A model of nitrogen efficiency in contrasting grass-based dairy systems

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ABSTRACT

Nitrogen (N) efficiency is one of the key drivers of environmentally and economically sustainable agricultural production systems. An N balance model was developed, evaluated, and validated to assess N use efficiency and N surplus and to predict N losses from contrasting grass-based dairy production systems in Ireland. Data from a 5-yr study were used to evaluate and validate the model. Grass-based and high-concentrate production systems combined with 3 divergent strains of Holstein-Friesian (HF) dairy cows—high-production North American (HP), high-durability North American (HD), and New Zealand (NZ)—were evaluated. As concentrate input increased, N surplus per hectare increased and N use efficiency per hectare decreased (23 and 10%, respectively). When the N required to rear replacement animals to maintain the production system was considered, the N surplus of the HP genetic strain was greater (156 kg of N/cow) than that of the HD (140 kg of N/cow) or the NZ (128 kg of N/cow). The model estimated N leaching of 8.1 mg of $\text{NO}_3\text{-N/L}$, similar to that measured by others at the same site. The model creates awareness of methods and indicators available to assess the most suitable and environmentally sustainable grass based dairy production systems.

Key words: nitrogen balance, grassland, dairy, nitrogen use efficiency

INTRODUCTION

Grassland-based agricultural production is the most important component of livestock production systems in Ireland and in other temperate regions (Dillon et al., 2005) because of the competitive economic advantage of grazed grass within such a system. In recent years, increased world demand for food and a continual reduction in market prices has resulted in increased focus on grass-based systems of production. In Ireland and other temperate regions, intensive grass-based milk production systems generally rely on inputs of nitrogen (N)

in the form of chemical fertilizer to produce sufficient herbage (grazed grass or grass silage), and strategic concentrate supplementation during times of herbage deficit, to sustain milk output per hectare at economically viable levels. In 2007, the average Irish dairy farm had a stocking rate of 1.9 livestock units (LU)/ha, fed approximately 700 kg of concentrates per cow, and applied 175 kg of N/ha, although concentrate feeding and N application varied with stocking rate (Teagasc, 2007).

Despite the positive effect of N fertilizer use on agricultural production (Whitehead, 1995), the poor efficiency with which N is utilized within animal-based systems is well documented (Watson and Atkinson, 1999). As N cycles through the farm system unavoidable losses occur by 3 major loss pathways: nitrate (NO_3^-) leaching, nitrous oxide (N_2O) emissions, and ammonia (NH_3) volatilization (Whitehead, 1995).

Achieving the optimum balance between profitable agriculture and environmental protection is challenging. When production is maximized and output is near equilibrium, all further N inputs are lost to the environment (Rotz et al., 2005). Generally, as feed N intake increases, N output in feces, urine, and milk increases (Castillo et al., 2000); NH_3 emissions increase (Miselbrook et al., 2006); N_2O emissions increase (Hyde et al., 2005); and NO_3^- leaching increases (Ledgard et al., 1999; Richards, 1999). However, negative relationships were found between N input and the level of N utilization; often increasing N inputs decreases N use efficiency. Humphreys et al. (2003) noted that reducing N input by 246 kg of N/ha on an intensive dairy production system while maintaining similar levels of production improved N use efficiency by 29%. However, an increase of N use efficiency may come at the expense of animal and plant production (Laws et al., 2000), highlighting that a balance has to be achieved between N use efficiency and N losses to maintain a sustainable dairy production system.

European Union (EU) policy such as the Water Framework Directive (2000/60/EC) and the Nitrates Directive (SI 378 2006), as well as recent sharp increases in the cost of N fertilizer, have increased the focus on N use efficiency. The Nitrates Directive sets limits

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Table 1. Herd performance data generated by the Moorepark Dairy Systems Model for 9 contrasting pasture-based dairy production systems¹

Item	High stocking rate			High concentrate			Moorepark		
	HP	HD	NZ	HP	HD	NZ	HP	HD	NZ
Average number of cows	106.9	107.6	107.9	97.4	97.9	98.2	97.4	97.8	98.1
Milk yield per cow (kg/cow)	6,571	6,527	6,255	7,724	7,587	6,598	6,751	6,656	6,333
Milk fat percentage	4.28	4.29	4.76	4.18	4.18	4.65	4.23	4.26	4.88
Milk protein percentage	3.55	3.63	3.71	3.61	3.66	3.81	3.51	3.63	3.74
Milk solids yield (kg of MS/cow)	493.3	496.7	508.4	576.8	572.0	535.8	501.5	504.8	523.9
Stocking rate (livestock units/ha)	2.63	2.69	2.69	2.43	2.44	2.45	2.43	2.44	2.45
Grazed grass intake (kg of DM/cow)	3,811	3,888	3,892	3,447	3,535	3,223	3,867	3,953	3,997
Silage intake (kg of DM/cow)	1,161	1,071	1,005	1,041	991	887	1,169	1,088	1,024
Concentrate intake (kg of DM/cow)	317	316	318	1,369	1,359	1,354	317	316	318
Culling or replacement rate (%)	37.0	24.7	17.9	37.2	24.8	17.9	37.2	24.7	17.9
Average BW (kg)	525	518	496	529	550	506	525	538	506

¹Divergent strains of Holstein-Friesian cows consisting of high-production North American (HP), high-durability North American (HD), and New Zealand (NZ).

on stocking rate and N fertilizer use per hectare. In Ireland, water quality surveys, including NO₃⁻ levels, over the last 2 decades show a steady decrease in water quality, which has largely been attributed to agricultural activity (EPA, 2006).

Estimates of the potential quantities of N that may be released into the environment from dairy farms have been calculated using N budgets and models within numerous production systems (Scholefield et al., 1991; Mounsey et al., 1998; Watson and Atkinson, 1999; del Prado et al., 2006; Humphreys et al., 2008) with surpluses ranging from 2.1 to more than 300 kg of N/ha (Mounsey et al., 1998; Watson et al., 2002). Few of these budgets attempt to quantify and model the N flows and losses associated with the different levels of production and the related environmental and economic consequences.

