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ANIMAL RESEARCH PAPER

The effect of grazing season length on nitrogen utilization efficiency and nitrogen balance in spring-calving dairy production systems

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SUMMARY

There is a continual requirement for grass-based production systems to optimize economic and environmental sustainability through increased efficiency in the use of all inputs, especially nitrogen (N). An N balance model was used to assess N use efficiency and N surplus, and to predict N losses from grass-based dairy production systems differing in the length of the grazing season (GS). Data from a 3-year grazing study with a 3 × 3 factorial design, with three turnout dates (1 February, 21 February and 15 March) and three housing dates (25 October, 10 November and 25 November) were used to generate estimates of N use efficiency and N losses. As the length of the GS increased by a mean of 30 days, milk production, milk solids production and milk N output increased by 3, 6 and 6%, respectively. The increase in milk production as the length of the GS increased resulted in a 2% decline in N surplus and a 5% increase in N use efficiency. Increasing GS length increased the proportion of grazed grass in the diet, which increased N cycling within the system, resulting in an 8% increase in milk solids/ha produced/kg of surplus N. The increased cycling of N reduced the quantity of N partitioned for loss to the environment by 8%. Reducing fertilizer N input by 20% increased N use efficiency by 22% and reduced total N losses by 16%. The environmental and production consequences of increased length of the GS and reduced N loss are favourable as the costs associated with N inputs increase.

INTRODUCTION

The main source of feed for ruminant livestock in Ireland is grazed grass. In Ireland, the key to economic low cost milk production is to maximize milk produced from grazed grass (Dillon *et al.* 1995) using flexible grassland management systems (O'Riordan & O'Kiely 1996) and by maximizing the length of the grazing season (GS) (O'Donovan *et al.* 2002; Shalloo *et al.* 2004; Hennessy *et al.* 2006; Dillon *et al.* 2008; Ryan *et al.* 2010). Options for maximizing the length of the GS in low cost production systems involving a high intake of grazed grass (Dillon *et al.* 2008) are limited to managing stocking rate, fertilizer nitrogen (N) application, rotation length and grazing severity (Brereton & McGilloway 1999). Although increasing the proportion of grazed grass utilized for milk production improves the economic sustainability of the system (Dillon *et al.* 2008), there are environmental concerns in relation to N loss from systems based on extended length of the GS (Schroder *et al.* 2003).

Intensive grass-based dairy farming generally relies on inputs of fertilizer N to produce sufficient herbage in the form of grazed grass or grass silage to sustain milk output per hectare (ha) at economically viable levels. The intensity of the production system is maintained through altering the levels of N purchased in the form of chemical fertilizer and purchased concentrate.

As N cycles through the farm system unavoidable losses occur such as nitrate (NO_3^-) leaching, denitrification and ammonia (NH_3) volatilization (Whitehead 1995). Improving N utilization has become increasingly important in recent years because of economical and environmental concerns, as well as European Union (EU) policy such as the Water Framework Directive and Nitrates Directive (European Council 1991).

A farm system nutrient balance measures the difference between N inputs and N outputs from an

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agricultural system. This provides estimates of N use efficiency, with the quantity of N utilized in production and the quantity that may be released into the environment being estimated (Scholefield *et al*. 1991; Ledgard *et al*. 1998; Watson & Atkinson 1999; Ryan *et al*. 2011). Increasing N inputs reduces the proportion of N that is utilized within the system, and results in losses that can have negative consequences on the quality of soils, ground water, surface water and the atmosphere (Ryan *et al*. 2006, 2011). Richards (1999) found that 21–24% of N input was removed in animal product, and on light-textured soils large N surplus are vulnerable to leaching, which may result in increased N concentration in drainage waters. Humphreys *et al*. (2003) showed differences in N utilization ranging from 19·6% on intensive dairy production systems with N imports (fertilizer and concentrate) of 365 kg/ha/yr to 48·9% on extensive dairy production systems with N imports of 119 kg/ha/yr. Ryan *et al*. (2011) investigated contrasting dairy production systems and showed that as concentrate N input increased, N surplus/ha increased and N use efficiency/ha decreased (23 and 10%, respectively).

The objectives of the current study were to calculate the N balances, N surpluses, N use efficiency and N losses associated with spring-calving dairy production systems with different lengths of the GSs.

MATERIALS AND METHODS

Dairy production system physical performance

The physical performance data for the dairy systems were obtained from a 3-year study (2007–2009) conducted at Dairygold Research Farm, at the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (50°07′N, 8°16′W; 46 m a.s.l.). The Moorepark soil type is described as a free-draining brown earth soil of sandy loam to loam texture. The grazing experiment was a 3 × 3 factorial design, with three spring turnout dates (1 February, 21 February and 15 March) and three autumn housing dates (25 October, 10 November and 25 November; Table 1), giving nine GS length treatments (described in detail in the scenario investigation and sensitivity analysis section). There were five cows per treatment. Cows were blocked by calving date and parity. Cow breed was a mixture of Holstein Friesian, Montbelliarde, Montbelliarde cross, Normande cross and Norwegian Red cross, with at least one Holstein Friesian per group. There were two first lactation animals per group and three second lactation or older. Each treatment was managed as an individual farmlet, with a land area of 2·025 ha stocked at 2·47 livestock units (LU)/ha. There were separate grazing only and grazing and silage areas within each farmlet.

