The multi-year cumulative effects of alternative stocking rate and grazing management practices on pasture productivity and utilization efficiency

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ABSTRACT

The production and utilization of increased quantities of high quality pasture is of paramount importance in pasture-based milk production systems. The objective of this study was to evaluate the cumulative effects of alternative integrated grazing strategies, incorporating alternative stocking rate (SR) and grazing severities, on pasture productivity and grazing efficiency over multiple years within farm systems using perennial ryegrass dominant pastures. Three whole-farm SR treatments were compared over 4 complete grazing seasons (2009 to 2012 inclusive): low (2.51 cows/ha; LSR), medium (2.92 cows/ha; MSR), and high (3.28 cows/ha; HSR). Each system had its own farmlet containing 18 paddocks and remained on the same treatment for the duration of the study. Stocking rate had a significant effect on all grazing variables with the exception of soil fertility status and sward density. Increased SR resulted in increased total annual net pasture accumulation, improved sward nutritive value, and increased grazed pasture utilization. Total annual net pasture accumulation was greatest in HSR [15,410 kg of dry matter (DM)/ha], intermediate for MSR (14,992 kg of DM/ha), and least for LSR (14,479 kg of DM/ha) during the 4-yr study period. A linear effect of SR on net pasture accumulation was detected with an increase in net pasture accumulation of 1,164.4 (SE = 432.7) kg of DM/ha for each 1 cow/ha increase in SR. Pregrazing pasture mass and height and postgrazing residual pasture mass and height were greatest for LSR, intermediate for the MSR, and lowest for the HSR. In comparison with the LSR, the imposition of a consistently increased grazing severity coupled with increased whole farm SR in MSR and HSR treatments arrested the decline in sward nutritive value, typically observed during mid-season. Incorporating the individual beneficial effects of SR on pasture accumulation, nutritive value, and utilization

efficiency, total proportional energy (unité fourragère lait) utilization per hectare increased significantly with increasing SR (+0.026 and +0.081 for MSR and HSR, respectively). These results quantify the significant effect of grazing management practices on the feed production capability of modern perennial ryegrass pastures for intensive grazing dairy production systems. Furthermore, these results highlight the importance of consistently imposing grazing treatments over multiple years, and within integrated whole farm systems, to accurately assess the longer term effects of alternate grazing management practices on pasture productivity. **Key words:** stocking rate, grazing severity, sward nutritive value, pasture production and utilization

INTRODUCTION

Worldwide demand for dairy products has been increasing rapidly as a result of projected population growth, urbanization, and increases in per capita disposable income (Rae, 2002; Delgado, 2005). Commensurate with the increased global food demand, increased competition for land, water, and energy resources necessitates that global agricultural production becomes more productive based on systems that are also more environmentally and socially sustainable. In this regard, awareness is increasing of the multifunctional character and benefits of pasture-based farming (Jeangros and Thomet, 2004) due to its capability to be both highly productive (Macdonald et al., 2008; McCarthy et al., 2013a), environmentally benign (Nosberger and Rodriguez, 1996; Jankowska-Huflejt, 2006; Peyraud et al., 2010), financially efficient (Dartt et al., 1999; Dillon et al., 2008), and socially sustainable (Dartt et al., 1999; White et al., 2002), while providing products with advantageous nutritional characteristics (O'Brien et al., 1999; Coakley et al., 2007). Both Taube et al. (2013) and Baumont et al. (2014) have suggested that systemic improvements in pasture-based food production efficiency can be ascertained by increasing pasture utilization and placing less emphasis on external supplementary feed and fertilizer inputs.

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The efficient production of milk from grazing systems is dependent on the extensive use of cheap high-quality grazed pasture (Horan et al., 2005; Dillon et al., 2008). Previous studies have indicated that, in comparison with mechanically harvested or purchased feeds, grazed pastures provide a relatively inexpensive and energy efficient feed source for milk production (Dillon et al., 2008; Ramsbottom et al., 2015). The production performance of grazing systems is heavily reliant on the yield of utilizable energy and protein from grazed pastures and is consequently reliant on prevailing climatic conditions (Roche et al. 2009), which are beyond the control of the grassland farmer. Such inherent temporal variability necessitates the identification of grazing management practices that increase the yield and stability of high quality pasture to enhance the robustness and predictability of grazing systems in the future.

The agronomic objectives of technically efficient grazing management have been extensively studied and reviewed in the literature and the immediate influence of individual grazing management components on pasture accumulation, nutritive value, and utilization has been reported (Lee et al., 2007; Ganche et al., 2013b; Tuñon, 2013). Stocking rate (**SR**), defined as the number of animals per unit area of land used during a specified defined period of time (cows/ha, Allen et al., 2011) is widely acknowledged as the main driver of productivity from grazing systems (Hoden et al., 1991; Macdonald et al., 2008; Baudracco et al., 2010). Increasing SR is usually associated with an increase in grazing severity, and many studies have attributed the increased productivity of higher SR systems to an improvement in pasture utilization (Hoden et al., 1991; Macdonald et al., 2008). In contrast, the effect of increasing SR and defoliation severity on pasture production has been extensively studied but inconsistently reported (Donaghy and Fulkerson, 1998; Macdonald et al., 2008; Lee et al., 2009), and the evaluation of such effects is often complicated by alternative grazing decision rules (Clark et al., 2010) and the difficulties of extending the results of shorter term component-based or cutting experiments to field conditions (Anderson and Briske, 1995). Indeed, previous studies have also indicated that although variation in defoliation and plant regrowth patterns creates variability in sward structure and nutritive value (Possingham and Houston, 1990; Adler et al., 2001), the effects of such practices are frequently accentuated by the farm system SR (Laca and Dement, 1991). Despite the critical importance of grazing management practices to grazing science, and evidence of longer term conditioning effects of these practices (Hoogendoorn et al., 1992; Pulido and Leaver, 2003; Stakelum and Dillon, 2007), the integration and evaluation of alternative SR and grazing practice combina-

