



Randomized-controlled study assessing the effect of milking permission settings and concentrate supplementation on milking frequency and milk yield in a pasture-based automatic milking system

Roberta Matera,¹  Pablo Silva Boloña,^{2*}  and Bernadette O'Brien² 

¹Department of Veterinary Medicine and Animal Production, Federico II University, 80137 Naples, Italy

²Animal and Grassland Research and Innovation Centre, Teagasc Moorepark Fermoy Co. Cork, Ireland P61 C302

ABSTRACT

This study aimed to verify the effect of milking permission (MPE) and concentrate supplementation (CS) on milking frequency (milking per cow per day) and milk yield (kilograms per cow per day) in a farm using a pasture-based automatic milking system (AMS). Sixty-eight cows milked using this AMS unit were randomly assigned to 1 of 4 groups homogeneous for parity, DIM, and milk yield. Treatments used were frequent or restricted MPE, that granted cows permission to milk after 6 to 8 h or 9.6 to 14 h of the previous milking, respectively; and low (LC) or high (HC) CS of 0.5 kg or 3.5 kg/cow per day, respectively. The combination of the 2 levels of MPE and the 2 levels of CS resulted in the 4 treatment combinations (frequent HC [FHC], restricted HC [RHC], frequent LC [FLC], and restricted LC [RLC]). This study was designed as a 2 × 2 factorial arrangement with treatment crossover: each of the 4 cow groups was randomly assigned to 1 of the 4 treatment combinations for a 5-wk experimental period (1 pretreatment week and 4 treatment weeks), and after each 5-wk period groups crossed over to another treatment combination until they experienced all. Statistical analysis assessed the effect of MPE, CS, and their interaction on milk yield, milking frequency, box time, milking time, and average milk-flow rate. This was done using a mixed model analysis with repeated measures to account for repeated observations on the experimental unit (cow). Milk yield per cow per day and milkings per cow per day were significantly higher with the frequent compared with the restricted MPE (1.5 kg and 0.65 milkings, respectively). Milk yield per cow per day and milkings per cow per day were significantly higher with the HC compared with the LC CS (3.1 kg and 0.25 milkings, respectively). Additionally, milk yield per cow per day was affected by the interaction of MPE

and CS and it was highest with the FHC (20.1 kg) treatment combination, followed by RHC (18.2 kg) treatment combination. The number of milkings per cow per day were also affected by the interaction of MPE and CS. The highest estimated number of milkings per cow per day was recorded for the FHC (2.12) and the FLC (1.77) treatment combinations, followed by the RHC (1.38) and RLC (1.23) treatment combinations. Similarly, milking interval was 2.5 h longer for the RLC treatment combination compared with RHC. The shortest milking interval was observed for the FHC (11 h) and FLC (12.8 h) treatment combinations. In conclusion, the study showed that allowing access to the robot between 6 to 8 h after the previous milking was sufficient (even with a minimal level of CS) to achieve acceptable milk production and milking performance in a pasture-based AMS.

Key words: voluntary cow traffic, milking robot efficiency, automatic milking system, pasture-based

INTRODUCTION

Factors such as the labor intensive nature of milk harvesting and a deficit in the availability of skilled labor have led to a growing adoption of the automatic milking system (AMS) technology at farm level. Automatic milking systems offer the opportunity to increase productivity and profitability while potentially improving labor efficiency, milk production, animal welfare, and lifestyle (Jacobs and Siegford, 2012; Wildridge et al., 2018). Because AMS was originally developed for use in intensive indoor housing systems, early AMS installations were limited to countries where dairy production was characterized by high yielding cows and high production costs (Lind and Ipema, 2000). Only later was the combination of AMS and pasture introduced (Greenall et al., 2004; Jago et al., 2004). This combination is a positive solution; it has been widely reported that grass-based systems are associated with lower total costs of production (Dillon et al., 2005; O'Brien and Hennessy, 2017). Pasture-fed cows in AMS systems have also been associated with a

Received January 18, 2024.

Accepted April 9, 2024.

*Corresponding author: pablo.silvabolona@teagasc.ie

The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

superior quality of milk produced (O'Callaghan et al., 2016), and the green image associated with cows grazing pasture continues to appeal to consumers (Stampa et al., 2020). For these reasons, identifying solutions that increase the efficiency of the combination of the pasture grazing system and the benefits of AMS may further enhance the sustainability of the dairy sector.

The success of a pasture-based AMS relies on voluntary cow traffic from the pasture to the milking yard and then back to the pasture. This voluntary cow traffic may be influenced by pasture availability, nutrition offered at the robot, stage of lactation, and weather conditions (Scott et al., 2014; Shortall et al., 2018). The aim is to create motivation for cows to return for milking so that a relatively consistent cow traffic and milking event profile can be achieved throughout the day (Lyons et al., 2014). Within such a pasture-based AMS, average milking frequency (**MF**; number of milkings per cow per day) of 1.8 or greater has been observed (Lyons et al. 2013; Foley et al., 2015); however, achieving this is dependent on both cow traffic and milking permission (**MPE**; time since the last milking when a cow has permission to be milked again). Milking permission is generally set by the farmer or operator and is influenced by expected daily milk yield per cow, number of cows in the herd, and the MF being targeted.

Several studies have been carried out with a focus on improving the efficiency of the integrated pasture-based AMS (Jago et al., 2006; Lyons et al., 2013; Scott et al., 2014). Various management strategies, such as manipulation of MPE, concentrate supplementation (**CS**), or both, have been examined with a view to maximizing output from the AMS. Foley et al. (2015) reported no significant effect of 3 versus 2 times daily MPE on milk yield per cow per day (19.0 vs. 18.4 kg of milk/cow per day) even though MF was significantly higher for cows with a MPE of 3 times compared with 2 times/d (MF of 2.0 vs. 1.4 times/d, respectively). Shortall et al. (2018) investigated the effect of low and high CS levels in the early and late periods of lactation on milk production and cow traffic in a pasture-based AMS. That study showed that CS in early lactation had no effect on milk production or cow traffic. However, supplementation at a high concentrate level in late lactation resulted in increased milk production, a shorter milking interval, and a shorter return time for cows from pasture (Shortall et al., 2018).

The relationship between MF and CS on milk production and cow traffic is complex, and several factors and interactions of factors can influence it, such as stage of lactation and level of nutrition (Shortall et al., 2018). Understanding the interaction between feed and the traffic management of cows is critically important in optimizing the production efficiency of the AMS. Due to the limited time available for milking on the AMS system (e.g., 24

h/d, excluding washing events), an increase in MF or an increase in milk yield can put downward pressure on herd size. Thus, the parameters of milk yield, MF, and CS need to be examined individually and at an interactive level.

Therefore, the aims of this study in a pasture-based context were to (1) evaluate the effect of increasing MPE on MF and milk yield per cow; (2) investigate the effect of increased CS on MF and milk yield per cow; and (3) define how the manipulation of MPE and CS interact with each other. Secondary objectives included evaluating the effect of MPE and CS on box time (time the cows spend inside the robot box, min), milking time (duration of each milking, min), milking interval (time between milkings, h), and the average milk-flow rate (kg/min).