Grazing, fertilizer and slurry management

Experimental paddocks were predominantly perennial ryegrass (*Lolium perenne* L.) with the majority reseeded in 2005. No legumes were present in the sward. Rules were applied to grassland management decisions based on previous grassland research at Moorepark (e.g. Dillon *et al*. 2005; Kennedy *et al*. 2005, 2009; Horan *et al*. 2006). Cows were assigned to groups after calving and were turned out to grass or remained housed and were fed silage until the appropriate turnout date. Groups turned out on 1 February and 21 February grazed the designated first cut silage area first and then the remainder of the farmlet. If there was insufficient herbage on the grazing only paddocks at the end of the first rotation, these turnout date treatments grazed a portion of the silage area twice. Cows turned out to grass on the 15 March did not graze the area that was designated for first cut silage in the spring. Following turnout, all treatments grazed by day and were housed by night and fed silage for the first 10 days post turnout date each year. During periods of high rainfall, when ground conditions were unsuitable for full-time grazing, restricted access to grazing was practised (Kennedy *et al*. 2009), and in extreme conditions if ground conditions were unsuitable for grazing cows were housed and fed grass silage *ad libitum*. All paddocks were divided into set areas (0·168 ha) and these set areas were grazed rotationally throughout the GS, with *c*. 3 days residency (depending on pre-grazing herbage mass). Rotation length varied depending on the time of year from *c*. 20 days in the mid-GS to 45–60 days in spring and autumn.

There were two main silage harvests. First cut silage was harvested in late May each year. Second cut silage was harvested in mid-July and surplus herbage was either harvested at the time of planned silage or as baled silage in July and August (Table 2). After first cut silage, proportions of 0·10–0·40 (depending on treatment) of the first cut area were closed for second cut silage, and after second cut silage was harvested, each treatment had full access to the whole farmlet for grazing.

Table 1. *Average number of days grazing per year, average milk, fat, protein and lactose production per cow for cows turned out to grass on three dates in spring (1 February, 21 February and 15 March) and housed on three dates in autumn (25 October, 10 November and 25 November)*

Treatment	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9	s.e.m.	*P*-value
Turnout date	1 Feb	1 Feb	1 Feb	21 Feb	21 Feb	21 Feb	15 Mar	15 Mar	15 Mar		
Housing date	25 Oct	11 Nov	25 Nov	25 Nov	25 Oct	10 Nov	25 Oct	10 Nov	25 Nov		
Average number of grazing days	266	282	297	246	262	277	224	240	255	–	–
Average milk production kg cow	5377	5356	5178	5338	4909	5392	5191	4878	5060	218·5	NS
Average kg fat produced per cow	221	227	214	211	201	228	215	204	204	10·0	NS
Average kg protein produced per cow	183	188	185	181	166	186	177	167	173	7·5	NS
Average kg lactose produced per cow	248	244	237	243	226	246	238	224	233	10·0	NS

s.e.m., standard error mean; NS, not significant.

Table 2. *Herd performance data generated by the MDSM for nine spring calving grass-based milk production systems turned out to grass on three dates in spring (1 February, 21 February and 15 March) and housed on three dates in autumn (25 October, 10 November and 25 November)*

Treatment	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9
Turnout date	1 Feb	1 Feb	1 Feb	21 Feb	21 Feb	21 Feb	15 Mar	15 Mar	15 Mar
Housing date	25 Oct	10 Nov	25 Nov	25 Nov	25 Oct	10 Nov	25 Oct	10 Nov	25 Nov
Average number of cows	98	98	98	98	98	98	98	98	98
Milk yield per cow (kg/cow)	5377	5356	5178	5338	4909	5392	5191	4878	5060
Milk fat (%)	4·21	4·38	4·26	4·08	4·19	4·37	4·28	4·32	4·19
Milk protein (%)	3·44	3·56	3·60	3·43	3·41	3·50	3·46	3·47	3·48
Milk solids yield (kg MS/cow)	403	414	398	391	366	414	390	370	375
Stocking rate (LU/ha)	2·44	2·44	2·44	2·44	2·44	2·44	2·44	2·44	2·44
Grazed grass intake (kg DM/cow)	2864	3110	3218	2836	2848	3228	2730	2765	2952
Silage intake (kg DM/cow)	1611	1333	1190	1620	1513	1309	1679	1488	1269
Concentrate intake (kg DM/cow)	415	408	420	400	402	403	396	408	422
Culling%*	17·8	17·8	17·8	17·8	17·8	17·8	17·8	17·8	17·8
Average liveweight (kg/cow)*	535	535	535	535	535	535	535	535	535

* Based on the average of five cows per treatment; no significant difference between treatments, therefore average culling % and bodyweight used.

All paddocks were grazed to a residual sward height of *c.* 40 mm, and any paddocks with an excessive (>60 mm) residual sward height were topped to 40 mm using a rotor flail blade topper (Abbey Farm Machinery Ltd, Ireland). All paddocks were either topped once during July or harvested in the first or second silage cuts, ensuring sward quality was maintained.