tions over multiple years to evaluate the cumulative systemic effects on pasture productivity have seldom been undertaken.

Consequently, the objective of this study is to evaluate the cumulative effects of alternative integrated grazing strategies, incorporating alternative SR and grazing severities, on grassland productivity and grazing efficiency over multiple years within farm systems using perennial ryegrass dominant pastures.

MATERIALS AND METHODS

This study was undertaken at the Animal and Grassland Research and Innovation center, Teagasc Moorepark, Ireland (50°7N; 8°16W), over a 4-yr period (2009, 2010, 2011, and 2012). It formed part of a larger study designed to examine the biological and economic effects of alternative SR grassland systems, and a more detailed description of the animals, treatment, and experimental design has been reported previously (McCarthy et al., 2012). The on-site pastures used were predominantly perennial ryegrass (*Lolium perenne* L.) and had been reseeded over the previous 1 to 9 yr.

Experimental Design, Treatments, and Herd Management

In spring 2009, 138 high economic 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 that may be appropriate in a post-European Union milk quota, spring-calving, pasture-based milk production system. The experimental herd in the study was composed of elite animals (McCarthy et al., 2013b) and was managed with a compact spring-calving pattern that was closely aligned with the average pasture growth capacity of the site (50% of all animals calving in the first 2 wk of February, 90% calved by mid-March, and with a mean calving date of February 20). As a pasture-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 pasture silage.

Grazing, Nutrient, and Feeding 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, pasture 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 18.4, 15.8, and 14.0 ha, respectively. Grazing management was accomplished by weekly monitoring of farm pasture cover within each SR treatment (O'Donovan, 2000). Similar to previous whole farm SR studies (Macdonald et al., 2008), weekly grazing management during the first rotation in spring (February 1 to April 1) was based on allocating an equal and increasing proportion of each farmlet to each treatment up to the start of rotation 2. To apply the SR effect consistently between paddocks during the main grazing season, 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 = 45 to 50 mm, MSR = 40 to 45 mm, and HSR 35 to 40 mm), and each group was moved independently of one another to the next paddock once this target was reached. Target pregrazing pasture mass was defined separately for each SR according to the following equation:

$$\begin{aligned} \text{target pregrazing pasture mass} = & [\text{SR; cows/} \\ & \text{ha} \times \text{ideal rotation length (21 d during main grazing} \\ & \text{season)} \times \text{daily pasture allowance per cow; kg of DM/} \\ & \text{cow per d}] + \text{residual pasture mass; kg of DM/ha.} \end{aligned}$$

When pregrazing pasture mass in the next grazing paddock exceeded the target level, the paddock was skipped and pasture was harvested as silage. A sample of pasture 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 pastures took place during the experiment.

Best practice nutrient management was applied to the management of each farmlet within the study and has been reported previously by Heubsch et al. (2013). Chemical N fertilizer application rates were common across SR treatments at 250 kg of N, 4 kg of P, and 8 kg of K per ha per yr 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 (>10 mm/h) 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 of 19,000 L/ha on 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 yr, and consequently, lower per cow as SR increased. Concentrate supplementation for all treatments commenced at 4 kg/cow per d post-calving, and was reduced and removed totally from the diet only when pasture supply exceeded animal demand for all treatments (usually by mid-March). During the main grazing season, concentrate and additional forage supplementation (in the form of baled silage) were occasionally used when pasture supply was in deficit of feed demand. Concentrate supplement was only used when a feed deficit occurred for each SR treatment and a similar supplementation rate per ha was imposed in all treatments on those occasions. When feed deficits arose for individual SR treatments, conserved silage produced within the specific treatment was used to supplement feed supply.

Pasture Measurements

The grazing period was broken down into 3 distinct seasons: spring (February 1 to March 31), mid-season (April 1 to July 30), and autumn (August 1 to November 20). Spring corresponds to the first rotation where all the area within each farmlet is available for grazing before paddocks are closed off for silage during the summer period. During autumn, the entire farmlet area is again available for grazing. Grazing data were collected on each paddock during each grazing rotation each year according to the procedures outlined by McCarthy et al. (2013b). Pregrazing pasture mass (>3.5 cm) was determined before grazing on each paddock by harvesting 2 strips (1.2 m × 10 m) of pasture with an Etesia mower (Etesia UK Ltd., Warwick, UK). All mown pasture 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 bulk density (henceforth, sward density) was calculated as follows (Delaby and Peyraud, 1998):

$$\begin{aligned} \text{sward density (kg of DM/cm per ha)} = & \text{pasture mass} \\ & (\text{kg of DM/ha})/(\text{precutting CSH} - \text{postcutting CSH}). \end{aligned}$$

