that are resilient in the future. On top of this, changing subsidy frameworks, fluctuating prices for imported feed and increasing costs for energy (and therefore inputs such as synthetic fertiliser), labour, machinery and housing, and environment and animal welfare concerns associated with intensive systems, have sparked increasing interest in improving production and utilisation of home-grown pasture and crops (e.g. Peyraud *et al.*, 2014).

This is where the challenge for European and New Zealand dairy systems meet: there is a common need to determine how crops and forages can be used to increase the efficiency of N flows through the soil-plant-dairy cow system, while improving or maintaining productivity and profitability. This paper assesses the current N efficiency and N losses of well-managed dairy farms in New Zealand and in two European countries, the Netherlands and Ireland, and how the weaker points have been targeted by recent research on the use of home-grown pasture and crops. Experiences from both sides of the world could complement each other to deliver profitable, highly productive and eco-efficient dairy farms.

Structure of New Zealand, Dutch and Irish dairy sectors

The New Zealand dairy industry produced in the June 2013 – May 2014 season a total of 1.83×10^9 kg milk solids (fat plus protein, MS; LIC and DairyNZ, 2014). This is nearly double the production in the 1999-2000 season (0.98×10^9 kg MS), while the number of herds declined in the same period from 13,861 to 11,927. Apart from a rapid growth in number of cows per herd (from 236 to 413 cows per herd), accompanied by a growth in farm size (from 93 to 144 effective hectares per farm), MS produced per cow and per hectare also increased: from 288 kg MS cow^{-1} and 768 kg MS ha^{-1} in 1999-2000 to 371 kg MS cow^{-1} and 1,063 kg MS ha^{-1} in 2013-2014. The majority of herds calve once per year, in late winter-early spring, making the New Zealand dairy industry highly seasonal.

Regional differences are apparent. The two regions with the highest number of dairy cows are the Waikato and Canterbury, with 24% and 18% of the national herd respectively. Waikato has traditionally been the largest milk-producing region, with rain-fed, summer-dry pasture-based systems. Canterbury has seen a rapid increase in dairying in the past decade, with dryland pastures previously grazed by sheep converted to irrigated pastures and crops for winter grazing. Farms in Canterbury are larger and more intensive than in the Waikato (average 232 ha stocked at 3.49 cows ha^{-1} versus 112 ha and 2.95 cows ha^{-1}, respectively). Note that these statistics refer only to effective hectares on the dairy platform (i.e. pasture area grazed during lactation). This excludes off-farm cropping areas where many non-lactating cows are wintered in Canterbury.

Beukes *et al.* (2012) estimated the N surplus and eco-efficiency for the Waikato region to be 155 kg N ha^{-1} $year^{-1}$ and 6.4 kg MS kg N $surplus^{-1}$, respectively. Earlier, Ledgard *et al.* (1997) estimated an N surplus of 131 kg N ha^{-1} $year^{-1}$ and an eco-efficiency of 4.6 kg MS kg N $surplus^{-1}$ for the average New Zealand farm of that time. The increase in N surplus and eco-efficiency between 1997 and 2011 illustrates the increased use of inputs, and increased productivity, of NZ dairy systems over that period.

Dutch milk production systems are based on year-round calving, predominantly restricted grazing during spring, summer and autumn, and housing of cows during late autumn, winter and early spring. Virtually all systems use supplements throughout the year, both roughage and concentrates. Regulations dictate that manure is exported off-farm where imported nutrients are above a certain threshold. Growing maize on the dairy farm, in rotation with pasture, is common.

The Dutch dairy industry produced 107×10^6 kg MS (converted as MS = $(l/0.97) \times 0.08$) in 2014, similar to 1998 (96×10^6 kg MS). The number of farms declined in the same period from 32,000 to 17,000 and the number of cows declined from 1.6×10^6 to 1.5×10^6. The average number of dairy cows per farm increased from 48 to 75, and the average milk production per cow increased from 594 to 660 kg MS cow^{-1} from 1998 to 2014 (Land- en tuinbouwcijfers: www3.lei.wur.nl/ltc; Centraal Bureau voor de Statistiek: www.cbs.nl; Zuivel.nl www.zuivel.nl). The average N surplus in the Netherlands was 180 kg N ha^{-1} $year^{-1}$ in 2011; a substantial reduction from 330 kg N ha^{-1} $year^{-1}$ in 1998, reflecting the tighter environmental regulations. Nitrogen use efficiency (NUE) improved from 20% to 31% in the same period (Oenema *et al.,* 2011).