MATERIALS AND METHODS

This study was carried out with a single-unit Lely AMS (Lely Holding BV, Maassluis, the Netherlands) situated on a 25.2-ha farm located in the south of Ireland on the Teagasc Moorepark Dairygold Research Farm (Fermoy, Co. Cork, Ireland, 50°07' N, 8°16' W). This experiment did not require an ethical approval because it did not practice any "procedures" on animals as defined by the Health Products Regulatory Authority (HPRA). Concentrate supplementation, milking permission, and grass allocation were within normal ranges for commercial AMS operations. The cows enrolled in the study remained in the herd after the study was completed. Sixty-eight cows were milked using this AMS unit, which operated a free-flow cow traffic system, whereby cows entered the yard and then the milking robot granted permission for cows to be milked or not (based on permission guidelines) and subsequently released them for their return to the paddock. Cows were spring calving and were full-time grazing. The farm area was a permanent grassland site, with a soil type described as a free-draining brown earth soil of sandy loam to loam texture. The grass sward was a predominantly perennial ryegrass sward (*Lolium perenne* L.).

Experimental Design

This experimental study was conducted between May 2, 2022, and September 18, 2022. Cows in the AMS herd were classified based on daily milk yield (4 categories: <19 kg, 19–23 kg, 24–29 kg, and ≥30 kg), and cows within each category were randomly assigned to 1 of 4 groups (1–4). The resulting groups were homogeneous for parity (2.9 ± 0.1), DIM (48.8 ± 2.1), and milk yield (24.8 ± 0.4). Before implementation of treatments (previous 4 wk; April 4–May 1) all cows had MPE set at a maximum of 3 milkings/d. Milking permission was granted based on target milkings per day. Default setting in this AMS

Table 1. Descriptive statistics of cow and milking system characteristics during the 4-wk pretrial start (n = 68 cows, 1 AMS)

Variable	Mean	SD	Minimum	Maximum
Milkings/AMS per day	124.7	12.3	97	146
Failed milkings/AMS per day	2.7	1.5	1	5
Refused milkings/AMS per day	31.3	13.0	17	54
DIM	48.9	21.0	7	89
Lactation number	2.9	1.4	1	6
Milking interval (h)	13.6	4.0	7.9	20.9
Box time/milking (min)	7.9	2.0	5.1	17.0
Milking time/milking (min)	6.1	2.0	3.2	15.2
Milk yield/AMS per day (kg)	1,592	128.2	1,350	1,808
Milk yield/cow per milking (kg)	12.9	2.7	5.5	20.6
Milk yield/cow per day (kg)	24.8	6.9	12.3	38.3
Milkings/cow per day (n)	1.9	0.5	1.1	3.0
Average milk-flow rate (L/min)	2.5	0.8	0.7	4.7
Peak milk-flow rate (L/min)	3.4	0.9	1.6	5.7
Concentrate feed/cow per day (kg)	1.9	0.1	1.5	2.3
Fat (%)	4.4	0.1	4.2	4.5
Protein (%)	3.7	0.1	3.7	3.8
Lactose (%)	4.9	0.03	4.82	4.93
SCC ($\times 10^3$ cells/mL)	96	40.4	34	166
Milk solids/cow per day (kg)	2.03			

granted a minimum of 2 milkings/d (therefore every 12 h) with a progressive increase to 3 times (therefore every 8 h) per day for higher yielding cows. Cows received 1.8 kg/d concentrate in the robot as they were milking. Descriptive statistics of cows during this pre-experimental period are presented in Table 1.

This study was designed as a 2×2 factorial arrangement with treatment crossover. Each cow group was randomly assigned to 1 of 4 treatment combinations for a 5-wk experimental period (this 5-wk period included 1 pretreatment week and 4 treatment weeks). After each 5-wk period, groups crossed over to another treatment so that all groups experienced each treatment. The first week of each 5-wk period was used as a pretreatment, or washover week, to ensure that each cow group had adjusted to each diet and MPE treatment when the 4-wk treatment period commenced. The cow milk yields and MF data for the 4 washover weeks are reported in Appendix Figure A1 and Appendix Figure A2.

The treatments consisted of 2 levels of MPE and 2 levels of CS. A frequent MPE was set by establishing a minimum of 3 milkings/cow per day and a maximum of 4 milkings/cow per day. A restricted MPE was set by indicating a minimum of 1.7 milkings/cow per day and a maximum of 2.5 milkings/cow per day. Therefore, the frequent and restricted MPE represented permission to milk 6 to 8 h and 9.6 to 14 h after the previous milking, respectively. This was achieved by adjusting the MPE settings on the robot, which would allow the robot to decide if a cow was due for milking or not. A previous pilot study on this AMS highlighted that setting a MPE of 10 to 14 h resulted in a MF of ~ 1.8 milkings/d during the main milk production period. We aimed for a “frequent”

MPE that would allow us to detect a relevant difference in MF from 1.8 milkings/cow per day; therefore, we chose a MPE of 6 to 8 h (allowing 3–4 milkings daily).

Concentrate supplementation levels were 0.5 kg of concentrate/cow per day (low concentrate, **LC**) or 3.5 kg of concentrate/cow per day (high concentrate, **HC**). The low CS level was representative of a cow diet in a seasonal calving pasture-based dairy system, where grazed grass makes up the vast majority ($\sim 75\%$) of the diet, with some CS and grass silage being fed in both spring and autumn (Timlin et al., 2021). To aim for a detectable difference in our outcomes between CS treatments, we chose an increased CS level of 3.5 kg/cow per day for this study. These treatments were set up using Lely’s farm management software T4C (Lely Holding BV, Maassluis, the Netherlands), including a fixed concentrate feeding routine independent of milk yield. Both the high and low CS levels used within the treatments were representative of the range of actual concentrate levels offered to spring-calved pasture-based cows on commercial farms at a similar stage of lactation. The combination of the 2 levels of MPE and the 2 levels of CS resulted in the 4 treatment combinations as follows: (1) frequent milking permission and HC (**FHC**); (2) frequent milking permission and LC (**FLC**); (3) restricted milking permission and HC (**RHC**); and (4) restricted milking permission and LC (**RLC**). The group transitions between each treatment combination in the different experimental periods are shown in Table 2.

We estimated the sample size for this experiment using the formula by Snedecor and Cochran (1989), with data from the AMS farm during 2021 (the year prior to the study). To detect a 10% difference in MF with an average

Table 2. Treatment combinations¹ applied to cow groups during experimental treatment periods²

Period	Group 1	Group 2	Group 3	Group 4
Period 1	FLC	RLC	FHC	RHC
Period 2	RLC	RHC	FLC	FHC
Period 3	RHC	FHC	RLC	FLC
Period 4	FHC	FLC	RHC	RLC

¹Treatment combinations: FHC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), high concentrate supplementation (3.5 kg/d); FLC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), low concentrate supplementation (0.5 kg/d); RHC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), high concentrate supplementation (3.5 kg/d); RLC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), low concentrate supplementation (0.5 kg/d).