Pre- and postgrazing sward height were determined on each paddock before and after grazing by taking between 30 and 50 height measurements using the rising pasture plate meter across the diagonal of the paddock. The average paddock pregrazing pasture mass above a cutting height of 3.5 cm (kg of DM/ha) was then calculated according to the following formula (Delaby and Peyraud, 1998):

$$\begin{aligned} \text{pregrazing pasture mass (kg of DM/ha)} = \\ (\text{pregrazing CSH (cm)} - 3.5 \text{ cm}) \times \text{sward density} \\ (\text{kg of DM/cm/ha}). \end{aligned}$$

Pasture utilized (kg of DM/ha) at each grazing was calculated using the following formula (Delaby and Peyraud, 1998):

$$\begin{aligned} \text{pasture utilized (kg of DM/ha)} = \\ (\text{pregrazing CSH} - \text{postgrazing CSH}) \\ \times \text{sward density (kg of DM/cm per ha)}. \end{aligned}$$

Net pasture accumulation was calculated weekly from the increase in pasture mass on ungrazed paddocks using the method of O'Donovan (2000). The efficiency of grazing was determined using the method proposed by Delaby and Peyraud [1998; pasture utilized/pregrazing pasture mass (>3.5 cm) at each grazing]. Pasture utilized was calculated as the difference between the pregrazing pasture mass (>3.5 cm) and the postgrazing pasture mass (above the postgrazing CSH) within the same rotation. Total net pasture utilization was calculated as the sum of the pasture utilized at each grazing for each treatment. Daily net pasture accumulation was calculated by dividing the pasture accumulated between grazings by the inter-grazing interval (d).

Chemical Analyses

Pasture samples were collected from each paddock, prior to grazing, for each SR treatment and were dried at 40°C for 48 h and milled through a 1-mm sieve. Samples were bulked by SR by week and analyzed for DM, ash, ADF, NDF (Van Soest, 1963), CP (Leco FP-428; Leco Australia Pty Ltd., Baulkham Hills, New South Wales, Australia), and organic matter digestibility (OMD; Morgan et al., 1989). The energy (NE_L, expressed as "unité fourragère lait," UFL; Beaumont et al., 2007) value of the pasture within each SR at each grazing was also subsequently calculated. Soil samples were collected (20 cores per plot to a depth of 100 mm) in January of each year before fertilizer and slurry ap-

plication. Soil available P and K were determined using Morgan's extracting solution (10% Na-acetate in 3% acetic acid buffered at pH 4.8; Peech and English, 1944; Byrne, 1979) and expressed as milligrams per liter of soil. Soil pH was also measured according to standard methods (Byrne, 1979).

Meteorological Data

Daily measurements of average air temperatures 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.

Statistical Analysis

The effect of SR, season, and year on pregrazing pasture mass, pre- and postgrazing height, grazing efficiency, and the chemical composition of the pasture was determined using mixed models (Proc MIXED, 2006, SAS Institute Inc., Cary, NC) with rotation included as a repeated effect. Individual paddocks were considered as the experimental unit. A compound symmetry covariance structure among records within paddock provided the best fit to the data. Total net pasture accumulation and utilization were also determined using mixed models (Proc MIXED, 2006, SAS Institute Inc.) with block and block $\times$ SR included as random effects. The linear and quadratic effects of SR were also evaluated for both pasture accumulation and net energy utilization by including SR as a continuous variable within the mixed model. Soil P and K data were analyzed using a generalized linear model (Proc GLM, 2006, SAS Institute Inc.).

RESULTS

Climate Data

Total annual rainfall averaged 1,030 mm during the 4-yr study period compared with 1,027 mm during the 2000 to 2010 period. Mean monthly rainfall and temperature data for each year of the study and the 10-yr mean are presented in Table 1. Climatic conditions varied significantly between years during the study. During both 2009 and 2012, total rainfall was above the 10-yr average (+269 and +72 mm, respectively) with April (+43 mm), July (+72 mm), August (+42 mm), and November (+141 mm) in 2009 and June (+145 mm) and August (+106 mm) in 2012 being particularly high rainfall months. In contrast, total rainfall was

Table 1. Monthly total rainfall (mm) and mean soil temperature (°C) during the experimental period compared with the 10-yr (2000 to 2010) average

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall (mm)												
2009	194	16	56	107	89	52	154	117	41	127	260	83
2010	107	39	88	59	38	53	143	23	102	83	98	37
2011	57	92	28	26	81	62	55	35	99	83	157	81
2012	69	34	21	71	61	215	90	181	24	99	126	108
2000–2010	107	65	83	64	73	70	82	75	83	117	118	90
Mean soil temperature (°C)												
2009	4.5	5.1	7.1	8.9	11.0	14.6	14.8	14.9	12.9	11.8	7.8	3.2
2010	2.2	3.0	5.4	8.5	10.9	15.4	15.8	14.3	13.6	9.9	5.4	0.6
2011	3.4	7.1	6.4	10.7	11.4	12.2	14.1	13.2	13.5	11.5	9.7	6.2
2012	7.5	7.7	8.4	7.2	11.1	13.0	14.2	15.4	12.4	9.1	6.0	5.9
2000–2010	5.4	5.5	6.9	8.8	11.4	14.5	15.8	15.4	13.6	10.6	7.7	5.5