Milk production in Ireland comes predominately from grass-based seasonal compact spring-calving systems. The current national average milk production per cow for Ireland is 358 kg MS cow^{-1}; stocking rate is 1.90 cows ha^{-1}, and 875 kg of concentrates per cow and 148 kg of synthetic N ha^{-1} are used. Based on this, the average surplus N ha^{-1} on Irish dairy farms is 144 kg, and the eco-efficiency 4.7 kg MS kg N $surplus^{-1}$ (Teagasc, 2013). Studies carried out before the introduction of the Good Agricultural Practice regulations in 2006 (Anonymous, 2006) would suggest that N surplus, both per ha and per kg MS,

Table 1. Farm characteristics of nutrient-efficient dairy farms in New Zealand (NZ-C = Canterbury; NZ-W = Waikato; farmlets in the research project Pastoral 21), the Netherlands (NL-1 = certified organic; high N-use efficiency; NL-2 = high productivity; NL-3 = overall optimisation including grazing; farms in the project cows & opportunities) and Ireland (IL-S = Solohead; IL-C = Curtin; research farms).

	New Zealand		the Netherlands			Ireland	
	NZ-C	NZ-W	NL-1	NL-2	NL-3	IL-S	IL-C
Climate							
Average annual rainfall (mm)	594	1121	750-900	750-900	750-900	1,036	1,022
Mean annual temperature (°C)	11.8	13.7	10.0	10.0	10.0	9.6	9.8
Annual potential evapotranspiration (mm)	886	835	560-590	560-590	560-590	510	545
Farm size (ha)							
Grassland	8.5	13	43	31	26	10	48
Grassland with restrictions (nature conservation)	0	0	0	4	0	0	0
Maize	0	0	13	11	12	0	0
Kale (winter grazing); oats	1.6	0	0	0	0	0	0
Other crops	0	0	8	0	0	0	0
Pasture							
Pasture production (Mg DM ha^{-1} yr^{-1})	16.1	15.3	9.6	14.4	11.8	12.8	14.9
Harvested as silage (Mg DM ha^{-1} yr^{-1})	0.8	0.5	8.9	14.4	7.7	4.3	2.5
Kale + oats production (Mg DM ha^{-1} yr^{-1})	12 + 7.7	0	0	0	0	0	0
Stocking rate (cows ha^{-1} pasture + crop)	2.9	2.6	1.6/2.2[1]	2.9/4.0	2.3/3.2	2.3	2.9
Average liveweight dairy cows (kg)	527	495	600-650	600-650	600-650	572	540
Ration lactating cows							
Grazing time cows pasture + crop (h $year^{-1}$)	7,540	5,840	477	0	1,800	5,610	6,840
Crude protein ration during lactation (%)	22	20	14	15	15	18	14
MS production (kg fat + protein; NL: MS = (l/0.97) × 0.08)							
kg MS cow^{-1} $year^{-1}$	510	442	561	668	668	482	441
kg MS ha^{-1} $year^{-1}$	1,513	1,158	915	1,872	1,537	1,108	1,280
Soil type	freely drained sandy loam/ stony silt loam	silt loam; some pugging in wet periods	sand; freely drained	clay; some pugging in wet periods	sand; freely drained	poorly drained clay loam	freely drained acid brown earth
Years	11-14	11-14	00-05	00-09	00-09	01-12	00-11

[1] For NL stocking rate is given as cows ha^{-1} without and with young stock; young stock were reared on farm. NZ and IL farms did not rear young stock on farm.

have significantly decreased since that time (by 40 and 32%, respectively) and NUE increased (by 27%), mostly due to decreased synthetic fertilizer N input and improvements in N management, with a notable shift towards spring application of organic manures.

Performance of well-managed dairy farms in New Zealand, the Netherlands and Ireland

Data have been collected from examples of well-managed dairy farms in New Zealand (NZ), the Netherlands (NL) and Ireland (IL); i.e. with productivity and N efficiency above average for the respective countries (Table 1). The two New Zealand examples are research farmlets in the project Pastoral 21, and aim to demonstrate the gains in efficiency of production and N use, and reductions in N leaching, through improved management practices plus animals of high genetic merit as compared with

Table 2. Nitrogen (N) balance and N losses of nutrient-efficient dairy farms in New Zealand (NZ-C = Canterbury; NZ-W = Waikato; farmlets in the research project Pastoral 21), the Netherlands (NL-1 = certified organic; high N use efficiency; NL-2 = high productivity; NL-3 = overall optimisation including grazing; farms in the project cows & opportunities) and Ireland (IL-S = Solohead; IL-C = Curtin; research farms).