²Experimental treatment period: period 1 = from May 9, 2022, to June 5, 2022; period 2 = from June 13, 2022, to July 10, 2022; period 3 = from July 18, 2022, to August 14, 2022; period 4 = from August 22, 2022, to September 18, 2022.

of 1.8 milkings/cow per day, a sample of 41 cows were needed. To detect a 10% difference in milk yield/cow per day with an average of 24 kg/cow per day, we estimated a sample of 57 cows needed for the experiment.

Data Description

Data from each cow visit to the AMS unit were recorded electronically in the T4C and extracted as Excel (Microsoft Corp.) spreadsheets for analysis. Milking data recorded by the AMS included cow number, date and time of milking, DIM, parity, whether the milking was recorded as successful, failed, or refused, milk yield per milking (kg), milking interval (hours after previous milking), milking time (min/cow per milking), box time (min/cow per milking), average milk-flow rate (kg/min), and concentrate offered per cow per milking (kg). The T4C management software also provided data on AMS total milk yield per day (kg), number of milkings per day, and the daily distribution of milkings. Herd SCC data (cells/mL) were obtained from the milk purchasing or processing co-operative.

Grazing Management

Cow grazing was managed by a 3-way grazing system (ABC). The grazing platform was divided into 3 grazing sections: A (7.7 ha); B (9 ha); C (8.5 ha), with 1 grass allocation made available daily in each section. Cows moved voluntarily to and from the milking unit as they passed between the grazing sections. The herd had access to new pasture from 0000 to 0800 h in A, 0800 to 1600 h in B, and 1600 to 0000 h in C. An allocation of 20 kg of grass DM/cow per day was offered across the 3 grazing sections in each 24-h period. As the daily grass allocation in each section was depleted gradually, cows initiated

movement toward the next section, where they knew that a fresh grass allocation awaited them. In the movement to the new grass allocation or section, cows were first directed to the milking unit; here they were milked or not milked depending on MPE settings, and then further directed to the new grass section. In this way, the grazing management, and specifically the grass allocation, influence the frequency of voluntary cow movement to the AMS unit. Once access to a grazing section had closed, no further cows were allowed into that section; however, cows that were already present in that grazing section were allowed to remain there until they chose to leave voluntarily (within 24 h). Cows that did not leave the paddock voluntarily within 24 h were fetched once daily. The average distance that cows had to walk from the AMS unit to a paddock was 325 m (range of 25–650 m).

The farm was walked weekly to assess farm pasture cover using a plate meter (Jenquip, Fielding, New Zealand). Paddocks, which were deemed to have a pasture cover (>4 cm) greater than the target (1,300–1,500 kg of DM/ha), were removed from the grazing rotation. Cows were strip-grazed within each paddock, with cows receiving a new strip in each section (A, B, C) over each 24-h period. Average sward heights before and after grazing (measured above ground level using the plate meter) were 8.0 and 4.0 cm, 7.8 and 4.0 cm, and 8.2 and 4.2 cm in sections A, B, and C, respectively. The pasture received fertilization of 250, 3, 8, and 25 kg/ha per year of nitrogen, phosphorus, potassium, and sulfur, respectively.

Statistical Analysis

We analyzed the effect of treatments (MPE and CS) and their interactions between milkings per cow per day, milk yield per cow per day, milk yield per cow per milking, milking interval per milking, box time per milking, milking time per milking, average flow rate per milking, and feed intake per day. This was carried out using a mixed model procedure (PROC MIXED) in SAS v9.3 (SAS Institute Inc., Cary, NC), with repeated measure statements to account for the repeated observations on the experimental unit (cow). Statistical significance was determined at the $P < 0.05$ level. All experimental periods were analyzed together. The following model statement was used for analysis:

$$y_{ij} = \mu + \text{DIM}_i + \text{parity}_j + \text{permission} \\ + \text{concentrate} + \text{permission} \times \text{concentrate} + e,$$

where y_{ij} is the dependent-response variable (milk yield per cow per day, milk yield per cow per milking, milkings per cow per day, milking interval per milking, box

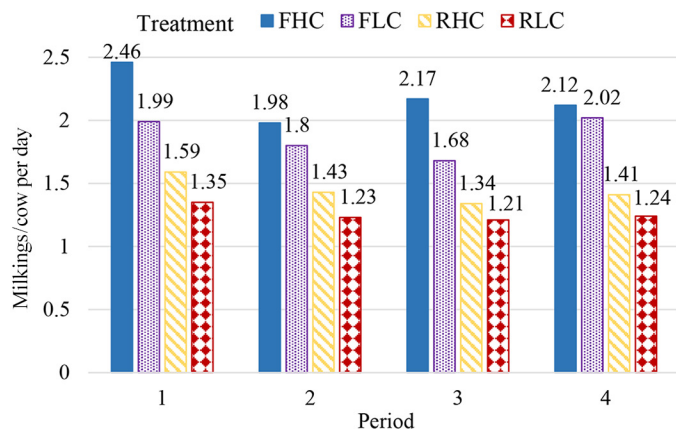


Figure 1. Arithmetic mean for number of milkings per cow per day (n) across the trial periods. Period 1 = from May 9, 2022, to June 5, 2022; period 2 = from June 13, 2022, to July 10, 2022; period 3 = from July 18, 2022, to August 14, 2022; period 4 = from August 22, 2022, to September 19, 2022. Treatment: FHC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), high concentrate supplementation (3.5 kg/d); FLC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), low concentrate supplementation (0.5 kg/d); RHC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), high concentrate supplementation (3.5 kg/d); RLC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), low concentrate supplementation (0.5 kg/d).

time per milking, milking time per milking, or average flow rate per milking); μ is the overall mean; DIM_i is the fixed effect of DIM for the i th cow; $parity_j$ is the fixed effect of the j th parity (first, second, or $\geq$ third); permission is the fixed effect of the 2 levels of MPE (frequent or restricted); concentrate is the fixed effect of the 2 levels of CS (low concentrate or high concentrate); permission $\times$ concentrate is the effect of the interaction between MPE and CS; e represents the residual error.

RESULTS

Descriptive Data

A total of 68 cows, divided into 4 groups of 16 cows each, were used in this study. Each group transitioned through all the treatment combinations at different times of the study (Table 2). Total daily concentrates offered (kg/cow) on the FHC, FLC, RHC, and RLC treatment combinations were 3.33 kg/cow per day (SD = 0.64 kg), 0.46 kg/cow per day (SD = 0.13 kg), 3.17 kg/cow per day (SD = 0.88 kg), and 0.44 kg/cow per day (SD = 0.12 kg), respectively. Mean concentrate chemical composition was CP = 156 g/kg DM, ash = 90 g/kg DM, and NDF = 263 g/kg DM.

