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The effect of stocking rate on soil solution nitrate concentrations beneath a free-draining dairy production system in Ireland

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ABSTRACT

Economically viable and productive farming systems are required to meet the growing worldwide need for agricultural produce while at the same time reducing environmental impact. Within grazing systems of animal production, increasing concern exists as to the effect of intensive farming on potential N losses to ground and surface waters, which demands an appraisal of N flows within complete grass-based dairy farming systems. A 3-yr (2011 to 2013) whole-farm system study was conducted on a free-draining soil type that is highly susceptible to N loss under temperate maritime conditions. Soil solution concentrations of N from 3 spring-calving, grass-based systems designed to represent 3 alternative whole-farm stocking rate (SR) treatments in a post-milk quota situation in the European Union were compared: low (2.51 cows/ha), medium (2.92 cows/ha), and high SR (3.28 cows/ha). Each SR had its own farmlet containing 18 paddocks and 23 cows. Nitrogen loss from each treatment was measured using ceramic cups installed to a depth of 1 m to sample the soil water. The annual and monthly average nitrate, nitrite, ammonia, and total N concentrations in soil solution collected were analyzed for each year using a repeated measures analysis. Subsequently, and based on the biological data collated from each farm system treatment within each year, the efficiency of N use was evaluated using an N balance model. Based on similar N inputs, increasing SR resulted in increased grazing efficiency and milk production per hectare. Stocking rate had no significant effect on soil solution concentrations of nitrate, nitrite, ammonia, or total N (26.0, 0.2, 2.4, and 32.3 mg/L, respectively). An N balance model evaluation of each treatment incorporating input and output data indicated that the increased grass utilization and milk production per hectare at higher SR resulted in a

reduction in N surplus and increased N use efficiency. The results highlight the possibility for the sustainable intensification of grass-based dairy systems and suggest that, at the same level of N inputs, increasing SR has little effect on N loss in pastoral systems with limited imported feed. These results suggest that greater emphasis should be attributed to increased grass production and utilization under grazing to further improve the environmental impact of grazing systems.

Key words: stocking rate, grass utilization, nitrate leaching, milk production

INTRODUCTION

During the next half century, global agricultural production faces 2 fundamental challenges: to produce enough food for the growing numbers of, on average, increasingly affluent and longer living people, and simultaneously preserve natural resources and the environment. Current figures estimate that 26% of global land area is covered by grasslands, which provide an important feed source for livestock and contributes positively to environmental protection (FAO, 2014). Consequently, it is essential that improvements in productivity are achieved within grassland agriculture but, without adverse effects on the natural environment. The process of producing more food, while reducing the environmental impact of dairy production systems, has become a global challenge and requires what has been referred to as sustainable intensification (Pretty, 1997; Royal Society, 2009) of global agricultural production. Despite the positive effect of N fertilizer use on agricultural production (Whitehead, 1995), the efficiency with which N is used is variable (Watson and Atkinson, 1999). As N moves within grassland systems, unavoidable losses occur through 3 major loss pathways: NO_3^- leaching, N_2O emissions, and NH_3 volatilization (Whitehead, 1995). In recent years, agricultural production systems within the European Union (EU) have increasingly been subjected to stringent environmental restrictions to reduce losses of bioavailable forms of N to water and air (Stark

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and Richards, 2008; Richards et al., 2009). Grazing is accompanied by localized deposition of N in urine and dung patches, which can contribute to environmental N pollution either as NH_3 and N oxides in air or as NO_3^- in soil and ground water (Tamminga, 1992). Nitrate leaching losses are problematic within grazing systems (Haynes and Williams, 1993; Ledgard et al., 1999), as elevated N applications via urine deposition by grazing animals is poorly attenuated within the soil (Haynes and Williams, 1993; Decau et al., 1997).

Within the EU, the abolition of milk quotas in April 2015 is anticipated to result in a redistribution of regional milk production (Lips and Reider, 2005). By virtue of lower production costs, milk production from grass-based systems in Ireland and northwest Europe are anticipated to expand based on the production and utilization of increased quantities of high-quality grass (Lips and Reider, 2005; O'Donnell et al., 2008; DAFM, 2011). Stocking rate (SR; cows/ha), defined as the number of animals per unit area of land used during a specified period of time, is well accepted as the main driver of productivity within grazing systems (Hoden et al., 1991; Macdonald et al., 2008; McCarthy et al., 2011), and recent studies have highlighted the beneficial effects of a high SR on animal productivity, grazed grass utilization, and overall farm system efficiency (Kelly et al., 2012; McCarthy et al., 2013a). Notwithstanding these beneficial effects, previous studies have also indicated that where increased SR are associated with increased chemical fertilizer N application and off-farm supplementary feed importation, N surpluses increase and N utilization is reduced, resulting in increased N loss to ground water and the general environment (Di and Cameron, 2002a; Treacy et al., 2008; Ryan et al., 2011).

Previous studies have identified the necessity to reduce N output through animal excretions by improving N utilization by the animal (Jonker et al., 1998). However, the opportunity to mitigate N losses are considerably reduced within grazing systems where a large proportion of the total diet consists of grazed grass (Dillon et al., 2005) and N utilization of grazing animals is often lower than 25% (Tas et al., 2006; Jarvis et al., 2011). From an overall farm systems perspective, previous studies have highlighted excessive N inputs in fertilizer and feed supplements, heterogeneous N deposition on the available area, and the cultivation of high-N soils as key reasons for inefficient N use (Gourley et al., 2012). Consequently, increasing international emphasis has focused on various N fertilizer application, animal, dietary, sward, and soil manipulation strategies to reduce NO_3^- N loss (Di and Cameron, 2002b; Moir et al., 2012; O'Connor et al., 2013). In practice, how-

ever, it is not possible to implement a combination of individual management effects, as these are interrelated within an overall system and there remains a paucity of quantitative data on N losses from intensive farming systems incorporating best practice N and grazing management practices. In response to this information gap, a 3-yr field experiment was uniquely designed to investigate the effect of overall farm SR on N use efficiency within intensive grass-based production systems. Consequently, the objective of the current study was to evaluate the effect of alternate whole-farm grass-based SR on N loss beneath a free-draining soil type within farming systems based on highly productive grassland swards combined with best practice grazing and N management over 3 consecutive years. The hypothesis of our study was that increases in overall farm system SR would have no deleterious effect on N losses in soil solution to 1 m of soil depth where the increased SR was derived from increased grazed grass utilization, based on fixed N inputs, and best practice agronomic and N management practices.