Treatment groups were housed in the autumn based on their treatment housing dates (Table 1). All cows were housed together and fed silage. Silage only was fed during the dry period. All cows received similar quantities of concentrate once calved, regardless of treatment. Concentrate was fed in the spring and autumn, and during the year when herbage supply was in deficit of herd demand. The mean quantity of concentrate fed was 408 kg/cow/yr (s.d. = 9 kg/cow) (Table 2). All slurry produced during the housing period was contained in a single tank.

Fertilizer N was applied between 15 January and 15 September, as specified in the Nitrates Action Plan (S.I.

378) as described in the Code of Good Agricultural Practice (Department of Agriculture, Fisheries and Food 2008), using a Rauch Aero 2224 fertilizer spreader (Rauch Agricultural Machinery Ltd, Germany). Similar annual N fertilizer quantities, 240 kg N/ha (s.d. = 0·31 kg), were applied on all treatments, although the timing and quantities at each application varied between treatments and years (Table 3) depending on the turnout date and area closed for silage.

Slurry was applied to areas closed for first cut silage in February for the 15 March turnout treatments and following grazing on the 1 February and 21 February turnout treatments, and in the case of the treatment with the 15 March turnout and 25 October housing the remaining slurry was applied immediately after first cut silage on ground to be harvested for second cut silage. Slurry was applied proportionately to the length of the housing period, therefore the slurry produced within a treatment was reapplied to each treatment and no slurry was exported. Slurry was applied using a downward-facing splash-plate.

Sward measurements

Herbage mass (>40 mm) was determined weekly by harvesting two strips (0·7 m × 10 m) with an Agria auto-scythe mower (Agria-Werke GmbH, Möckmuhl, Germany). Ten grass height measurements were recorded before and after harvesting on each cut strip using an electronic plate meter (Urban & Caudal 1990) with a plastic plate (300 × 300 mm and 4·5 kg/m^2; Agrosystèmes, Choiselle, France). This allowed the calculation of the sward density (herbage mass (kg dry matter (DM)/ha)/(pre-cutting height − post-cutting height) = kg DM/mm/ha). All mown herbage from each strip was collected, weighed and sampled (0·3 kg). A sub-sample of the herbage sample was dried for 15 h at 95 °C to determine DM content. Pre-grazing and post-grazing sward heights were measured immediately before cows entered a paddock and as soon as grazing of the paddock was complete, with the electronic plate meter described above. Forty measurements were taken at random across the grazed strip in a 'W' formation. Daily herbage removed per cow was calculated using the following equation:

$$\text{Daily herbage removed} = \frac{\text{Sward density(kg DM/ha)} \times (\text{pre grazing height(mm)} - \text{post grazingheight (mm)})}{\text{Number of cows} \times \text{number days in paddock}}$$

Prior to silage harvesting, herbage mass (>40 mm) was determined by harvesting one strip (0·70 × 10 m) using an 'Agria' auto-scythe as described above.

Animal measurements

All production data were recorded using the methods described by Horan *et al.* (2005) and Kennedy *et al.* (2007). Milking took place at 07·30 and 15·30 h daily during lactation. Individual milk yields (kg) were recorded at each milking using DairyMaster milk meters (Dairymaster, Causeway, Co. Kerry, Ireland). Milk fat, protein and lactose concentrations were calculated weekly from one successive evening (Monday) and morning (Tuesday) milking for each animal. MilkoScan 203 (DK-3400, Foss Electric, Hillerød, Denmark) was used to determine the concentrations of fat and protein in the milk. Solids corrected milk (SCM) yield was calculated using the equation of Tyrell & Reid (1965). Body weight (BW) was recorded weekly using an electronic portable weighing scale and the Winweigh software package (Tru-test Limited, Auckland, New Zealand).

Data were subjected to analysis of variance using GLM in SAS (SAS 2006) to compare differences between spring turnout and autumn housing date treatments. The physical performance of each dairy production system used for the scenarios assessed is described in Table 1.

Weather measurements

The metrological data used were the 3-year (2007–2009) mean monthly rainfall recorded at the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, *c.* 1 km from the experimental site. Effective rainfall was calculated using the soil moisture deficit (SMD) model described by Schulte *et al.* (2005) and effective drainage of 479 mm was used in the model to calculate the quantity of NO_3^- leached.

Moorepark Dairy Systems Model (MDSM)

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 a farm over a number of output indicators that can be physical, environmental or economic. The model integrates

Table 3. *The annual farm gate N balance per ha for nine spring calving grass-based milk production systems turned out to grass on three dates in spring (1 February, 21 February and 15 March) and housed on three dates in autumn (25 October, 10 November and 25 November)*