Figure 1 shows the average number of milkings per cow per day for each treatment combination summarized by the trial period (each 4-wk period cows spent in

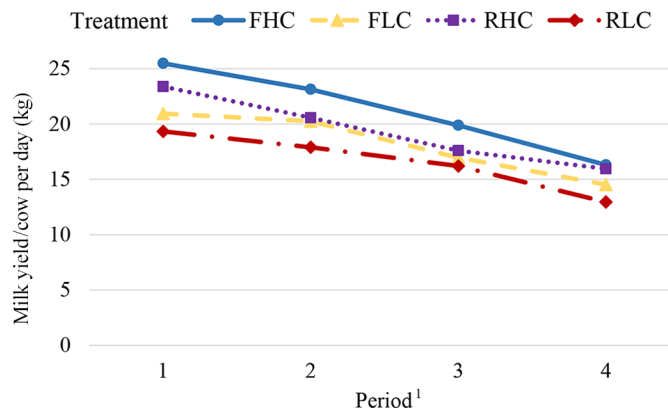


Figure 2. Arithmetic mean for milk yield per cow per day (kg) across the trial periods. Period 1 = from May 9, 2022, to June 5, 2022; period 2 = from June 13, 2022, to July 10, 2022; period 3 = from July 18, 2022, to August 14, 2022; period 4 = from August 22, 2022, to September 19, 2022. Treatment: FHC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), high concentrate supplementation (3.5 kg/d); FLC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), low concentrate supplementation (0.5 kg/d); RHC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), high concentrate supplementation (3.5 kg/d); RLC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), low concentrate supplementation (0.5 kg/d).

each of the treatment combinations). Milkings per cow per day ranged from a maximum of 2.46 ± 0.18 for the cows of the FHC treatment in the first trial period (from May 9, 2022, to June 5, 2022) to a minimum of 1.21 ± 0.16 for the cows in the RLC treatment in the third trial period (from July 18, 2022, to August 14, 2022; Figure 1). Figure 2 shows the average milk yield per cow per day summarized by trial period for each treatment group. Milk yield per cow per day ranged from a maximum of 26.3 ± 1.36 kg/d for the cows of the FHC treatment in the first trial period to a minimum of 11.6 ± 1.67 kg/d for the cows of the RLC treatment in the fourth trial period. Similar decreasing trends in milk yield were observed for all 4 treatments from the commencement to the end of the trial period, indicating a stage-of-lactation effect.

Statistical Analysis

Both MPE and CS had significant effects on milking and cow parameters. The milk yield per cow per day and milkings per cow per day were higher ($P < 0.001$) with the frequent (compared with the restricted) MPE and with the HC (compared with the LC) CS. The milk yield per milking was higher ($P < 0.001$) with the restricted MPE compared with the frequent MPE (13.4 ± 0.20 kg/cow vs. 9.9 ± 0.20 kg/cow, respectively), and it was higher with the HC compared with the LC CS level (11.8 ± 0.20 kg/cow vs. 11.5 ± 0.20 kg/cow). Restricted MPE increased the box time per milking compared with

Table 3. Least squares means of the main effect of milking permission¹ (frequent and restricted) and concentrate² (high and low) on milking and cow parameters

Parameter	Permission ¹		SEM	P-value	Concentrate ²		SEM ³	P-value
	Frequent	Restricted			High	Low		
Milk yield/cow per day (kg)	18.4	16.9	0.47	<0.001	19.2	16.1	0.47	<0.001
Milk yield/milking (kg)	9.9	13.4	0.20	<0.001	11.8	11.5	0.20	<0.001
Milkings/cow per day (n)	1.95	1.30	0.04	<0.001	1.75	1.50	0.04	<0.001
Milking interval/milking (h)	11.9	17.9	0.09	<0.001	13.9	16.0	0.09	<0.001
Box time/milking (min)	6.5	7.8	0.18	<0.001	7.2	7.2	0.18	0.12
Milking time/milking (min)	4.9	6.0	0.21	<0.001	5.4	5.5	0.21	0.02
Average flow/milking (L/min)	2.44	2.56	0.08	<0.001	2.53	2.47	0.08	<0.001

¹Milking permission: frequent permission, permission to milk after 6 to 8 h of previous milking; or restricted permission, permission to milk after 9.6 to 14 h of previous milking.

²Concentrate supplementation: low concentrate, 0.5 kg/cow per day; and high concentrate, 3.5 kg/cow per day.

frequent MPE (7.8 min/milking vs. 6.5 ± 0.18 min/milking), whereas CS did not affect box time per milking ($P = 0.12$). Milking time per milking was also higher for restricted MPE compared with frequent (6.0 min/milking vs. 4.9 ± 0.21 min/milking, respectively, $P < 0.001$) and for the LC compared with the HC (5.5 vs. 5.4 ± 0.20 min/milking, respectively, $P = 0.02$). The average milk-flow rate per milking was also significantly and independently affected by MPE and CS. A higher milk-flow rate per milking was observed with the restricted MPE (2.56 ± 0.08 L/min) compared with the frequent MPE (2.44 ± 0.08 L/min) and with the HC (2.53 ± 0.08 L/min) compared with the LC (2.47 ± 0.08 L/min) level. Table 3 shows the LSM estimates for the main effects of all the analyzed parameters.

The milk yield per cow per day was affected by the interaction of MPE and CS ($P = 0.02$; Table 4). Milk yield was highest with the FHC treatment combination (20.1 ± 0.48 kg/cow per day), followed by the RHC treatment combination (18.2 ± 0.48 kg/cow per day). The FLC treatment combination had an estimated 16.7 kg/cow per day (± 0.48), and the RLC treatment had 15.5 kg/cow

per day (± 0.48). The number of milkings per cow per day were also affected by the interaction of MPE and CS ($P < 0.001$). The highest estimated number of milkings per cow per day was recorded for the FHC (2.12 ± 0.04) and the FLC (1.77 ± 0.04) treatment combinations, followed by the RHC (1.38 ± 0.04) and RLC (1.23 ± 0.04) treatment combinations. Similarly, milking interval was longer for the RLC treatment combination (19.2 ± 0.10 h, $P < 0.001$) and RHC (16.7 ± 0.09). The shortest milking interval per milking was observed for the FHC (11.0 ± 0.07) and FLC (12.8 ± 0.08) treatments. Significant interaction effects between the treatments were not observed for the milk yield per milking ($P = 0.16$), box time per milking ($P = 0.61$), milking time per milking ($P = 0.37$), or the average milk-flow rate per milking ($P = 0.08$).

DISCUSSION

The functioning efficiency of a pasture-based AMS is dependent on consistent voluntary and relatively evenly distributed traffic of cows to the robot and their subse-

Table 4. Least squares means of the effect of the interaction between milking permission¹ (frequent and restricted) and concentrate supplementation² (high and low) level on milking and cow performance

Item	Frequent		Restricted		SEM	P-value
	High	Low	High	Low		
Milk yield/cow per day (kg)	20.1 ^A	16.7 ^C	18.2 ^B	15.5 ^D	0.48	0.02
Milk yield/milking (kg)	10.0	9.8	13.6	13.3	0.21	0.16
Milkings/cow per day (n)	2.12 ^A	1.77 ^B	1.38 ^C	1.23 ^D	0.04	<0.001
Milking interval/milking (h)	11.0 ^D	12.8 ^C	16.7 ^B	19.2 ^A	0.10	<0.001
Box time/milking (min)	6.5	6.6	7.8	7.8	0.18	0.61
Milking time/milking (min)	4.9	5.0	6.0	06.0	0.21	0.37
Average flow/milking (L/min)	2.46	2.42	2.60	2.53	0.85	0.08

^{A-D}Mean values in the same row with different superscripts differ significantly ($P < 0.001$).