MATERIALS AND METHODS

Site Characteristics

The experiment was conducted over a 3-yr period (2011 to 2013) on a permanent grassland site at Curtins Research Farm, Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland (52°9'N, 8°16'W). The area has a mild moist oceanic climate without extremes in temperature. The soil on site (to a depth of 2.5 m) is a freely drained acid brown earth, derived from mixed sandstone-limestone glacial till overlying a karstified limestone bedrock aquifer with bedrock commonly occurring at an average of 2.5 m below the ground surface (Bartley and Johnston, 2006; Gibbons et al., 2006). This site is representative of soils vulnerable to NO_3^- leaching, and represents between 4 and 10% of the riskier soils in Ireland (Ryan et al., 2006). The on-site swards were predominantly perennial ryegrass (*Lolium perenne* L.) and had been reseeded over the previous 1 to 9 yr.

Experimental Design, Treatments, and Herd Management

The current experiment formed part of a larger study designed to examine the biological and economic effect of SR in the context of the removal of EU milk quotas; a more detailed description of the animals, treatment, and experimental design has previously been reported (McCarthy et al., 2013b). In spring 2011, 138 high Eco-

nomic Breeding Index, spring-calving Holstein Friesian dairy cows were randomly assigned, precalving, based on parity, expected calving date, and Economic Breeding Index to 1 of 3 whole-farm SR treatments: low (2.51 cows/ha; **LSR**), medium (2.92 cows/ha; **MSR**) and high (3.28 cows/ha; **HSR**). Treatments were designed to represent alternative whole-farm SR which may be appropriate in a post-milk quota EU, spring-calving, grass-based milk production system. The experimental herd on the study comprised genetically elite animals (McCarthy et al., 2013b) and were managed with a compact spring-calving pattern that was closely aligned with the average grass growth capacity of the site (50% of all animals calving in the first 2 wk of February, 90% calved by mid-March; mean calving date of February 20). As a grass-based production system, grazing commenced as cows calved in early February and the grazing season concluded in late November of each year. During December and January, all cows were dried off and housed on a diet of conserved grass silage.

Grazing, Feeding, and Nutrient Management

A total of 48.1 ha of permanent grassland, containing greater than 80% perennial ryegrass, were used for the duration of the experiment. Eighteen blocks were created, balanced on location, sward age, and soil type. Within each block, paddocks were randomly assigned to SR treatment to create a farmlet for each treatment, and paddocks remained in the same treatment farmlet for the duration of the experiment. Total farmlet areas for the LSR, MSR, and HSR were 9.17, 7.87, and 7.01 ha, respectively. Grazing management was accomplished by weekly monitoring of farm grass cover within each SR treatment (O'Donovan, 2000). To apply the SR effect consistently between paddocks, the residency time within each paddock, ranging from 1.5 to 2.5 d per paddock, was determined by achieving the target postgrazing residual sward height (LSR = 4.5 to 5.0 cm, MSR = 4.0 to 4.5 cm, and HSR 3.5 to 4.0 cm). Each group was moved independently of one another to the next paddock once the target postgrazing residual sward height was reached. Rotation lengths during the main grazing season (April to August) were also allowed to vary between SR treatments. When pregrazing herbage mass in the next grazing paddock exceeded the target level, the paddock was skipped and herbage was harvested as silage. All silage was conserved in bales (259 ± 44.7 kg of DM). A sample of herbage was taken before baling for DM determination and bales from each paddock were weighed to give an estimate of the amount of feed conserved from each paddock (Macdonald et al., 2008). No mechanical topping of the swards took place during the experiment.

Best practice nutrient and agronomic management was applied to the management of each farmlet within the study and has been reported previously by Huebsch et al. (2013). Chemical N fertilizer (a combination of urea and calcium ammonium nitrate, depending on the time of year) application rates were common across SR treatments at 250 kg of N/ha per year and were applied according to recommended rates and timings (Teagasc, 2009). During the winter months between late November and early February, all animals were housed and all animal slurry was collected and stored. During periods of excessive rainfall during the grazing season, animals were occasionally housed and on-off grazing (Kennedy et al., 2009) was used as a management tool to facilitate grazing and to avoid soil structural damage.

All animal slurry generated by the animals during winter was reapplied to each farmlet over the first 4 mo of the following grazing season and at a rate consistent with the overall SR of each farmlet. As the experiment was designed to maintain similar N inputs to each SR treatment, target concentrate supplementation was similar for each SR at 850 kg of DM/ha per year and, consequently, lower per cow as SR increased. The ingredient composition of the concentrate feed was 25% barley, 26% corn gluten, 35% beet pulp, 11% soybean meal, and 3% minerals plus vitamins. Mean concentrate quality was 14.0% CP, 27.0% NDF, 8.1% crude fiber, and 9.6% ash. Mean silage quality was 15.1% CP, 55.3% NDF, 37.8% ADF, and 9.4% ash.

Concentrate supplementation for all treatments commenced at 4 kg/cow per day postcalving, and it was reduced and removed totally from the diet only when herbage supply exceeded animal demand for all treatments (usually in mid-March). Concentrate and additional forage supplementation (in the form of baled silage) were used occasionally during the 3-yr study when grass supply was in deficit of feed demand. Concentrate supplement was only used when a feed deficit occurred, due to reductions in grass growth, for each SR treatment and at a similar rate per hectare in all treatments on those occasions. When feed deficits arose for individual SR treatments, conserved forage produced within each treatment was used to supplement feed supply.

Milk Production Measurements

Cows were milked twice daily throughout lactation across the 3 yr of the study. Milking took place at 0700 and 1530 h daily. Weekly milk production was derived from individual cow milk yield (kg) recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland). Milk fat, protein, and lactose concentrations were determined in successive evening and morning samples

of milk each week using Milkoscan 203 (Foss Electric, Hillerød, Denmark) and weekly fat, protein, and lactose yields were calculated.