below the 10-yr average in both 2010 and 2011 (–157 and –171 mm, respectively) with total rainfall in the months of May (–35 mm), June (–17 mm), and August (–52 mm) in 2010 and January (–60 mm), March (–55 mm), April (–38 mm), and August (–40 mm) in 2011 being particularly low rainfall months. Mean daily temperatures were 0.4, 1.3, 0.1, and 0.3 degrees lower than the 10-yr average in 2009, 2010, 2011, and 2012, respectively, with the first 3 mo of 2010 being particularly cold (–2.4°C).

Grazing Characteristics and Net Pasture Accumulation

Both SR and year had a significant effect on total annual net pasture accumulation during the study period (Figure 1). Significant paddock to paddock variation in annual net pasture accumulation was evident, ranging from a minimum of 9,749 kg of DM/ha to a maximum of 20,208 kg of DM/ha per yr. Annual cumulative net pasture accumulation (SD) was greatest in HSR [15,410 (2,103) kg of DM/ha], intermediate for MSR [14,992 (2,151) kg of DM/ha], and least for LSR [14,479 (2,435) kg of DM/ha] during the 4-yr study period. A linear effect ($P < 0.001$) of SR on net pasture accumulation was detected with an increase in net pasture accumulation of 1,164.4 (SE = 432.7) kg of DM/ha for each 1 cow/ha increase in SR. Net pasture accumulation ($\pm$ SD) was 14,442 (2,456), 14,647 (2,004), 14,880 (2,064), and 15,872 (2,259) kg of DM/ha during 2009, 2010, 2011, and 2012, respectively. The higher overall net pasture accumulation of MSR and HSR was also consistent through each month of the year (Figure 2). No significant year $\times$ SR treatment interaction was found for grazing characteristics, and consequently only the main effects of SR are detailed in Table 2. Stocking rate had a significant effect on all grazing variables with the exception of sward density (274 kg of DM/cm per ha). Pregrazing pasture mass and CSH and postgrazing

residual sward mass and CSH were greatest for LSR, intermediate for the MSR, and lowest for the HSR ($P < 0.01$). Stocking rate treatment had no significant effect on soil fertility parameters, which remained stable during the experimental period (soil pH = 6.4, soil P content = 10.8 mg/L, soil K content = 122.8 mg/L).

Pasture Nutritive Value

Both SR and season had a significant effect on pasture nutritive value, and an interaction was also found between SR and season for all of the nutritive value variables measured. The nutritive value of the pasture available (>3.5 cm) improved as SR increased (Table 3 and Figure 3). Although the absolute differences in nutritive value between treatments were modest, the higher SR treatments consistently produced pasture of increased nutritive value during the study and in particular during mid-season and autumn. Crude protein content was highest ($P < 0.001$) for HSR, intermediate for MSR, and lowest for LSR. Similarly, OMD was greater for HSR compared with both LSR and MSR. The HSR also consistently had the lowest ($P < 0.001$) NDF, ADF, and ash concentration, whereas LSR was highest and MSR was intermediate. As a consequence of the increased OMD, and reduced NDF and ADF content, pasture from the HSR also consistently had the greatest ($P < 0.001$) energy content (0.96 UFL/kg of DM), whereas LSR was least (0.93 UFL/kg of DM) and MSR was intermediate (0.94 UFL/kg of DM). The mean monthly variation in OMD, CP, and UFL in each SR treatment is presented in Figure 3. Crude protein content was highest in spring (233.3 g/kg compared with 202.4 and 204.5 g/kg for mid-season and autumn, respectively). Organic matter digestibility was also highest in spring (790.4g/kg), intermediate in mid-season (787.2 g/kg), and least in autumn (761.7 g/kg). Neutral detergent fiber content was lower in spring and mid-season compared with autumn (465.0, 466.7,

Figure 1. Effect of stocking rate (SR) treatment (low SR = 2.51 cows/ha, black bar; medium SR = 2.92 cows/ha, white bar; and high SR = 3.28 cows/ha, gray bar) on annual total net pasture accumulation.

and 485.6 g/kg, respectively), whereas ADF content was lowest in summer (269.9 g/kg), intermediate in spring (282.2 g/kg), and highest during autumn (286.8

g/kg). Similar to OMD, ash content of experimental pastures was highest in spring (156.6 g/kg), least in autumn (114.6 g/kg), and intermediate during mid-season

Figure 2. Effect of stocking rate (SR) treatment (low SR = 2.51 cows/ha, ▲; medium SR = 2.92 cows/ha, ■; and high SR = 3.28 cows/ha, ◆) on mean daily net pasture accumulation during the grazing season.