	New Zealand		the Netherlands			Ireland	
	NZ-C	NZ-W	NL-1	NL-2	NL-3	IL-S[1]	IL-C
Input (kg N ha^{-1})							
Synthetic fertiliser	179	46	0	158	128	110	250
Fixation clover[2]	157	201	26	7	2	84	0
Supplements imported	9	3	75	309	199	47	25
Manure imported	0	0	2	0	24	0	0
Rainfall (deposition)	2	2	36	36	36	6	6
Irrigation	10	0	0	0	0	0	0
Removed (kg N ha^{-1})							
Milk and meat	113	88	65	145	115	80	98
Supplements	17	0	1	0	0	0	0
Farm dairy effluent/manure	35	7	0	108	64	0	0
N surplus farm (kg ha^{-1}) [3]	168/228 (192)	157	73	257	210	167	183
NUE farm (%) [4]	46	38	47	50	46	32	35
Eco-efficiency (kg MS kg N surplus^{-1})	7.9	7.4	12.5	7.3	7.3	6.6	7.0
Losses estimated (kg N ha^{-1} year^{-1}) [3]							
Volatilisation (NH_3-N)	80/52 (79)	72	50	76	52	61	n/a
of which from urine	73/14 (64)	47	n/a[4]	n/a	n/a	27	n/a
Denitrification (N_2O-N and N_2-N)	5/69 (15)	41	n/a	n/a	n/a	64	n/a
Nitrate leaching	24/159 (46)	17	40	<5	72	12	25

[1] The results shown for IL-S are based on the average for 2010 and 2011. The results for the other farm systems are for the years given in Table 1.

[2] For NZ farms N fixation of clover is modelled with Overseer, using an assumed, medium clover content, pasture production estimated from N intake required to sustain measured milk production and supplement N input; synthetic N input results in an estimated reduction in N fixation. For NL farms N fixation is calculated as % clover × pasture production (Mg DM) × 45 kg N ha^{-1}. For IL farms N_2 fixation was measured using the difference method in the earlier years and the ^{15}N natural abundance method in more recent years. In both instances a correction factor of 1.27 for N assimilated in below-ground plant matter was used (Burchill, 2014).

[3] Values for NZ-C are given for the milking platform (pasture used during lactation; first value) and for the support block where kale is grown for winter grazing, followed by an oats catch crop harvested for silage (second value). The value in brackets is for the whole farm system.

[4] NUE = nitrogen use efficiency; n/a = not available.

current practice in New Zealand (Chapman *et al.*, 2013; Glassey *et al.*, 2014). They reflect the differences between Waikato (NZ-W) and Canterbury dairy systems (NZ-C), as described above. Management practices were defined through modelling (Beukes *et al.,* 2011, 2012), and expected N loss was estimated using Overseer® (Wheeler *et al.,* 2006; 'Overseer' from this point), a nutrient model commonly used in New Zealand to estimate the N flows. Grazed pasture provides 90-95% of the lactation diet; pastures are predominantly of perennial ryegrass-white clover swards. The farmlets implement a range of options to mitigate N leaching: reduced synthetic N use and optimal timing of N application (NZ-C and NZ-W), including herbs (chicory and plantain) in pastures on the milking platform and low-N forage crops in winter to reduce CP content of the diet (NZ-C). They also use loafing pads for part of the day to reduce the time that cows are on pasture in autumn (late lactation) and winter (dry cows) (NZ-W), and optimal application regimes for farm dairy effluent (FDE; soiled water from the milk shed with dry matter (DM) content below 2%, Houlbrooke *et al.*, 2011) (NZ-W; no FDE application at NZ-C), and tight control of pasture quality (NZ-C and NZ-W). Young stock being raised off-farm and using high genetic merit cows allow reduced stocking rate (cows ha^{-1}) and high utilisation of pasture grown. Loafing pads allow for capturing excreta, which is then, usually together with FDE, applied on pasture or crops

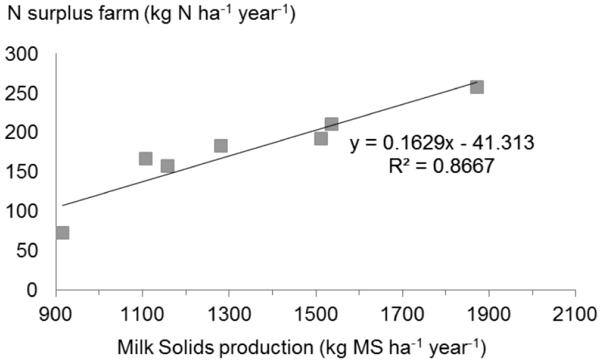

Figure 1. Relationship between N surplus and milk solids production of seven nutrient efficient dairy farms from New Zealand, the Netherlands and Ireland (see Tables 1 and 2).

more evenly as compared with grazing, and at times when pasture or crop productivity ensures good responses (Aarts, 2000; Oenema *et al.*, 2006). Reducing grazing intensity in autumn and winter may contribute to reduced nitrate leaching, as the utilisation by pasture or crop of N from excreta declines with lower temperatures and reduced light (Cuttle and Bourne, 1993; Lord, 1993; Titchen *et al.*, 1993; Verloop *et al.*, 2006). Reductions in nitrate leaching of 30-40% have been measured in New Zealand trials when cows were taken off pasture over the autumn and winter months (De Klein *et al.*, 2010). An additional benefit of restricted duration of grazing is reduced sward damage in wet periods; hence improved pasture production (Beukes *et al.*, 2013).