Herbage Measurements

Grazing data were collected on each paddock during each grazing rotation according to the procedures outlined by McCarthy et al. (2013a). Pregrazing herbage mass (>3.5 cm) was determined before grazing on each paddock for each of the 3 systems by harvesting 2 strips (1.2 × 10 m) of grass with an Etesia mower (Etesia UK Ltd., Warwick, UK). All mown herbage from each strip was collected and weighed and a 0.1-kg (fresh weight) subsample was taken and dried for 16 h at 90°C for DM determination. Ten compressed sward-height (CSH) measurements were recorded before and after harvesting on each cut strip using a rising pasture plate meter with a steel plate (Jenquip, Feilding, New Zealand). Based on the above measurements, sward density was calculated as (Delaby and Peyraud, 1998):

$$\text{Sward density (kg of DM/cm per hectare)} = \frac{\text{herbage mass (kg of DM/ha)}}{(\text{precutting CSH} - \text{postcutting CSH})}$$

Pre- and postgrazing sward height was determined on each paddock before and after grazing by taking between 30 and 50 measurements across the diagonal of the paddock. The average paddock pregrazing herbage mass above a cutting height of 3.5 cm (kg of DM/ha) was then calculated according to the following formula

$$\text{Pregrazing herbage mass (kg of DM/ha)} = [\text{pregrazing CSH (cm)} - 3.5 \text{ cm}] \times \text{sward density (kg of DM/cm per hectare)}$$

Herbage used at each grazing was calculated using the following formula (Delaby and Peyraud, 1998):

$$\text{Herbage used (kg of DM/ha)} = (\text{pregrazing CSH} - \text{postgrazing CSH}) \times \text{sward density (kg of DM/cm per hectare)}$$

The efficiency of grazing was determined using the method proposed by Delaby and Peyraud (1998; herbage used/pregrazing herbage mass (>3.5 cm, at each grazing). Herbage accumulation between grazings was calculated as the difference between pregrazing herbage mass (>3.5 cm) and the postgrazing herbage mass of

the previous rotation. Herbage used (above the post-grazing CSH) was calculated within the same rotation as defined previously. Total herbage accumulation and herbage use was calculated as the sum of the herbage accumulated and used at each grazing for each treatment. Daily grass regrowth was calculated by dividing the herbage accumulated between grazings by the intergrazing interval.

Chemical Analyses

Herbage samples were collected from each paddock before grazing for each treatment and were dried at 40°C for 48 h and milled through a 1-mm sieve. Samples were bulked by SR treatment by week and were subsequently analyzed for CP content (Leco FP-428; Leco Australia Pty Ltd., Baulkham Hills, New South Wales, Australia). Subsequently, herbage N content was calculated as CP × 0.16.

Meteorological Data

Daily measurements of average, minimum, and maximum air temperatures, total solar radiation, and daily rainfall were recorded automatically by a meteorological station approximately 3 km from the experimental site at the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork. Weekly effective drainage (ED) was calculated using a water balance approach. The ED was calculated by subtracting the effects of evapotranspiration (ET), determined by the FAO Penman-Monteith method (Allen et al., 1998), and soil moisture deficits (SMD), using the Aslyng scale (Aslyng, 1965), from recorded rainfall amounts. The Aslyng scale adjusts ED to account for SMD >30 mm. Daily meteorological input parameters (rainfall, air temperature, and sunshine hours) were entered into the hybrid model for Irish grasslands developed by Schulte et al. (2005) to elucidate daily SMD, actual ET, and ED.

Ceramic Cup Installation and Nitrate Measurement

Ceramic suction cups (Van Walt Ltd., Haslemere, Surrey, UK) and sampling methods followed the same procedures as reported in detail in previous experiments (Ryan et al., 2006; Hooker et al., 2008; Premrov et al., 2012). Briefly, the porous suction cups with tubing attached were inserted into the soil, each having a bentonite seal at 1 m of depth. A total of 144 ceramic cups, 48 per treatment, were installed during autumn 2010 across 3 blocks in each farmlet (equivalent to 18% of the total farmlet area). The ceramic cups were installed

with 16 cups per paddock in a grid type arrangement. Soil solution was sampled by applying suction (50 kPa) to the cups using a hand-held pump 1 d before sample collection. Each of the 16 individual cups were sampled and then bulked into a single container for each paddock within each farmlet. Sampling took place every second week during the drainage period (from September to April) and once per month during the summer (May to August). On collection, the samples were stored in a cold box at 4°C and transported to the laboratory. The samples were stored in a freezer (<−14°C) until analysis was undertaken. The samples were calorimetrically analyzed for total oxidizable N, NO₂[−]N, NH₄⁺N, and total N (TN) using the Aquakem 600 Discrete analyzer (Aquakem 600A, 01621 Vantaa, Finland). Nitrate-N was determined by subtracting NO₂[−]N from total oxidizable N, which showed that 99.3% of total oxidizable N was NO₃[−]N. Ammonium-N concentrations were below the method detection limit (Premrov et al., 2012). Finally, total annual N losses (kg of N/ha per year) were calculated as the product of effective rainfall and N concentration in the respective samples during each month.

Statistical Analysis

For all analyses undertaken, the individual paddock was considered to be the experimental unit. The effect of SR, block, year, and the interaction of SR and year on herbage utilization and chemical composition was determined using mixed models in SAS (Proc Mixed; SAS Institute, 2006); rotation was the repeated measure, and block and the interaction between SR and block were included as a random effect in the model. A compound symmetry covariance structure among records within paddock provided the best fit to the data. Tukey's test was used to determine differences between treatment means. Concentrate and silage supplementation per hectare and N fertilizer use per hectare were analyzed by variance analysis in SAS with the effect of year, block, SR, and their interactions included in the model.

Modeling N Surplus and N Use Efficiency

Due to the complexity and number of interactions within grazing systems, the efficiency of N use was modeled to further understand the processes underpinning each farm system treatment within each year of the current study 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. The annual farm gate N surplus is the sum of annual N inputs less N outputs in the form

of agricultural products. The N outputs from the farm system describe the N leaving the system in products (milk, meat, exported feedstuffs, and exported manure). Nitrogen in milk and N exported in livestock leaving the farm was calculated based on methods described by 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 (N in milk and BW; Watson and Atkinson, 1999). As is typical of farming practices in Ireland, the replacement heifers were 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).

