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Effects of grazing platform stocking rate on productivity and profitability of pasture-based dairying in a fragmented farm scenario

F. Fenger,[1,2,3]* I. A. Casey,[2] C. Buckley,[4] and J. Humphreys[1]
[1]Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Co. Cork, P61 P302 Ireland
[2]Department of Chemical and Life Sciences, South East Technological University, Waterford, X91 K0EK Ireland
[3]Thünen Institute of Organic Farming, 23847 Westerau, Germany
[4]Teagasc, Mellows Campus, Athenry, Co. Galway, H65 R718 Ireland

ABSTRACT

The area adjacent to the milking parlor, accessible for grazing by lactating dairy cows (i.e., the grazing platform [GP]), can be limited on fragmented pasture-based dairy farms. Such farms, with a moderate overall farm stocking rate, typically have a much higher stocking rate of dairy cows on the GP. This study quantified the effects of farm fragmentation on milk and herbage production and profitability in a whole-farm systems-scale study over 3 yr (2017–2019). Four systems, each with an overall farm stocking rate of 2.5 cows/ha but with different grazing platform stocking rates (GPSR), were examined. The proportions of the overall farm area within the GP were 100%, 83%, 71%, and 63% in each of the 4 systems, respectively. Hence, the 4 systems had a GPSR of 2.5, 3.0, 3.5, and 4.0 cows/ha. The GP was used for grazing and silage (ensiled herbage) production, and the non-GP portion of each GPSR system was used solely for silage production. Concentrate supplementation per cow was the same across all GPSR systems; approximately 10% of the annual feed budget. All systems were compact spring-calving with 24 cows per system. We discovered a lower proportion of grazed herbage in the diet with higher GPSR. All silage produced on the non-GP areas was required to support higher GPSR on each of the systems. Annual herbage production and milk production per cow were not different between GPSR systems, resulting in similar milk production per hectare of the overall system area. The economic implications of different GPSR on fragmented farms were modeled in 2 scenarios: (1) quantifying the cost associated with different levels of farm area fragmentation; (2) investigating the optimum GPSR on fragmented pasture-based dairy farms, depending on variable criteria. A greater level of farm fragmentation lowered the profitability of pasture-based dairy production. Costs of production increased with higher GPSR and longer distances between GP and non-GP areas. At a fixed GP area, it was most profitable to increase GPSR up to 4 cows/ha on the GP when milk price was high, land rental price was low, and shorter distance existed between GP and non-GP areas.
Key words: grazing management, pasture-based dairy production, farm fragmentation, profitability, grazing platform stocking rate

INTRODUCTION

It is a common feature of many farms that they are fragmented into more than one parcel of land (del Corral et al., 2011; Lu et al., 2018; Holohan et al., 2021). In Ireland, the majority of dairy farms are fragmented, with an average of 6 parcels of land per farm (Bradfield et al., 2021). The grazing platform (**GP**) is the parcel of land adjacent to the milking parlor that is accessible for grazing by lactating dairy cows. On average the GP represents 42% of the total farm area of dairy farms in Ireland (Bradfield et al., 2021). The abolition of the EU milk quota has led to an increase in milk output in many European countries (Shalloo et al., 2020). In Ireland milk production increased by +47% between 2014 and 2020, mainly driven by an increase in dairy cow numbers and stocking rates on farms (Läpple and Sirr, 2019; CSO, 2021). Hence, the area of the GP and the stocking rate that can be sustained on it have become increasingly important constraints on pasture-based dairy production systems (Dillon et al., 2006; Läpple and Hennessy, 2012; Ramsbottom et al., 2015).

In traditional pasture-based systems in higher latitudes, the calving date and feed demands of the lactating dairy herd are synchronized to coincide with the period of herbage growth. The farm stocking rate is set at a level that attempts to match the herbage production potential of the farm (Roche et al., 2017). Ideally, sufficient herbage for grazing by lactating cows is available during the main grazing season (April to October in Ireland) with minimal inputs of purchased

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*Corresponding author: friederike.fenger@thuenen.de

supplements. Surplus herbage mass in mid-season is harvested and stored as silage to meet winter feed requirements (Dillon et al., 2005). Pasture-based systems are typically almost self-sufficient in home-produced feed. Such systems tend to be the most profitable due to the high proportion of low-cost grazed herbage in the diet (Finneran et al., 2012; Hanrahan et al., 2018; Ruelle et al., 2018).

On fragmented farms, all lactating dairy cows are usually concentrated on the GP, which means that the grazing platform stocking rate (**GPSR**) is typically much higher than the overall farm stocking rate. Non-GP areas are typically used for rearing of replacement heifers and silage production or alternative enterprises such as beef production. These non-GP areas are often underutilized and have considerable potential for increased pasture productivity (O'Donnell et al., 2008). High GPSR results in higher daily feed demand for grazed herbage per hectare. This demand can exceed daily herbage growth rates, particularly during the spring and autumn; hence the need to supplement grazed herbage with silage produced on non-GP areas, which increases feed costs (Finneran et al., 2012; Hanrahan et al., 2018). Furthermore, farm fragmentation also increases costs of production due to lower machinery and labor efficiency, as a consequence of increased travel times between GP and non-GP areas (del Corral et al., 2011; Latruffe and Piet, 2014; Bradfield et al., 2021).

Several previous studies have highlighted the importance of stocking rates for the productivity and profitability of pasture-based systems. Higher stocking rates can increase herbage utilization and milk output per hectare but can also decrease milk production per cow (Macdonald et al., 2008; McCarthy et al., 2011, 2014). Furthermore, higher stocking rates can mean a shorter grazing season and increased need for alternatives to grazed herbage, such as silage, or for purchased feed (Macdonald et al., 2008; Patton et al., 2016). A lower proportion of grazed herbage in the diet and, hence, an increase in the quantity of silage fed to cows, can negatively affect milk production per cow (Dillon et al., 2002; Claffey et al., 2019).

Few studies have quantified the effects of higher GPSR on milk and herbage production and profitability of pasture-based dairy systems. The overall objectives of this study were (1) to determine how GPSR affects herbage production, the length of the grazing season, and milk production where silage produced on non-GP areas is incorporated into the diet of lactating dairy cows to fill feed deficits during the grazing season, along with meeting winter feed requirements; and (2) to identify a potential tipping point where the benefits of higher milk output from the GP are counterbalanced by increased costs associated with fragmentation to (3) determine the optimum GPSR of fragmented pasture-based dairy farms on which the utilization of home-produced feed is ≥90% of total feed requirements.

MATERIALS AND METHODS

Site Description

The experiment was conducted at Solohead Research Farm (52°30′N, 08°12′W, 95 m above sea level) in southwest Ireland. Soils on the farm include poorly drained Gleysols (90%) and Podzols (10%) with a clay loam texture (36% sand and 28% clay) in the A1 horizon overlaying Devonian sandstone at a depth of 5 to 10 m below ground level (FAO, 2015). Topographic relief causes variation in shallow groundwater, with the water table depth ranging from 0 to 2.2 m below ground level. Much of the farm area is seasonally wet or waterlogged. The local climate is humid temperate oceanic, with a long potential growing season (~10 mo). The land has been under permanent grassland with predominantly perennial ryegrass and white clover swards for well over 50 yr, and approximately 5% of the grassland was renovated each year.

Experimental Systems, Setup, and Design

The experiment was carried out over 3 consecutive years from 2017 to 2019. Four systems (each 9.75 ha) were established, with each supporting 1 herd of 24 spring-calving dairy cows at an overall stocking rate of 2.5 cows/ha. Differing proportions of each system area were available as GP, resulting in 4 different GPSR systems, of 2.5 (**GP2.5**), 3.0 (**GP3.0**), 3.5 (**GP3.5**), and 4.0 (**GP4.0**) cows/ha (Table 1). The GP area was available for grazing and silage (ensiled herbage) production, whereas the non-GP areas on the 3 fragmented systems (GP3.0, GP3.5, and GP4.0) were used solely for silage production.

Ethical approval for this study was sought from Teagasc Animal Ethics Committee (TAEC) and received as TAEC 146-2017. All 4 herds used in the experiment were compact spring-calving, with a mean calving date of February 19. The herd is composed of cows with varying degrees of cross-breeding between Irish Holstein and Jersey. Each spring all cows were divided into 4 main groups based on lactation number (1, 2, 3, and ≥4) and then subdivided into subgroups of 4 on the basis of calving date. One cow from each subgroup was randomly assigned to each herd. Herds were randomly assigned to each of the GPSR systems. The experimental area was divided into 6 blocks based on soil type and drainage status before the beginning of the experiment. Each block was divided into 4 paddocks. One paddock

Table 1. Effects of grazing platform stocking rate (GPSR) system on length of the grazing season and stocking densities during the 3 yr of the experiment

Item	GPSR system[1]				
	GP2.5	GP3.0	GP3.5	GP4.0	SEM[2]
Overall system stocking rate (cows/ha)	2.5	2.5	2.5	2.5	
Overall system area available as grazing platform (%)	100	83	71	63	
Grazing platform stocking rate (cows/ha)	2.5	3.0	3.5	4.0	
Start of the grazing season					
2017	Mar 01	Mar 01	Mar 01	Mar 01	
2018	Feb 21	Feb 22	Mar 09	Mar 20	
2019	Feb 05	Feb 05	Feb 05	Feb 05	
End of the grazing season					
2017	Nov 14	Nov 14	Nov 14	Nov 14	
2018	Nov 23	Nov 23	Nov 23	Nov 16	
2019	Nov 20	Nov 12	Nov 10	Nov 09	
Days at pasture[3]					
2017	239[a]	230[b]	214[c]	213[c]	2.1***
2018	231[a]	216[b]	199[c]	183[d]	1.0***
2019	260[a]	249[b]	235[c]	218[d]	3.0***
Mean	243[a]	232[b]	216[c]	205[d]	9.7***
Mean calving date					
2017	Feb 19	Feb 19	Feb 21	Feb 19	4.2[NS]
2018	Feb 25	Feb 26	Feb 25	Feb 24	4.5[NS]
2019	Feb 13	Feb 14	Feb 13	Feb 14	4.5[NS]
Mean	Feb 19	20 Feb	Feb 20	Feb 19	4.6[NS]
Monthly stocking densities on grazing platform when removal of areas harvested for silage were accounted for (cows/ha)					
February to March	2.49[d]	3.03[c]	3.52[b]	4.02[a]	0.01***
April to June	3.65	3.89	3.94	4.17	0.126[NS]
July to August	2.87[c]	3.37[b]	3.64[b]	4.08[a]	0.106**
September to December	2.47[d]	3.01[c]	3.52[b]	4.02[a]	0.005***
Mean	2.84[d]	3.29[c]	3.64[b]	4.06[a]	0.042***

[a–d]Mean values in the same row with different superscripts differ between GPSR systems ($P < 0.05$).

[1]GPSR, cows per hectare: GP2.5 = 2.5 cows/ha, GP3.0 = 3 cows/ha, GP3.5 = 3.5 cows/ha, GP4.0 = 4 cows/ha.

[2]SEM = standard error of GPSR system means.

[3]When herbage mass was too low to sustain herd demand during the grazing season, cows were fed silage indoors.