Treatment	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9
Turnout date	1 Feb	1 Feb	1 Feb	21 Feb	21 Feb	21 Feb	15 Mar	15 Mar	15 Mar
Housing date	25 Oct	10 Nov	25 Nov	25 Nov	25 Oct	10 Nov	25 Oct	10 Nov	25 Nov
Fertilizer application rate (kg N/ha)	240	240	240	240	240	240	240	240	240
Concentrate N consumed (kg N/ha)	22·7	22·2	22·9	22·0	22·0	21·7	21·7	22·3	23·1
N input in the replacement cows (kg N/ha)	4·3	4·3	4·3	4·3	4·3	4·3	4·3	4·3	4·3
Total kg N input (kg N/ha)	275·5	274·8	275·3	274·8	275·8	275·3	274·6	275·6	276·1
Milk N (kg N/ha)	69·8	71·3	70·0	68·8	63·2	70·8	67·3	63·5	65·9
Calf N (kg N/ha)	2·8	2·8	2·8	2·8	2·8	2·8	2·8	2·8	2·8
Cull cow N (kg N/ha)	6·4	6·5	6·5	6·5	6·5	6·5	6·5	6·5	6·5
Total N output (kg N/ha)	79·1	80·6	79·2	78·1	72·5	80·1	76·6	72·8	75·2
Nitrogen surplus (kg N/ha)	196·5	194·2	196·1	196·8	202·8	195·2	198·1	202·8	201·0
Nitrogen use efficiency	0·287	0·293	0·288	0·284	0·263	0·291	0·279	0·264	0·272
Surplus N kg/kg MS ha	0·200	0·193	0·203	0·206	0·227	0·194	0·208	0·224	0·219

animal inventory and valuation, milk production, feed requirements, land and labour utilization, an economic analysis and greenhouse gas (GHG) emissions. Land area is treated as an opportunity cost, with additional land rented in 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 reseeding), fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity and insurance) and prices (calf, milk and cow) are based on management data for farm planning (Teagasc 2008). The MDSM was used to calculate herd performance for a 40 ha farm based on the physical performance of the treatments in the grazing experiment. The quantity of each feed offered (grazed 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). Grass intake was calculated based on milk and milk solids yield, turnout and housing dates, concentrate fed (as measured in parlour) and average silage intake (based on group feeding). Total energy requirement for milk production, growth, maintenance and gestation, less the energy fed in concentrate and silage gave the total grass energy consumed. This was then converted to kg DM/ha (Shalloo *et al.* 2004).

Nitrogen-balance model description

The flow or cycle of N within a system was analysed using the N balance model described by Ryan *et al.* (2011). The model quantifies the movement of N among the various reservoirs possible in a grass-based system. Within any grass-based production system, N enters the system in the form of imported inorganic and organic fertilizers, concentrate feed and symbiotic and non-symbiotic N capture (Jarvis *et al.* 1995; Ryan *et al.* 2011). 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. NH_4^+ to NO_3^-. Livestock cause chemical and biological transformations to the N cycling through digestion, excretion and exportation (Jarvis *et al.* 1995). Nitrogen within the herbage is also relocated through the grazing process, where N in herbage grazed from a large area will be relocated to small, highly concentrated areas through the deposition of urine and faeces (Haynes & Williams 1993). Ingested N is transformed into N exports such as milk and meat sold, re-cycled N, or N lost to the environment (Whitehead 1995).

The N balance model is described in detail by Ryan *et al.* (2011). Briefly, the annual farm gate N balance is the sum of annual N inputs less N outputs in the form of agricultural products. Imports and exports of N can be expressed on per hectare basis (kg/ha), per cow basis (kg/cow) or per unit of product sold basis (kg milk solids (MS)/ha). Nitrogen use efficiency was calculated as the proportion of imported N recovered in agricultural products.

The N imported into the farm system consists of fertilizer (kg N/ha), feed stuffs (quantity of feed multiplied by crude protein divided by 6·25; McDonald *et al.* 1995) and livestock (in the form of replacements or purchased animals). Nitrogen input into the individual cow consists of N in feed consumed and N content of replacement animals. Other N imports are atmospheric deposition, assumed to be 9 kg N/ha/yr as estimated by Ryan *et al.* (2006), and soil N mineralization was estimated at 114 kg N/ha/yr based on the 3-year average growth (2007–2009) from plots receiving zero N fertilizer at the experimental site using the equation described by Ryan *et al.* (2011).

The N outputs from the farm system can be divided into two 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 and leaching. Nitrogen in milk was calculated as milk protein content 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 from the system (or that died) and multiplying it by the N content. The N content of exported calves born on the farm and dairy cows sold from the farm was estimated at 0·029 and 0·024 kg N/kg live weight, respectively (ARC 1994). Cows entering the farm system as replacements were estimated to have a mean BW 20% less than that of the lactating cows to simulate a younger cow replacing an older cow. Slurry produced during the housed period was calculated as total N input consumed by the housed animals less N output (Watson & Atkinson 1999). The N content of cow excreta was estimated by subtracting N in milk 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 the following equation:

$$\text{N in dairy cow dung} = 0{\cdot}15 \times \text{N animal intake} + 28{\cdot}47$$

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

Losses of NH_3 through volatilization from grazed grassland were estimated using the methods described by Misselbrook *et al.* (2006). Losses of N ammonia during agitation and application of slurry were assumed to be 0·60 of NH_3–N in the slurry (Pain *et al.* 1989, 1990) and a housing emission factor of 34·5 g NH_3–N/LU/day was also included (Hyde *et al.* 2003).

The annual accumulation and addition of soil organic N were estimated as the sum of N from ungrazed herbage and faecal N deposited to the soil during the GS (Hutchings & Kristeensen 1995), plus N transferred to roots, based on an annual root production of 5000 kg/ha (Whitehead 1995), with a root N content of 1·2% (Whitehead 1970).