The Dutch examples are well-managed commercial dairy farms, participants of the long-running project 'cows and opportunities' (Oenema *et al.*, 2001). This project was initiated by the Dutch farmers' union and government in 1998 to explore options for commercial dairy farmers to meet strict environmental targets, and followed the prototype developed on experimental farm 'De Marke' (Aarts, 2000). Intensive coaching by researchers and extension specialists was provided.

Management changes implemented to reduce nutrient losses were reduced synthetic N fertiliser applications and optimised use of home-produced organic manure, reduced crude protein (CP) content of the ration, restricted grazing, reduced relative number of young stock on farm and sowing a catch crop after harvesting maize. The three Dutch farms in Tables 1 and 2 were identified from the group of 17 participants as being the 'best farms' in terms of N-use efficiency (NL-1; certified organic farm), productivity (NL-2; high input farm) or overall optimisation including grazing (NL-3). These farms illustrate the relatively high dependency of Dutch milk production systems on imported feed, the restricted use of grazing (if any), and therefore high proportion of pasture being harvested for silage.

The Irish examples are two research farms: a system with perennial ryegrass-white clover pastures at Solohead Research Farm (IL-S; Burchill, 2014; Humphreys *et al.*, 2008a, 2009; Necpálová *et al.*, 2013; Tuohy *et al.*, 2014), and the Curtin Research Farm (IL-C; Heubsch *et al.*, 2013; McCarthy *et al.*, 2015). The IL-C site is representative of soils vulnerable to nitrate leaching, and represents between 4 and 10% of the riskier soils in Ireland (Ryan *et al.*, 2006). Nitrate N concentrations in the aquifer below the farm declined from 16 mg l^{-1} in 2002 to 6.6 mg l^{-1} in 2011 (Huebsch *et al.*, 2013), well below the drinking water standard of 11.3 mg NO_3-N or 50 mg NO_3 l^{-1}. This was associated with a reduction in synthetic fertilizer usage, improvement in timing of slurry application, moving an FDE irrigation system to a less-karstified area of the farm, the use of low-N supplements to reduce N surplus intake by the animals, and the use of minimum cultivation reseeding on the farm. At IL-S, nitrate leaching has been consistently low

(<35 kg N ha^{-1} year^{-1}) over 11 years (Humphreys *et al.*, 2007; 2008b; Necpálová *et al.*, 2012), associated with the impermeable nature of the soil.

MS production per cow was highest for the Dutch farms, but only the highest-input farm (NL-2) achieved a higher MS production per hectare (Table 1). The N balance and N loss of the example farms are shown in Table 2. The N surplus was highly correlated with MS production (Figure 1). The eco-efficiency, expressed as kg MS kg N surplus^{-1}, was remarkably similar; only the Dutch organic farm achieved a much higher eco-efficiency than the other farms. The NUE varied between systems, but was not related to MS production or N surplus. Soil type and climate impact on the ability of plants to utilise nutrients efficiently. For example, the NUE of NL-2 (clay) was similar to that of NL-3 (sand), and NUE of Canterbury (irrigated) was similar to that of Waikato (summer-dry) even though N applied to pasture (synthetic N, manure, clover N fixation, irrigation) was significantly higher for the NL-2 and Canterbury systems.

Compared with the respective country averages, the example farms achieved better efficiency of N inputs (NUE) and eco-efficiency (kg MS produced per kg N surplus). NUE and eco-efficiency are important indicators for impact on the environment on a global scale. The N surplus of the New Zealand and Irish farms and the highest-input Dutch farm, however, are above the average for their respective countries. N surplus is often seen as an indicator of the impact on the local environment, but soil type, climate and gaseous losses control how much of the N surplus eventually leaches to groundwater.