**$P < 0.01$; ***$P < 0.001$; NS: $P > 0.05$.

from each block was randomly assigned to each GPSR system, resulting in 6 paddocks (9.75 ha) per system. In the fragmented systems (GP <100%), paddocks were randomly assigned to either GP or non-GP areas, resulting in the following number of paddocks on the GP per system: 6 (GP2.5); 5 (GP3.0); 5 (GP3.5); and 4 (GP4.0). Similar studies at the site (Phelan et al., 2013; Tuohy et al., 2015; Fenger et al., 2022) indicated that the study design is sufficient to give high probability of detecting a significant difference between the GPSR systems.

Management of the Grazing Herds

All GPSR systems were managed according to the same grazing and cow management guidelines in a whole-farm system approach with equitable management rules to remove bias toward one GPSR system over another (Macdonald and Penno, 1998). The grazing management decision rules were based on the goal of matching daily herbage DM allowance per herd with herbage DM growth rate and on the principle of maximizing grazed herbage in the diet. Cows were turned out to pasture approximately 3 d after calving and dried off and housed in late November and December. Cows were also housed during or at the end of lactation depending on ground conditions and availability of herbage for grazing (see below). Strip grazing with temporary fencing was practiced in all GPSR systems. Each herd was moved to the next strip when a post-grazing sward height of 4 cm was reached (as measured with a rising plate meter). Herbage mass available for grazing (>4 cm above ground level [**AGL**]) in each GPSR system for the purposes of feed budgeting was measured once per week during the grazing season. On each occasion, compressed sward height was recorded using a Filips rising plate meter (Grasstec, Mallow, Cork, Ireland) on each paddock. Herbage height >4 cm AGL was converted into herbage DM (kg of DM per hectare) using a sward density of 240 kg of DM per hectare per centimeter. Stocking density on the GP in each GPSR system was adjusted on a weekly basis in line with average herbage DM daily growth rates and a daily allowance of 16 kg of herbage DM per cow per day. Excess herbage DM mass on the GP of each GPSR system was identified and removed as silage throughout the grazing season (see below). Hence, average herbage DM mass on each GPSR system was managed during the main grazing season (April to August) to set up a feed wedge with a pregrazing herbage DM mass of between 1,400 and 1,600 kg/ha (>4 cm AGL), with an average herbage DM mass on the area in grazing rotation in that week within the range of 700 to 800 kg/ha.

Approximately 95% of the feed (grazed and ensiled herbage) was produced within the system boundary (overall area). A combination of silage and concentrates was fed in the early spring and late autumn, targeting a maximum mean concentrate input of ≤10% of the annual feed budget on a DM basis. In early lactation (February to April), cows received up to 6 kg of concentrate per cow per day. During the rest of the grazing season (from May onward), between 0 and 6 kg of concentrate per cow per day was fed, depending on availability of herbage mass for grazing. Concentrate supplementation was used only when a feed deficit occurred in all GPSR systems. Concentrate supplementation per cow was the same across all GPSR systems. Feed deficits within individual GPSR systems were filled by feeding silage produced within each GPSR system.

During the grazing season, cows were housed when ground conditions were too wet (vol. soil moisture >60%) or when herbage mass was too low to sustain herd demand, which occurred when herbage growth rates were below herd demand and pregrazing herbage mass was <1,000 kg DM/ha. Under such circumstances, cows were housed either at night only or day and night and received silage ad libitum and concentrates when necessary, as described above. Cows turned out to pasture full-time were allocated no silage. Mean composition of silage fed to dry cows during the experiment (±SD) was 86 ± 12.2 g/kg ash, 666 ± 45.3 g/kg DM digestibility, 129 ± 15.0 g/kg CP, and 0.73 ± 0.05 unité fourragère lait (**UFL**; Jarrige, 1989). Mean composition of silage fed to lactating cows was 88 ± 11.5 g/kg ash, 712 ± 44.9 g/kg DM digestibility, 146 ± 24.1 g/kg CP, and 0.80 ± 0.06 UFL. Energy content of the concentrate feed (35% beet pulp, 26% barley, 26% maize gluten, and 12% soybean meal) was 0.95 UFL.

The end of the grazing season (cows housed for the winter) was determined by an average herbage mass of 500 kg DM/ha across all the paddocks in each GPSR system. Between August and the end of the grazing season, silage or zero-grazed herbage harvested off the non-GP areas (see below) was introduced to the diets of cows in each herd to (1) maintain a similar average herbage cover per herd per week during this timeframe and (2) achieve similar closing dates and average closing herbage covers in all GPSR systems at the end of the grazing season. Cows were fed silage or zero-grazed herbage indoors and were housed for this purpose between 1 and 4 d/wk, depending on the feed budget for each herd. This approach maintained at least some grazed herbage in the diet of each herd during the autumn and early winter. Furthermore, there were similar average herbage covers in all GPSR systems during the closed period over the winter. These management decisions were also influenced by rainfall and volumetric soil moisture content, as outlined above.

Excess herbage mass on the GP of each GPSR system was harvested as silage. This was generally the case when herbage growth rate was substantially higher than feed demand of each herd, resulting in pregrazing herbage masses >1,600 kg DM/ha between April and July and >2,000 kg DM/ha from August onward. Hence, areas and times of harvests differed between GPSR systems. On the non-GP areas, silage was harvested 3 times per year (mid-May, mid-July, and end of August), and herbage mass was harvested and fed directly to housed cows (zero-grazed) during October and November. The zero-grazed herbage was included in the diet depending on the feed budget of each of the herds on the 3 fragmented systems (GP3.0, GP3.5, and GP4.0) as described above.

Mean composition of zero-grazed herbage fed during the experiment (±SD) was 114 ± 15.4 g/kg ash, 822 ± 40.1 g/kg organic matter digestibility (**OMD**), and 224 ± 33.5 g/kg CP.

Each GPSR system received an annual nitrogen input of 280 kg N/ha in the form of mineral fertilizer, which was applied in the form of urea from February to April (35%) and in the form of calcium ammonium nitrate from May to September (65%), evenly distributed at monthly intervals. On average, each GPSR system received an annual input of 65 kg N/ha in the form of dairy cow slurry across all paddocks. Slurry of all GPSR systems was stored together. The annual proportion of annual dairy cow slurry applied to non-GP paddocks was 41% (GP3.0), 56% (GP3.5), and 65% (GP4.0). The remaining proportion, and all slurry in GP2.5, was applied on grazing paddocks, typically during February and March.

Measurements

Meteorological Data. Soil temperature (°C; at soil depth of 10 cm), rainfall (mm), wind speed (m/s) and direction (°), and solar radiation (J/cm) were measured at an automated weather station on the research farm. Volumetric soil moisture content (m^3/m^3) was measured daily at the weather station in the upper 5 cm of the soil using an ML2x soil moisture measurement kit (Delta-T Devices Ltd., Burwell, Cambridge, UK).

Herbage Production, Utilization, and Nutritive Value of the Sward. Exclusion plots (13 × 3 m) surrounded by electrified wire were set up in each GP paddock. Plots were moved 2 times per year to an adjacent area. Before each grazing event, pregrazing herbage mass was determined by harvesting 2 strips (1.2 × 10 m) of herbage using an Etesia Hydro 124DS Lawnmower (Etesia UK Ltd., Shenington, Oxon, UK) set at a cutting height of 4 cm AGL, one strip from inside the exclusion plot and one outside, adjacent to the exclusion plot. All mown herbage from each strip was collected and weighed. A 100-g (fresh weight) subsample from each strip was taken and dried for 16 h at 90°C for determination of DM content, which was then used for determination of pregrazing herbage mass (kg DM/ha). Herbage masses of harvests for silage were determined likewise. Total annual herbage production for each paddock was the sum of herbage mass from pregrazing and presilage harvests of herbage from inside each exclusion plot. Herbage growth rate was calculated for each cut by dividing herbage mass by regrowth interval.

A 100-g subsample of herbage from the strip cut outside of the exclusion plot was freeze-dried and milled through a 0.2-mm sieve before analyses for ash content (550°C muffle furnace for 12 h), CP (N content; Leco 528 auto-analyzer, Leco Corp., St. Joseph, MI), NDF (Van Soest, 1990), and in vitro OMD as described by Morgan et al. (1989).

When silage was fed, it was sampled on a weekly basis throughout the experiment by taking a grab sample of approximately 100 g before feeding, which was then analyzed for ash, OMD, and CP using near infrared spectroscopy (model 6500, Foss-NIR System, Hillerød, Denmark).

Days at Pasture. The length of the grazing season was measured in terms of days at pasture per cow. One day at pasture was defined as when each lactating cow was out day and night, and one half-day when each lactating cow was out only by day. Nonlactating cows were kept indoors before calving in spring and after the end of lactation. Furthermore, days or half-days when cows were kept indoors during lactation, for reasons outlined above, were also taken into account when accounting for the annual number of days at pasture per cow.

Feed Intake, Milk Production, BW, and BCS. The amount of concentrate fed per cow was recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland). Silage fed was measured when the cows were housed based on the difference between what was fed and discards. Intake of grazed herbage for each cow was estimated as the difference between net energy provided from silage and concentrates and the net energy requirements for milk production, maintenance and pregnancy (Jarrige et al., 1986; Jarrige, 1989; O'Mara, 1996). Requirements for activity and walking were included in requirements for maintenance as an increase of 10% for each day indoors and 20% for each day at pasture, as described by Shalloo et al. (2004).

Cows were milked at 0730 and 1530 h daily throughout lactation. Milk yield from each cow was recorded at each milking, and milk composition was measured twice weekly from the morning and evening milking using a Milkoscan 203 (Foss Electric DK-3400, Hillerød, Denmark). The liveweight of each cow was recorded at 2-wk intervals using a weighing scale and the Winweigh software package (Tru-Test Limited, Auckland, New Zealand). The BCS (Edmonson et al., 1989) of each cow was recorded at 2-wk intervals throughout each year.

Statistical Analysis

The effect of GPSR system on herbage and milk production variables was determined using a mixed model, with GPSR system as a fixed effect and year and block as random effects in an ANOVA using the MIXED procedure in SAS 9.4 (SAS Institute Inc., 2014). Individual paddocks were considered the experimental units for field-based variables, and individual cows were considered the experimental units for animal-related variables. For measurements that were calculated at GPSR system basis, year was used as the replicate: herbage mass harvested as pre-silage or pre-grazing cuts, monthly stocking densities on the GP when areas closed for silage were accounted for, and the proportion of GP area harvested for silage. Linear and quadratic effects of GPSR were also evaluated in a general linear model by including GPSR as a continuous variable in the GLM procedure in SAS. Means are presented as least squares means ± standard error of the mean.

Economic Analysis

A 2-step (scenarios 1 and 2) farm modeling approach was employed to investigate the economic implications of farm area fragmentation and altering GPSR.