Table 2. Effect of stocking rate (SR)¹ on average pre- and postgrazing pasture mass, sward height, pasture density, and pasture accumulation during 4 complete grazing seasons

Item	SR			SEM	P-value
	Low	Medium	High		
Average pregrazing sward characteristics ²					
Pasture mass (kg of DM/ha)	1,505	1,448	1,451	14.5	0.01
Sward height (mm)	88.1	87.4	86.2	0.52	0.01
Pasture density (kg of DM/cm per ha)	275	273	274	1.1	0.42
Average postgrazing pasture characteristics					
Residual pasture mass (kg of DM/ha)	233	105	0	5.2	0.001
Residual compressed sward height (mm)	43.1	39.3	34.7	0.22	0.001
Average net pasture accumulation (kg of DM/ha)	1,298	1,325	1,401	13.8	0.001

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

²Estimated based on the method of Delaby and Peyraud (1998).

(126.3 g/kg). Finally, the energy content of the pastures grazed during the study were similar in spring and mid-season (0.95 and 0.96 UFL/kg of DM, respectively) but reduced during autumn (0.92 UFL/kg of DM).

Pasture Utilization

The effect of SR on total and seasonal pasture utilization is presented in Table 4 and the mean monthly pre- and postgrazing pasture height and grazing efficiency are illustrated in Figure 4. Season had a significant

effect on pasture utilization with 58% of total pasture utilization achieved during mid-season (April to July inclusive, equivalent to 7,231 kg of DM/ha) compared with just 18% during spring (January to March inclusive, 2,244 kg of DM/ha) and 24% during autumn (August to November inclusive; 2,992 kg of DM/ha). In spring, average pre- and postgrazing pasture masses and postgrazing residual CSH were low for all SR treatments (788 kg of DM/ha, –166 kg of DM/ha, and 28.7 mm, respectively) compared with mid-season (1,419 kg of DM/ha, 150 kg of DM/ha, and 40.6 mm, respective-

Table 3. Effect of stocking rate (SR)¹ and season (S)² on pasture CP, organic matter digestibility (OMD), NDF, ADF, ash, and energy content during the 4-yr study period

Item	SR			SEM	P-value		
	Low	Medium	High		SR	S	SR × S
CP (g/kg of DM)	211.4	212.0	216.8	0.76	0.001	0.001	0.05
Spring	231.9	231.6	236.5				
Mid-season	202.0	201.3	204.0				
Autumn	200.4	203.1	210.0				
OMD (g/kg of DM)	774.9	776.2	788.6	0.88	0.001	0.001	0.30
Spring	786.3	791.2	793.7				
Mid-season	776.0	784.9	800.6				
Autumn	751.4	762.3	771.4				
NDF (g/kg)	485.6	467.0	465.1	0.97	0.001	0.001	0.001
Spring	475.2	469.7	450.3				
Mid-season	468.6	472.4	459.9				
Autumn	487.8	487.6	481.5				
ADF (g/kg)	286.3	277.9	274.7	0.70	0.001	0.001	0.12
Spring	292.1	280.0	274.5				
Mid-season	275.0	268.7	266.0				
Autumn	291.7	285.1	283.7				
Ash (g/kg)	134.2	132.1	131.1	0.91	0.05	0.001	0.001
Spring	163.3	155.5	151.0				
Mid-season	126.7	125.4	126.8				
Autumn	112.7	115.4	115.6				
Energy (UFL ³ /kg of DM)	0.93	0.94	0.96	0.002	0.06	0.001	0.04
Spring	0.93	0.96	0.97				
Mid-season	0.94	0.95	0.98				
Autumn	0.91	0.92	0.93				

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

²Spring (February 1 to March 31), mid-season (April 1 to July 30), and autumn (August 1 to November 20).

³UFL = unité fourragère lait.

Figure 3. Effect of stocking rate (SR) treatment (low SR = 2.51 cows/ha, ▲; medium SR = 2.92 cows/ha, ■; and high SR = 3.28 cows/ha, ◆) on (a) mean monthly organic matter digestibility (OMD), (b) CP content, and (c) energy content in unité fourragère lait (UFL energy units) during the grazing season.

ly) and autumn (1,821 kg of DM/ha, 158 kg of DM/ha, and 40.5 mm, respectively). Over the 4-yr study period, grazed pasture utilization (kg of DM/ha) increased linearly with increasing SR. Total pasture utilization did not differ significantly between treatments over the 4-yr period (12,468 kg of DM/ha; equivalent to 0.83 of