Computer simulation provides a tool for rapid and cost-effective synopsis of the performance of agriculture systems (Rotz et al., 2005). However, a limitation of this approach is developing confidence in the simulation results. Only through extensive verification and evaluation of the model will confidence be gained in the results and recommendations. Comparison of model results with actual recorded information is the only meaningful way to validate farm models (Shalloo et al., 2004).

The objectives of this study were to develop, evaluate, and validate an annual N balance model based on Irish grass-based dairy production systems. The balance is in monthly stages from January to December. The production and economic performance of the systems was generated by the Moorepark Dairy Systems Model (MDSM; Shalloo et al., 2004). The model developed and described in this paper evaluates N balances and quantifies N use efficiency by identifying surpluses and potential losses associated with contrasting levels of

production within grass-based, spring-calving dairy production systems.

MATERIALS AND METHODS

Dairy Production System Physical Performance

The dairy production systems that were simulated during model validation and scenario testing are on grass-based dairy systems with a February to April calving pattern. The physical performance data were obtained from a 5-yr study (2001–2006) conducted at Curtins Research Farm, Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland. Farm system production data were generated by the MDSM based on the physical performance at Curtins Farm. The study consisted of 3 divergent strains of Holstein-Friesian (**HF**) dairy cows: high-production North American (**HP**), high-durability North American (**HD**), and New Zealand (**NZ**), managed across a variety of Irish pasture-based production systems: the Moorepark Blueprint system (**MP**), a high concentrate input system (**HC**), and a high stocking rate system (**HS**). This study is described in detail by Horan et al. (2004) and McCarthy et al. (2007) (Table 1).

The physical performance of each dairy production system used for the scenarios assessed is described in Table 1. As the genetic strain of dairy cow and level of concentrate supplementation changed, the milk production, milk solids concentration, feed budgets, and overall farm stocking rate changed, as has previously been reported by McCarthy et al. (2007) (Table 1).

The land base for each treatment was similar (40 ha), and the grazing season length and housing periods were similar for all 9 treatments. The information includes the number of dairy cows per treatment, annual feed

budget (grazed grass, conserved silage, and purchased concentrate), and production performance (annual milk production). The meteorological data used were the 4-yr mean monthly rainfall recorded by Ryan et al. (2006). The quantity of annual effective rainfall (precipitation minus evapotranspiration; 459 mm) was used in the model to calculate the quantity of NO_3^- leached (Ryan et al., 2006). It is assumed in the validation of the model reported in this paper that all slurry produced within each farm system was recycled on that system.

Moorepark Dairy Systems Model

The MDSM (Shalloo et al., 2004) is a stochastic budgetary simulation model of a dairy farm. It allows investigation of the effects of varying biological, technical, and physical processes on farm profitability. The model integrates animal inventory and valuation, milk production, feed requirements, land and labor utilization, and an economic analysis of the production system. Land area is treated as an opportunity cost, with additional land rented when required and leased out when not required for on-farm feeding of animals. Variable costs (fertilizer, contractor charges, medical and veterinarian fees, artificial insemination, silage, and reseedling), fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity, and insurance), and prices (calf, milk, and cow) are based on 2008 management data for farm planning (Teagasc, 2008). The quantity of each feed offered (grass, grass silage, and concentrate) was determined by the MDSM to meet the net energy requirements of animals for maintenance, milk production, and BW change (Jarrige, 1989).

Model Description

The flow or cycle of N within a system is the movement of N between several reservoirs. Within any grass-based production system, N enters the system in the form of imported inorganic and organic fertilizers, concentrate feed, and symbiotic and nonsymbiotic N capture (Jarvis et al., 1995; Figure 1). This N resides temporarily in various reservoirs, including the plants and their residues and grazing or housed livestock, and may be exchanged from one form to another (e.g., from NH_4^+ to NO_3^-). Livestock cause chemical and biological transformations to the cycling N through digestion, excretion, and exportation (Jarvis et al., 1995). Nitrogen within the herbage is relocated through the grazing process, where N in herbage grazed from a large area will be redistributed to small, highly concentrated areas through the deposition of urine and dung (Haynes and Williams, 1993). Ingested N is also transformed into N

exports such as milk and meat sold, recycled N, or N lost to the environment (Whitehead, 1995).

Nitrogen Balance Calculations

The sum of the annual inputs less outputs in the form of agricultural products is the farm-gate N balance (Scholefield et al., 1991; Watson and Atkinson, 1999). The farm-gate N balance takes account of all N imported into the dairy system, circulated within, and exported from the dairy system (Figure 1). Imports and exports of N can be expressed on a per hectare (kg/ha) or a per cow (kg/cow) basis. Nitrogen use efficiency was calculated as the proportion of imported N recovered in agricultural products.

Nitrogen Inputs. The N imported into the farm system consisted of fertilizer, feedstuffs, and livestock (in the form of replacement or purchased animals). No legumes were present in the swards. Nitrogen input into the individual cow consisted of N in feed consumed (grazed grass, silage, and concentrates) and N required to replace the individual cow. Cows were replaced as culling occurred within the herd due to fertility, health, and production-related factors. The replacement rate for each system is shown in Table 1. Body weight of replacement animals was assumed to be 80% that of a mature cow to simulate a younger cow replacing an older cow with a similar N content. Other N inputs taken account of are atmospheric deposition and soil N mineralization (Scholefield et al., 1991; Watson and Atkinson, 1999).