Denitrification and leaching losses were assumed to be the difference between the 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 & 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, e.g. a free-draining sandy loam soil type is classified with a factor of 0·15, while a poorly drained heavy clay soil is classified with a factor of 0·80, i.e. less denitrification takes place on free-draining soils compared to 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).

Nitrogen was lost through volatilization, losses of ammonia–N during agitation and application of slurry, and during housing. Denitrification and leaching losses were assumed to be the difference between the N inputs to the soil (fertilizer, atmosphere mineralization, urine, faeces and dead plant material) and uptake by the plant component of the sward, NH_3 volatilization from urine and faeces (Scholefield *et al.* 1991) and N accumulation within the soil (Watson & Atkinson 1999). The potential N concentration in groundwater was also estimated. Unaccountable N was the difference between all N inputs and all N outputs (N in product exports and losses).

Scenario investigation and sensitivity analysis

Nine grass-based spring-calving milk production systems with contrasting length of the GS (as dictated by spring turnout date and autumn housing date) were compared (Table 1). The GS treatments were:

GS1 – 1 February turnout and 25 October housing.
GS2 – 1 February turnout and 10 November housing.
GS3 – 1 February turnout and 25 November housing.
GS4 – 21 February turnout and 25 October housing.
GS5 – 21 February turnout and 10 November housing.
GS6 – 21 February turnout and 25 November housing.
GS7 – 15 March turnout and 25 October housing.
GS8 – 15 March turnout and 10 November housing.
GS9 – 15 March turnout and 25 November housing.

The scenario analysis investigated the level of N utilization, N use efficiency and N losses of the nine dairy production systems, excluding the N required to rear replacement animals for the production system (from birth to first calving). Comparisons of farm gate N balance/ha, N utilization, N use efficiency and N losses/ha were made between the nine dairy production systems described above.

The sensitivity analysis investigated the effect of reducing fertilizer N application by 50 kg N/ha, while maintaining the same levels of production through improved grass utilization.

RESULTS

Herd biological performance

All treatments were turned out to grass on their respective turnout dates; however, due to grazing by day only for the first 10 days post turnout, combined with weather and/or soil conditions and a limited availability of herbage either in spring or autumn, no treatment grazed the maximum total number of grazing days allowed per treatment (Table 1). The average number of days spent grazing was 238 across treatments, ranging from 218 to 261 days (Table 1). The average number of days spent grazing for treatments turned out 1 February was 247 (230–262) days. The average number of days spent grazing for treatments turned out to grass on 21 February was 238 (227–253) days, and treatments turned out in March had an average of 231 (217–246 days) days grazing per year.

There was no significant treatment effect on milk production per cow (Table 1). The quantity of milk kg, fat and protein produced increased (Table 1) as the number of days spent grazing increased, though this was not significant. The average milk, fat and protein yields per cow per year were 5187 kg/cow, 214 kg and 178 kg, respectively (Table 1). There was no difference in overall replacement rate (17·8%) between treatments.

Modelled dairy herd performance

The average quantity of grazed herbage consumed per cow simulated by the MDSM was 2950 kg DM (S.D. = 190 kg DM/cow), and the average quantity of silage consumed per cow was 1446 kg DM (S.D. = 175 kg DM) (Table 2). The average milk solids (MS; kg fat plus kg protein) production was 953·8 kg MS/ha (S.D. = 42·4 kg MS/ha), ranging from 892·8 to 1007·6 kg MS/ha (Table 2), and the quantity of MS produced increased as the number of days spent grazing increased. As housing date was delayed from October to late November mean MS production was 963, 934 and 964 kg MS/ha for the 25 October, 10 November and 25 November housing dates, respectively.

Nitrogen input

The main sources of N input to the dairy production systems were feed, fertilizer and replacement animals. The same quantity of fertilizer was applied to all treatments – 240 kg N/ha (S.D. = 0·31), and similarly, the N imported in concentrate was the same across treatments (22·3 kg N/ha; S.D. = 0·49 kg) (Table 3). Soil mineralization was estimated to contribute 114·1 kg N/ha for all treatments based on the 3-year average growth from plots receiving zero N fertilizer. As the number of days spent grazing increased from 218 to 262, the quantity of N consumed in silage per cow declined and the quantity of N consumed in grazed grass increased. The average total N consumed per cow was 128 kg N (S.D. = 3·27 kg N/cow), ranging from 123 to 132 kg N/cow (Table 4).

Nitrogen outputs

Milk production was the main source of N exported, with N exported in milk ranging from 63·2 to 71·3 kg N/ha (Table 3) and GS2 and GS5 having the highest and lowest N exported, respectively. As the number of

Table 4. *The annual N balance per cow for nine spring calving grass-based milk production systems turned out to grass on three dates in spring (1 February, 21 February and 15 March) and housed on three dates in autumn (25 October, 10 November and 25 November)*