Scenario 1. Scenario 1 quantified costs associated with different degrees of farm area fragmentation. This scenario was based on the design of the experiment in the present study with the proportion of overall system area available as GP in the 4 GPSR systems (Table 1). Overall farm area (50 ha) and herd size (125 cows) were fixed across all modeled GPSR (2.5, 3.0, 3.5, and 4.0 cows/ha). Profitability of each GPSR was determined using a whole-farm spreadsheet model similar to those described by Fenger et al. (2022) and Humphreys et al. (2012). The 3-yr mean of the biological data of each GPSR system was used considering the statistical analysis of the data from the GPSR systems experiment; where no statistical difference occurred between GPSR systems, the mean of the GPSR systems was used in the economic model to ensure that differences caused by residual errors did not lead to differences in profitability. Where a significant linear relationship occurred between a variable and GPSR, the regression estimates were used to calculate the variable for each GPSR step in the economic model. Hence, no ANOVA was undertaken on the results of the economic analysis.

All costs and input and output prices were set to be representative of prices during the time of the experiment. Dairy replacements were reared at a total cost of €947 per animal, based on a cost of €1.30/d per animal (Teagasc, 2013a). Likewise, surplus calves were sold at approximately 3 wk of age at €250 per female calf and €50 per male calf. Culled cows were sold off the farm at the end of lactation in December at €550 per cow. Dairy cow replacement rate was 21%. Silage was produced on the GP and, where applicable, on non-GP areas to meet winter feed requirements. Surpluses and deficits were calculated as the difference between preserved and consumed silage per GPSR system. Surpluses of silage were sold each year, and deficits were met by purchased silage at €130/t of DM.

Basic annual labor requirement for all GPSR was set as 26.7 h per cow per year, the national average of spring-calving pasture-based dairy farms in Ireland (Donnellan et al., 2020). Labor requirements were assumed to be higher in systems where cows spent more time indoors and needed more management: feeding of silage, cleaning cubicles, and slurry application (compared with no feeding while at pasture). Hence, labor requirements increased by 2 h/d for each day that cows were housed longer, relative to the system with the highest number of days at pasture (2.5 cows/ha). The amount of slurry produced was calculated for each GPSR based on days housed, with 0.06 m^3 slurry produced per cow per day spent indoors (Teagasc, 2013b). For the economic interpretation, secondary data resources were used for input and output prices, such as the Central Statistics Office of Ireland (CSO, 2020), Teagasc National Farm Survey (Donnellan et al., 2020), Teagasc Management Data for Farm Planning (Teagasc, 2013b), and Contracting Charges Guide (FCI, 2019; Table 2). Costs of contracting charges were assumed to increase with increasing distance between GP and non-GP areas. Hourly rates for the transport of slurry, silage, and zero-grazed herbage (Table 2) were included in the calculation at a travel speed of 25 km/h To quantify the effects of varying distance between GP and non-GP areas, a sensitivity analysis at 2-, 10-, and 20-km distance was conducted. Estimates for fixed costs were based on the results of the Teagasc National Farm survey (Donnellan et al., 2020), due to unavailability of representative fixed costs for each GPSR. Based on per-hectare of overall farm area, a cost of €858/ha was used in all GPSR, which included the costs of car, electricity, phone, interests, machinery use and depreciation, buildings maintenance and depreciation, land improvement maintenance and depreciation, and other miscellaneous fixed costs such as insurance and advisory fees.

Table 2. Economic data used in the economic analysis

Item	Value
Concentrate feed (€/t)	280
Fertilizer urea (€/t)	360
Fertilizer calcium ammonium nitrate (€/t)	260
Labor (€/h)	15
Veterinary and artificial insemination (€/cow)	90
Silage harvest (€/bale)	20
Silage transport[1] (€/h)	63
Slurry spreading and transport (€/h)	65
Zero-grazing (€/load[2])	65
Fertilizer spreading (€/t)	37

[1]With 17 bales per load.

[2]At 1.2 t of DM per load.

Profitability was expressed as net profit, which was calculated as total receipts (milk, livestock) less variable (feed, fertilizer, veterinary, artificial insemination, and contractor charges) and fixed costs (as outlined above). No farm subsidy payments were included in the calculation. All land area was considered to be owned. Opportunity costs of land were included as the difference between the returns on the best forgone option and the returns on the chosen option. The current land rental price at the time of the study (€450 per ha; Coulter et al., 2020) was defined as the best forgone option. If net profit per hectare (returns on chosen option) was lower than income from land rental (returns on best forgone option), the difference was applied as opportunity costs. In this way, opportunity costs of land represented the cost of not choosing the better alternative; in this instance, renting out the land for a higher profit per hectare compared with that generated by milk production. The analysis was conducted at a base milk price of €0.29/L with a reference content of 33 g/kg milk protein and 36 g/kg milk fat at a relative price ratio of 1:1.5 (fat:protein) in a multiple-component payment system (A + B − C; Geary et al., 2010).

Scenario 2. Scenario 2 was designed to identify the optimum GPSR on pasture-based dairy farms at a fixed degree of fragmentation. Hence, this scenario tested the effect of increasing GPSR on a farm with a fixed GP size, to evaluate the extent to which higher costs associated with farm area fragmentation were counterbalanced by higher milk outputs associated with a higher number of dairy cows. Fragmentation was fixed at 63% of the farm area available as GP (31 ha GP) in all 4 GPSR. Herd size was dictated by GPSR and increased from 78 cows (2.5 cows/ha) to 125 cows (4.0 cows/ha) per farm. Overall farm stocking rate on all GPSR was 2.5 cows/ha. The remaining land on non-GP paddocks was assumed to be rented out at the land rental price outlined above.

Profitability in scenario 2 was calculated in the same manner as for scenario 1 with following additions: (1) income was generated from land rental where applicable; (2) electricity costs were assumed to increase with higher cow numbers, due to factors such as operating milking machines, and were calculated at a rate of 1.15 cent/L of milk produced; and (3) increasing herd size incurred costs for expansion in the form of additional animals, new buildings, and associated interest costs. The system with 2.5 cows/ha served as the baseline for the calculation of expansion costs. Where a sufficient number of replacement heifer calves were not born on the farm, requirements for additional dairy cows compared with the baseline were filled by rearing additional replacements or a combination of additional replacements and in-calf dairy heifers, purchased at €1,200 per animal. The total annual costs for additional animals consisted of the net present value of the animals (value of animal minus value of culled cow divided by a lifetime period of 5 yr; Schulz and Gunn, 2016) and annual interest cost for a loan for the total costs of additional animals (annual interest rate of 6.45% and loan repayment period of 5 yr; UlsterBank, 2021). Total costs for new buildings (winter housing, including slurry storage, additional silage storage space, milking parlor extension, larger milk tank, expansion of farm road infrastructure, paddock water system, and fencing) were calculated at €4,500 per additional cow (Tuohy et al., 2017). Annual costs for new buildings consisted of annual depreciation for the total value of the new buildings over a period of 20 yr and annual interest cost for a loan for the total costs of new buildings (annual interest rate of 4.2% and loan repayment period of 15 yr; UlsterBank, 2021). The marginal benefit was estimated from the additional benefit in net profit per farm that arose from an increase in the number of cows. For each GPSR (for example, 3.5 cows/ha) this was determined based on the additional net profit per farm compared with the lower GPSR (for example, 3 cows/ha) divided by the additional number of dairy cows per farm compared with the lower GPSR (i.e., 3 cows/ha). Similar to scenario 1, the influence of distance between GP and non-GP areas was evaluated in a sensitivity analysis. To further investigate the effects of varying land rental and base milk prices, a sensitivity analysis was carried out across 3 different land rental prices (€300, €450, and €600/ha) and 3 different base milk prices (€0.24, €0.29, and €0.34/L). Linear and quadratic effects of GPSR on profitability were evaluated in a general linear model by including GPSR as a continuous variable in the GLM procedure in SAS.

RESULTS

Meteorological Data and Grazing Season

Relatively high rainfall in February and March in 2017 (Figure 1a) resulted in a relatively late turnout date at the start of the grazing season in all GPSR systems in 2017 (Table 1). In contrast, the exceptionally mild winter of 2018/19 (Figure 1b) allowed a much earlier turnout date in 2019. The turnout date in 2018 differed between GPSR systems, with later turnout dates at higher GPSR (Table 1). The 11-d difference in the end of the grazing season between GPSR systems in 2019 was influenced by very high rainfall in October and November 2019 (Figure 1a). An exceptionally prolonged period of drought conditions and high temperatures in 2018 (Figure 1) affected herbage growth during the summer months (Figure 2).

We found a significant effect of year on days at pasture per cow ($P < 0.001$): Across all GPSR systems, 2018 had the lowest mean days at pasture (207 d/cow) and 2019 the highest (240 d/cow). In all years, days at pasture per cow decreased with higher GPSR (Table 1). For each increase in GPSR of 1 cow/ha, days at pasture per cow per year decreased ($P = 0.01$) by 26 ± 7.98 d (18 in 2017, 32 in 2018, and 27 d in 2019).

Herbage Production and Nutritive Value of Herbage

We detected no effect of GPSR system on pre-grazing herbage mass, postgrazing sward height, rotation length, herbage growth rate, or nutritive value of the grazed herbage on the GP (Table 3). Total herbage mass harvested (pre-grazing and harvests for ensiling) was not different between GPSR systems on either the GP (mean: 15.2 t DM/ha, SEM 1.27, $P = 0.99$) or on the overall system area (GP + non-GP paddocks; 15.4 t DM/ha, SEM 0.82, $P = 0.94$, Table 3). On the non-GP paddocks, mean total herbage production was 15.9 t DM/ha, with 13.9 t DM/ha harvested for silage and 2.1 t DM/ha harvested as zero-grazed herbage. Total herbage production on the overall system area was different between years, with the highest yield in 2017 (16.6 t DM/ha), intermediate in 2019 (15.6 t DM/ha), and lowest in 2018 (14.0 t DM/ha, SEM 0.30, $P < 0.01$). This was similar on the GP area.

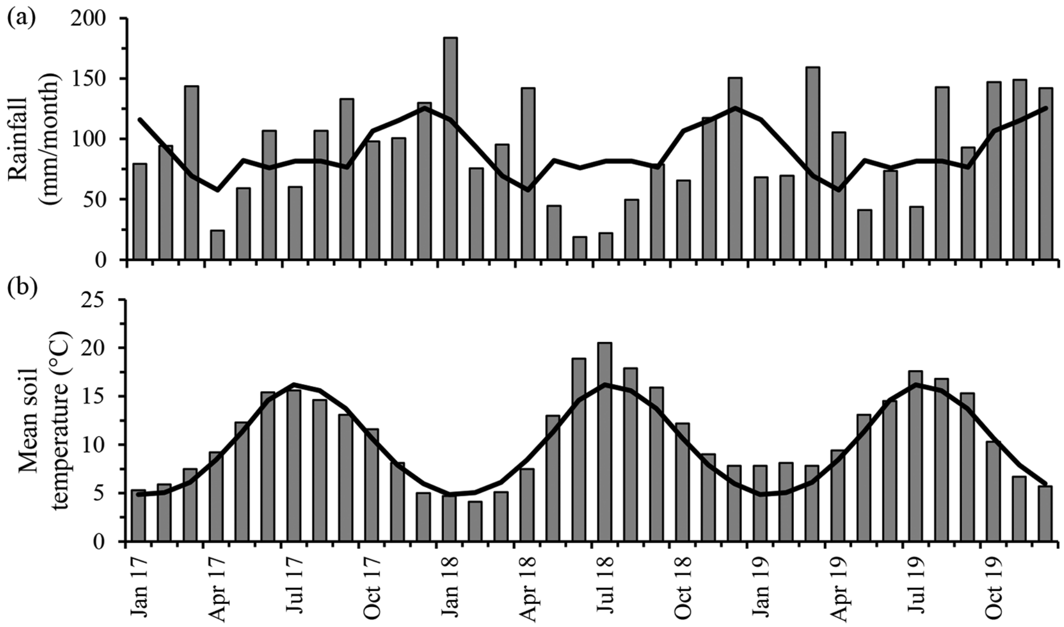

Figure 1. (a) Monthly rainfall (mm) and (b) mean monthly soil temperature (°C, below 10-cm soil surface) during the study between 2017 and 2019 (gray bars) compared with 15-yr average (black line).