Nitrogen imported in the form of chemical fertilizer was expressed as kilograms of N applied per hectare. Nitrogen imported in concentrate feed was calculated by multiplying the total quantity of concentrate fed by its CP content and dividing by 6.25 (McDonald et al., 1995). The N content of the grazed grass and grass silage harvested was calculated by dividing the CP by 6.25 (McDonald et al., 1995). The quantity of atmospheric N deposited each year was taken as 9 kg/ha per year, as estimated by Ryan et al. (2006).

Nitrogen Outputs. The N outputs from the farm system can be divided in 2 categories: (1) N leaving the system in products (milk, meat, exported feedstuff and exported manure); and (2) N immobilized in the soil or lost through volatilization, denitrification, or leaching.

Nitrogen in milk exported from the farm was calculated from recorded milk protein content of milk (milk protein divided by 6.39; ARC, 1994) multiplied by milk volume. Nitrogen exported in livestock leaving the farm was calculated by estimating the total live weight of the livestock sold (or died) from the system (Horan et al., 2004; McCarthy et al., 2007) and multiplying it by

Figure 1. Flow diagram of N inputs, N outputs, and flows, and the major pathways for N losses within a grass-based dairy system.

the N content. The N content of exported calves born on the farm and dairy cows sold from the farm was estimated as 0.029 and 0.024 kg of N/kg of live weight, respectively (ARC, 1994).

Nitrogen Cycling Within the System. Nitrogen produced as slurry during the housed period was calculated as total N intake (in the form of grazed grass, silage, and concentrate) consumed by the housed animals less N output from these animals and N used for growth and maintenance (Watson and Atkinson, 1999). The slurry was reapplied to the land area within the farm system.

Soil Nitrogen. Soil N mineralization (average annual N flux) was estimated using the 5-yr mean of N harvested in herbage (kg of N/ha) from grass growth plots receiving no fertilizer N (methodology described by Corrall and Fenlon, 1978) at the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, and the methods described by del Prado et al. (2006) as shown in equation [1]:

$$\text{SNM (kg of N/ha)} = \{[(\text{Harvested, kg of N/ha} \times 1.4) \times \text{Pcf}] \times \text{Dstf}\} - \text{Ad}, \quad [1]$$

where SNM = soil N mineralization, Pcf = previous cropping history combined with sward age adjustment factor (long-term pasture >2 yr Pcf = 1), Dstf = drainage age and soil texture adjustment factor (good drainage

on sandy loam soil type Dstf = 0.75), and Ad = atmosphere deposition (kg of N/ha).

The annual accumulation and addition of soil organic N was estimated as the sum of N from ungrazed herbage and fecal N deposited to the soil during the grazing season (Hutchings and Kristeensen, 1995), plus N transferred to roots, based on an annual root production of 5,000 kg/ha (Whitehead, 1995), with a root N content of 1.2% (Whitehead, 1970).

Animal Excreta. The N content of cow excreta was estimated by subtracting N in milk, maintenance, and live weight gain from total N intake (del Prado et al., 2006). The N portion of dung in excreta was calculated by the methods described by del Prado et al. (2006) and shown in equation [2]:

$$\text{N in dairy cow dung} = 0.15 \times \text{N}_{\text{animal intake}} + 28.47. \quad [2]$$

Nitrogen content of urine was calculated from total N in the excreta minus the N in dung (del Prado et al., 2006).

Nitrogen Losses

Nitrogen Losses from Volatilization. Losses of NH_3 through volatilization from grazed grassland were estimated using the methods described by Misselbrook et al. (2006) and shown in equation [3]:

$$\text{NH}_3\text{-N emission (g/LU per day)} = -0.51 + 0.0742X, \quad [3]$$

where X = input of fertilizer N (kg of N/ha per yr).

Losses of $\text{NH}_3\text{-N}$ during agitation and application of slurry were assumed to be 0.60 of $\text{NH}_3\text{-N}$ in the slurry (Pain et al., 1989, 1990). A housing emission factor of 34.5 g of $\text{NH}_3\text{-N}$ /LU per day was also included (Hyde et al., 2003).

Nitrogen Losses from Denitrification and Leaching and Unaccountable N. Denitrification and leaching losses were assumed to be the difference between N inputs to the soil (fertilizer, atmosphere mineralization, urine, dung, and dead plant material) and N uptake by the plant component of the sward, NH_3 volatilization from urine and dung (Scholefield et al., 1991), and N accumulation within the soil (Watson and Atkinson, 1999). The proportion of N attributed to denitrification loss was derived according to soil type and a drainage category factor of 0.15, as described by Scholefield et al. (1991). This factor is related to the texture and type of soil; for example, a free-draining sandy loam soil type is classified with a factor of 0.15, whereas a poorly drained heavy clay soil is classified with a factor of 0.80; thus, less denitrification takes place on free-draining soils compared with poorly drained soils. The proportion of the remaining loss was attributable to leachable N and so was obtained by difference (Scholefield et al., 1991; del Prado et al., 2006).

The potential N concentration in groundwater was estimated using the crop and soil type specific leaching fraction of 0.24. This was based upon the specific crop, previous management, and soil type, using methods described by Boumans et al. (2001), Fraters et al. (2005), and Schroder et al. (2009), and shown in equation [4]:

$$\text{NO}_3 \text{ in groundwater (mg/L)} = \frac{N_{\text{sal}} \times C_{\text{slf}}}{\text{Effective rainfall (mm)}}, \quad [4]$$

where N_{sal} = surplus N available for leaching (kg of N/ha), C_{slf} = crop and soil type specific leaching fraction of 0.24, and effective rainfall (mm) = precipitation – evapotranspiration.

Unaccountable N was the difference between N inputs and N outputs and measured or calculated N losses.

Scenario Investigation, Sensitivity Analysis, and Model Validation

Two scenarios were investigated in the evaluation and validation of the model. Scenario 1 (**S1**) investigated the N utilization, N use efficiency, and N losses

of the contrasting dairy production systems described by Horan et al. (2004) and McCarthy et al. (2007), excluding the N required to rear replacement animals from birth to first calving necessary for the production system. An N value for the animal used to replace culled cows is included. This scenario is the typical farm-gate N balance and is calculated on a per hectare basis to allow comparison with previously published work, and on a per cow basis to compare N use efficiency between contrasting dairy cow strains.