Treatment	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9
Turnout date	1 Feb	1 Feb	1 Feb	21 Feb	21 Feb	21 Feb	15 Mar	15 Mar	15 Mar
Housing date	25 Oct	10 Nov	25 Nov	25 Nov	25 Oct	10 Nov	25 Oct	10 Nov	25 Nov
Grazed pasture N intake (kg N/cow)	83·7	90·2	92·0	82·8	81·9	92·4	79·3	79·1	84·0
Silage kg N intake (kg N/cow)	36·1	29·8	26·7	36·3	33·9	29·2	37·6	33·3	28·4
Concentrate N intake (kg N/cow)	9·3	9·1	9·4	9·0	9·0	9·0	8·9	9·1	9·5
Dairy cow replacement N (kg N/cow)	1·7	1·8	1·8	1·8	1·7	1·8	1·8	1·8	1·8
Total N intake (kg N/cow)	130·8	130·9	129·9	129·8	126·5	132·5	127·5	123·4	123·6
Milk N output (kg N/cow)	28·6	29·3	28·7	28·2	25·9	29·1	27·6	26·0	27·0
Calf kg N output (kg N/cow)	1·2	1·2	1·2	1·2	1·2	1·2	1·2	1·2	1·2
Cull cow N output (kg N/cow)	2·6	2·7	2·6	2·6	2·6	2·7	2·7	2·6	2·7
Total N output (kg N/cow)	32·4	33·1	32·5	32·0	29·7	32·9	31·4	29·8	30·8
N surplus (kg N/cow)	98·4	97·8	97·3	97·7	96·8	99·5	96·1	93·5	92·8
N use efficiency	0·248	0·253	0·251	0·247	0·235	0·248	0·246	0·242	0·249

Table 5. *The nitrogen (N) surplus and estimated annual losses per ha for nine spring calving grass-based milk production systems turned out to grass on three dates in spring (1 February, 21 February and 15 March) and housed on three dates in autumn (25 October, 10 November and 25 November)*

Treatment	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9
Turnout date	1 Feb	1 Feb	1 Feb	21 Feb	21 Feb	21 Feb	15 Mar	15 Mar	15 Mar
Housing date	25 Oct	10 Nov	25 Nov	25 Nov	25 Oct	10 Nov	25 Oct	10 Nov	25 Nov
N in faeces excreta (kg N/ha)	32·5	32·5	32·4	32·4	32·3	32·5	32·4	32·2	32·3
N in urine excreta (kg N/ha)	161·6	156·9	155·7	157·0	158·1	161·1	153·3	147·6	145·8
Ammonia emissions (kg N/ha)	37·5	37·2	37·3	37·3	37·3	37·3	37·2	37·3	37·4
N accumulation in the soil (kg N/ha)	88·6	88·6	88·5	88·5	88·5	88·7	81·0	81·0	81·0
N lost through denitrification (kg N/ha)	33·4	29·8	29·6	33·4	33·0	30·4	34·1	32·3	30·7
N available for leaching (kg N/ha)	189·6	168·7	167·7	189·3	187·3	172·3	193·0	182·9	174·1
N content in ground water (mg NO_3/litre)	9·49	8·45	8·39	9·47	9·38	8·36	9·66	9·16	8·72
Unaccountable N (kg N/ha)	35·0	13·4	10·3	34·1	26·2	16·7	29·5	13·6	5·5

days spent grazing increased, so did the quantity of N exported, ranging from 72 to 81 kg N/ha, mainly due to the variation in milk N output (Table 3). The average quantity of slurry N produced and reapplied within each treatment ranged from 44·5 to 65·3 kg N/cow (s.d. = 8·03 kg N/cow), increasing as days at grass decreased. Nitrogen immobilization/accumulation within the soil ranged from 80·96 to 88·6 kg N/ha (s.d. = 3·80 kg), increasing as the number of grazing days increased (Table 5).

Nitrogen use efficiency

The mean farm gate N surplus/ha (N inputs less N outputs) for the different turnout dates was 195, 198 and 200 kg N/ha for 1 February, 21 February and 15 March turnout dates, respectively (Table 3). The mean farm gate N surplus for the different housing date treatments was 197, 199 and 197 kg N/ha for the treatments housed on 25 October, 10 November and 25 November, respectively (Table 3).

At the farm gate, N use efficiency ranged from 0·263 to 0·293 (Table 3). The mean N use efficiency for the different turnout dates was 0·289, 0·279 and 0·272 for 1 February, 21 February and 15 March turnout dates, respectively, and 0·283, 0·274, and 0·284 for 25 October, 10 November and 25 November closing dates, respectively. N use efficiency increased with increases in the number of days spent grazing, but the trend was not significant. The average N use efficiency was 0·276 for the three shortest GS treatments (average 225 days) and the average N use efficiency for the three longest GS treatments was 0·291 (average 255 days). On a per cow basis all treatments utilized N at similar efficiencies, at a mean of 0·246 per cow (S.D. = 0·005) (Table 4). When surplus N (kg N/ha) is compared with MS produced, the mean quantity of surplus N per kg of MS produced was 0·21 kg surplus N/kg MS, ranging from 0·19 to 0·23 (Table 3). When the three longest GS are compared to the three shortest GS, the efficiency at which surplus N is utilized to produce MS increased by a mean of 8% as the number of grazing days increased (Table 3).