Pathways to reduce N losses while maintaining productivity

Modelling and measurements in the Netherlands have shown that the average soil-N surplus for grassland should not exceed 103 kg N ha^{-1} on dry sandy soils, 168 on wet sandy soils and 273 on clay soils to achieve ground water quality at drinking water standard (Schröder and Neeteson, 2008). The same soil N surplus results in higher leaching from dry sandy soils compared with soils with higher plant available water. For arable land these values are 48, 87 and 141 kg N ha^{-1}, respectively, reflecting that the same soil N surplus results in higher leaching from arable land compared with grasslands. The results from the example farms show that these levels of N surplus are still challenging. Only the organic farm achieved an N surplus well below the levels given by Schröder and Neeteson (2008).

The skill level demonstrated by the example farms may not be replicable on the majority of commercial farms, and the nutrient loss seen on these farms may not be sufficient in some regions. Therefore, while maximising nutrient utilisation remains paramount, new, easily adoptable and cost-efficient pathways to reduce N losses while maintaining productivity are needed for many dairy farms. A mixture of European and New Zealand options may provide these solutions: use of multispecies pastures, N-efficient crops and crop rotations, and capture and efficient use of effluents and manures through restricted-duration grazing. This is explored further in the following sections.

Use of multispecies swards to maintain pasture productivity, intake and milk production when reducing synthetic N use

The simplicity of managing grass monocultures and the low price of synthetic N have, in the past, inhibited the use of legumes for forage production under intensive systems (Peyraud *et al.*, 2014). However, increasing political emphasis on environmental preservation, combined with sharp increases in the price of synthetic N, have encouraged greater emphasis on incorporating legumes into high-output ruminant production systems. Strategically designed multispecies swards can potentially improve the delivery of provisioning services from pasture-based production systems. Finn *et al.* (2013) compared mixture and monoculture swards across a large number of European sites using cutting managements. They reported significant and consistent over-yielding in mixtures. In order to expand the applicability of these findings to other production systems, a common experiment was carried out within the recently-completed EU FP7 project 'Multisward' comparing highly-fertilised grass monoculture and moderately-fertilised legume-based multispecies swards under rotational grazing in terms of primary (plant biomass) and secondary (animal) production (Collins *et al.*, 2014). The objective was to establish whether multispecies swards could capitalise on the species diversity effects observed by Finn *et al.* (2013) and thus provide productive grazed pastures. The results for primary production in multispecies swards under rotational grazing by sheep, beef cattle and dairy cows clearly showed that there was no detriment to DM yield in legume-based multispecies swards compared with perennial ryegrass monocultures receiving high external N inputs (Collins *et al.*, 2014). Indeed, in some instances multispecies swards were more productive than the latter. Consequently, considerable N-savings can be achieved through the use of multispecies swards.

The benefits of greater herbage production and nutritive value are not realised unless the grazing animal efficiently consumes and utilises the herbage (Sanderson *et al.*, 2013). Previous grazing trials with dairy cows on multispecies swards have demonstrated either no differences in milk production or herbage intake (Soder *et al.*, 2006), or a positive effect on herbage intake and milk yield (summarised by Lüscher *et al.* (2014)). Inclusion of one legume species (white clover) in a perennial ryegrass pasture already showed increased herbage intake and milk yield (Pfimlin, 1993; Schils *et al.*, 1997; Ribeiro-Filho *et al.*, 2003). Thus, there remains considerable scope for further evaluation of the effects of multispecies swards on animal production and product quality compared with monocultures of perennial ryegrass or binary mixtures of perennial ryegrass and white clover. A number of experiments were carried out within the Multisward project in which multispecies swards were grazed directly or were used in zero-grazed experimental systems. Some common themes emerged from these experiments. In many of the studies, animal intake (in sheep, beef cattle and dairy cows) was positively related to mixture complexity. In the study using dairy cows (Roca-Fernández *et al.*, 2014), milk output was greater from multispecies swards compared with perennial ryegrass monocultures, despite the fact that the total number of grazing days per season was unaffected by pasture treatment. Annual milk output per ha was greater on a mixture of perennial ryegrass plus two legumes than on monocultures of perennial ryegrass, with no further increase between the former treatment and two multispecies sward treatments in which chicory and tall fescue were added. Thus, it appeared that the presence of legume species in the sward was the critical factor involved in increasing milk output per ha. This higher output was due to higher forage intake, resulting in higher milk production per cow, rather than greater pasture productivity or major differences in forage quality between the sward types. Feed conversion efficiency observed for milk production was not affected by sward type, and any increase in herbage intake in the multispecies swards was recovered in milk yield.

These results suggest that using multispecies swards comprising a small number of strategically chosen species (perennial ryegrass and clover) for forage production would be a viable option for achieving sustainable intensification of grassland-based agricultural production, and a decrease in the environmental burden of forage production through a reduction in synthetic N inputs.