net pasture accumulation). Average net pasture accumulated and utilized per rotation was greater for MSR (1,299 and 1,348 kg of DM/ha, respectively) and HSR (1,382 and 1,460 kg of DM/ha, respectively) compared with LSR (1,269 and 1,279 kg of DM/ha, respectively). Pasture grazing efficiency at each grazing event was greatest for the HSR (100%) and least for LSR (84%), whereas MSR was intermediate (92%). Stocking rate had a significant effect on all seasonal feed utilization parameters. In spring, the HSR treatment achieved the lowest postgrazing residual pasture mass and CSH (−202 kg of DM/ha and 27.2 mm, respectively) and the greatest grazing efficiency (126%), compared with both the LSR (−134 kg of DM/ha, 30.0 mm, and 117%, respectively) and MSR (−162 kg of DM/ha, 28.9 mm, and 120%, respectively) treatments. Total pasture utilized was lower for LSR (920 kg of DM/ha) compared with both the MSR and HSR treatments (974 and 968 kg of DM/ha, respectively). Midseason pregrazing pasture masses were similar for each SR (1,419 kg of DM/ha). Both MSR and HSR treatments achieved greater quantities of pasture utilized (1,273 and 1,374 kg of DM/ha, respectively) due to reduced postgrazing residual pasture masses (137 and 22 kg of DM/ha, respectively) and CSH (40.1 and 35.9 mm, respectively), and consequently increased grazing efficiency (90 and 98%, respectively) compared with LSR (290 kg of DM/ha, 45.8 mm, and 80%, respectively). Similarly, the higher SR treatments achieved increased quantities of pasture utilized (MSR, 1,619 kg of DM/ha; HSR, 1,768 kg of DM/ha) and increased grazing efficiency (MSR, 91%; HSR, 98%) in autumn compared with LSR (1,601 kg of DM/ha and 85%, respectively) based on reduced postgrazing pasture masses (LSR, 279 kg of DM/ha; MSR, 157 kg of DM/ha; HSR, 38 kg of DM/ha) and increased grazing severity (LSR, 44.8 mm; MSR, 40.4 mm; HSR, 36.2 mm). When pasture utilization was corrected for differences in nutritive value, cumulative grazed pasture and total energy utilization increased linearly with increasing SR. Net grazed and total energy utilized were greater for MSR (9,526 and 11,164 UFL/ha, respectively) and HSR (10,115 and 11,764 UFL/ha, respectively) compared with LSR (8,728 and 10,882 UFL/ha, respectively). A significant linear effect ($P < 0.01$) of SR on total net energy utilization was detected with an increase of 1,027.4 (SE = 289.00) UFL utilized/ha for each 1 cow/ha increase in SR.

DISCUSSION

Although many studies have reported the isolated and immediate effects of specific grazing practices (Lee et al., 2007; McEvoy et al., 2009; Ganche et al., 2013b)

on various facets of pasture productivity, recent publications have highlighted the necessity for an integrated whole-farm systems approach to the evaluation of biological efficiencies within grazing systems (Clark et al., 2010; Baumont et al., 2014). Such experiments are difficult to interpret because of both the important effect of experimental decision rules and the interplay of factors that influence sward characteristics within integrated farm systems (Clark et al., 2010). In this study, the longer term and cumulative pasture productivity effects of alternate whole farm SR and grazing severity combinations were evaluated within whole-farm systems with limited external supplementary (feed and fertilizer) inputs over a 4-yr study period. Similar to Macdonald et al. (2008), and unlike classical SR experiments, the grazing management decision rules used in this experiment attempted to optimize the pasture performance within each SR treatment. Consequently, different target postgrazing residual CSH were adopted within this study to allow the SR effects to be consistently

imposed. As a consequence, the results of this study indicate the likely implications of increasing SR when associated with an increase in grazing severity on pasture productivity. Although the differential in postgrazing sward height between treatments is relatively small in comparison with previous grazing severity comparisons (Binnie and Harrington, 1972; Grant et al., 1981), this differential represents the likely range of practical grazing severity within pasture-based systems at SR of 2.5 to 3.3 cows/ha and where up to 90% of the diet comes from grazed pasture (Ramsbottom et al., 2015).

Net pasture accumulation in this study is the sum of all pasture accumulated between successive grazings and incorporating winter growth between individual grazing seasons. Average net pasture accumulation of 14,977 kg of DM/ha was realized over the 4 yr of the current study and is indicative of excellent soil fertility (Tunney et al., 2010), proactive pasture renewal using high productivity ryegrasses (McEvoy et al., 2011), and best practice grazing management practices

Table 4. Effect of stocking rate (SR)¹ on cumulative and seasonal pasture characteristics and energy utilization² during the 4-yr study period

Item	SR			SEM	P-value
	Low	Medium	High		
Cumulative pasture utilization (kg of DM/ha per yr)					
Grazed pasture	9,345	9,891	10,161	329.6	0.033
Conserved pasture	2,988	2,454	2,524	295.2	0.213
Total	12,320	12,358	12,726	256.5	0.233
Average pasture utilized (kg of DM/ha/rotation)	1,279	1,347	1,460	12.1	0.001
Average grazing efficiency (% utilization/rotation)	84	92	100	0.3	0.001
Seasonal pasture utilization					
Spring ³					
Pregrazing pasture mass ⁴ (kg of DM/ha)	785	812	766	19.3	0.26
Postgrazing residual pasture mass ⁴ (kg of DM/ha)	-134	-162	-202	8.0	0.001
Pasture utilized (kg of DM/ha)	920	974	968	24.0	0.10
Postgrazing residual CSH ⁵ (mm)	30.0	28.9	27.2	0.33	0.001
Grazing efficiency (%)	117	120	126	1.5	0.001
Midseason ³					
Pregrazing pasture mass (kg of DM/ha)	1,450	1,410	1,396	19.0	0.11
Postgrazing residual pasture mass (kg of DM/ha)	290	137	22	7.6	0.001
Pasture utilized (kg of DM/ha)	1,160	1,273	1,374	15.7	0.001
Postgrazing residual CSH (mm)	45.8	40.1	35.9	0.37	0.001
Grazing efficiency (%)	80	90	98	0.5	0.001
Autumn ³					
Pregrazing pasture mass (kg of DM/ha)	1,880	1,776	1,806	22.5	0.01
Postgrazing residual pasture mass (kg of DM/ha)	279	157	38	6.3	0.001
Pasture utilized (kg of DM/ha)	1,601	1,619	1,768	19.5	0.001
Postgrazing residual CSH (mm)	44.8	40.4	36.2	0.30	0.001
Grazing efficiency (%)	85	91	98	0.5	0.001
Cumulative energy utilization (UFL ⁶ /ha per yr)					
Grazed pasture	8,728	9,526	10,115	344.8	0.001
Conserved pasture	2,154	1,638	1,649	305.2	0.15
Total	10,882	11,164	11,764	289.8	0.01

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

²Estimated based on the method of Delaby and Peyraud (1998).