RESULTS

Climatic Data

Average daily rainfall was greatest ($P < 0.05$) in November and December (3.7 ± 0.17 and 3.9 ± 0.16 mm/d, respectively; means \pm SEM) and least in March (1.4 ± 0.17 mm/d). Average total annual rainfall for the duration of the study was 996 (± 52.2) mm. Due to the free-draining soil and location of the site on a karst limestone plateau, runoff was deemed to be negligible. Table 1 shows the mean monthly rainfall and ED for both the experimental period (2011 to 2013) and the 30-yr average (1980 to 2010). Monthly average rainfall and ED from the 2011 to 2013 period was 81.0 (± 7.53) and 35.4 (± 5.38) mm, respectively, and were similar to the 30-yr averages (85.0 ± 8.14 and 45.4 ± 6.75 mm, respectively). Over the 3 yr of the study, the greatest ($P < 0.01$) maximum daily temperatures were recorded in July ($19.6 \pm 0.01^\circ\text{C}$), whereas the lowest ($P < 0.001$) average minimum daily temperature occurred in March ($2.2 \pm 0.12^\circ\text{C}$). Solar radiation was greatest ($P < 0.05$) during summer ($1,513 \pm 8.7$ J/cm² per day) and least in winter (163 ± 11.0 J/cm² per day). Mean ED (calculated as daily rainfall less ET) was greatest ($P < 0.01$) in November (2.8 ± 0.12 mm/d) and least ($P < 0.01$) in September (0.1 ± 0.04 mm/d).

Grazing System Characteristics, Milk Production, Herbage Utilization, and Herbage N Content

Concentrate and fertilizer N inputs were similar for each SR treatment (1,068 kg of concentrate DM/ha per year and 209 kg of N/ha per year, respectively). The total lactation milk production performance of animals in each SR has been reported previously (McCarthy et al., 2013b); thus, only the main effects of SR in each

Table 1. Monthly total rainfall [mm (SD)] and drainage [mm (SD)] at the experimental site during the experimental period (2011 to 2013) compared with the 30-yr (1981 to 2010) average

Month	Rainfall (mm)		Drainage (mm)	
	30-yr average	2011–2013	30-yr average	2011–2013
January	109 (47)	109 (33)	88 (46)	89 (29)
February	80 (48)	61 (31)	58 (45)	38 (17)
March	85 (34)	79 (35)	51 (30)	39 (26)
April	66 (30)	61 (26)	26 (23)	18 (14)
May	69 (39)	78 (11)	17 (25)	19 (9)
June	70 (34)	75 (97)	14 (19)	10 (67)
July	64 (39)	86 (18)	9 (17)	19 (14)
August	84 (56)	69 (80)	26 (41)	23 (59)
September	77 (48)	74 (40)	25 (29)	13 (5)
October	112 (48)	108 (35)	70 (45)	62 (17)
November	104 (56)	115 (53)	79 (57)	89 (46)
December	102 (41)	81 (47)	82 (39)	59 (41)

year of the study are summarized in Table 2. The LSR treatment achieved the greatest milk production per cow in each year whereas HSR was least. Notwithstanding the lower individual animal performance, HSR achieved the greatest milk production per hectare, as a consequence of the increase in SR, whereas LSR was least. There was no significant SR effect on milk fat and protein content (46.6 and 37.3 g/kg, respectively). Grazing days per hectare were greatest for HSR (886 d), intermediate for MSR (797 d), and least for LSR (699 d). Grazing season length was unaffected by SR treatment and was, on average, 277 d per year during the experiment.

There was no significant year or year \times SR treatment interaction effects on grazing characteristics, herbage use, and herbage N content observed; consequently, only the main effects of SR are detailed in Table 3. No difference was observed in net herbage accumulation (14,637 \pm 329 kg of DM/ha per year), concentrate supplementation (1,068 \pm 452 kg of DM/ha per year), or the amount of N fertilizer applied to the grazing area (209 \pm 46 kg of N/ha per year) between SR. However, there were differences in net herbage accumulation (14,879 \pm 325, 15, 869 \pm 328, and 13,164 \pm 326 kg of DM/ha in 2011, 2012, and 2013, respectively) and concentrate supplementation (1,007 \pm 420, 949 \pm 382, and 1,249 \pm 463 kg of DM/ha in 2011, 2012, and 2013, respectively) between years. Stocking rate had a significant effect on all grazing variables, with the exception of pregrazing herbage mass (1,690 \pm 57.0 kg of DM/ha) and herbage N content (33.6 \pm 0.59 g of N/kg of DM). Daily herbage allowance, postgrazing residual mass, and postgrazing residual sward height were greatest for LSR and least for HSR ($P < 0.001$). Average herbage removed per rotation was greater for MSR and HSR (1,698 \pm 53.3 and 1,643 \pm 57.8 kg of DM/ha, respectively) compared with LSR (1,503 \pm 49.4 kg of DM/ha). Grazing efficiency

at each grazing event was greatest ($P < 0.01$) for the HSR (107 \pm 2.1%) and least ($P < 0.05$) for LSR (95 \pm 2.2%), whereas MSR was intermediate (102 \pm 2.1%). Conversely, average daily grazing area allowance per cow was greatest ($P < 0.001$) for LSR (108.4 \pm 2.5 m²), least ($P < 0.001$) for HSR (90.6 \pm 2.6 m²), whereas MSR was intermediate (100.2 \pm 2.6 m²).