Maintaining sufficient clover content in grazed pastures to deliver productivity benefits

Capturing the benefits of white clover may be limited by the fact that the proportion of white clover in long-term pasture is typically low (<20%), and subject to large temporal and spatial variability (e.g. Steele and Shannon, 1982), for reasons that have been elucidated by Schwinning and Parsons (1996). Grazing management is an important tool for promoting higher clover content with low (<4 cm) defoliation height favouring clover (Acuña and Wilman, 1993; Frame and Boyd, 1987). This effect is generally attributed to reduced shading of the clover growing points and stolon nodes by grass (Thompson, 1993), inducing increased stolon branching and successful development of new clones (Pinxterhuis, 2000). Continuous, hard grazing by sheep in spring, followed by rotational grazing, will increase the proportion of clover in pasture (Brock, 1988). Similar clover responses have been observed in some (Hoogendoorn *et al.*, 1992), but not all (Phelan *et al.*, 2013) studies with dairy cows.

Even with optimal grazing management and fertiliser regimes, the proportion of clover in long-term pastures remains low. Alternative approaches, such as spatially (e.g. strips side by side) and temporally (offering at different times of day) separating grass and clover within the same field to reduce interspecific competition (Sharp *et al.*, 2012a) may increase the overall proportion of clover in the pasture and diet (Rutter *et al.*, 2010; Sharp *et al.*, 2012b). However care must be taken to ensure that N fixed by the clover becomes available to associated non-legume pasture species, otherwise nitrate leaching losses from the pure white clover swards can be as high as from heavily N-fertilised grass (MacDuff *et al.*, 1990). Spatial separation removes the senescence pathway, but transfer of N via dung and urine of the grazing animals will still occur.

Use of herbs to reduce urinary N excretion of dairy cows otherwise grazing on perennial ryegrass-white clover pastures

Care must be taken to focus not only on production and exchange of synthetic N by legume fixed N. In New Zealand perennial ryegrass-white clover pasture-based systems, N intake often substantially exceeds animal requirements (Brookes and Nichol, 2007; Pacheco and Waghorn, 2008), increasing the urinary N excretion. It is well established that urinary N excretion of grazing animals is the largest contributor to nitrate leaching risk in pasture-based grazed systems, due to the spatial distribution pattern of urine during grazing and its high N concentrations (Ball and Ryden, 1984; Di and Cameron, 2002; Eriksen *et al.*, 2004; Haynes and Williams, 1993; Jarvis, 2000; Ryden *et al.*, 1984; Scholefield *et al.*, 1993; Verloop *et al.*, 2006; Whitehead, 1995). Multispecies swards containing herb species may offer a strategy to reduce the environmental footprint of livestock farming, through affecting the amount and/or concentration of N excreted in urine while maintaining productivity. In an indoor study with cut forage, Woodward *et al.* (2012) found that both urinary N concentration and urinary N output were lower from cows fed a multispecies sward containing ryegrass, white clover, chicory and plantain than a simple perennial ryegrass-white clover pasture (2.6 g versus 6.2 g N l^{-1} and 100 versus 200 g N cow^{-1} day^{-1}, respectively). This result may be due to the lower N intake of the cows offered multi-species rather than simple forage (350 vs 466 g N cow^{-1} day^{-1}), reflecting the well-defined relationship between N intake and urinary N output (Kebreab *et al.*, 2001). In related grazing work, milk production was similar but urinary N concentration and estimated urine N excretion were lower for cows grazing multispecies swards containing chicory and/or plantain compared with standard perennial ryegrass-white clover pastures (Totty *et al.*, 2013). The lower N concentration per urine patch should increase the fraction of urinary N that is captured by the plants before it is leached or lost to the atmosphere (Di and Cameron, 2007). Recent modelling of the potential of diverse pastures to reduce leaching at the whole of farm scale has indicated a reduction of 11 and 19%, where 20 and 50% of the farm area was sown to diverse pastures, respectively (Beukes *et al.*, 2014).

A further approach to reduce nitrate leaching is to increase the uptake of N from soil once excreted in the urine patch. Modelling has suggested that diverse pastures containing deeper rooted species have a greater potential to limit nitrate leaching (Snow *et al.*, 2013). In a lysimeter-based study, however, nitrate leaching from urine patches with the same N loading was similar in perennial ryegrass-white clover pasture and pastures containing additional herbs (Malcolm *et al.*, 2014). Although roots were found deeper in the soil profile in the diverse pasture, cool season growth of the chicory and plantain was lower which limited the uptake of N from soil during winter. Mixtures based on plant species with greater cool-season growth (e.g. Italian ryegrass; *Lolium multiflorum* Lam.) reduced nitrate leaching to a greater degree (Malcolm *et al.*, 2014).