³Spring (February 1 to March 31), mid-season (April 1 to July 30) and autumn (August 1 to November 20).

⁴Estimated above 35 mm compressed sward height.

⁵Compressed sward height.

⁶UFL = unité fourragère lait.

Figure 4. Effect of stocking rate (SR) treatment (low SR = 2.51 cows/ha, Δ ; medium SR = 2.92 cows/ha, $\blacksquare$; and high SR = 3.28 cows/ha, $\blacklozenge$) on (a) mean monthly pregrazing (upper figures) and postgrazing (lower figures) residual pasture heights, and (b) mean monthly grazing efficiency during the grazing season.

(Kennedy et al., 2009; Chapman et al., 2011; Ganche et al., 2013a). The overall level of pasture productivity achieved compares favorably with previous studies at this experimental site under comparable average climatic conditions and using lower levels of applied chemical fertilizer than previously reported (Dillon et al., 2005; McCarthy et al., 2007). In addition, the large range in annualized pasture yields for individual paddocks within each farmlet has also been reported previously and is indicative of the potential for further increases in pasture productivity within such systems (Clark et al., 2010; 9,500 to 26,100 kg of DM/ha per yr). In comparison with the LSR, the imposition of a consistently increased grazing severity coupled with increased whole farm SR in MSR and HSR treatments resulted in a significant increase in annual net pasture accumulation (+0.035 and +0.064, respectively) over the 4-yr period. Previous studies have provided conflicting evidence of the effect of defoliation severity on pasture accumulation, and the interpretation of reported results is complicated by variation in previous pasture management (pregrazing pasture masses, rota-

tion lengths, grazing severity, and so on). Michell and Fulkerson (1987) reported that severe grazing severity reduced net pasture accumulation and has been associated with a substantial reduction in the rate of photosynthesis (Brougham, 1956; Parsons et al., 1988) due to the removal of all leaf material. In contrast, Ganche et al. (2013b) reported no detrimental effect of grazing severity on annual pasture accumulation when postgrazing residual CSH of 27, 35, and 42 mm were compared in spring, and Lee et al. (2007) similarly reported no negative effect of severe grazing residuals on subsequent pasture accumulation. In addition, both Kristensen (1988) and Parsons et al. (2000) have reported accelerated pasture regrowth following severe defoliation of high leaf content perennial ryegrass pastures and Lee et al. (2008) reported a quadratic effect of postgrazing residual pasture mass on pasture accumulation, with pasture accumulation declining at either excessively low (20 mm) or high (80 mm) CSH grazing residuals. The beneficial effect of increased grazing severity, particularly in spring, and increased SR on cumulative pasture accumulation was linear and equivalent to an increase in net herbage accumulation of 1,164 kg of DM/ha for a 1 cow/ha increase in SR. The results of this study are consistent with the findings of Macdonald et al. (2008) within a similar multi-year SR experiment, who reported a linear increase of 986 kg of DM/ha for every 1 cow/ha increase in SR. Higher summer regrowth rates have also been reported for pastures that were severely grazed in the spring (Michell and Fulkerson, 1987), and this has been associated with an increase in the number of developed vegetative tillers within the pasture (Korte et al., 1984). Furthermore, the existence of a significant SR effect on net pasture accumulation suggest that future grazing research should increasingly consider the longer term and potentially cumulative effects of alternate grazing management practices within farm systems that are imposed over multiple grazing seasons to incorporate the cumulative conditioning and adaptation effects on pastures arising from consistently imposed treatments.

The consistently increased immediate regrowth rate of plant tissue following more severe defoliation (Figure 2) of higher SR treatments was also associated with an increase in leaf content (+0.10) and a reduction in sheath length within the high SR pastures of this study (Tuñon et al., 2014). The increased regrowth rate may have been due to increased photosynthesis capacity of residual leaf laminae and pseudostem and changes in gene expressions associated with carbohydrate metabolism within the consistently severely grazed higher SR pastures (Booyesen and Nelson, 1975; Lee et al., 2011). Similarly, Chapman and Lemaire (1993) concluded that where ryegrass pastures were continuously

severely defoliated, the pasture adapted to maximize leaf area in the sub-grazing horizon by reducing sheath length and maintaining additional leaf tissue below the grazing height to increase photosynthetic capability and accelerate regrowth. The beneficial effects of the higher SR treatments on net pasture accumulation within this study are also consistent with the conceptual model of pasture growth and senescence proposed by Bircham and Hodgson (1983) and indicates that, although pregrazing pasture mass tends to increase within laxly grazed pastures, net pasture accumulation is reduced, as increased quantities of residual stem and decaying material that are less photosynthetically active than younger leaves (Gay and Thomas, 1995; Lee et al., 2007) are contained within the regrown material. Similarly, L'Huillier (1987) reported that whereas total (live and dead) pasture accumulation increased in laxly grazed pastures, green (total less senescent) pasture accumulation was unaffected by grazing severity.