Scenario 2 (**S2**) investigated the N utilization, N use efficiency, and N losses on each of the 9 dairy production systems described by Horan et al. (2004) and McCarthy et al. (2007), including the N required to rear replacement animals from birth to first calving. The N balance for this scenario was calculated on a per cow basis to quantify the level of efficiency at which the cow utilizes N for production purposes.

A sensitivity analysis was undertaken in which the effect of reducing fertilizer N application by 50 kg of N/ha while maintaining the same levels of production through improved grass utilization was examined. Comparisons of farm-gate N balance on a per hectare basis, N utilization, N use efficiency, and N losses per hectare were made.

The model was validated using data from Ryan et al. (2006) in which NO_3^- -N leaching to a depth of 1 m from management areas determined to be representative of the major variables on a dairy grassland farm were measured over a 4-yr period (2001–2005) at the same site (Ryan et al., 2006). The data were used to obtain the NO_3^- leaching results for comparison with the model results, and therefore model validation.

RESULTS

Nitrogen Input

The main sources of N input to the dairy production systems were feed, fertilizer, and replacement animals. The average quantity of fertilizer applied was 289 kg of N/ha (SD = 1.1 kg of N/ha) for all treatments investigated in S1 (noninclusion of the heifer rearing component; Table 2). The quantity of N imported per cow in the form of concentrate varied between treatments, ranging from 7 to 31 kg of N/cow (Table 3).

Nitrogen input for S2 (inclusion of the heifer rearing component) increased from 166 kg of N/cow to 206 kg of N/cow (Table 4) as the replacement rate increased from 18% for the NZ strain to 37% for the HP strain, with a mean N input increase of 66 kg of N/ha across the different production systems (Table 4). The quantity of N utilized in the form of grazed pasture, silage, and concentrate in S2 for heifer rearing varied between

Table 2. The annual farm-gate N balance (kg of N/ha) and N use efficiency for scenario 1, in which N required for the rearing of replacement was not included in the N budget of 9 dairy production systems¹

Item	High stocking rate			High concentrate			Moorepark		
	HP	HD	NZ	HP	HD	NZ	HP	HD	NZ
Concentrate N consumed	18.9	19.0	19.2	74.5	74.4	74.4	17.2	17.3	17.4
Fertilizer N	295.9	296.7	297.3	298.2	98.6	299.5	296.9	297.5	298.2
N input in the replacement cows	10.1	6.3	4.4	8.3	5.8	4.0	9.1	6.2	4.1
Total N input	324.9	322.0	320.9	381.0	378.8	377.9	323.2	321.0	319.7
Milk N	94.4	96.6	94.8	102.9	103.0	93.5	87.6	89.6	88.0
Calf N	3.1	3.1	3.1	2.8	2.8	2.8	2.8	2.8	2.8
Cull cow N	13.9	9.0	6.6	11.5	8.4	6.1	12.4	8.9	6.2
Total N output	111.4	108.8	104.5	117.2	114.3	102.4	102.8	101.3	97.1
Nitrogen surplus	213.5	213.2	216.3	263.8	264.5	275.5	220.4	219.8	222.6
Nitrogen use efficiency	0.343	0.338	0.326	0.308	0.302	0.271	0.318	0.315	0.304

¹Divergent strains of Holstein-Friesian cows consisting of high-production North American (HP), high-durability North American (HD), and New Zealand (NZ).

genetic strain, with means of 57, 83, and 123 kg of N/ha for the NZ, HD, and HP genetic strains, respectively (Table 4).

The total N intake per cow consumed by dairy replacement animals in S2 (0–2 yr old) varied between genetic strains, depending on replacement rate. It was 23, 33, and 49 kg of N/cow consumed for the NZ, HD, and HP genetic strains, respectively (Table 4).

Nitrogen supplied from soil mineralization was estimated, using equation [1], to be 82 kg of N/ha for all treatments, based on the 5-yr average grass growth rates from plots receiving zero N fertilizer.

Nitrogen Outputs

Milk production was the main source of exported N from all dairy production systems, with N exported in milk ranging from 88 to 103 kg of N/ha (Table 2). The increase in replacement rate had a positive effect on the quantity of N exported in the form of meat in S1

and S2, ranging from 6 to 14 kg of N/ha (Table 2) or 2 to 5 kg of N/cow (Table 3). The overall quantity of N exported per hectare in the form of product varied from 97 to 117 kg/ha (Table 2).

The quantity of slurry produced and reapplied within each system ranged from 73 to 80 kg of N/ha, depending on the number of dairy cows within the system (range from 97 to 108 cows). The number of days housed was the same across treatments (85 d). Nitrogen immobilization or accumulation within the soil was consistent between treatments at approximately 79 kg of N/ha (SD = 0.2 kg of N/ha; Table 5).