Nitrogen losses

As the number of days spent grazing increased from 218 to 262, the quantity of surplus N available for loss reduced (Table 3). The length of the GS had little effect on NH_3 emissions; average NH_3 emissions predicated by the N balance model were 37·5 kg N/ha (S.D. = 0·18 kg N/ha) (Table 5). Mean N losses from denitrification were 31·8 kg N/ha (S.D. = 1·74 kg N/ha), ranging from 29·5 to 34·0 kg N/ha for GS3 and GS7, respectively (Table 5), with denitrification reducing as GS increased (Table 5). The mean quantity of N available for leaching predicted by the N balance model was 180·5 kg N/ha, ranging from 167·6 to 192·9 kg N/ha for GS3 and GS7, respectively (Fig. 1 and Table 5). As the number of grazing days increased the quantity of N available for leaching reduced, though not significantly (Fig. 1). When the N available for leaching was used to estimate the potential loss of NO_3–N to groundwater using the N balance model, the N concentrations in groundwater ranged from 8·39 to 9·66 mg N/l for GS3 and GS7, respectively (Table 5). When all the N outputs and losses associated with the production systems were calculated, the remaining N that could not be accounted for ranged from 5·4 to 34·9 kg N/ha for GS9 and GS1, respectively, which tended to reduce as the number of days spent grazing increased (Table 5).

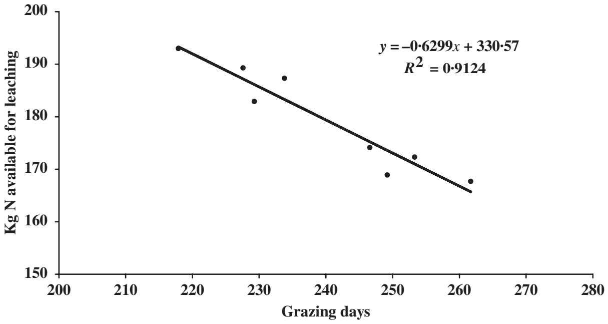

Fig. 1. The relationship between kg N available for leaching and the total number of days spent grazing.

Sensitivity analysis

Reducing N fertilizer input by 50 kg N/ha while maintaining production increased N use efficiency by a mean of 22% and reduced N surplus by a mean of 25%. Ammonia emissions were reduced by 14% on average; N available for leaching was reduced by a mean of 17%; denitrification losses were reduced by a mean of 5·5 kg N/ha; and ground water N concentrations were reduced by a mean of 1·56 mg NO_3/l (17%). Reducing fertilizer N input reduced the quantity of N loss from the different pathways.

DISCUSSION

In Ireland, commercial dairy farming operates under the influence of society's increasingly multifunctional expectations. Farming must be sustainable within a range of economic, social and environmental expectations. The EU Nitrates Directive, implemented in Ireland in 2006 (S.I. 06/378; Department of Agriculture, Fisheries and Food 2008), aims to reduce the risk of N loss to groundwater and surface water from agricultural sources. This requires each farmer to manage their dairy business according to a specific set of rules that largely centre on predefined stocking rates, slurry storage requirements, inorganic N fertilizer allowances and closed periods for the application of both organic and inorganic fertilizers.

Dairy system and surplus N

The dairy systems investigated had N surpluses (198 kg N/ha) similar to Humphreys & O'Connell (2006) and Ledgard *et al.* (1997) who calculated a mean N surplus of *c.* 200 kg N/ha from a range of grass-based dairy production systems. In the current study, surplus N reduced, though not significantly, as GS length increased. Similarly, when surplus N and MS production are compared, 8% more MS were produced/kg of surplus N as the length of the GS increased. Although no significant effects of GS length were observed in the current study, many other authors have reported positive effects on milk production as GS increased (Dillon *et al*. 1995; Kennedy *et al*. 2005). The important results to consider from the current study are the comparisons between the different production systems simulated, rather than the absolute values generated for any particular system.

GS length and N losses

Nitrogen use efficiency was 5% greater on the three longest GS treatments compared to the three shortest GS. This increase in N use efficiency reduced total N loss by 8%. Nitrogen loss through NH_4 volatilization was static between treatments, N loss through denitrification reduced by a maximum of 4 kg N/ha and N available for leaching was reduced by a mean of 10%. The three longest GS length treatments had an average of 30 days more grazing compared to the three shortest GS length treatments and had an annual average reduction in N available for leaching of 18 kg N/ha. The increase in the length of the GS allowed N within the system to be utilized by the growing herbage and therefore by the grazing animal, increasing N output and reducing N loses from the system (Cuttle & Scholefield 1995), and resulted in increased N use efficiency. The increased N use efficiency reported in the current paper is somewhat different to results reported in some previous studies. Decau *et al*. (2003) noted that the quantity of N lost from grazed swards can be greater than from cut swards. Similarly, Duru *et al*. (2007) noted that increasing the length of the GS in spring or autumn may cause increased N leaching as plant N uptake may be low and N concentration in excreta high. Webb *et al*. (2005) reported that extending the GS by *c*. 1 month increased NO_3 leaching by 15–30 kg N/ha; however, the increase in NO_3 leaching was attributed to the application of fertilizer N in late September and October, rather than the faeces and urine deposition by animals. No fertilizer N was applied to the treatments reported in the current paper after mid-September, as per the Nitrates Directive.