Less herbage mass was harvested for silage per hectare of GP with higher GPSR ($P = 0.001$, Table 3). From the overall system area, more herbage mass was harvested for silage with higher GPSR ($P = 0.01$), mainly from the non-GP paddocks. On average over the 3 yr, the effect of GPSR on herbage mass harvested for silage was linear ($P = 0.001$), with 2.1 ± 0.46 t DM/ha less harvested from the GP area and 1.6 ± 0.37 t DM/ha more harvested from the overall system area with each increase of 1 cow/ha of GP. No difference was detectable between years in herbage mass harvested pre-grazing at low GPSR but a large variation between years at high GPSR; in 2018 we found no effect ($P = 0.63$) of GPSR system on herbage mass harvested pre-grazing on the GP area, whereas in 2019 herbage mass harvested pre-grazing increased linearly ($P = 0.03$) with increasing GPSR.

Figure 2. Weekly herbage growth rate (3-wk rolling average) at Solohead Research Farm in 2017 (short dash), 2018 (dotted line), and 2019 (dash dot) compared with average of the previous 14 yr (solid line).

Table 3. Effects of grazing platform stocking rate (GPSR) system on annual herbage production and nutritive value of grazed herbage (mean of 3 yr)

Item	GPSR system[1]				
	GP2.5	GP3.0	GP3.5	GP4.0	SEM[2]
Pregrazing herbage mass[3] (kg DM/ha)	1,695	1,614	1,820	1,709	118.5[NS]
Postgrazing sward height (cm)	4.75	4.77	4.55	4.66	0.262[NS]
Rotation length (d)	27.9	27.5	27.9	28.0	2.27[NS]
Nutritive value of the grazed herbage (g/kg DM)					
CP	232	235	238	233	12.2[NS]
Ash	118	113	110	116	4.7[NS]
NDF	415	417	424	411	15.1[NS]
OM digestibility	812	808	813	819	8.3[NS]
Herbage mass harvested on the grazing platform (t DM/ha)					
Harvested for ensiling	4.5[a]	3.4[a]	2.2[b]	1.3[b]	0.58**
Harvested pregrazing	10.8	11.9	13.1	13.8	0.92[NS]
Total	15.2	15.4	15.3	15.2	1.27[NS]
Herbage mass harvested on the overall system area[4] (t DM/ha)					
Harvested for ensiling[5]	4.5[c]	5.7[b]	6.3[ab]	7.0[a]	0.44**
Harvested pregrazing	10.8	9.8	9.2	8.5	0.59[NS]
Total	15.2	15.5	15.5	15.5	0.82[NS]

[a–c]Mean values in the same row with different superscripts differ between GPSR systems ($P < 0.05$).

[1]See Table 1 for a description of the GPSR systems.

[2]SEM = standard error of GPSR system means.

[3]>4 cm above ground level.

[4]Grazing platform + nongrazing platform paddocks.

[5]Including zero-grazed herbage.

**$P < 0.01$; NS: $P > 0.05$.

Feed Intake

We detected a significant effect of year on the components of the diet (intake of concentrates, silage, and grazed herbage) of dairy cows across all GPSR systems ($P < 0.001$): in 2018 average intake of silage (2044 kg DM per cow) and intake of concentrate feed (837 kg DM per cow) was highest. In 2019 average intakes of silage (1,516 kg DM per cow) and concentrate feed (410 kg DM per cow) were lowest. The GPSR system affected the intake of grazed herbage and silage in all years except for 2017 ($P < 0.001$, Table 4). Intake of grazed herbage decreased while intake of silage increased with higher GPSR. In 2017 we found no detectable difference in the intake of grazed herbage between GPSR systems. The majority of the differences in components of the diet between GPSR systems occurred between August and November of each year (Figure 3).

Intake of grazed herbage per hectare of GP increased ($P = 0.04$) by 1,926 ± 812.1 kg DM/ha for each increase in GPSR of 1 cow/ha. The amount of silage DM fed per cow during lactation increased with higher GPSR (684 [GP2.5], 830 [GP3.0], 1,010 [GP3.5], and 1,154 kg [GP4.0], SEM 199.8, $P < 0.001$). The increase in silage fed during lactation with each increase in GPSR of 1 cow/ha was highest in 2018 (410 ± 11.8 kg DM per cow, $P < 0.001$) and lowest in 2017 (225 ± 26.3 kg DM per cow, $P = 0.01$).

Milk Production

We found no effect ($P > 0.05$) of GPSR system on milk yield per cow, milk composition, BW, BCS, or DIM (Table 5). No difference ($P > 0.05$) was detected in daily milk yield and daily milk solids yield between GPSR systems for each week of lactation (data not shown).

Milk and milk solids yield per hectare of GP increased linearly with higher GPSR ($P < 0.01$). On average over the 3 yr of the study, this was an increase of 5,686 ± 357.6 kg/ha of milk and 470 ± 26.1 kg/ha of milk solids for each increase in GPSR of 1 cow/ha of GP. Milk production per hectare of overall system area was not affected by GPSR system (annual milk yield 14,790 kg/ha, SEM 324.4, $P = 0.75$, annual; milk solids yield 1,218 kg/ha, SEM 22.0, $P = 0.74$).

Economic Analysis

At the medium price levels (milk price of €0.29/L, land rental price of €450/ha) and a distance of 2 km between GP and non-GP paddocks, gross output was the same across all GPSR (Table 6) due to lack of effect of GPSR system on milk production per cow. The higher total costs in each of the fragmented systems (GPSR >2.5 cows/ha) compared with the nonfragmented system (2.5 cows/ha) were caused by higher variable costs

Table 4. Effects of grazing platform stocking rate (GPSR) system on feed intake during the 3 yr of the experiment

Annual feed intake (kg DM per cow)	GPSR system[1]				
	GP2.5	GP3.0	GP3.5	GP4.0	SEM[2]
Grazed herbage					
2017	3,324	3,322	3,198	3,134	82.4
2018	2,565[a]	2,395[b]	2,319[b]	1,961[c]	83.9***
2019	3,390[a]	3,212[b]	3,009[c]	2,857[c]	92.0***
Mean	3,093[a]	2,976[b]	2,842[c]	2,651[d]	301.1***
Silage[3]					
2017	1,300[c]	1,426[b]	1,600[a]	1,617[a]	29.3***
2018	1,733[d]	1,932[c]	2,166[b]	2,347[a]	33.8***
2019	1,111[d]	1,237[c]	1,362[b]	1,563[a]	29.4***
Mean	1,381[d]	1,532[c]	1,709[b]	1,842[a]	220.7***
Concentrate					
2017	494	486	476	491	18.0[NS]
2018	838	840	837	835	12.6[NS]
2019	413	408	411	409	14.3[NS]
Mean	582	578	574	578	131.9[NS]

[a–d]Mean values in the same row with different superscripts differ between GPSR systems ($P < 0.05$).

[1]See Table 1 for a description of the GPSR systems.

[2]SEM = standard error of GPSR system means.

[3]Including zero-grazed herbage.

***$P < 0.001$; NS: $P > 0.05$.

(84% of difference in total costs) and, to a lesser extent, by higher labor costs (16% of difference; Table 6). The majority of the higher variable costs were feed-related costs (silage purchase, harvest, and transport, and zero-grazing), which accounted for 62% of the difference in variable costs compared with the system with 2.5 cows/ha. The remainder of the difference comprised higher slurry spreading and transport costs. At the distance of 2 km, these proportions were very similar across all GPSR. Labor requirements increased from 26.7 (2.5) to 27.3 h per cow per year (4.0 cows/ha) due to more time spent indoors. As a result, net profit decreased linearly ($P < 0.001$) with higher GPSR, by €4,995 ± 60 per farm or €100 ± 1 per hectare for each 1-cow/ha increase in GPSR (2-km distance).

The increase in costs with longer distances between GP and non-GP paddocks was steeper at higher GPSR with a smaller GP (Figure 4). Hence, total costs per hectare increased ($P < 0.001$) by €5.8 at 3.0 cows/ha, whereas total costs per hectare increased ($P < 0.001$) by €15.9 at 4.0 cows/ha with each additional kilometer between GP and non-GP paddocks. The proportion of the increase in total costs from 2.5 to 4.0 cows/ha caused by transport costs (for silage, slurry, and zero-grazing) was 21% at 2-km distance and 73% at 20-km distance. Nonetheless, net profits per hectare with 10- and with 20-km distance between GP and non-GP paddocks were greater than the land rental price in all GPSR (Table 6).

In scenario 2, gross output increased linearly ($P < 0.001$) with higher GPSR by €62,710 per farm or €1,254 per hectare for each increase in GPSR of 1 cow/ha (milk price of €0.29/L, Table 7), due to a higher number of cows and, hence, more milk output. Total costs were higher with higher GPSR; compared with the baseline (2.5 cows/ha) there were higher variable costs (47% of increase in total costs compared with the system at 2.5 cows/ha), higher labor costs (23%), higher fixed costs (4%), and higher expansion costs (26%, Table 7). Higher variable costs were caused by feed-related costs (concentrate, silage, and zero-grazing, 43%), animal-related costs (rearing replacements, artificial insemination, and veterinarian, 33%), fertilizer and reseeding (13%), and slurry-related costs (spreading and transport; 11% of increase in variable costs compared with the system at 2.5 cows/ha). At a distance of 2 km, these proportions were very similar across all GPSR.

The relationship between GPSR (x) and (1) total costs per hectare (y) and (2) net profit per hectare (y) was improved with the addition of a quadratic function ($P < 0.01$). The increase in total costs was larger with higher GPSR ($y = 24x^2 + 1025x - 104$). Likewise, the increase in net profit was smaller with higher GPSR ($y = -24x^2 + 228x + 555$). This is also indicated by the lower marginal benefit per each additional cow with higher GPSR (Table 7).