Nitrogen Use Efficiency (Farm Gate)

The annual farm-gate N surplus per hectare (N inputs less N outputs in products) ranged from 213 kg of N/ha for HP-HS to 275 kg of N/ha NZ-HC, with a mean N surplus of 234 kg of N/ha for all systems (Table 2). A negative relationship was found between N surplus

Table 3. The annual N balance per cow (kg of N/cow) and N use efficiency for scenario 1, in which N required for the rearing of replacement was not included in the budget for 9 dairy production systems¹

Item	High stocking rate			High concentrate			Moorepark		
	HP	HD	NZ	HP	HD	NZ	HP	HD	NZ
Grazed pasture N intake	109.6	112.1	112.4	99.3	102.1	93.2	111.2	114.0	115.4
Silage kg N intake	26.0	24.0	22.5	23.3	22.2	19.9	26.2	24.4	22.9
Concentrate N intake	7.1	7.1	7.1	30.7	30.4	30.3	7.1	7.1	7.1
Dairy cow replacement N	3.8	2.3	1.6	3.4	2.4	1.6	3.7	2.5	1.7
Total N intake	146.4	145.5	143.6	156.7	157.2	145.0	148.2	148.0	147.1
Milk N output	35.4	36.0	35.2	42.3	42.2	38.2	36.0	36.7	36.0
Calf N output	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Cull cow N output	5.2	3.4	2.5	4.7	3.5	2.5	5.1	3.6	2.5
Total N output	41.7	40.5	38.8	48.2	46.8	41.8	42.3	41.5	39.6
N surplus	104.71	105.0	104.83	108.46	110.38	103.19	105.95	106.49	107.50
N use efficiency	0.285	0.278	0.270	0.308	0.298	0.288	0.285	0.280	0.269

¹Divergent strains of Holstein-Friesian cows consisting of high-production North American (HP), high-durability North American (HD), and New Zealand (NZ).

Table 4. The annual N balance per cow (kg of N/cow) and N use efficiency for scenario 2, in which all N required for the rearing of replacement was included in the N budget of 9 dairy production systems¹

Item	High stocking rate			High concentrate			Moorepark		
	HP	HD	NZ	HP	HD	NZ	HP	HD	NZ
Grazed pasture N intake	109.6	112.1	112.4	99.3	102.1	93.2	111.2	114.0	115.4
Silage N intake	26.0	24.0	22.5	23.3	22.2	19.9	26.1	24.4	22.9
Concentrate N intake	7.1	7.0	7.1	30.7	30.4	30.3	7.1	7.1	7.1
Dairy cow replacement N	3.8	2.3	1.6	3.4	2.4	1.6	3.7	2.5	1.6
Heifer intake grazed pasture	33.7	22.5	15.5	34.0	22.6	15.6	34.0	22.5	15.5
Heifer intake silage	9.7	6.5	4.5	9.8	6.5	4.5	9.8	6.5	4.5
Heifer intake concentrate	5.5	3.7	2.5	5.5	3.7	2.5	5.5	3.7	2.5
Total kg N input	195.4	178.2	166.2	205.9	190.0	167.6	197.5	180.7	169.7
Milk N output	35.4	36.0	35.1	42.3	42.1	38.1	36.0	36.7	37.0
Calf kg N	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Cull cow N output	5.2	3.3	2.5	4.7	3.4	2.5	5.1	3.6	2.5
Total N output	41.7	40.5	38.8	48.2	46.7	41.8	42.2	41.5	39.6
N surplus	153.7	137.7	127.4	157.8	143.2	125.8	155.2	139.2	130.0
N use efficiency	0.214	0.227	0.234	0.234	0.246	0.249	0.214	0.230	0.234

¹Divergent strains of Holstein-Friesian cows consisting of high-production North American (HP), high-durability North American (HD), and New Zealand (NZ).

and the proportion of grazed herbage in the diet, with the HC feeding systems producing the greatest N surplus while consuming the least amount of grazed grass (Table 2).

When comparing the milk solids (MS) produced (kg of MS/ha) and N surplus per hectare, little difference was observed between genetic strains in S1, with a mean of 6 kg of MS/ha (SD 0.1) produced for every 1 kg of surplus N. Differences were found between feeding systems in S1, with 5.1, 5.6, and 6.2 kg of MS/ha produced per kg of N surplus per ha for the HC, MP, and the HS feeding systems, respectively. In S2, strains HD and NZ produced 50 kg of milk/kg of surplus N, which was 10% more than that of the HP genetic strain.

In the S1 farm-gate N balance, the mean level of N use efficiency was 0.31, ranging from 0.27 to 0.34 (Table 2). As the level of concentrate supplementation increased, a negative effect on N use efficiency was

found, ranging from a combined mean N use efficiency of 0.32 for the HS and MP feeding systems to 0.29 for the HC feeding system (Table 2). The quantity of surplus N available for loss increased as the level of N efficiency decreased (Table 2). The N balance on a per cow basis for S1 shows that the HP genetic strain utilized N most efficiently, at a mean N use efficiency per cow of 0.29 (Table 3).

In S2, when the full dairy production system (including N required for the heifer rearing component) N balance was calculated, the N surplus for the different genetic strains was 323, 353, and 390 kg of N/ha for the NZ, HD, and HP genetic strains, respectively.

Milk solids production per cow per kg of surplus N in S2 ranged from 3.2 for the HP strain to 3.9 for the HD and NZ strains. Feeding system had little effect on MS produced per cow per kg surplus N, with a mean of 3.7 kg of MS/cow (SD 0.20) produced per kg of surplus N.

Table 5. The nitrogen (N) surplus (kg of N/ha unless otherwise noted) and estimated annual losses (kg of N/ha) for 9 dairy production systems from scenario 1¹

Item	High stocking rate			High concentrate			Moorepark		
	HP	HD	NZ	HP	HD	NZ	HP	HD	NZ
N in dung excreta	33.4	33.4	33.3	33.2	33.3	32.9	33.0	33.0	33.0
N in urine excreta	188.6	190.3	190.3	181.2	186.8	168.9	175.5	177.5	180.4
Ammonia emissions	51.4	52.1	52.4	43.6	44.1	44.4	43.4	43.8	44.2
N accumulation in the soil	79.2	79.2	79.2	79.1	79.2	78.9	78.9	78.9	78.9
N lost through denitrification	25.9	25.3	25.1	29.7	29.3	29.7	27.3	26.7	26.6
N available for leaching	146.9	143.1	142.1	168.5	166.3	168.4	154.8	151.5	150.5
N content in groundwater (mg of N/L)	7.68	7.48	7.43	8.81	8.69	8.81	8.09	7.92	7.87
Unaccountable N ²	-6.1	-2.7	1.3	26.4	29.3	37.5	-0.4	2.3	6.0

¹Divergent strains of Holstein-Friesian cows consisting of high-production North American (HP), high-durability North American (HD), and New Zealand (NZ).