Trends in Soil Solution Concentrations and Losses of NO₃⁻N, NH₄⁻N, and NO₂⁻N

Soil solution concentrations of NO₃⁻N, NH₄⁻N, and NO₂⁻N exhibited significant variation during the 3-yr study period (Figure 1). Total N, NO₂⁻N, and NO₃⁻N concentrations were greatest ($P < 0.01$) in yr 1 (41.6 \pm 7.0, 0.5 \pm 0.07, and 31.2 \pm 4.1 mg/L, respectively), lowest ($P < 0.01$) in yr 2 (26.5 \pm 7.0, 0.3 \pm 0.08, and 16.4 \pm 4.1 mg/L, respectively), and intermediate during yr 3 (33.8 \pm 7.0, 0.4 \pm 0.08, and 24.2 \pm 4.1 mg/L, respectively). The greatest concentration levels of NO₂⁻N and NH₄⁻N were recorded during midsummer, whereas NO₃⁻N concentrations were high during both the summer and autumn periods in each year. Across all treatments and years, NO₃⁻N losses explained 80% of TN loss, with a further 9% lost as NH₄⁻N. Stocking rate treatment had no significant effect on soil solution concentrations (Table 4 and Figure 1) or TN loss (Table 5), although a significant interaction was noted between SR treatment and year for all soil solution concentrations due to the comparably higher concentrations of all treatments in yr 1 in contrast to subsequent year. Effective drainage only occurred when rainfall exceeded ET and consequently climatic conditions had a large effect on actual N loss during the study period. Total annual N loss was similar during the study (at 136 \pm 15.3, 139 \pm 12.6, and 131 \pm 12.0 kg of N/ha during yr 1, 2, and 3, respectively).

Table 2. The effect of stocking rate on the characteristics of grass-based milk production during a 3-yr study (2011 to 2013)

Item	2011 ¹			2012 ¹			2013 ¹		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Stocking rate (livestock unit/ha)	2.51	2.92	3.28	2.51	2.92	3.28	2.51	2.92	3.28
Concentrate input (kg of DM/cow)	384	346	319	372	327	292	486	436	383
Concentrate input (kg of DM/ha)	964	1,010	1,046	933	955	958	1,220	1,272	1,256
Fertilizer N (kg of N/ha)	203	200	199	195	202	195	232	225	228
Milk yield (kg/cow)	5,804	5,606	5,335	5,453	5,330	4,914	5,578	5,468	5,124
Milk yield (kg/ha)	14,568	16,370	17,499	13,687	15,564	16,117	14,001	15,967	16,807
Milk fat content (g/kg)	43.7	43.1	45.2	48.3	48.5	50.9	46.0	45.8	48.1
Milk protein content (g/kg)	36.5	37.0	37.2	37.5	37.3	37.7	37.0	37.2	37.5
Net herbage accumulation (kg of DM/ha)	13,576	15,106	15,956	15,299	16,065	16,242	13,426	12,923	13,144
Grazing season length (d)	273	265	267	284	281	273	279	273	270
Grazing days (n/ha)	685	774	876	713	821	895	700	797	886

¹Stocking rate: low = 2.51 cows/ha; medium = 2.92 cows/ha; high = 3.28 cows.

N inputs, Outputs, and Utilization Efficiency

The overall biological efficiency of N use for each treatment during each year of the study was modeled using the N efficiency model developed by Ryan et al. (2011) and based on the biological performance of each farming system, which is summarized in Table 2. The modeled effect of SR on annual farm gate N inputs, outputs, and surplus is presented in Table 6. The main sources of N input to the dairy production systems were feed, N fertilizer, and replacement animals. Although the maximum permitted quantity of chemical fertilizer N allocated for each treatment was set at 250 kg of N/ha per year, actual N applied across the 3 treatments for the 3-yr trial was 209 kg of N/ha. As concentrate input per hectare was similar for each SR treatment within year but varied between year due to variation in grass growth and climatic conditions, the quantity of N imported in feed was similar for each treatment but varied between years. As replacement rate and individual herd parity structure was maintained at a constant level for each SR treatment during the experimental period, the quantity of N imported as replacement animals was similar for each SR treatment. Total N input per hectare, consequently, was similar for each SR treatment in each year and averaged 225, 218, and 261 kg of N/ha for 2011, 2012, and 2013, respectively. The average quantity of N exported per hectare annually in the form of product was 116, 111, and 98 kg of N/ha for the HSR, MSR, and LSR, respectively, over the 3-yr period. Milk production was the main source of exported N from all dairy production systems, at 109, 102, and 90 kg of N/ha per year for HSR, MSR, and LSR, respectively (Table 6). The quantity of N exported in the form of calf sales was 4, 3, and 3 kg of N/ha per year for the HSR, MSR, and LSR, respectively, whereas cull cow sales was 9, 8, and 7 kg of N/ha per year, respectively. The average annual farm-gate N surplus per hectare (N inputs less N outputs) differed with SR and was 136, 124, and 121 kg of N/ha per year for LSR, MSR, and HSR, respectively. Similarly, mean N use efficiency (N outputs/N inputs) for all systems was 46%, and was highest for HSR (49%), lowest for LSR (42%), and intermediate for MSR (47%).

DISCUSSION

Within an EU context, Ireland currently has excellent water quality, with 86% of groundwater aquifers classified at good status or better (EPA, 2010). Maintaining the delicate balance between productive agriculture and groundwater quality is a constant challenge and requires a broad overall farm systems perspective over different time and dimensional scales, and recent

Table 3. Effect of stocking rate¹ (SR) on grazing characteristics and utilization over 3 grazing seasons (2011 to 2013)

Item	Low	Medium	High	SEM	<i>P</i> -value
Pregrazing mass (kg of DM/ha)	1,677	1,763	1,631	57.0	0.3
Postgrazing mass (kg of DM/ha)	174 ^a	65 ^b	-12 ^c	27.2	***
Postgrazing height (cm)	4.0 ^a	3.7 ^{ab}	3.4 ^b	0.09	***
Herbage allowance (kg of DM/cow per day)	16.5 ^a	15.5 ^b	13.1 ^c	0.43	***
Herbage used ² (kg of DM/ha)	1,503 ^b	1,698 ^a	1,643 ^a	53.5	*
Grazing efficiency ³ (%)	95 ^c	102 ^b	107 ^a	2.1	**
Grazing area allocation (m ² /cow per day)	108.4 ^a	100.2 ^b	90.6 ^c	2.56	***
Herbage N content (g/kg)	33.0	33.8	33.9	0.59	0.4

^{a-c}Means within a row with different superscripts differ.

¹Stocking rate: Low = 2.51 cows/ha, Medium = 2.92 cows/ha, High = 3.28 cows/ha.

²Herbage used (kg of DM/ha) = (pregrazing sward height - postgrazing sward height) × sward density (kg of DM/cm per ha; Delaby and Peyraud, 1998).