Milk price showed the greatest influence on net profit in the sensitivity analysis. At the high milk price, a higher GPSR (up to 4.0 cows/ha) was always more profitable compared with the system at 2.5 cows/ha (Supplemental Figure S1; https://doi.org/10.6084/m9.figshare.23452286.v3; Fenger, 2023). At the low milk

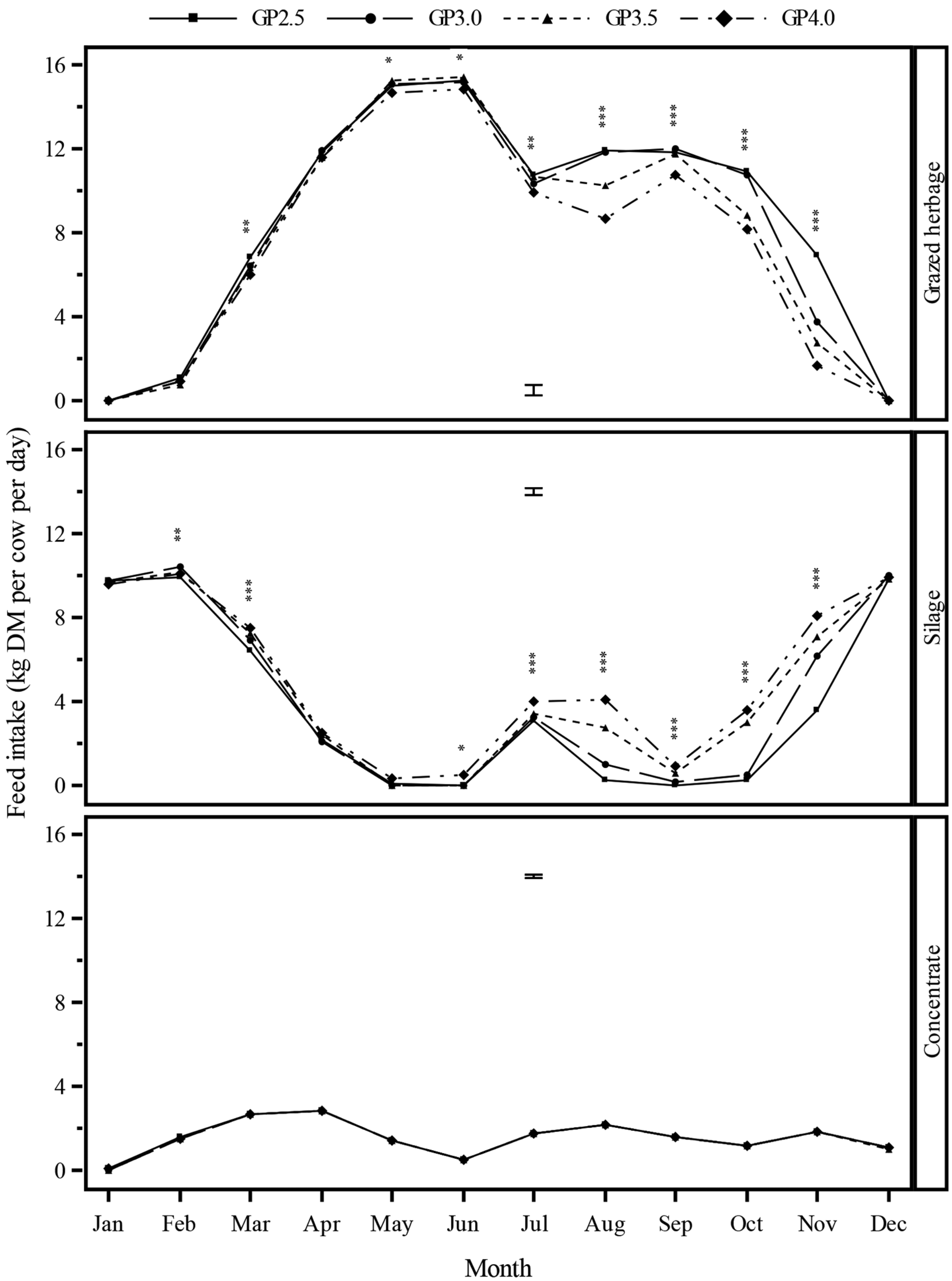

Figure 3. Effects of month and grazing platform stocking rate (GPSR) system (GP2.5, GP3.0, GP3.5, GP4.0) on 3-yr mean daily feed intake as grazed herbage ($P < 0.001$), silage (including zero-grazed herbage; $P < 0.001$), and concentrates ($P = 0.99$; see Table 1 for a description of the GPSR systems). Differences between GPSR systems within a month are indicated with *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. Error bars show the standard error of the interaction between month and GPSR system mean.

Table 5. Effects of grazing platform stocking rate (GPSR) system on 3-yr mean annual milk production and composition, BW, and body condition of dairy cows

Item	GPSR system[1]				SEM[2]
	GP2.5	GP3.0	GP3.5	GP4.0	
Milk yield (kg/cow)	5,916	5,945	6,000	5,803	159.7[NS]
Milk solids yield[3] (kg/cow)	487	490	492	479	13.9[NS]
Milk fat content (g/kg)	46.2	46.3	45.8	46.4	0.50[NS]
Milk protein content (g/kg)	36.3	36.3	36.4	36.2	0.21[NS]
Milk lactose content (g/kg)	46.1	46.1	45.8	45.8	1.11[NS]
Body weight (kg/cow)	554	556	558	555	17.1[NS]
BCS	3.00	3.01	2.97	3.01	0.013[NS]
DIM	293	292	291	292	3.2[NS]

[1]See Table 1 for a description of the GPSR systems.

[2]SEM = standard error of GPSR system means. NS: $P > 0.05$.

[3]Total milk solids yield = kg of milk fat + protein.

price, increasing GPSR always resulted in a lower net profit (Supplemental Figure S2; https://doi.org/10.6084/m9.figshare.23452286.v3; Fenger, 2023). The lower profitability caused by increasing GPSR at the low milk price resulted in opportunity costs for land, which was even greater at a higher land rental price. At the medium milk price, the effect of increasing GPSR on profitability depended on distance and land rental price (Figure 5). At a land rental price of €450/ha, the system at 4 cows/ha was the most profitable up to a distance of 6 km between GP and non-GP paddocks. Between 6 and 9 km distance, the system at 3.5 cows/ha was most profitable, and between 9 and 12.5 km the system at 3 cows/ha was most profitable. From 13 km onward, the system at 2.5 cows/ha generated the highest net profit. Similarly, we found optimums of GPSR for each distance at low and high land rental prices (Figure 5). Net profit per cow was always lower at higher GPSR (Table 7). Marginal benefit per cow decreased for each additional increase of 1 cow/ha by €77 at 2-km distance and by €189 at 20-km distance (at medium to high milk price).

Table 6. Profitability of the 4 grazing platform (GP) stocking rate models in scenario 1 (increasing degree of fragmentation) at a base milk price of €0.29/L, a land rental price of €450/ha, and at distances of 2, 10, and 20 km between the grazing platform and nongrazing platform paddocks

Item	Grazing platform stocking rate (cows/ha)			
	2.5	3.0	3.5	4.0
Farm area (ha)	50	50	50	50
Overall system area available as grazing platform (%)	100	83	71	63
Grazing platform (ha)	50	42	36	31
Cows (no.)	125	125	125	125
Milk produced (kg)	737,000	737,000	737,000	737,000
Milk solids[1] output (kg)	60,782	60,782	60,782	60,782
Gross output (€)	273,331	273,331	273,331	273,331
2-km distance between GP and non-GP paddocks				
Variable costs (€)	95,203	97,207	99,319	101,512
Labor cost (€)	50,063	50,456	50,850	51,243
Fixed cost excluding labor (€)	42,876	42,876	42,876	42,876
Total costs (€)	188,141	190,539	193,044	195,631
Net profit (€)	85,189	82,792	80,287	77,700
Net profit per hectare (€/ha)	1,704	1,656	1,606	1,554
Net profit per cow (€/cow)	682	662	642	622
10-km distance between GP and non-GP paddocks				
Net profit (€)	85,189	80,480	75,909	71,355
Net profit per hectare (€/ha)	1,704	1,610	1,518	1,427
Net profit per cow (€/cow)	682	644	607	571
20-km distance between GP and non-GP paddocks				
Net profit (€)	85,189	77,591	70,437	63,424
Net profit per hectare (€/ha)	1,704	1,552	1,409	1,268
Net profit per cow (€/cow)	682	621	563	507

[1]Kilograms of milk fat + protein.

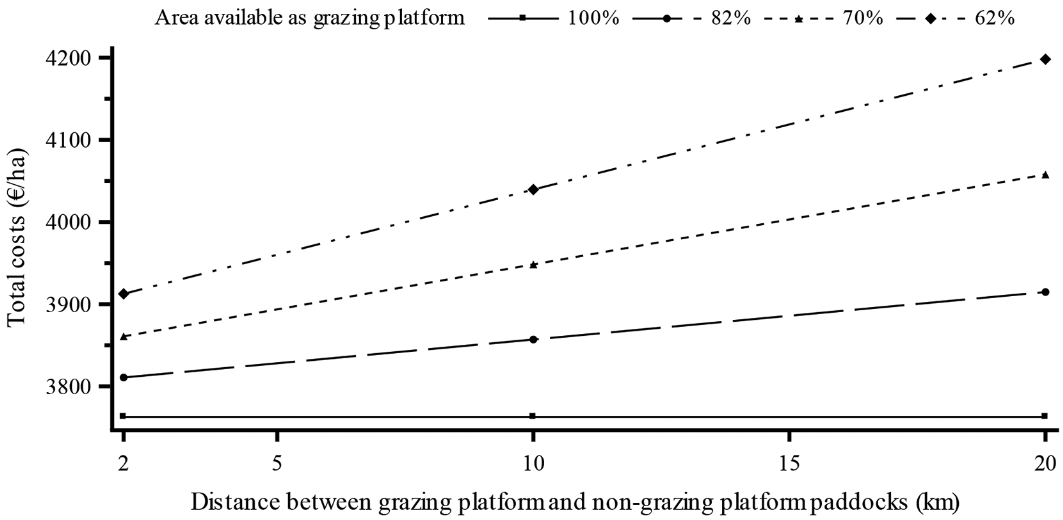

Figure 4. Effects of distance between the grazing platform (GP) and non-GP paddocks on total costs per hectare, depending on the proportion of whole-farm area available as GP in scenario 1.

DISCUSSION

Effects of GPSR System on Herbage Production, Nutritive Value of Herbage Available for Grazing, and Milk Production

In the present study the herd demand for feed on each GPSR system was closely aligned with the production of home-produced feed on the overall system area. We observed no underutilization of herbage mass, overgrazing of pastures, or underfeeding of dairy cows in any GPSR system, as indicated by similar pre-grazing herbage masses and postgrazing sward heights across all GPSR systems. As a result, annual herbage production, nutritive value of the grazed herbage, and milk production per cow was not different between GPSR systems. This is in agreement with Patton et al. (2016), where higher GPSR (3.1 vs. 4.5 cows/ha) did not affect herbage production, nutritive value of herbage available for

Table 7. Profitability of grazing platform stocking rate models in scenario 2 (fixed degree of fragmentation and increasing herd size) at a milk price of €0.29/L, a land rental price of €450/ha, and a distance of 2 km between the grazing platform (GP) and non-GP paddocks

Item	Grazing platform stocking rate (cows/ha)			
	2.5	3.0	3.5	4.0
Farm area (ha)	50	50	50	50
Overall system area available as gP (%)	63	63	63	63
GP (ha)	31	31	31	31
Cows (no.)	78	94	109	125
GP stocking rate (cows/ha)	2.5	3.0	3.5	4.0
Milk produced (kg)	460,625	552,750	644,875	737,000
Milk solids[1] output (kg)	37,988	45,585	53,183	60,782
Land rented out (ha)	19	13	6	0
Gross output (€)	179,265	210,618	241,971	273,331
Variable costs (€)	59,502	72,905	86,904	101,512
Labor (€)	31,289	37,940	44,592	51,243
Total fixed cost excluding labor (€)	39,697	40,757	41,816	42,876
Annual net present value and interest of additional animals (€)	0	2,677	5,355	8,033
Annual depreciation and interest for new buildings (€)	0	5,154	10,308	15,462
Total annual expansion costs (€)	0	7,831	15,663	23,496
Total costs (€)	130,488	159,433	188,975	219,126
Opportunity costs for land (€/ha)	0	0	0	0
Net profit (€)	48,777	51,185	52,996	54,205
Net profit per hectare (€/ha)	976	1,024	1,060	1,084
Net profit per cow (€/cow)	624	546	485	434
Marginal benefit per cow (€/cow)		154	116	77

[1]Kilograms of milk fat + protein.