Effects of extending the GS on N movement

The N movement within the production system varied depending on the length of the GS. All treatments had the same annual total N input, but had different N input patterns based on the systems' requirements throughout the year. The shorter GS treatments had greater N input in the first half of the year compared to the longer GS treatments, due to greater silage production and less area available for grazing combined with a shorter GS. This may have resulted in more surplus N available for loss in the spring and summer (Soder & Rotz 2001). Mayers *et al*. (1994) noted that when N supply and demand are out of synchrony, losses to the environment occur. Hoogendoorn *et al*. (2011) noted that high rainfall events in the summer can be a significant contributor to annual mineral N leaching. This creates conflict between the agronomic requirements and environmental considerations.

Humphreys & O'Connell (2001) reported a reduced risk of N loss as the year progresses into the summer, as drainage will have more or less ceased, and therefore the potential for N loss is low. However, increased quantities of N applied at this time combined with N excretion by grazing animals increases the quantity of N available for loss (Cuttle & Scholefield 1995). Similarly, avoiding fertilizer N applications at the end of the season when the growth response to N is decreasing reduces the probability of N loss (Laidlaw & Mayne 2000) and lengthening the GS by deferring grazing increases the efficiency of N uptake (Duru *et al*. 2007).

Grazing swards in early spring and late autumn stimulates increased growth rates of new plant tissue (Hennessy *et al*. 2006; Ryan *et al*. 2010), which in turn increases N utilization from the soil for the purpose of growth. It also reduces sward senescence and decay (Hennessy *et al*. 2008; Ryan *et al*. 2010), which could lead to increased leaching during the winter months (Laidlaw & Mayne 2000) as N is lost from the soil and plant material. Herbage utilized between mid-October and late November, and early February and mid-March can account for N uptake of 50 kg N/ha in the herbage DM (Brereton 1995). Hence, herbage growth during the winter for early spring grazing can retain a considerable quantity of N and avoid losses during this high risk time of the year. When the three longest GS treatments are compared to the three shortest GS treatments, there was *c*. 14% more N utilized in the form of grazed grass. Combining extended grazing with restricted access time to paddocks (Kennedy *et al*. 2009) during unfavourable conditions reduces the animal residency time on the paddock in early spring and late autumn, and reduces N excretion as faeces and urine patches in the paddock at a time when grass growth is low.

Deposition of faeces and urine over a long GS can result in soil N accumulation. Grassland has been shown to fix N and 'lock up' soil N, thereby reducing the amount of N available for loss (Watson *et al.* 2007). However, other authors have correlated N leaching losses to high soil N content (Wachendorf *et al.* 2004).

Reducing N input

The main components of the grassland N cycle are the soil, the plant and the animal. The productivity and sustainability of a system is determined by the overall efficiency with which N is transferred around the cycle. Previous authors have noted that matching N supply to the requirements of the production system and maintaining economically sustainable levels of production can create conflicting targets (Crosson *et al.* 2007). In the sensitivity analysis undertaken in the current study, reducing N fertilizer input by 50 kg while maintaining system performance reduced the N surplus by 25% and total N losses by 16%. Although it could be considered that reducing N input will reduce herbage production and therefore animal performance, other authors (Humphreys & O'Connell 2006; Humphreys *et al.* 2007) have reported similar production/ha (935 ha MS/ha) with similar dairy cow genetic potential, fertilizer N input (190 kg N/ha) and concentrate input.

The N balances of the different production systems investigated in the current study show that N input is in excess of the systems requirements and there is surplus N unaccounted for within all systems, which is similar to Humphreys *et al.* (2007) and Ryan *et al.* (2011). The level of N unaccounted for ranged from 5 to 35 kg N/ha, declining as GS length increased, though this decline was not significant. This could be due to the over/under prediction of N inputs, N outputs and N pathways (Cuttle & Jarvis 2005). In any system, the level of background N will vary between locations (Hassink 1995) and will be related to the soil organic matter content (O'Connell *et al.* 2003), which is difficult to predict (Shepherd *et al.* 1999). Gill *et al.* (1995) showed that soil N mineralization depends more on previous management and build-up of readily mineralizable materials than on current fertilizer input. In the current study, the soil N mineralization was estimated at 114 kg N/ha/yr. Previous authors found soil N mineralization to supply between 90 and 200 kg N/ha/yr (Ryan 1974; O'Connell *et al.* 2003). Although N output and losses have been calculated based on the available values in the literature, there is still potential for underestimation of the different N pathways. Ball & Ryden (1984) estimated that between 4 and 41% of N in urine and 3% of N in faeces (Ryden *et al.* 1987) is volatilized. Hoogendoorn *et al.* (2011) measured similar N leaching values on highly porous soil with a higher annual rainfall where no fertilizer N was applied.

Implications

Overall increases in N use efficiency and decreases in N surpluses and hence N losses achieved through increasing the length of the GS are quite small on a 40 ha farm, as described in the current paper. However, scaling this to a national level would have a big effect on N losses to the environment. GS is just one component of grass-based production systems; if N use efficiency is increased by small amounts in all the components of grass-based systems the combined effect can have a significant impact in reducing N losses to the environment.

In conclusion, increasing the length of the GS increased the efficiency at which N was utilized to produce MS and increased the recycling of N within the farm system, which resulted in a reduced quantity of N available for loss. The environmental and production consequences of increased length of the GS and reduced N loss are favourable as the costs associated with N inputs increase.

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