¹Milking permission: frequent permission, permission to milk after 6 to 8 h of previous milking; or restricted permission, permission to milk after 9.6 to 14 h of previous milking.

²Concentrate supplementation: low concentrate, 0.5 kg of concentrate per cow per day; and high concentrate, 3.5 kg of concentrate per cow per day.

quent return to the pasture. However, a balance needs to be in place between herd size and MF, as only a limited number of milkings can take place in any 24-h period. A critical performance indicator of an AMS is the volume of milk that is harvested from it. This is influenced by the size of the herd and the milk yield per cow. Castro et al. (2012) reported that milk yield per AMS per year was better predicted by the number of cows per AMS and milk-flow rate. Additionally, Siewert et al. (2018) mentioned a positive association between daily milk yield per AMS and cow MF, cow milking speed, number of cows per AMS, and daily amount of concentrate offered per cow in the AMS. Our study focused on improving AMS efficiency through examination of the causal effect of MPE and CS at both an individual and interactive level on performance parameters such as milk yield per cow per day and MF, milking interval, and box time per milking. Overall milk yields and their seasonal trends in our study were similar to that reported in other studies conducted with seasonally calved herds in conventional milking systems (CMS; Horan et al., 2005; O'Sullivan et al., 2020). This is influenced by the stage of lactation and the deterioration of grass quantity and quality that is normally observed in such production systems as the autumn months progress (McCarthy et al., 2016).

In the current study, an increased MF (1.95 vs. 1.30 milkings/cow per day) was observed following the increase in MPE (milking allowed after 6–8 h vs. 9.6–14 h). This effect was also observed in the study of Foley et al. (2015) in which 2 levels of MPE (2 and 3 times/d) resulted in MF of 1.5 and 1.8, respectively; the corresponding milk yields were 19 and 18.4 kg/cow per day, which were not significantly different, indicating the potential to reduce MF without adverse production effects (Foley et al., 2015). In an AMS reducing MF would increase AMS free time and may permit more cows to be milked on a single robot. The MF has been shown previously to have an effect on milk yield per cow in both CMS and AMS. The positive effects of increased MF on milk yield were initially shown on CMS farms when 2 and 3 milkings/d regimens (at regular intervals) were compared (Friggens and Rasmussen, 2001). Smith et al. (2002) reported that milk yield was increased by up to 14% by increasing MF in a CMS from 2 to 3 milkings/d, whereas McNamara et al. (2008) showed that milk yield was reduced by 24% when MF was decreased from 2 to 1 milkings/d. O'Brien et al. (2002) also showed that once (compared with twice) daily milking in late lactation reduced milk yield by 29% and milk-solids yield by 24%. Increased milk yield recorded with increased fixed-frequency milking in CMS may be associated with alteration of secretory cells and mammary functions. However, the effects of higher MF on milk yield in AMS may be more complex, as milking intervals become variable from cow to cow and even

for the same cow on a daily basis. Rémond et al. (2009) found that cows could compensate for a long milking interval (MI), if the following milking occurred shortly after. However, Sharipov et al. (2020) did show that daily milk yield per cow increased significantly as MF increased from 2 to 5 times/d, within an AMS, whereas Lyons et al. (2013) observed the alternative scenario of reduced milk yield associated with reduced MF, also on AMS farms. Furthermore, Penry et al. (2018) observed a 2% reduction in milk production per hour of MI increase (increased MI is associated with reduced MF).

Concentrate supplementation has also been shown to affect milk yield in both CMS and AMS. Reid et al. (2015) showed a milk response of 0.96 kg of milk per kg of concentrate when a grass diet was supplemented with 3 kg of concentrate in late lactation within a CMS. A study by Shortall et al. (2018) examined the effect of different CS levels in the early and late periods of lactation on milk production in a pasture-based AMS; high and low concentrate levels in early and late lactation were 4.4 and 2.3 kg/cow per day and 0.5 and 2.7 kg/cow per day, respectively. The CS in early lactation had no effect on milk production, whereas in late lactation, cows receiving high (compared with low) CS levels had a greater milk yield per day (12.4 and 10.9 kg/cow, respectively) resulting in a milk response of 0.75 kg of milk/kg of concentrate (Shortall et al., 2018). This aligns with the view of Kellaway and Harrington (2004) that milk response to CS is dependent on growth rate and availability of grass, which is reduced during the autumn/late lactation stage of a pasture-based, seasonal calving system. Our results are in broad agreement with the study of Shortall et al. (2018), as the treatment indicating the highest MF and CS level (FHC) also showed the highest milk yield while the treatment indicating the lowest MF and CS level also showed the lowest milk yield. Lyons et al. (2013) also reported an associated 33% increase in daily milk yield when milking events increased from 1 to 2 per cow per day and a 13% increase in daily milk yield when they increased from 2 to 3 per cow per day. The increase in MPE (frequent compared with restricted MPE) implemented in the current study was accompanied by an estimated increase in milk yield of 1.5 kg/cow per day. In part, this could be explained by more frequent removal of a negative feedback protein (FIL, feedback inhibitor of lactation; Wilde et al., 1995; Vijayakumar et al., 2017) as well as other proteins such as serotonin that are responsible for having a negative effect on milk production (Collier et al., 2012). Conversely, a higher MF could have a positive effect on daily milk production through increased secretory cell activity (Capuco et al., 2003).

The estimated 3.1 kg/cow per day response in milk yield to the increased CS (average 0.45 kg/cow per day for LC vs. 3.25 kg/cow per day for HC) in this study

resulted in a conversion efficiency of 1.1 kg of milk/kg of concentrate, approximately. This response was greater than the response obtained by Shortall et al. (2018); however, that study was conducted in late lactation when the baseline milk yield was ~50% lower than in the current study, and the difference in CS treatments was also lower at 2.5 kg/cow per day. In this study, the increase in MPE resulted in an increase in MF of 0.65 milkings/cow per day, and this was associated with an increase in milk production of 1.5 kg/cow per day; the increase in CS level resulted in an increase in MF of 0.25 milkings/cow per day. This is in contrast to the study of Halachmi et al. (2005) who observed similar MF at the concentrate levels of 3.5 and 5.0 kg/cow per day, and Bach et al. (2007) who observed similar milk yield and MF in cow groups receiving concentrate levels from 3 to 8 kg/cow per day. However, both of these studies were conducted with an indoor AMS, where MF is generally higher than in a pasture system (Lyons et al., 2013). Jago et al. (2007) described a study in a pasture-based AMS where 0 versus 1 kg/d concentrate was offered to cows at the milking unit; an effect on MF was not observed but a milk production increase of 1.12 kg/cow per day was. Similarly, a more recent study by Lessire et al. (2017), conducted with grazing dairy cows, found that supplementation with 4 versus 2 kg/cow per day did not result in increased milkings but did increase milk yield (by 1.06 kg/cow per day). The lower difference between CS treatments in those studies (1 and 2 kg/cow per day, respectively) compared with ours may explain our findings in terms of increased MF and milk yield. We detected a significant interaction effect on MF between MPE and CS in our study. The frequent (compared with restricted) MPE resulted in significantly higher MF at both high and low CS levels, however it was highest for the FHC combination. As the MI has an inverse relationship with MF, the MI also showed a significant interaction, and the RLC and the FHC showed the longest and shortest intervals, respectively. These intervals have a practical importance; Davis et al. (1998) has shown that milk secretion is linear up to ~16 h after milking; therefore, intervals longer than 16 h could reduce milk yield through the FIL effect, and long intervals may also represent a welfare issue for the cow (e.g., discomfort in lying down), particularly in the early stages of lactation, near peak milk production. A study by O'Driscoll et al. (2010) indicated that cows milked once and twice daily spent a similar proportion of time lying per hour during the hours before morning milking, and this showed that any udder discomfort associated with once daily milking was not severe enough to inhibit lying behavior at this time. However, Österman and Redbo (2001) did find that cows milked less frequently spent more time standing before milking than cows milked more frequently. But their measures were

within 4 wk of calving, when milk yields would have been relatively high; it is important to monitor milking intervals from a welfare perspective, particularly in early lactation.