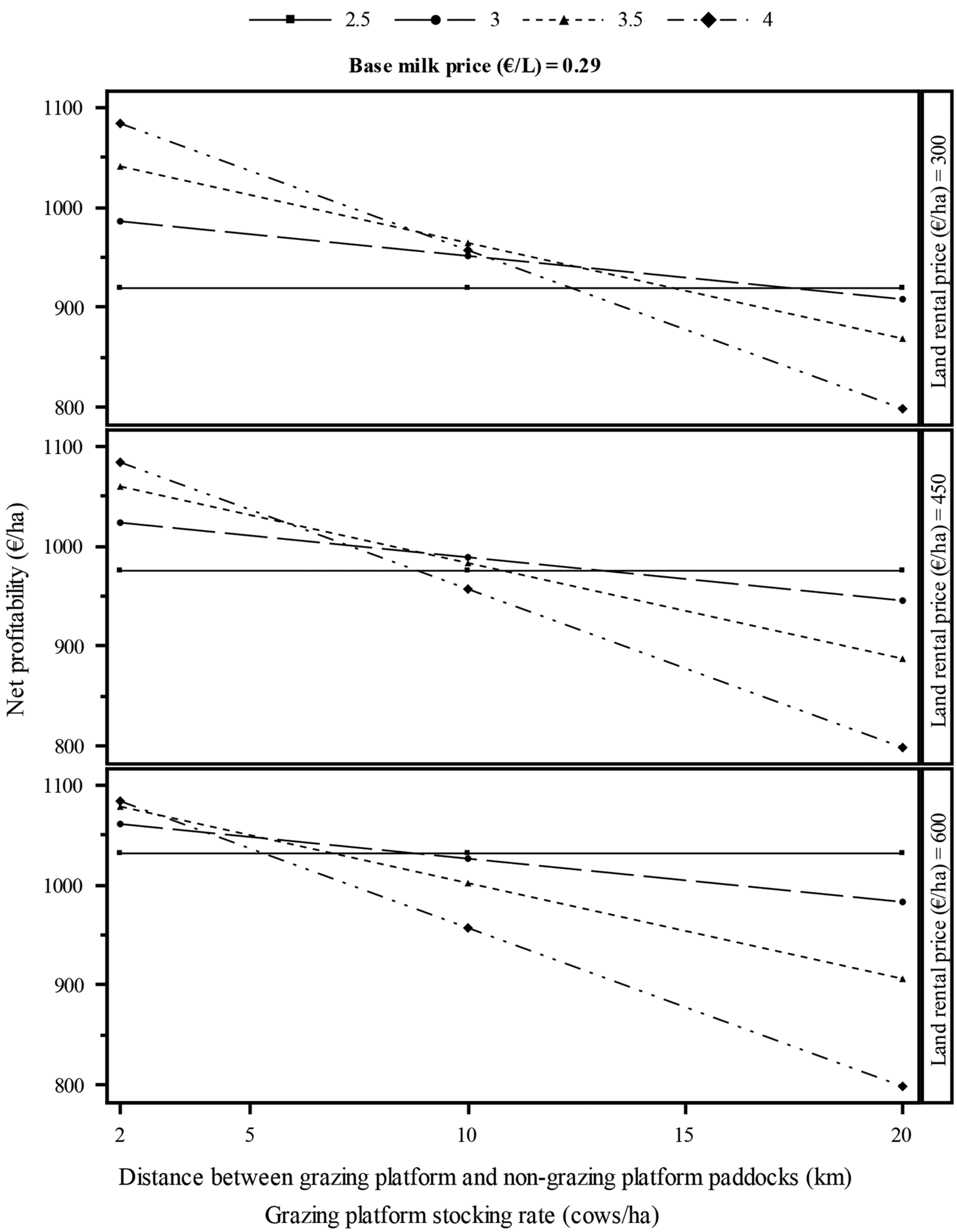

Figure 5. Effects of distance between the grazing platform and nongrazing platform paddocks on net profit per hectare overall farm area, depending on the grazing platform stocking rate across varying land rental prices in scenario 2 at a milk price of €0.29/L.

grazing, or milk production per cow when postgrazing sward height was the same for both GPSR. Similarly, other studies have shown that herbage production and milk production per cow were not affected where the grazing management practices implemented were similar across stocking rate treatments (Valentine et al., 2009; Fariña et al., 2011).

This is in contrast to various studies which have reported that higher GPSR was associated with alternative grazing management such as a lower postgrazing sward height or a shorter lactation per cow as part of the decision rules governing grazing management. Differences in herbage production, nutritive value of herbage available for grazing, and milk production per cow were caused by differences in postgrazing sward height rather than GPSR per se (Macdonald et al., 2008; McCarthy et al., 2011, 2014, 2016). Where a higher GPSR was concomitant with a lower postgrazing sward height, lower allowances of herbage for grazing per cow were not sufficiently substituted by alternative feed (such as grass silage), and, hence, DMI and milk production per cow declined with postgrazing sward height and, by association, GPSR. In addition to the lower availability of herbage for grazing, Macdonald et al. (2008) attributed 24% of the decline in milk production per cow to a shorter lactation length with higher GPSR. In the latter study cows were dried off once a scarcity of herbage for grazing on the GP was detected, as part of the decision rules governing management practices, which was a very different approach to that implemented in the present study.

In contrast to the present study, Fales et al. (1995) reported a positive effect of GPSR on herbage production but, similar to the present study, no effect on milk production per cow. However, it was also reported by Fales et al. (1995) that at the low stocking rate (2.47 cows/ha) more herbage was wasted due to trampling, fouling, and rejection. The protocol in the latter study dictated rotations based on time (2 d per paddock) and not sward height, to evaluate effects of GPSR on herbage growth and accumulation, which resulted in underutilization of the herbage available for grazing at the low GPSR. This, again, was a very different approach to that implemented in the present study.

Effect of GPSR System on the Length of the Grazing Season, Feed Budgets, Nutritive Value of Annual Diets, and Milk Production

The relationships between the various aspects of nutritive value of diets and subsequent dairy cow performance are complex and multifaceted and were likely influenced by weather conditions, grazing conditions, and grazing or feeding behaviors, as discussed by Fenger et al. (2022). In the present study, cows were kept indoors for longer and fed a higher proportion of silage as part of their overall annual diet with higher GPSR. This had no effect on milk production per cow in the present study, in contrast to an earlier study at Solohead Research Farm, where keeping cows indoors for longer to avoid poaching damage in the spring and autumn resulted in a higher proportion of silage in the diet, lower milk protein content, lower milk solids production, and lower BCS compared with cows grazed outdoors (Fenger et al., 2022). In the latter study, this was attributed mainly to the higher nutritive value of grazed herbage compared with grass silage, which is typically harvested at a later stage of maturity than grazed herbage and undergoes changes such as loss of water-soluble carbohydrate content, proteolysis, and deamination during the ensiling process, which lowers nutritive value (Keady et al., 2013). As a result, grazed herbage had higher digestibility and CP and lower NDF than the silages fed in the study of Fenger et al. (2022) and in the present study (Table 3). Both experiments were managed to the same general grassland management rules, except that soil moisture conditions determined the turnout and housing dates in Fenger et al. (2022) whereas the availability of herbage for grazing relative to GPSR-dependent demand for grazed herbage determined the turnout and housing dates in the present study. In the study of Fenger et al. (2022) the main difference between systems in the quantity of silage fed to cows was during the first half of lactation (between February and June), whereas in the present study the main differences in silage fed to cows between GPSR systems occurred from July onward (Figure 3). Dillon et al. (2002), Kennedy et al. (2005), and Claffey et al. (2020) reported lower milk solids production when silage was fed to dairy cows in early lactation compared with grazed herbage, similar to the results reported by Fenger et al. (2022). In contrast, Claffey et al. (2020) and Reid et al. (2015) found that when additional silage was mainly fed during late summer and autumn (August to November), no difference in milk solids production per cow occurred, similar to the results of the present study. This can be attributed to cows having lower dietary requirements during the second half of lactation compared with early lactation (Jarrige, 1989; Erickson and Kalscheur, 2020) and also to declining nutritive value of herbage available for grazing compared with earlier in the grazing season; the differential in the nutritive value of silage relative to herbage available for grazing declines as the grazing season progresses (Humphreys et al., 2009; Beecher et al., 2015).

The deficit of herbage available for grazing during the second half of the grazing season can be explained by a combination of daily herbage growth and grazing management. From February to March, dairy cows were turned out to pasture as they calved with a high input of concentrates (up to 6 kg per cow per day). Hence, the demand of herbage for grazing by each lactating herd was relatively low when yet-to-calve and freshly-calved cows were still indoors. Herbage growth was generally sufficient to meet demand for grazed herbage in all GPSR systems during this timeframe. From April to June, demand for grazed herbage increased, but herbage growth rates were also highest during this timeframe. There were surpluses of herbage on the GP of all GPSR systems, which were harvested for silage production; the lower the GPSR, the greater the areas harvested. As a result, monthly stocking densities were not different between GPSR systems during this timeframe (albeit numerically increasing with higher GPSR; Table 1). In mid-season (July to August), declining herbage growth rates and higher stocking densities in the higher GPSR (Table 1) resulted in lower availability of herbage for grazing per cow compared with the lower-stocked GPSR systems. With lower GPSR, greater capacity to accumulate and store herbage mass in situ was also used to extend the length of the grazing season (Fenger et al., 2021). From August onward, increasing amounts of silage were fed per cow at higher GPSR to maintain similar average herbage covers across the 4 GPSR systems. Although this did not negatively affect milk production per cow in the present study, it increased requirements for high-quality silage compared with traditional pasture-based systems where silage, often of poorer quality, is mainly fed to nonlactating cows during winter (Roche et al., 2017).

The GPSR systems reacted differently to the effects of low rainfall and soil moisture deficits in the present study. We observed greater flexibility with a low or moderate GPSR with regard to the management of grazing paddocks. When herbage growth was restricted by soil moisture deficit in 2018, paddocks that were allocated for silage production could instead be grazed to maintain low-cost grazed herbage in the diet, whereas little or no flexibility was possible with higher GPSR. In contrast, non-GP paddocks in systems with higher GPSR provided a stable supply of herbage for ensilage. One advantage attributed to higher GPSR was the capacity to utilize more grazed herbage per hectare of GP (Macdonald et al., 2008; McCarthy et al., 2016; Patton et al., 2016). However, this capacity was evident in the present study only when herbage growth was sufficient to meet herd demand. In 2018, the same amount of herbage was grazed per hectare of GP from each of the GPSR systems in the present study.