The above points to the importance of carefully selecting functionally complementary grass, legume and herb species, if productivity and environmental benefits of multispecies grazed pastures are to be achieved (Pembleton *et al.*, 2014).

Integration of crops on dairy farms to increase productivity and N use efficiency

In the Netherlands, grazing by continuous stocking during the growing season is being replaced by continuous housing or restricted grazing coupled with supplementary feeding (Van den Pol-van Dasselaar, 2011). Continuous stocking is currently practised on only about 10-20% of farms, with 30% having no grazing of lactating cows and 50-60% practising some form of restricted grazing. With continuous stocking, pasture intake and quality are variable and difficult to quantify. Restricted grazing and the use of supplements allow better control over diet and other factors (e.g. weather) (Reijs *et al.*, 2013), and reduce the urinary N excretion on pasture. For example, feeding maize silage can reduce the N content of urine by up to 70% compared with grass silage (Ledgard, 2006) and reduce the kg NO_3-N leached per kg MS produced by 21-32% compared with continuous pasture (Ledgard *et al.*, 2006).

To achieve their industry's goals for increased production (3.6% per annum; Luxton, 2005), New Zealand dairy farms will also need to increase use of supplementary feeds (Clark *et al.*, 2001; Minneé *et al.*, 2009). At present, fodder crops are often grown as a break crop when renewing pasture. Forage crops that can be grazed are often selected to fill a demand for feed during periods of low pasture production, e.g. winter wet or summer dry conditions (Bryant *et al.*, 2010). On experimental dairy farms, crops on 12.5% of the farm area have been shown to increase the total amount of ME and milk solids produced as well as the operating profit (MacDonald *et al.*, 2012).

There are a number of forage crops (e.g. kale, fodder beet, maize, turnip, oats, triticale) that are well suited to supply feed during periods of low pasture production (Beare *et al.*, 2006; De Ruiter *et al.*, 2009; Minneé *et al.*, 2009; Wilson *et al.*, 2006). Recent research in New Zealand has focussed on crops and crop management systems that meet the physiological requirement of dairy cows (i.e. dry and lactating) while reducing the nutrients returned (especially N) in excreta (urine and dung) in grazed systems. However, because the returns in excreta can vary considerably (Selbie *et al.*, 2014), other research emphasises the partitioning of N to urine and dung and their individual constituents (e.g. urea, creatinine, hippuric acid), the formation of secondary compounds and their effects on N transformation (e.g. nitrification, denitrification) and transport in the soil following deposition.

Sustaining high levels of DM production while reducing the risk of N losses may depend on the type and sequence of crops grown and the soil management practices used during crop establishment and grazing. Very high levels of annual supplementary feed production (>45 Mg DM ha^{-1} $year^{-1}$ in New Zealand) can be achieved from tight-fitting crop sequences that are based on seasonally adapted crops with a high efficiency of light capture (De Ruiter *et al.*, 2009). However, achieving these levels of production also requires high inputs of water and nutrients (especially N) that may increase the risk of N losses during crop production and following winter grazing (Beare *et al.*, 2010). Improving the ability to predict the availability of mineral N and its uptake by various crops (as for Dutch conditions with the online tool NDICEA, www.ndicea.nl) is important for identifying high production crops and crop sequences that improve N use efficiency and minimise the excess consumption of N and its return to the environment in urine and dung.

Winter feeding of forage crops in New Zealand usually involves strip grazing at high stocking rates to harvest the DM (>10 Mg DM ha^{-1}) under wet conditions. This is associated with a high risk of soil compaction from stock treading and high loadings of livestock excreta that pose an increased risk of NO_3 leaching, N_2O emissions and P in run-off (Judson *et al.*, 2010; Monaghan *et al.*, 2007). One approach to mitigate the N losses in these systems is to manipulate the diet so that animals consume less N relative to requirements (Jenkinson *et al.*, 2014; Miller *et al.*, 2012). However, the concentration of N in urine of cows grazing kale and fodder beet can already be low (1.9 to 3.0 g N l^{-1}) (Edwards *et al.*, 2014), reflecting the low CP content and overall N intake of these crops. This means that it may be challenging to reduce N excretion further, and alternative strategies may be needed to manage animal performance and environmental outcomes. Options are restricted-duration grazing of crops (Jenkinson *et al.*, 2014); early establishment of crops (e.g. multi-graze crops or crop mixtures) or cool season grasses (e.g. Italian ryegrass) following winter grazing of crops, to 'mop up' excess N and, thereby, reduce the risk of N losses in late winter or early spring (Malcolm *et al.*, 2014); and using no-tillage at establishment of forage crops, which has been shown to markedly reduce soil compaction during winter grazing on imperfectly drained soils, the associated emission of N_2O that follows urine deposition, and the regrowth of multi-graze crops such as triticale (Thomas *et al.*, 2008, 2013).