We showed that increasing CS level can increase MF; however, it results in an increase between 0.15 and 0.35 more milkings per cow per day depending on the MPE settings. It seems that it would not be an economical decision to increase CS up to 3 kg for a marginal increase in MF. This agrees with Lessire et al. (2017) who suggested that considering high concentrate levels as an incentive for robot visitation might be questioned due to its limited response. A more efficient strategy to increase MF with a view to increasing milk yield would be to adjust MPE settings, as we showed in this study that an increase of 0.54 and 0.74 extra milkings per cow per day (depending on the level of CS) resulted in increased milk yield.

Furthermore, the significant difference in daily milk yield observed between the RHC and FLC treatments means that an economic benefit associated with increased yield (from increased MF) is obtained without the associated increased cost of concentrate. Thus, from an economic perspective and a welfare perspective, the frequent MPE settings would be preferable, as achieved with the FLC treatment. Although the MI of the FHC was significantly shorter than the FLC treatment, this difference (11.0 vs. 12.8 h) was not considered biologically significant and would not necessitate the higher CS level; the desire to achieve a MF of as close as possible to 2 milkings per cow per day is acknowledged. Lessire et al. (2022) studied the effects of high CS combined with a short MI within an AMS; they found that a higher concentrate allocation induced an increase in milk yield but did not affect MF, whereas a shorter milking interval (4 h) was correlated with higher MF without an effect on milk yield. In our study, the minimum permission to milk was after between 6 to 8 h of the previous milking compared with the 4 h minimum MI considered by Lessire et al. (2022). The current study also showed that the interaction between MPE and CS was significant for milk yield and did increase the number of milkings per cow per day, with results more evident in treatments involving frequent MPE and high concentrate. We used an ABC rather than an AB grazing management system, as used in the Lessire et al. (2022) study, and this may be relevant because variable grass allocation or availability does influence cow traffic (Lyons et al., 2013). Also, our study was conducted over a considerable portion (~47%) of the herd lactation, whereas, many studies have focused on more short-term experimental treatments.

In conclusion, our study aimed to compare 2 management strategies (manipulation of MPE and CS) to improve the operation of an AMS within a pasture-based system. The study showed that allowing access to the robot be-

tween 6 to 8 h after the previous milking was sufficient (even with a minimal level of CS) to achieve acceptable milk production and milking performance. Regardless, future studies are needed to further evaluate the effect of MPE and CS on MF, milk production, and milking performance characteristics of the AMS in different herd sizes; modeling of such data would outline the economic effect of alternative strategies, which may be used to plan systems that best fit individual farm situations.

NOTES

This research was funded by Dairy Research Ireland (project number 1473) and Lely International (Maassluis, the Netherlands; agreement 20211473). We acknowledge the contribution of Jerry Foley (formerly with Teagasc, Moorepark, Fermoy, Co. Cork, Ireland) in conducting this experiment. This experiment did not require an ethical approval because it did not practice any “procedures” on animals as defined by the Health Products Regulatory Authority (HPRA, Dublin, Ireland). The authors have not stated any conflicts of interest.

Nonstandard abbreviations used: AMS = automatic milking system; CMS = conventional milking systems; CS = concentrate supplementation; FHC = frequent milking permission and HC; FIL = feedback inhibitor of lactation; FLC = frequent milking permission and LC; HC = high concentrate; LC = low concentrate; MF = milking frequency; MI = milking interval; MPE = milking permission; HC = restricted milking permission and HC; RHC = restricted milking permission and HC; RLC = restricted milking permission and LC.