The immediate positive effect of severe defoliation on sward nutritive value (and in particular in ADF, NDF, OMD, and UFL) within both higher SR and more severely defoliated pastures, both individually and collectively, has been reported previously (Stakelum and Dillon, 2007; Macdonald et al., 2008; Peyraud and Delagarde, 2013). The general seasonal effects on sward nutritive value have also been widely reported (Hacker and Minson, 1981; Korte et al., 1984; Coleman et al., 2010). The magnitude of the nutritive value superiority of higher SR pastures in mid-season and autumn within this study is also similar to previous studies. Stakelum and Dillon (1990) reported an increase of 39 g/kg of DM in OMD within leafy vegetative high SR mid-season pastures and Lee et al. (2007) reported an increase of 29 g/kg of DM in OMD within more severely grazed pastures. Likewise, both Stakelum and Dillon (1990) and O'Donovan and Delaby (2008) reported greater OMD values within pastures that were grazed to low relative postgrazing heights and hence had greater proportions of live leaf and less senescent material. Consistent with these previous studies, the current results illustrate the potential for more severe grazing at higher SR to efficiently harvest pastures during the early reproductive stage to arrest the decline in sward nutritive value, typically reported during mid-season (Korte et al., 1984; Gibb et al., 1989; Tuñon et al., 2014). Notwithstanding the beneficial effects of SR treatment on sward nutritive value, the nutritive value within the LSR pastures of the current study was also high relative to previous studies (Stakelum and Dillon, 2007; O'Donovan and Delaby, 2008) and is indicative of the relatively narrow differential in grazing residuals between treatments within this study, particularly dur-

ing spring and autumn. Consequently, whereas many other grazing severity component studies have reported a substantial decline in sward nutritive value and botanical composition within laxly grazed pastures and recommended that such residual material be mechanically removed (Stakelum, 1996), these results indicate that the judicious use of silage conservation after inflorescence may be an effective strategy to correct and maintain pasture nutritive value within LSR pastures and can possibly negate the requirement for additional mechanical intervention (topping). In comparison with the pronounced effect of SR treatment on net pasture accumulation, sward nutritive value was not consistently higher due to the increased grazing severities within this study.

In addition to the increase in net pasture accumulation and improved sward nutritive value at higher SR, the lower postgrazing residual CSH of the MSR and HSR treatments, resulted in an increase in grazing efficiency and grazed pasture utilization within the higher SR treatments, as additional grazing animals consumed an increasing proportion of the available pasture. Similar to previous studies (Ganche et al., 2013a; Tuñon, 2013), the efficiency of pasture utilization under grazing (grazing efficiency; pasture utilized/pregrazing pasture mass >3.5 cm) increased as SR increased within the present study. Although it is widely accepted that an increase in pasture utilization can be achieved by decreasing postgrazing residual CSH (Pérez-Prieto et al., 2011; Ganche et al., 2013b) or increasing SR, or both (McMeekan and Walsh, 1963; Fales et al., 1995; Macdonald et al., 2008), the total quantity of feed utilized (kg of DM/ha) is seldom reported. Within an overall farm systems context, the overall effect of SR treatment on total pasture utilization (kg of DM/ha) is complicated by the differential requirements for grazed pasture between SR treatments, and consequently, the utilization of pasture as conserved pasture silage must also be considered (Fales et al., 1995; Macdonald et al., 2008). Similar to both Valentine et al. (2009) and Farina et al. (2011), grazed pasture utilization and grazing efficiency increased at higher SR and total pasture utilization (grazed plus conserved pasture; kg of DM/ha) was unaffected by SR within systems where surplus pasture was efficiently removed and conserved as silage. Consequently, and similar to Macdonald et al. (2008), total pasture utilization (expressed as a proportion of net pasture utilization) was consistently 0.8 of the net pasture accumulation across all SR treatments. Furthermore, when grazed and conserved pasture utilization were adjusted to incorporate the additional beneficial effects on pasture energy value (UFL content) and pasture utilization efficiency, the total proportional

energy utilization per ha was significantly increased at higher SR (+0.026 and +0.081 for MSR and HSR, respectively).

The detailed measurement methodology adopted in this study allows the accumulated effects of alternate grazing strategies to be accurately quantified over 4 complete grazing seasons. These results indicate that grazing management practices have an important effect on the feed production capability of modern perennial ryegrass pastures for intensive grazing dairy production systems.

CONCLUSIONS

In the range of treatments studied, increased SR in combination with increased grazing severity resulted in grassland pastures of higher productivity characterized by increased annual net pasture accumulation, improved pasture nutritive value, and increased grazed pasture and energy utilization capacity. Furthermore, these results suggest that future grazing research should increasingly consider the longer term effects of consistently imposed grazing management practices within farm systems over multiple grazing seasons to incorporate the potentially cumulative conditioning and adaptive effects on pastures productivity.

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