³Grazing efficiency (%) = (Herbage used/Pregrazing herbage mass) × 100.

P* < 0.05, *P* < 0.01, ****P* < 0.001.

studies have highlighted the necessity for estimates of nutrient efficiency to be integrated within technical efficiency evaluation criteria for productive farming systems (Shani et al., 2007; Dudley et al., 2008). The range of SR treatments evaluated within the current experiment are relatively intensive in comparison with commercial practice in Ireland [1.9 livestock units (dairy cow equivalents)/ha; NFS, 2012]. However, these high-SR farms must be considered in terms of the comparably high productivity of the grassland swards at the experimental site. The LSR treatment represents the control SR, whereas MSR and HSR represent 2 incremental increases in SR.

Previous studies evaluating the efficacy of increased farm system SR within grazing systems have conclusively illustrated beneficial effects on per-hectare milk production (Hoden et al., 1991; Macdonald et al., 2008; McCarthy et al., 2013b), pasture quality and utilization (Horan et al., 2005; Macdonald et al., 2008; McCarthy et al., 2013a), and overall farm system economic performance (Shalloo et al., 2004; McCarthy et al., 2007; McDonald et al., 2013). The biological effects of increased overall farm SR on milk production per hectare observed within our study are consistent with previous findings and further substantiate the potential for increased biological efficiency within higher-SR grazing systems. Similar to both Valentine et al. (2009) and Fariña et al. (2011), SR had no significant effect on net herbage accumulation but, as a consequence of the increased efficiency of herbage removal and increased grazing severity at higher SR, resulted in increased grazed grass utilization. Both Baudracco et al. (2010) and McCarthy et al. (2011) have previously likened an increase in SR to a reduction in daily herbage allowance. In the current study, increasing SR resulted in reduced daily herbage allowance, reduced total lactation milk production per cow, and increased

milk production per hectare, which is consistent with previous experiments at similar SR (Macdonald et al., 2008; Fariña et al., 2011). Unlike Fariña et al. (2011), who attributed much of the increase in milk production per hectare at higher SR to increased supplementation, the increased milk production per hectare achieved at higher SR in the present study is directly related to an increase in grazed herbage as supplementary feed imports were similar for each SR treatment (1,060 kg/ha per year). The overall level of milk production per hectare achieved within our study greatly exceeds that obtained commercially on Irish dairy farms (9,120 kg of milk/ha per year; NFS, 2012), and is indicative of the potential productivity of Irish grass-based systems post-milk quota in the EU.

The efficacy of ceramic cup evaluations of N losses from freely draining soils has been validated by Webster et al. (1993) and has been reported previously within intensive grazing systems (Ryan et al., 2006). The overall quantity of NO₃⁻N and TN leached from the farm system is dependent on the volume of water drained from the soil and the concentration of NO₃⁻N in the drainage water (Cooper et al., 2007; Huebsch et al., 2013). The average rainfall and ED during the study were similar to the 30-yr average, and so the observed results are consistent with normal expected weather and drainage conditions for this site. Total N, NO₂⁻N, NH₄⁻N, and NO₃⁻N concentrations reported in our study (32.3, 0.2, 2.4, and 26.0 mg/L, respectively) were similar to the concentrations in soil solution reported previously by Ryan et al. (2006), whereas the large inherent variation in mean NO₃⁻N and TN concentrations in soil solution both within and between year (Figure 1) has also previously been reported (Richards et al., 1996; Sprosen et al., 2002). Total N losses were similar to those measured in dairy systems on similar soils in New Zealand using ceramic cups after the application