The results of the present study have shown that fragmented pasture-based systems can be managed without a loss in herbage and milk production up to a GPSR of 4 cows/ha when the grassland management imposed ensures optimum utilization of grazed herbage. The increase in milk production per hectare of GP with higher GPSR was solely driven by importing silage from the non-GP paddocks. This is supported by the studies of Valentine et al. (2009) and Patton et al. (2016), where an increase in milk output per hectare of GP with increasing stocking rate was entirely attributed to an increase in imported feed. Ramsbottom et al. (2015) has shown that there is a risk that grazed herbage can be substituted by imported feed and, hence, a need exists for careful management of grazing and of supplemental silage to avoid this. In the present study, herbage utilization on the GP did not decline with higher amounts of silage fed to cows. This can be attributed to the supplementary silage being fed during the grazing season to cows indoors rather than at pasture. The amount of silage fed was allocated in line with the length of time that cows were housed. Hence, cows were allowed back out to pasture with an appetite for fresh herbage.

Optimum GPSR

In the present study, systems with higher GPSR were less profitable due to their higher reliance on silage. Several studies have shown that fragmentation decreases technical efficiency of farms, increases production costs, and decreases profitability (del Corral et al., 2011; Latruffe and Piet, 2014; Bradfield et al., 2021). Bradfield et al. (2021) highlighted that particularly long distances between GP and non-GP paddocks decreased technical efficiency. This is in agreement with the results of the present study. Nevertheless, the farm income generated by the system with the smallest GP and the highest GPSR (4.0 cows/ha in scenario 1) was still high relative to the national average family farm income in 2019 of €1,118/ha (Donnellan et al., 2020).

The GPSR that maximized net profit in the present study (scenario 2) mainly depended on external factors such as milk price and distances between GP and non-GP paddocks. This is in contrast to the results of Macdonald et al. (2011), who reported a quadratic relationship between grazing platform stocking rate and profitability irrespective of milk price. In most cases in the present study, it was either more profitable to increase to the maximum GPSR tested or not to increase GPSR at all. This can be explained by the following factors: (1) milk production per cow did not decline with higher GPSR, and, hence, gross output increased linearly with increasing GPSR; and (2) taking expansion costs and transport costs into account in the economic model, the effect of the diminishing rate of increase in profitability with higher GPSR was relatively small. Baudracco et al. (2010) highlighted that the optimum stocking rate in pasture-based systems depends on the genetic potential of the cows, the value of milk, and the cost of feeding supplements and managing additional cows. Similar to the present study, Fales et al. (1995) reported no effect of GPSR on milk production per cow and, hence, no economic optimum within the range of GPSR tested (2.47 to 3.95 cows/ha). Maximum profitability was determined by input and output factors and their interactions, which was also the case in the present study. However, we found cases where a moderate increase in GPSR was more profitable than the baseline and more profitable than a higher increase in GPSR, indicating an economic optimum GPSR at that point (Figure 5). The results of the present study have shown that higher milk prices, shorter distances, and lower land rental prices increase the optimum GPSR of fragmented systems and vice versa.

It is possible that a point exists where milk production per cow is negatively affected by shorter grazing seasons and higher inclusion rates of silage than those tested in the present study, especially under circumstances where the availability of herbage for grazing is limited during early lactation to a greater extent than in the present study. In the 3 yr of this study, herbage growth during autumn was notably higher than average growth rates (Figure 2). Low-to-average autumn herbage growth could limit the length of the grazing season at higher GPSR to a greater extent than recorded in the present study, which has implications for feed costs.

The higher GPSR were less efficient and less profitable per cow compared with the baseline of 2.5 cows/ha, due to costs caused by fragmentation and feed imports onto the GP. Furthermore, the results of the present study showed that the profitability of the system at 2.5 cows/ha was less vulnerable to changes in milk price. Recent developments in the dairy sector and changes in climate and production potential of pasture-based dairy farms have dramatically increased volatilities in milk price and input costs: feed and fertilizer, for example. Hence, dairy farms that expand and increase cow numbers on their GP under circumstance of a favorable price environment could be more significantly affected by these volatilities. An investigation into differences in environmental footprints of the different GPSR would further determine the environmental impact of increasing GPSR.

CONCLUSIONS

The shorter grazing season with higher GPSR in the present study did not affect total herbage production or milk production per cow, albeit with a lower proportion of grazed herbage in the diet. Profitability declined with increasing fragmentation, mainly due to higher variable costs, particularly feed and transport costs. Variable costs increased with smaller GP and longer distances between GP and non-GP paddocks. At a fixed GP area, the profitability of increasing GPSR from the baseline of 2.5 cows/ha was mainly determined by external factors: higher milk prices, shorter distances, and lower land rental price increased the optimum GPSR of fragmented systems and vice versa. Within the range of GPSR tested in this study, no specific point was detected where the benefits of higher milk sales from the GP was more than counterbalanced by higher costs associated with farm fragmentation. It was possible to achieve an acceptable farm income from dairy production on fragmented farms by optimizing GPSR within the range investigated in the present study depending on the area of the GP, milk and land prices, and distance between GP and non-GP paddocks.

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REFERENCES

Baudracco, J., N. Lopez-Villalobos, C. W. Holmes, and K. A. Macdonald. 2010. Effects of stocking rate, supplementation, genotype and their interactions on grazing dairy systems: a review. N. Z. J. Agric. Res. 53:109–133. https://doi.org/10.1080/00288231003777665.

Beecher, M., D. Hennessy, T. Boland, M. McEvoy, M. O'Donovan, and E. Lewis. 2015. The variation in morphology of perennial ryegrass cultivars throughout the grazing season and effects on organic matter digestibility. Grass Forage Sci. 70:19–29. https://doi.org/10.1111/gfs.12081.

Bradfield, T., R. Butler, E. Dillon, T. Hennessy, and P. Kilgarriff. 2021. The effect of land fragmentation on the technical inefficiency of dairy farms. J. Agric. Econ. 72:486–499. https://doi.org/10.1111/1477-9552.12413.

Claffey, A., L. Delaby, T. M. Boland, and M. Egan. 2020. Implications of adapting autumn grazing management on spring herbage production—The effect on late lactation milk production and the subsequent response in early lactation animal performance. Livest. Sci. 231:103870. https://doi.org/10.1016/j.livsci.2019.103870.

Claffey, A., L. Delaby, N. Galvin, T. M. Boland, and M. Egan. 2019. The effect of spring grass availability and grazing rotation length on the production and quality of herbage and milk in early spring. J. Agric. Sci. 157:434–448. https://doi.org/10.1017/S0021859619000613.

Coulter, S., E. McAuley, T. Donnellan, K. Hanrahan, and J. Loughrey. 2020. Annual SCSI/Teagasc Agricultural Land Market Review and Outlook. Accessed Mar. 10, 2021. https://www.teagasc.ie/media/website/publications/2020/SCSI-Agri-land-property-report.pdf.

CSO. 2020. Agricultural Input and Output Absolute Prices. Central Statistics Office, Ireland. Accessed Mar. 1, 2021. https://data.cso.ie/product/OIIAP.

CSO. 2021. Milk Production Statistics—Intake of Cows Milk by Creameries and Pasteurisers by Source, Year and Statistic. Accessed Jul. 12, 2021. https://www.cso.ie/px/pxeirestat/Statire/SelectVarVal/saveselections.asp.

del Corral, J., J. A. Perez, and D. Roibas. 2011. The impact of land fragmentation on milk production. J. Dairy Sci. 94:517–525. https://doi.org/10.3168/jds.2010-3377.

Dillon, P., S. Crosse, B. O'Brien, and R. W. Mayes. 2002. The effect of forage type and level of concentrate supplementation on the performance of spring-calving dairy cows in early lactation. Grass Forage Sci. 57:212–223. https://doi.org/10.1046/j.1365-2494.2002.00319.x.

Dillon, P., T. Hennessy, L. Shalloo, F. Thorne, and B. Horan. 2006. Long Term Vision for the Irish Dairy Industry. Teagasc National Dairy Conference Proceedings. https://www.teagasc.ie/media/website/publications/2006/dairy2006conferenceproceedings.pdf.

Dillon, P., J. R. Roche, L. Shalloo, and B. Horan. 2005. Optimising financial return from grazing in temperate pastures. Pages 131–147 in Utilisation of Grazed Grass in Temperate Animal Systems: Proceedings of a satellite workshop of the XXth International Grassland Congress, Cork, Ireland. Wageningen Academic Publishers.

Donnellan, T., B. Moran, J. Lennon, and E. Dillon. 2020. Teagasc National Farm Survey 2019 Results. Teagasc, Agricultural Economics and Farm Surveys Department, Rural Economy Development Programme. Accessed Mar. 12, 2023. https://www.teagasc.ie/media/website/publications/2020/Teagasc-National-Farm-Survey-2019.pdf.

Edmonson, A. J., I. J. Lean, L. D. Weaver, T. Farver, and G. Webster. 1989. A body condition scoring chart for Holstein dairy cows. J. Dairy Sci. 72:68–78. https://doi.org/10.3168/jds.S0022-0302(89)79081-0.

Erickson, P. S., and K. F. Kalscheur. 2020. Chapter 9: Nutrition and feeding of dairy cattle. Pages 157–180 in Animal Agriculture. F. W. Bazer, G. C. Lamb, and G. Wu, ed. Academic Press. https://doi.org/10.1016/B978-0-12-817052-6.00009-4.

Fales, S., L. Muller, S. Ford, M. O'sullivan, R. Hoover, L. Holden, L. Lanyon, and D. Buckmaster. 1995. Stocking rate affects production and profitability in a rotationally grazed pasture system. J. Prod. Agric. 8:88–96. https://doi.org/10.2134/jpa1995.0088.

FAO. 2015. World reference base for soil resources 2014. Accessed Jul. 15, 2021. http://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/.

Fariña, S. R., S. C. Garcia, W. J. Fulkerson, and I. M. Barchia. 2011. Pasture-based dairy farm systems increasing milk production through stocking rate or milk yield per cow: pasture and animal responses. Grass Forage Sci. 66:316–332. https://doi.org/10.1111/j.1365-2494.2011.00795.x.

FCI. 2019. FCI Contracting Charges Guide 2019. Farm and Forestry Contractors in Ireland. Accessed Oct. 15, 2020. https://9d54bb03-8960-4a76-80d5-3f66cf06cadd.filesusr.com/ugd/162a95_d1759440755a4cb59afe79139d609de6.pdf.

Fenger, F. 2023. Supplemental Files for Fenger et al. (2023): The effect of grazing platform stocking rate on the productivity and profitability of pasture-based dairying in a fragmented farm scenario. figshare. Figure. https://doi.org/10.6084/m9.figshare.23452286.v3.