²The difference between N inputs and N outputs and measured or calculated N losses.

In S2, the N balance per cow shows that the HP genetic strain was the least efficient production system, with mean N use efficiency of 0.23 per cow, whereas the NZ genetic strain was the most efficient production system, with mean N use efficiency of 0.24 per cow (Table 4). In S2, the NZ genetic strain had the lowest overall mean N surplus (128 kg of N/cow; Table 4) and produced 4.1 kg of MS/kg of surplus N. Overall, the NZ genetic strain produced approximately 33% more MS (kg/cow) per kg of surplus N than the HP and HD genetic strains.

Nitrogen Losses

Nitrogen losses to the environment were estimated from S1, as this scenario is typical of farming practice in Ireland, with replacement heifers reared as a separate enterprise to milk production on the farm (usually on an outside block of land away from the milking cow grazing area). Mean NH_3 emissions were 47 kg of N/ha (Table 5). Ammonia emissions increased from 43 to 52 kg of N/ha as stocking rate and N input increased (Table 5).

Nitrogen losses from denitrification did not vary hugely between treatments. The mean N loss from denitrification was 27 kg of N/ha, ranging from 25 to 30 kg of N/ha (Table 5). A negative trend was observed between N efficiency and N loss through denitrification (Table 5).

The mean N available for leaching was 155 kg of N/ha across the dairy production systems, ranging from 142 to 169 kg of N/ha (Table 5). The quantity of N available for leaching tended to change with feeding system. As stocking rate and quantity of grazed grass in the diet increased, the quantity of N available for leaching decreased. The quantity of concentrates in the diet had a positive effect on the amount of N available for leaching (Table 5). The mean N available for leaching was 157, 154, and 154 kg of N/ha (Table 5) for the HP, HD, and NZ genetic strains, respectively.

When the N available for leaching is used to estimate the potential loss of NO_3^- to groundwater, the mean N concentrations in groundwater was 8.09 mg of N/L, ranging from 7.4 to 8.8 mg of N/L. As feeding system changed from low concentrate input (MP and HS) to high concentrate input (HC), the estimated N concentration of groundwater increased from 7.8 to 8.8 mg of N/L, respectively (Table 5).

As the quantity of surplus N increased, so too did the quantity of N that was unaccounted for (Table 5). When all the N outputs and losses associated with the different production systems were calculated, the unaccounted-for N ranged from -6.1 kg of N/ha for HP-HS to 37.6 kg of N/ha for NZ-HC.

Sensitivity Analysis

Reducing N fertilizer input by 50 kg of N/ha while maintaining production reduced the N surplus by a mean of 22% (SD 0.02) relative to S1, with individual treatment reductions ranging from 18 to 23%. The N use efficiency increased on all treatments by an average of 17% (SD 0.01) with reduced N fertilizer application, and NH_3 emissions were reduced by an average of 14%. The N available for leaching was reduced by a mean of 19% (29 kg of N/ha; SD 0.5 kg of N/ha), denitrification losses were reduced by 5 kg of N/ha (SD 0.1 kg of N/ha) across all treatments, and groundwater N concentrations were reduced by a mean of 1.5 mg of N/L (SD 0.26 mg of N/L).

Validation of Production Systems

The N surplus per hectare and N use efficiency estimated for treatments used by Ryan et al. (2006) were 233 kg of N/ha and 0.32, respectively. Similar N surpluses and N efficiencies were calculated by the model reported in this paper. The N surpluses per cow in S1 and S2 were 107 and 140 kg of N/cow, respectively, and N use efficiency per cow in S1 and S2 was 0.29 and 0.23, respectively.

Nitrogen losses from NH_3 emissions and from denitrification reported by Ryan et al. (2006) were 47 and 27 kg of N/ha, respectively, which were slightly lower than those estimated by the model. The model estimated similar quantities of N available for leaching as that reported by Ryan et al. (2006; 154 kg of N/ha). The N concentration in groundwater calculated by the model was 8.1 mg of NO_3^- /L, which is similar to the concentration measured by Ryan et al. (2006) of 8.2 mg of NO_3^- /L (Table 6).

DISCUSSION

Production System N Utilization

The methods used in this study combine field experiments and simulations to understand the dynamics of N balance in dairy production systems. Modeling the production system showed a mean surplus N of 234 kg of N/ha, with N utilization efficiency ranging from 27 to 34%.

Other studies have reported poor N use efficiency in Ireland in high N input systems. Mounsey et al. (1998) and Treacy et al. (2008) reported N surpluses greater than 300 kg/ha per year as a result of excessive N input and moderate N output per hectare. This is because of the inability of systems to utilize additional N inputs above those required for herbage and animal production (Whitehead, 1995). The treatments examined in

this paper had similarly high N inputs. In S2 (inclusive of heifer rearing component), as the level of N input increased between the different feeding systems (HS, MP and HC), so did N output in the form of production. However, 40% of the extra N input was lost to the environment, highlighting the law of diminishing returns as N input increases (Rotz et al., 2006). Regardless of production system, at the animal level, over 70% of N consumed was excreted in dung or urine. The mean efficiency at which N was utilized was similar to levels of N efficiency observed by Castillo et al. (2000), who noted that 72% of N intake was excreted. The distribution of excreted N between dung and urine reflects the concentration of N in the diet (Van Vuuren and Meijs, 1987; Delaby et al., 2007). Excretion of N in the dung is not affected by changes in the N concentration of the diet and tends to remain constant at approximately 8 g of N per kg of DM consumed (Whitehead, 1995). A change in the N concentration of the diet is therefore reflected in the amount of N excreted in the urine (Van der Meer, 1983; Van Vuuren and Meijs, 1987; Jarvis et al., 1989; Peyraud et al., 1997; Peyraud and Astigarraga, 1998). In the production systems examined, changes in the N concentration of milk are small relative to the large increases in N excreted in urine that occurred with increasing N concentration of the diet. Verite and Delaby (2000) showed that, at grazing, an increase in CP content of the diet from 18 to 22% resulted in a 30% increase in daily excreted N, of which >70% was eliminated in the urine.