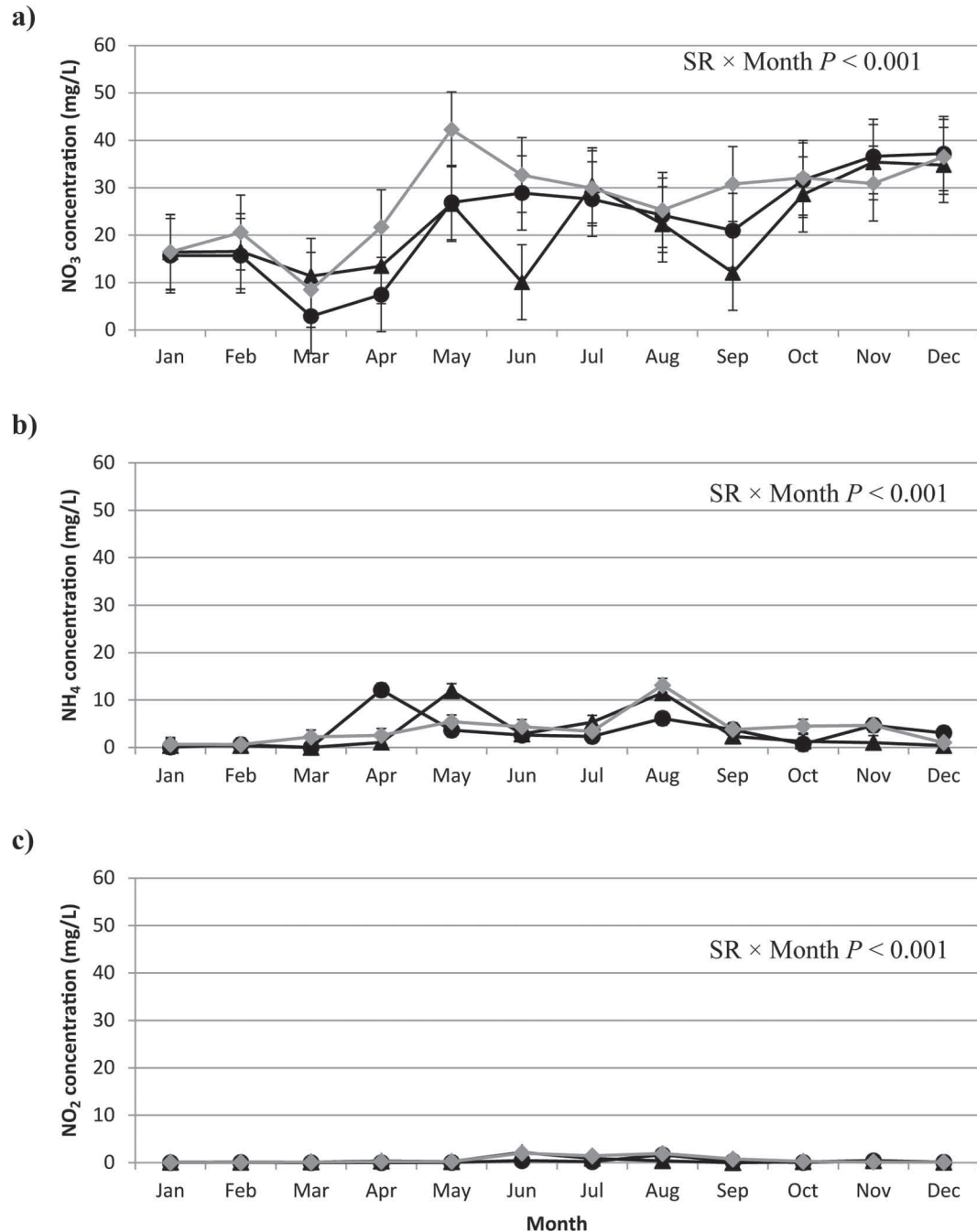


Figure 1. The effect of stocking rate (SR) on mean average monthly soil solution concentrations of (a) nitrate-N (NO_3^- -N), (b) ammonium-N (NH_4^+ -N), and (c) nitrite-N (NO_2^- -N) for the low (2.51 cows/ha; ▲), medium (2.92 cows/ha; ◆), and high (3.28 cows/ha; ●) SR treatments during the 3-yr study period.

of 200 kg of N/ha as mineral fertilizer (NO_3^- -N leaching losses of 101 kg of N/ha per year; Ledgard et al., 1997). Although NO_3^- -N concentrations in soil solution (26.0 mg of NO_3^- -N/L) consistently exceeded the current EU standard for NO_3^- -N in drinking water (11.3 mg/L) for all SR treatments, previous studies have indicated that soil solution concentrations of NO_3^- -N are likely to be a

poor reflection of absolute losses to groundwater (Ryan et al., 2006). Huebsch et al. (2013) has reported mean NO_3^- -N concentrations of 7.0 mg/L in groundwater beneath the experimental site during the same measurement period. The same study (Huebsch et al., 2013), which evaluated groundwater NO_3^- -N concentrations over an 11-yr period, also observed no significant effect

Table 4. Effect of stocking rate¹ (SR) on annual total N (TN), nitrate N (NO₃-N), nitrite N (NO₂-N), and ammonium N (NH₄-N) concentrations (mg/L) over 3 grazing seasons (2011 to 2013)

Item	SR			SEM	P-value		
	Low	Medium	High		SR	Year	SR × year
TN concentration (mg/L)							
Average	35.4	36.1	30.4	12.1	0.9	***	***
2011	44.1	44.4	36.2				
2012	31.1	28.7	19.8				
2013	31.1	35.2	35.1				
NO ₃ -N concentration (mg/L)							
Average	21.5	27.3	23.0	7.06	0.9	***	***
2011	29.1	34.9	29.5				
2012	17.4	19.0	12.9				
2013	18.1	28.1	26.6				
NO ₂ -N concentration (mg/L)							
Average	0.4	0.6	0.2	0.13	0.2	**	***
2011	0.6	0.6	0.2				
2012	0.3	0.6	0.2				
2013	0.3	0.6	0.4				
NH ₄ -N concentration (mg/L)							
Average	5.2	4.5	2.1	0.93	0.4	***	***
2011	4.1	4.5	2.0				
2012	4.1	3.3	2.0				
2013	5.6	3.7	5.3				

¹Stocking rate: low = 2.51 cows/ha; medium = 2.92 cows/ha; high = 3.28 cows/ha.

** $P < 0.01$, *** $P < 0.001$.

of SR on N loss and concluded that intensive grass-based systems of production incorporating efficient N management practices can lead to an achievement of the water quality targets. The large disparity in N loss estimates between soil solution and groundwater concentrations evidenced by these results suggest that

further research is needed to understand the complex dynamics of N transformations and movement from surface to groundwater.

In the current study, the evaluation of SR effects under grazing occurs under a common level of drainage; thus, the effect of SR on NO₃-N leaching is considered

Table 5. Effect of stocking rate¹ (SR) on annual total nitrogen N (TN), nitrate N (NO₃-N), nitrite N (NO₂-N), and ammonium N (NH₄-N) loss (kg N/ha) over 3 grazing seasons (2011 to 2013)

Item	SR			SEM	P-value		
	Low	Medium	High		SR	Year	SR × Year
TN loss (kg/ha per year)							
Average	127.8	136.6	141.2	15.10	0.8	0.9	0.3
2011	129.2	136.8	142.2				
2012	144.1	152.9	119.9				
2013	110.1	120.0	161.5				
NO ₃ -N loss (kg/ha per year)							
Average	99.9	109.6	113.1	15.22	0.7	†	0.6
2011	113.1	118.4	123.2				
2012	88.6	102.2	86.9				
2013	97.9	108.2	129.1				
NO ₂ -N loss (kg/ha per year)							
Average	1.1	1.8	1.1	0.64	0.7	**	†
2011	1.5	0.3	0.2				
2012	1.5	4.8	2.1				
2013	0.2	0.3	0.9				
NH ₄ -N loss (kg/ha per year)							
Average	10.2	13.3	12.8	4.69	0.9	†	†
2011	3.3	11.7	5.8				
2012	22.7	23.1	10.1				
2013	4.5	5.2	22.5				

¹Stocking rate: low = 2.51 cows/ha; medium = 2.92 cows/ha; high = 3.28 cows/ha.

† $P < 0.10$, ** $P < 0.01$.