REFERENCES

- Bach, A., C. Iglesias, S. Calsamiglia, and M. Devan. 2007. Effect of amount of concentrate offered in automatic milking systems on milking frequency, feeding behavior, and milk production of dairy cattle consuming high amounts of corn silage. *J. Dairy Sci.* 90:5049–5055. <https://doi.org/10.3168/jds.2007-0347>.
- Capuco, A. V., S. E. Ellis, S. A. Hale, E. Long, R. A. Erdman, X. Zhao, and M. J. Paape. 2003. Lactation persistency: Insights from mammary cell proliferation studies. *J. Anim. Sci.* 81(15_suppl_3):18–31. https://doi.org/10.2527/2003.81suppl_318x.
- Castro, A., J. M. Pereira, C. Amiama, and J. Bueno. 2012. Estimating efficiency in automatic milking systems. *J. Dairy Sci.* 95:929–936. <https://doi.org/10.3168/jds.2010-3912>.
- Collier, R. J., L. L. Hernandez, and N. D. Horseman. 2012. Serotonin as a homeostatic regulator of lactation. *Domest. Anim. Endocrinol.* 43:161–170. <https://doi.org/10.1016/j.domaniend.2012.03.006>.
- Davis, S. R., V. C. Farr, P. J. A. Copeman, V. R. Carruthers, C. H. Knight, and K. Stelwagen. 1998. Partitioning of milk accumulation between cisternal and alveolar compartments of the bovine udder: Relationship to production loss during once daily milking. *J. Dairy Res.* 65:1–8. <https://doi.org/10.1017/S0022029997002562>.
- 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*. J. J. Murphy, ed. Proceedings of a Satellite Workshop of the 20th International Grassland Congress, Cork, Ireland.
- Foley, C., J. Shortall, and B. O'Brien. 2015. Milk production, cow traffic and milking duration at different milking frequencies in an automated milking system integrated with grazing. Pages 40–47 in *Proceedings of the Precision Livestock Farming*, Milan, Italy.
- Friggens, N. C., and M. D. Rasmussen. 2001. Milk quality assessment in automatic milking systems: Accounting for the effects of variable intervals between milkings on milk composition. *Livest. Prod. Sci.* 73:45–54. [https://doi.org/10.1016/S0301-6226\(01\)00228-7](https://doi.org/10.1016/S0301-6226(01)00228-7).
- Greenall, R. K., E. Warren, and M. Warren. 2004. Integrating automatic milking installations (AMIs) into grazing systems—Lessons from Australia. Pages 273–279 in *Automatic Milking—A Better understanding*. A. Meijering, H. Hogeveen, and C. J. A. M. de Koning, ed. Wageningen Academic Publishers, Wageningen, the Netherlands.
- Halachmi, I., S. Ofir, and J. Miron. 2005. Comparing two concentrate allowances in an automatic milking system. *Anim. Sci.* 80:339–343. <https://doi.org/10.1079/ASC40480339>.
- Horan, B., P. Dillon, D. P. Berry, P. O'Connor, and M. Rath. 2005. The effect of strain of Holstein–Friesian, feeding system and parity on lactation curves characteristics of spring-calving dairy cows. *Livest. Prod. Sci.* 95:231–241. <https://doi.org/10.1016/j.livprodsci.2004.12.021>.
- Jacobs, J. A., and J. M. Siegford. 2012. Invited review: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare. *J. Dairy Sci.* 95:2227–2247. <https://doi.org/10.3168/jds.2011-4943>.
- Jago, J., K. Bright, P. Copeman, K. Davis, A. Jackson, I. Ohnstad, R. Wieliczko, and M. Woolford. 2004. Remote automatic selection of cows for milking in a pasture-based automatic milking system. *Proc. N.Z. Soc. Anim. Prod.* 64:241–245.
- Jago, J. G., K. L. Davis, P. J. Copeman, I. Ohnstad, and M. M. Woolford. 2007. Supplementary feeding at milking and minimum milking interval effects on cow traffic and milking performance in a pasture-based automatic milking system. *J. Dairy Res.* 74:492–499. <https://doi.org/10.1017/S002202990700283X>.
- Jago, J. G., K. L. Davis, P. J. Copeman, and M. M. Woolford. 2006. The effect of pre-milking teat-brushing on milk processing time in an automated milking system. *J. Dairy Res.* 73:187–192. <https://doi.org/10.1017/S002202990500155X>.
- Kellaway, R., and T. Harrington. 2004. *Feeding Concentrates: Supplements for Dairy Cows*. Rev. ed. Landlinks Press, CSIRO, Collingwood, Victoria, Australia.
- Lessire, F., E. Froidmont, J. Shortall, J. L. Hornick, and I. Dufrasne. 2017. The effect of concentrate allocation on traffic and milk production of pasture-based cows milked by an automatic milking system. *Animal* 11:2061–2069. <https://doi.org/10.1017/S1751731117000659>.
- Lessire, F., J.-L. Hornick, and I. Dufrasne. 2022. Effect of minimum milking interval on traffic and milk production of cows milked by a pasture based automatic milking system. *Animals (Basel)* 12:1281. <https://doi.org/10.3390/ani12101281>.
- Lind, O., A. H. Ipema, C. de Koning, T. T. Mottram, and H. J. Herrmann. 2000. Automatic milking. Pages 3–14 in *Bulletin of the IDF 348/2000*. IDF, Bruxelles, Belgium.
- Lyons, N. A., K. L. Kerrisk, and S. C. Garcia. 2013. Comparison of 2 systems of pasture allocation on milking intervals and total daily milk yield of dairy cows in a pasture-based automatic milking system. *J. Dairy Sci.* 96:4494–4504. <https://doi.org/10.3168/jds.2013-6716>.
- Lyons, N. A., K. L. Kerrisk, and S. C. Garcia. 2014. Milking frequency management in pasture-based automatic milking systems: A review. *Livest. Sci.* 159:102–116. <https://doi.org/10.1016/j.livsci.2013.11.011>.
- 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>.
- McNamara, S., J. J. Murphy, F. P. O'Mara, M. Rath, and J. F. Mee. 2008. Effect of milking frequency in early lactation on energy metabolism,

- milk production and reproductive performance of dairy cows. *Livest. Sci.* 117:70–78. <https://doi.org/10.1016/j.livsci.2007.11.013>.
- O'Brien, B., and D. Hennessy. 2017. Scientific appraisal of the Irish grass-based milk production system as a sustainable source of premium quality milk and dairy products. *Ir. J. Agric. Food Res.* 56:120–129. <https://doi.org/10.1515/ijaf-2017-0011>.
- O'Brien, B., G. Ryan, W. J. Meaney, D. McDonagh, and A. Kelly. 2002. Effect of frequency of milking on yield, composition and processing quality of milk. *J. Dairy Res.* 69:367–374. <https://doi.org/10.1017/S0022029902005605>.
- O'Callaghan, T. F., D. Hennessy, S. McAuliffe, K. N. Kilcawley, M. O'Donovan, P. Dillon, R. P. Ross, and C. Stanton. 2016. Effect of pasture versus indoor feeding systems on raw milk composition and quality over an entire lactation. *J. Dairy Sci.* 99:9424–9440. <https://doi.org/10.3168/jds.2016-10985>.
- O'Driscoll, K., D. Gleeson, B. O'Brien, and L. Boyle. 2010. Effect of milking frequency and nutritional level on hoof health, locomotion score and lying behaviour of dairy cows. *Livest. Sci.* 127:248–256. <https://doi.org/10.1016/j.livsci.2009.10.006>.
- O'Sullivan, M., L. Shalloo, K. M. Pierce, and F. Buckley. 2020. Economic assessment of Holstein-Friesian dairy cows of divergent Economic Breeding Index evaluated under seasonal calving pasture-based management. *J. Dairy Sci.* 103:10311–10320. <https://doi.org/10.3168/jds.2019-17544>.
- Österman, S., and I. Redbo. 2001. Effects of milking frequency on lying down and getting up behaviour in dairy cows. *Appl. Anim. Behav. Sci.* 70:167–176. [https://doi.org/10.1016/S0168-1591\(00\)00159-3](https://doi.org/10.1016/S0168-1591(00)00159-3).
- Penry, J. F., P. M. Crump, L. L. Hernandez, and D. J. Reinemann. 2018. Association of milking interval and milk production rate in an automatic milking system. *J. Dairy Sci.* 101:1616–1625. <https://doi.org/10.3168/jds.2016-12196>.
- 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>.
- Rémond, B., D. Pomiès, C. Julien, and J. Guinard-Flament. 2009. Performance of dairy cows milked twice daily at contrasting intervals. *Animal* 3:1463–1471. <https://doi.org/10.1017/S1751731109990371>.
- Scott, V. E., P. C. Thomson, K. L. Kerrisk, and S. C. Garcia. 2014. Influence of provision of concentrate at milking on voluntary cow traffic in a pasture-based automatic milking system. *J. Dairy Sci.* 97:1481–1490. <https://doi.org/10.3168/jds.2013-7375>.
- Sharipov, D., R. Kayumov, T. Akhmetov, R. Ravilov, and F. Akhmetzyanova. 2020. The effect of milking frequency and intervals on milk production and functional properties of the cows' udder in automatic milking systems. *BIO Web Conf.* 17:00036. <https://doi.org/10.1051/bioconf/20201700036>.
- Shortall, J., C. Foley, R. D. Sleator, and B. O'Brien. 2018. The effect of dairy cow breed on milk production, cow traffic and milking characteristics in a pasture-based automatic milking system. *Livest. Sci.* 209:1–7. <https://doi.org/10.1016/j.livsci.2018.01.002>.
- Siewert, J. M., J. A. Salfer, and M. I. Endres. 2018. Factors associated with productivity on automatic milking system dairy farms in the Upper Midwest United States. *J. Dairy Sci.* 101:8327–8334. <https://doi.org/10.3168/jds.2017-14297>.
- Smith, J. W., L. O. Ely, W. M. Graves, and W. D. Gilson. 2002. Effect of milking frequency on DHI performance measures. *J. Dairy Sci.* 85:3526–3533. [https://doi.org/10.3168/jds.S0022-0302\(02\)74442-1](https://doi.org/10.3168/jds.S0022-0302(02)74442-1).
- Snedecor, G. W., and W. G. Cochran. 1989. *Statistical Methods*. 8th ed. Iowa State University Press, Ames, IA.
- Stampa, E., C. Schipmann-Schwarze, and U. Hamm. 2020. Consumer perceptions, preferences, and behavior regarding pasture-raised livestock products: A review. *Food Qual. Prefer.* 82:103872. <https://doi.org/10.1016/j.foodqual.2020.103872>.
- Timlin, M., J. T. Tobin, A. Brodkorb, E. G. Murphy, P. Dillon, D. Hennessy, M. O'Donovan, K. M. Pierce, and T. F. O'Callaghan. 2021. The impact of seasonality in pasture-based production systems on milk composition and functionality. *Foods* 10:607. <https://doi.org/10.3390/foods10030607>.
- Vijayakumar, M., J. H. Park, K. S. Ki, D. H. Lim, S. B. Kim, S. M. Park, H. Y. Jeong, B. Y. Park, and T. I. Kim. 2017. The effect of lactation number, stage, length, and milking frequency on milk yield in Korean Holstein dairy cows using automatic milking system. *Asian-Australas. J. Anim. Sci.* 30:1093–1098. <https://doi.org/10.5713/ajas.16.0882>.
- Wilde, C. J., A. Prentice, and M. Peaker. 1995. Breast-feeding: Matching supply with demand in human lactation. *Proc. Nutr. Soc.* 54:401–406. <https://doi.org/10.1079/PNS19950009>.
- Wildridge, A. M., P. C. Thomson, S. C. Garcia, A. J. John, E. C. Jongman, C. E. F. Clark, and K. L. Kerrisk. 2018. Short communication: The effect of temperature-humidity index on milk yield and milking frequency of dairy cows in pasture-based automatic milking systems. *J. Dairy Sci.* 101:4479–4482. <https://doi.org/10.3168/jds.2017-13867>.