The optimal genetics for a production system are those that generate the greatest sustainable economic return (Shalloo et al., 2004). Pryce and Veerkamp (2001) observed a negative correlation between fertility and milk yield. This decline is clearly observed with the HP compared with the NZ genetic strain. The N use efficiency per cow in S2 for the HP genetic strain (22%) was less than that for the NZ genetic strain (24%; Table 4); however, the HP genetic strain produced 22% more surplus N because of the increased N required to rear extra replacement animals. The NZ strain produced an average of 523 kg of MS/cow, which was the equivalent of 4 kg of MS per kg of surplus N. The HP genetic strain produced 18% less MS per kg of surplus N.

Purchased feed and fertilizer are the most significant sources of N inputs to a dairy production system, accounting for more than 94% of all N inputs to intensive systems (Treacy et al., 2008). Milk and livestock sold are essentially the most significant forms of N exported (Treacy et al., 2008) and equate to the majority of the economic returns (Shalloo et al., 2004). Combining the economic performance reported by McCarthy et al. (2007) and the N efficiency reported in this paper, the NZ strain was the most efficient at converting N

Table 6. Herd performance data generated from the Moorepark Dairy Systems Model on the Ryan et al. (2006) dairy production system and environmental data, and reported mean NO₃ concentration

Item	Herd performance
Average number of cows	101.1
Average yield per cow (kg/cow)	6,911.2
Average fat percentage	4.24
Average protein percentage	3.64
Average milk solid yield (kg/cow)	523.64
Average stocking rate (livestock units/ha)	2.52
Grazing days per year (n)	279.7
Grazed grass intake (kg of DM/cow)	3,791.9
Average silage intake (kg of DM/cow)	1,050.0
Concentrate intake (kg of DM/cow)	664.0
Culling percentage	24.77
Average BW (kg)	535
Mean NO ₃ concentration (mg of NO ₃ /L)	8.05

into saleable product compared with the HP and HD strains.

Nitrogen Losses

In any intensive agricultural system, the major N dynamic processes involved in N loss are volatilization, denitrification, and leaching. The model simulated these processes with close agreement to other simulations and field investigations (Ledgard et al., 1999; Ryan et al., 2001, 2006; Rotz et al., 2006; Watson et al., 2007; Treacy et al., 2008) (Table 5). The pathways by which N is emitted to the environment are highly variable with a change in production system. Velthof and Oenema (1997) calculated N₂O emissions from fertilized grasslands in the Netherlands to range from 10 to 20 kg of N/ha per year and Hyde et al. (2005) measured N₂O emissions ranging from 2 to >24 kg of N/ha in Ireland. Dobbie et al. (1999) noted that N₂O emissions are highly variable depending on temperature and soil moisture. The methods used in this model to quantify losses associated with denitrification do not distinguish between the different forms of N; however, they do assess the quantity of N diverted away from product, and all losses simulated were similar to previously published losses (Ledgard et al., 1999; Ryan et al., 2001, 2006).

Ledgard et al. (1999) estimated NH₃ emissions of between 15 and 78 kg of N/ha for a range of dairy systems with N input levels ranging from 0 to 400 kg of N/ha. As N fertilizer input increases, so too does N concentration in herbage consumed (Thompson and Poppi, 1990). Excess N in the diet is excreted in the dung and urine. The localized deposition of N in dung and urine by dairy cows results in "hotspots" in the soil. These hotspots in the soil lead to increased risk of N loss through volatilization of ammonia, denitrification, or leaching of nitrate (Jarvis et al., 1989).

Comparisons made by del Prado et al. (2006) between estimated biological N outputs (kg of N/ha) from the NCYCLE model (Scholefield et al., 1991) and the NCYCLE_IRL model (del Prado et al., 2006) showed that N output in the form of N in milk, urine and dung increased almost linearly as N intake increased. However, N output values reported in the literature deviate by up to 80%. Huston et al. (1998) noted that direct measurements of N losses to air and water are difficult and the coefficient of variation associated with estimates of leaching, runoffs, and volatilization losses are typically in the range of 50 to 200%.

Differences between measured N loss and predicted N loss are likely due to inaccurate estimation of background N (O'Connell et al., 2003). The background N from soil mineralization predicted by this model (81.7 kg of N/ha) was similar to that in other studies. Watson and Atkinson (1999) calculated soil N mineralization ranging from 88 to 96 kg of N/ha on a similar soil type in Scotland.

Surplus N

Surplus N can be considered an indicator of the potential N loss (Scholefield et al., 1991) from dairy production systems. In the systems modeled in this paper, MS production per hectare increased as the N surplus increased, similar to results of Humphreys et al. (2008). The ratio of MS produced to surplus N declined with increasing N surplus. Nitrogen surpluses are assumed to be a good indicator of total N loss at system level (Scholefield et al., 1991), provided that the whole system can be accounted for. Brockstaller and Girardin (2003) reported that many indicators are not designed to be used to predict an actual effect but to supply information about the potential effect of a production system.

At the system level, N surplus estimates have proved to be a good predictor of NO_3^- leaching loss on sandy soils (Fraters et al., 1998; Vellinga et al., 2001), with up to 25% of N surplus being leached into groundwater (Fraters et al., 2005). However, the model reported here estimates that approximately 15% of surplus N is being leached. The differences may be due to greater N use efficiency in the systems reported compared with those reported by other authors (Oenema and Heinen, 1999; Fraters et al., 2005; Treacy et al., 2008).