Table 6. The modeled effect of stocking rate¹ on annual farm gate nitrogen (N) inputs, outputs, and surplus during the 3-yr study (2011 to 2013)

Item	2011			2012			2013		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
N input (kg of N/ha)									
Fertilizer	203	200	199	195	202	195	232	225	228
Feed	18	19	20	14	16	18	24	28	32
Annual replacement cows introduced	5	5	6	4	5	6	5	5	6
Total	226	224	225	213	223	219	261	258	266
N output (kg of N/ha)									
Milk	90	101	109	86	98	97	87	100	103
Meat	10	12	13	10	11	13	10	11	13
Total	100	113	122	96	109	110	97	111	116
N surplus (kg of N/ha)	126	111	103	117	114	109	164	147	150
N use efficiency	0.44	0.50	0.54	0.45	0.49	0.50	0.37	0.43	0.44

¹Stocking rate: low = 2.51 cows/ha; medium = 2.92 cows/ha; high = 3.28 cows.

in terms of N concentrations in soil solution. Similar to previous studies, the results of the current analysis indicate that although NO_3^- -N and TN concentrations in soil solution are high during summer as little N loss occurs during the February to October period due to low rainfall and increased ET. The important effect of climatic conditions on N losses observed in previous studies (O'Connell et al., 2004; Kurunc et al., 2011) is also evident in the current data. Similar to both De Klein and Ledgard (2001) and Laidlaw and Mayne (2000), the combination of high N concentrations and increased ED during the autumn and early winter months within the current data are indicative of the increased risk of N loss during this period. Sprosen et al. (2002) have also previously reported no significant SR effect on NO_3^- -N losses from grazing swards in New Zealand and concluded that this was due to the lower grass DMI and an earlier end to lactation and removal of cull cows in high-SR treatments. The results of the present study are in agreement with previous SR evaluation studies, both in Ireland (Ryan et al., 2006) and internationally (Sprosen et al., 2002; Monaghan et al., 2009), and indicate that within the range of production systems investigated and at similar N inputs, increasing SR has no effect on N losses from soil solution within a predominantly grass-based production system on a free-draining site. The significant interaction between SR treatment and year for all soil solution concentrations in the current study was due to the comparably higher concentrations of all treatments in yr 1 and indicates that such analysis must be undertaken over multiple years. Overall N inputs, outputs, and surpluses generated by the adoption of the production data to the N model of Ryan et al. (2011) are consistent with previous studies within grass-based systems (Ledgard et al., 1999). They indicated that the increased grass utilization and milk production per hectare at higher SR result in a reduction in N surplus and an increase in N

use efficiency. In the absence of extra N inputs (chemical fertilizer and concentrates), which are traditionally associated with increased SR and which result in increased N loss (Humphreys et al., 2003), the results of the experiment reported herein highlight the possibility for the sustainable intensification of Irish dairy systems through a combination of increased SR, greater grazing intensity, and increased herbage utilization.

Many studies report increased farm system productivity at higher SR (McCarthy et al., 2011), with increased performance within such systems being attributed to a combination of improved pasture utilization and increased chemical N fertilizer application and increased feed supplementation (Valentine et al., 2009; Fariña et al., 2011). Whitehead (1995) concluded that additional N applications at higher SR reduce N utilization due to the inability of such systems to use additional N inputs above those required for herbage and animal production, whereas Ryan et al. (2011) concluded that 40% of the extra N input is lost to the environment. Consequently, it is now widely acknowledged that the magnitude of N inputs to the farm system is generally the main factor determining the N surplus and therefore the potential for N loss (Treacy et al., 2008; Monaghan et al., 2009; Ryan et al., 2012). Previous estimates of between 19 and 24% N use efficiency based on overall farm SR of 2 to 3 livestock units/ha and N surpluses of 200 to 250 kg of N/ha per year have been reported for Irish dairy farms (Humphreys et al., 2008; Treacy et al., 2008; Mihailescu et al., 2014). Similarly, Ledgard et al. (1997) estimated the average New Zealand farm N use efficiency at 30% based on an N surplus of circa 130 kg of N/ha per year. In comparison with the aforementioned commercial farm data and previous grazing studies in Ireland (Horan et al., 2005; Coleman et al., 2010), the comparatively reduced total N inputs (235 kg/ha per year) and N surplus (127 kg/ha per year) from both chemical N and supplementary

feeds and increased milk production per hectare in the current experiment resulted in increased mean N use efficiency (46%), which is supported by the similarity in grass N content among SR treatments within our experiment. Furthermore, these results indicate that, as SR increased, further improvements in N surplus and N use efficiency are achieved at higher SR as N is recycled more efficiently within such systems. Peyraud and Delaby (2006) previously observed improvements in N use efficiency from both low N fertilization and increased SR and concluded that low N fertilizer input is critical to improve N use efficiency at high SR as N surplus is reduced to a greater extent than N exported in milk.

The efficiency of conversion of inputs to products is one of the main areas of improvement necessary in the search for more sustainable grass-based food production systems. The results reported in the current study provide an insight into the potential productivity and nutrient efficiency of technically focused grazing systems based on high-genetic potential dairy cattle and high-productivity grassland swards (14,637 kg of DM/ha per year) with medium total N inputs (235 kg of N/ha per year). In contrast, commercial farm data indicates that, based on increased N input, average grass DM production on intensive Irish dairy farms in Ireland is approximately 10,000 kg of DM/ha per year (Shalloo et al., 2010), resulting in reduced milk production per hectare (NFS, 2012), increased concentrate supplementation (Ramsbottom et al., 2012), and, ultimately, reduced N use efficiency (Treacy et al., 2008; Mihailescu et al., 2014). These differences indicate the potential contribution of improved basic agronomic and nutrient management practices at the farm level to increase grazed grass utilization, resulting in increased farm system productivity from highly N efficient grazing systems.

CONCLUSIONS

The results of this study indicate that NO_3^- -N and TN concentrations in soil solution did not differ significantly between SR treatments [LSR (2.51 cows/ha), MSR (2.92 cows/ha), and HSR (3.28 cows/ha)] when N inputs from chemical N fertilizer or additional external feed supplementation were restricted and increased grazed grass utilization was used to support the feed requirements of animals at higher SR. The results highlight the possibility for the sustainable intensification of Irish grass-based systems of milk production through increased grazed grass utilization within high-productivity grazing systems. Moreover, the results suggest that, at the same level of N inputs, increasing SR has little effect on N loss in pastoral systems as described with limited imported feed, and that greater empha-

sis should be attributed to increased grass production and utilization under grazing systems or conditions to further improve the environmental impact of grazing systems of production.

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