Fenger, F., I. A. Casey, N. M. Holden, and J. Humphreys. 2022. Access time to pasture under wet soil conditions: Effects on productivity and profitability of pasture-based dairying. J. Dairy Sci. 105:4189–4205. https://doi.org/10.3168/jds.2021-20752.

Fenger, F., I. A. Casey, and J. Humphreys. 2021. Accumulating herbage during autumn to extend the grazing season in pasture-based dairy systems. Grass Forage Sci. 76:522–532. https://doi.org/10.1111/gfs.12547.

Finneran, E., P. Crosson, P. O'Kiely, L. Shalloo, P. D. Forristal, and M. Wallace. 2012. Stochastic simulation of the cost of home-produced feeds for ruminant livestock systems. J. Agric. Sci. 150:123–139. https://doi.org/10.1017/S002185961100061X.

Geary, U., N. Lopez-Villalobos, D. J. Garrick, and L. Shalloo. 2010. Development and application of a processing model for the Irish dairy industry. J. Dairy Sci. 93:5091–5100. https://doi.org/10.3168/jds.2010-3487.

Hanrahan, L., N. McHugh, T. Hennessy, B. Moran, R. Kearney, M. Wallace, and L. Shalloo. 2018. Factors associated with profitability in pasture-based systems of milk production. J. Dairy Sci. 101:5474–5485. https://doi.org/10.3168/jds.2017-13223.

Holohan, C., T. Russell, F. J. Mulligan, K. M. Pierce, and M. B. Lynch. 2021. A survey analysis of farmer practices and perceptions of zero-grazing on Irish dairy farms. J. Dairy Sci. 104:5665–5674. https://doi.org/10.3168/jds.2020-19164.

Humphreys, J., I. A. Casey, and A. S. Laidlaw. 2009. Comparison of milk production from clover-based and fertilizer-N-based grassland on a clay-loam soil under moist temperate climatic conditions. Ir. J. Agric. Food Res. 48:189–207. http://hdl.handle.net/11019/645.

Humphreys, J., E. Mihailescu, and I. A. Casey. 2012. An economic comparison of systems of dairy production based on N-fertilized grass and grass-white clover grassland in a moist maritime environment. Grass Forage Sci. 67:519–525. https://doi.org/10.1111/j.1365-2494.2012.00871.x.

Jarrige, R. 1989. Ruminant Nutrition: Recommended Allowances and Feed Tables. John Libbey Eurotext. ISBN: 0-86196-247-8

Jarrige, R., C. Demarquilly, J. P. Dulphy, A. Hoden, J. Robelin, C. Beranger, Y. Geay, M. Journet, C. Malterre, D. Micol, and M. Petit. 1986. The INRA "Fill Unit" system for predicting the voluntary intake of forage-based diets in ruminants: A review. J. Anim. Sci. 63:1737–1758. https://doi.org/10.2527/jas1986.6361737x.

Keady, T., S. Hanrahan, C. Marley, and N. D. Scollan. 2013. Production and utilization of ensiled forages by beef cattle, dairy cows, pregnant ewes and finishing lambs—A review. Agric. Food Sci. 22:70–92. https://doi.org/10.23986/afsci.6852.

Kennedy, E., M. O'Donovan, J. P. Murphy, L. Delaby, and F. O'Mara. 2005. Effects of grass pasture and concentrate-based feeding systems for spring-calving dairy cows in early spring on performance during lactation. Grass Forage Sci. 60:310–318. https://doi.org/10.1111/j.1365-2494.2005.00481.x.

Läpple, D., and T. Hennessy. 2012. The capacity to expand milk production in Ireland following the removal of milk quotas. Ir. J. Agric. Food Res. 51:1–11. http://hdl.handle.net/11019/319.

Läpple, D., and G. Sirr. 2019. Dairy intensification and quota abolition: A comparative study of production in Ireland and the Netherlands. EuroChoices (Uckfield) 18:26–32. https://doi.org/10.1111/1746-692X.12213.

Latruffe, L., and L. Piet. 2014. Does land fragmentation affect farm performance? A case study from Brittany, France. Agric. Syst. 129:68–80. https://doi.org/10.1016/j.agsy.2014.05.005.

Lu, H., H. Xie, Y. He, Z. Wu, and X. Zhang. 2018. Assessing the impacts of land fragmentation and plot size on yields and costs: A translog production model and cost function approach. Agric. Syst. 161:81–88. https://doi.org/10.1016/j.agsy.2018.01.001.

Macdonald, K. A., D. Beca, J. W. Penno, J. A. S. Lancaster, and J. R. Roche. 2011. Short communication: Effect of stocking rate on the economics of pasture-based dairy farms. J. Dairy Sci. 94:2581–2586. https://doi.org/10.3168/jds.2010-3688.

Macdonald, K. A., and J. W. Penno. 1998. Management decision rules to optimise milksolids production on dairy farms. Proc. N.Z. Soc. Anim. Prod. 58:132–135.

Macdonald, K. A., J. W. Penno, J. A. Lancaster, and J. R. Roche. 2008. Effect of stocking rate on pasture production, milk production, and reproduction of dairy cows in pasture-based systems. J. Dairy Sci. 91:2151–2163. https://doi.org/10.3168/jds.2007-0630.

McCarthy, B., L. Delaby, K. M. Pierce, F. Journot, and B. Horan. 2011. Meta-analysis of the impact of stocking rate on the productivity of pasture-based milk production systems. Animal 5:784–794. https://doi.org/10.1017/S1751731110002314.

McCarthy, B., L. Delaby, K. M. Pierce, J. McCarthy, C. Fleming, A. Brennan, and B. Horan. 2016. The multi-year cumulative effects of alternative stocking rate and grazing management practices on pasture productivity and utilization efficiency. J. Dairy Sci. 99:3784–3797. https://doi.org/10.3168/jds.2015-9763.

McCarthy, J., B. McCarthy, B. Horan, K. M. Pierce, N. Galvin, A. Brennan, and L. Delaby. 2014. Effect of stocking rate and calving date on dry matter intake, milk production, body weight, and body condition score in spring-calving, grass-fed dairy cows. J. Dairy Sci. 97:1693–1706. https://doi.org/10.3168/jds.2013-7458.

Morgan, D. J., G. Stakelum, and J. Dwyer. 1989. Modified neutral detergent cellulase digestibility procedure for use with the 'Fibertec' system. Ir. J. Agric. Food Res. 28:91–92. https://www.jstor.org/stable/25556234.

O'Donnell, S., L. Shalloo, A. Butler, and B. Horan. 2008. A survey analysis of opportunities and limitations of Irish dairy farmers. J. Farm Manag. 13:419–434. https://doi.org/10.1111/j.1365-2494.2011.00784.x.

O'Mara, F. 1996. A net energy system for cattle and sheep. PhD thesis. Department of Animal Science and Production, University College Dublin.

Patton, D., K. M. Pierce, and B. Horan. 2016. Effect of stocking rate on milk and pasture productivity and supplementary feed use for spring calving pasture fed dairy systems. J. Dairy Sci. 99:5904–5915. https://doi.org/10.3168/jds.2015-10305.

Phelan, P., I. A. Casey, and J. Humphreys. 2013. The effect of target postgrazing height on sward clover content, herbage yield, and dairy production from grass-white clover pasture. J. Dairy Sci. 96:1598–1611. https://doi.org/10.3168/jds.2012-5936.

Ramsbottom, G., B. Horan, D. P. Berry, and J. R. Roche. 2015. Factors associated with the financial performance of spring-calving, pasture-based dairy farms. J. Dairy Sci. 98:3526–3540. https://doi.org/10.3168/jds.2014-8516.

Reid, M., M. O'Donovan, J. P. Murphy, C. Fleming, E. Kennedy, and E. Lewis. 2015. The effect of high and low levels of supplementation on milk production, nitrogen utilization efficiency, and milk protein fractions in late-lactation dairy cows. J. Dairy Sci. 98:5529–5544. https://doi.org/10.3168/jds.2014-9016.

Roche, J. R., D. P. Berry, A. M. Bryant, C. R. Burke, S. T. Butler, P. G. Dillon, D. J. Donaghy, B. Horan, K. A. Macdonald, and K. L. Macmillan. 2017. A 100-Year Review: A century of change in temperate grazing dairy systems. J. Dairy Sci. 100:10189–10233. https://doi.org/10.3168/jds.2017-13182.

Ruelle, E., L. Delaby, M. Wallace, and L. Shalloo. 2018. Using models to establish the financially optimum strategy for Irish dairy farms. J. Dairy Sci. 101:614–623. https://doi.org/10.3168/jds.2017-12948.

Schulz, L., and P. Gunn. 2016. Net Present Value of Beef Replacement Females. Ag Decision Maker, Iowa State University File B1-74:1-3. Accessed Feb. 10, 2023. https://www.extension.iastate.edu/agdm/livestock/pdf/b1-74.pdf.

Shalloo, L., P. Dillon, M. Rath, and M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. J. Dairy Sci. 87:1945–1959. https://doi.org/10.3168/jds.S0022-0302(04)73353-6.

Shalloo, L., D. O'Connor, L. Cele, and F. Thorne. 2020. An analysis of the Irish dairy sector post quota. Accessed Apr. 5, 2023. https://mathematics.cit.ie/contentfiles/Declan%20O'Connor/Final%20ReportDOC.pdf.

Teagasc. 2013a. Guidelines for the Contract Rearing of Replacement Heifers. Accessed Sep. 15, 2020. https://www.teagasc.ie/media/website/publications/2013/GuidelinesContractRearingReplacementHeifers.pdf.

Teagasc. 2013b. Management Data for Farm Planning. Teagasc Oakpark, Co. Carlow, Ireland. Accessed Feb. 10, 2023. https://www.teagasc.ie/news–events/news/2013/teagasc-management-data.php.

Tuohy, P., O. Fenton, N. M. Holden, and J. Humphreys. 2015. The effects of treading by two breeds of dairy cow with different live weights on soil physical properties, poaching damage and herbage production on a poorly drained clay-loam soil. J. Agric. Sci. 153:1424–1436. https://doi.org/10.1017/S0021859614001099.

Tuohy, P., J. Upton, B. O'Brien, P. Dillon, T. Ryan, and D. Ó hUallacháín. 2017. Dairy Farm Infrastructure Handbook. Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Ireland. Accessed Jan. 29, 2022. https://www.teagasc.ie/publications/2017/dairy-farm-infrastructure-handbook.php.

UlsterBank. 2021. Dairy Farm Expansion Loan. Accessed Mar. 10, 2021. https://digital.ulsterbank.ie/business/sector-expertise/agriculture.html.

Valentine, S., P. Lewis, R. Cowan, and J. DeFaveri. 2009. The effects of high stocking rates on milk production from dryland and irrigated Mediterranean pastures. Anim. Prod. Sci. 49:100–111. https://doi.org/10.1071/EA07071.

Van Soest, P. J. 1990. Use of detergents in the analysis of fibrous feeds. II. A rapid method for the determination of fiber and lignin. J. Assoc. Off. Anal. Chem. 73:491–497. https://doi.org/10.1093/jaoac/73.4.491.

ORCIDS

F. Fenger https://orcid.org/0000-0002-2770-9816
I. A. Casey https://orcid.org/0000-0002-6084-4972
C. Buckley https://orcid.org/0000-0002-9836-9783