Nitrogen loss studies on grazed swards have shown that calculated N surpluses generally exceed the measured N losses (Oenema and Heinen, 1999). The amount of N not accounted for in this study increases as N input increases, highlighting the fact that N movement within agricultural production systems is highly variable and "leaky" (Jarvis et al., 1995). It is possible

that the model underestimates N accumulation in the soil or N losses (Rotz et al., 2006; Watson et al., 2007), or both. Accumulation of organic N in the soil is highly variable because of variations in the history of the sward, soil, and climate conditions, as well as sward management (Whitehead, 1995; O'Connell et al., 2003; Rotz et al., 2006). Watson et al. (2007) reported that swards receiving 100 kg of N/ha per year had greater N accumulation than the input – output balance, without considering gaseous emissions, although over the long term, N within the soil may be leached if not utilized by a growing crop (Ryan et al., 2001).

Using N surplus as an indicator for estimating N loss to the environment (volatilized, denitrified, and leached) can sometimes result in an overestimation of losses, because much of the N surplus within a production system is usually locked up within the soil, crops, and animals. This surplus N is often in many forms, such as NH_4 , soluble organic N, and NO_3^- -N. The determination of NO_3 losses using the difference between the surplus N from the farm-gate N balance and the gaseous emissions has disadvantages of accumulating the uncertainties in the NO_3 losses (Kristensen et al., 1995) and therefore requires further field-scale investigation.

Model Validation

In this model, the estimated potential N leached into groundwater was predicted using the mean effective rainfall (precipitation – evapotranspiration) reported by Ryan et al. (2006) and the adjustment factors for soil type reported by Scholefield et al. (1991) and Schroder et al. (2009). The method used in this study was validated by comparing the groundwater NO_3 concentrations estimated by the model with those observed by Ryan et al. (2006). Ryan et al., (2006) studied N leaching for a 3-yr period at the site where Horan et al. (2004) and McCarthy et al. (2007) measured the biological and physical performance of the dairy production systems examined in this paper. The mean predicted concentration of NO_3 -N for the 9 treatments modeled was 8.1 mg of NO_3^- /L; Ryan et al. (2006) reported a mean concentration of 8.2 mg of NO_3 -N/L at the same site. Richards et al. (1998) observed much higher N leaching results on a similar soil type with double the N input (up to 677 kg of N/ha), with NO_3^- -N concentrations measured at 150 cm deep, ranging from 10 to 54 mg of N/L over a 2-yr period and a farm-gate N surplus ranging from 271 to 340 kg of N/ha. Ryan et al. (2001) measured NO_3 -N leaching concentrations ranging from 15.2 to 26.9 mg/L on fallow ground receiving no fertilizer, which equates to 244 kg of N/ha leached. Travel time of N to groundwater (Lord and Anthony,

2000; Dunn et al., 2004; Richards et al., 2005) is highly variable between soil types. Boumans et al. (2001) and Sonneveld et al. (2008) reported that varying levels of precipitation combined with contrasting N surpluses results in varying N concentrations in groundwater. Fraters et al. (2005) reported a reduction in NO_3^- -N concentration in groundwater, and that all known environmental factors could only account for 50% of the reduction in groundwater NO_3^- -N concentration.

Modeling N Use Efficiency

In recent years, N use management has become particularly important in grass-based systems, as the efficiency at which N is used strongly influences the production, agronomic, and environmental performance (Jarvis et al., 1995) of these systems. Recent changes in European policies dictate that N must be used more efficiently. However, N use management at the farm level is complex, and achieving a suitable balance between sustainable levels of production and minimizing N loss is challenging. Limited information exists on the management and monitoring of N flows in grassland at a whole-farm level with many unknowns in the pathways of N; for example, information on denitrification and soil N mineralization is limited (Whitehead, 1995; O'Connell et al., 2003; Watson et al., 2007).

The means by which the N surplus at a system level is calculated is crucial to ensure that all systems are represented accurately. The scenarios investigated in this paper show that the assessment of production systems using different system boundaries return different N surpluses and therefore different N use efficiency.

The production and economic consequences of alternative management practices and the genetic make-up of animals in production systems under Irish conditions has previously been reported by Dillon et al. (1995), Horan et al. (2004), Shalloo et al. (2004), and McCarthy et al. (2007). However, these authors did not investigate the effect of different production systems on N balance and efficiency, or potential environmental consequences.

Many researchers use farm-gate N inputs and N outputs to assess the potential N losses; this method of assessing N use efficiency may not fully account for all the N losses from that production system. In many N balance studies, the rearing of replacement animals required to maintain the production system (as described in S2) are not accounted for. Thus, the potential exists for misleading inference. The simple farm-gate balance calculated in S1 on a per cow basis highlights that the high-production genetic strain combined with the high stocking rate feeding system (HP-HS) utilized N most efficiently (0.34) when N required to rear replacement

animals was not accounted for; however, when the full production system was accounted for, in S2, the N surplus for the production system with NZ genetics, regardless of production system, produced an average of 21% less surplus N than the HP-HC production system and 15% more MS than the other genetic strains. Replacement animals are an integral part of the system and should be included, as they are in financial comparisons (Shalloo et al., 2004).

CONCLUSIONS

Models are effective tools to predict the effects of contrasting production systems and land-use options. The simulated results predicted N leaching with a close association to observed results at this site. These results create awareness and concerns about the indicators to assess environmental sustainability of intensive grassland systems. The results of the current study demonstrated that within pasture-based systems the lowest N losses and maximum profitability were observed with the Holstein-Friesian cows, combining high genetic potential for both production and fertility traits (HD and NZ strains), rather than those selected solely for increased milk production potential (HP strain). The whole-system approach of full accounting facilitates the comprehensive understanding of a system and an insight to the interactions and relationships between N flows and potential N losses, within and outside the farm boundaries, creating an indicator for management practices to assess the environmental consequences.

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