Use of farm dairy effluent and animal manure on crops to close nutrient cycles

The growth of New Zealand's dairy industry in the last 20 years has resulted in increasing volumes of FDE (Bolan *et al.*, 2009; Houlbrooke *et al.*, 2004). Increased use of off-paddock structures also increased the volume of other manures. The use of FDE and manures to grow crops is gaining interest in New Zealand as farmers look to 'close the loop' on N management between dairy and cropping farms. Some arable crops have a high demand for nutrients and are able to extract nutrients from a greater soil depth, compared with many pasture species. For example, maize crops grown on deep, free-draining soils can have an effective rooting depth of 150-180 cm (Grignani *et al.*, 2007) which is 2-3 times greater than many C3 pasture grasses (Kristensen and Thorup-Kristensen, 2004). The high DM yields of maize crops make them an effective sink for N, P and K, and capable of mopping up nutrients from depths well below the root zone of many pastures. Maize silage crops can be very effective at removing N (282-314 kg ha^{-1}), P (42-57 kg ha^{-1}) and K (267-566 kg ha^{-1}) from pastures that have received regular applications of FDE (Johnstone *et al.*, 2009, 2010). Johnstone *et al.* (2009) showed that average silage maize yields of 26.1 Mg DM ha^{-1} can be achieved in the first year of cropping FDE paddocks without any application of synthetic fertiliser. The nutrient reserves were adequate to meet all or most of the N requirements of second-year maize crops as well. Similar results were found in the Netherlands (Pinxterhuis *et al.*, 2013). This may provide a low cost approach to improving the nutrient-use efficiency and reducing the overall N footprint of the system. The high availability of mineral N following the cultivation of pasture, however, poses a risk of increased N leaching when the following crop does not fully utilise the N.

Between 20 and 50% of the total N applied in FDE may be released during the first year after application. The composition of FDE is highly variable and is affected by the age, breed and physiological state (e.g. dry vs lactating) of the cows, the composition of the feed (e.g. pasture and supplement) and the volume of wash-down water used. In the UK, the farmer decision tool MANNER is available that predicts the fertiliser N value of applied slurries and manures (Nicholson *et al.*, 2013). In the Netherlands manure is usually sampled and analysed, and standard calculations are available to predict the release of plant-available nutrients (Commissie Bemesting Grasland en Voedergewassen, 2012). On-going research in New Zealand is focussed on identifying a simple practical method for characterising the composition of FDE that can be applied to forecast the release of plant available nutrients over one or more growing seasons. Incorporating these projections into fertiliser forecasting tools such as AmaizeN (Li *et al.*, 2009) would help farmers to maximise crop yields and avoid excess fertiliser use.

Improved timing and advanced application technologies (surface or injected) are expected to enhance the nutrient-use efficiency and reduce the losses from FDE applied to pasture and crops in New Zealand. For example, shallow injection, trailing shoe and surface band spreading of slurry on pastures reduce ammonia volatilisation considerably compared with surface spreading, thereby making more N available to plants (Houlbrooke *et al.* 2011). On maize, placement in spring was associated with lower potential N leaching and higher DM yields as compared with autumn placement (Schröder *et al.*, 1993), and further improvements were seen when banded injection of cattle slurry was used to place developing maize plants in the proximity of the slurry injection slots (Schröder *et al.*, 1997).

Conclusions

Improved nutrient-use efficiency of dairy production systems, as shown by the New Zealand, Dutch and Irish farms presented in this paper, may well be sufficient to achieve environmental goals in many regions of Europe and New Zealand, but in other regions further reductions in nutrient losses may be necessary to achieve environmental goals. Where further mitigations are needed, multispecies swards containing functionally complementary species (grass, legume and herb), and integration of crops in nutrient efficient pasture/crop rotations, may provide viable options. Both options reduce the N surplus in the diet and therefore urinary N excretion. For New Zealand and Europe a combination of these options and current good practices seems interesting to explore: grazed pastures consisting of a combination of grasses, legumes and herbs; grazed crops in periods of the year where pasture production does not meet demand; loafing pads to restrict the duration of grazing of pastures and crops; application of captured manure and farm dairy effluent at places and times when maximal response can be expected; reducing or using no tillage when establishing crops or renewing pasture; and synchronising soil and synthetic N supply to plant demand.

Dairy production systems combining these options are likely to require a new skill-set of operators. Therefore the development of these systems must be in collaboration with these operators and must be accompanied by management information packages and decision tools to support on-farm change effectively.

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