ORCIDS

Roberta Matera  <https://orcid.org/0000-0003-2204-0022>
 Pablo Silva Boloña  <https://orcid.org/0000-0002-5866-6943>
 Bernadette O'Brien  <https://orcid.org/0000-0001-7821-0911>

APPENDIX

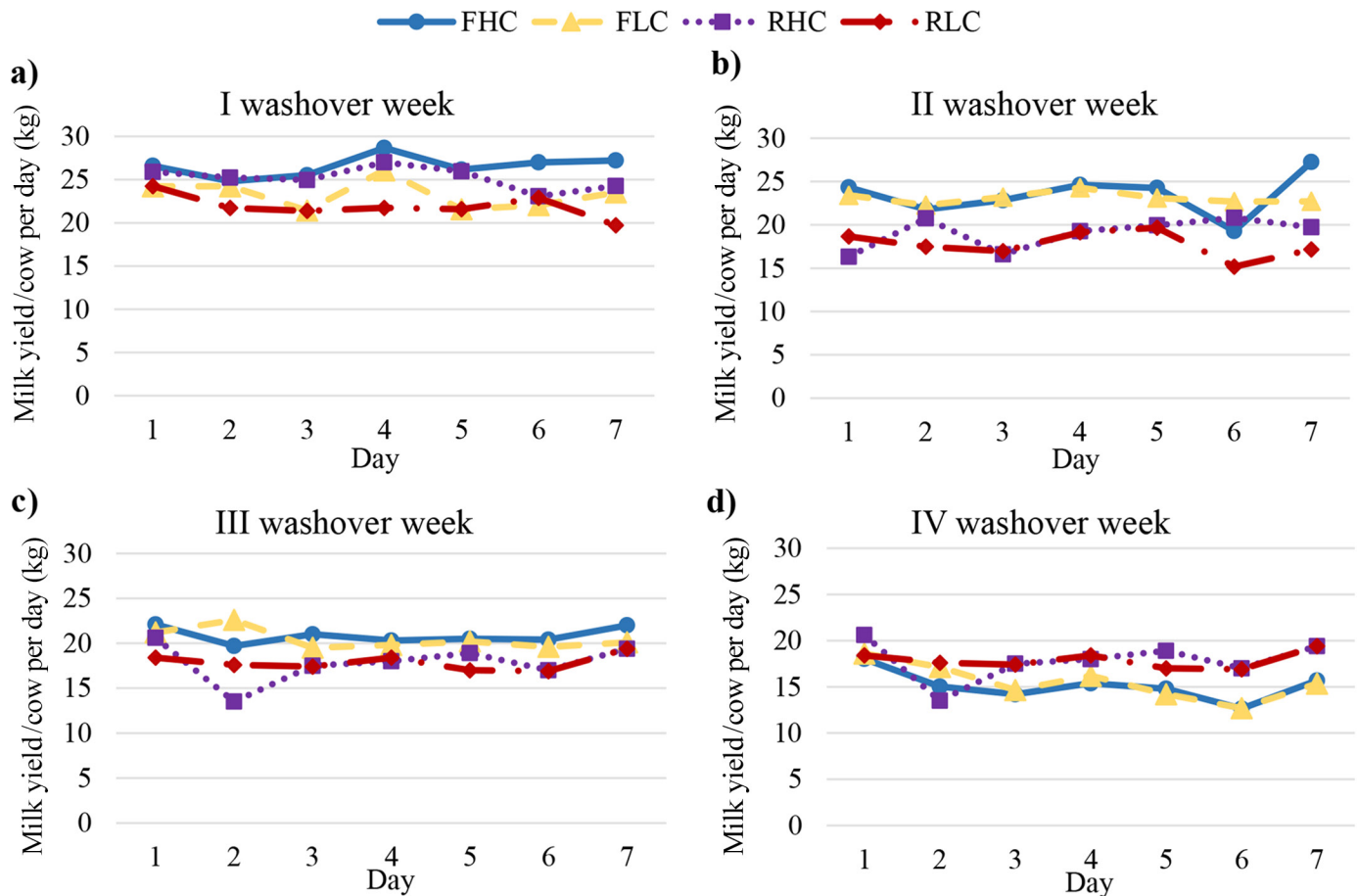


Figure A1. Milk yield per cow per day (kg) for each washover week for each treatment. Washover week: (a) washover wk 1 = from May 2, 2022, to May 8, 2022; (b) washover wk 2 = from June 6, 2022, to June 12, 2022; (c) washover wk 3 = from July 11, 2022, to July 17, 2022; (d) washover wk 4 = from August 15, 2022, to August 21, 2022. Treatment: FHC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), high concentrate supplementation (3.5 kg/d); FLC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), low concentrate supplementation (0.5 kg/d); RHC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), high concentrate supplementation (3.5 kg/d); RLC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), low concentrate supplementation (0.5 kg/d).

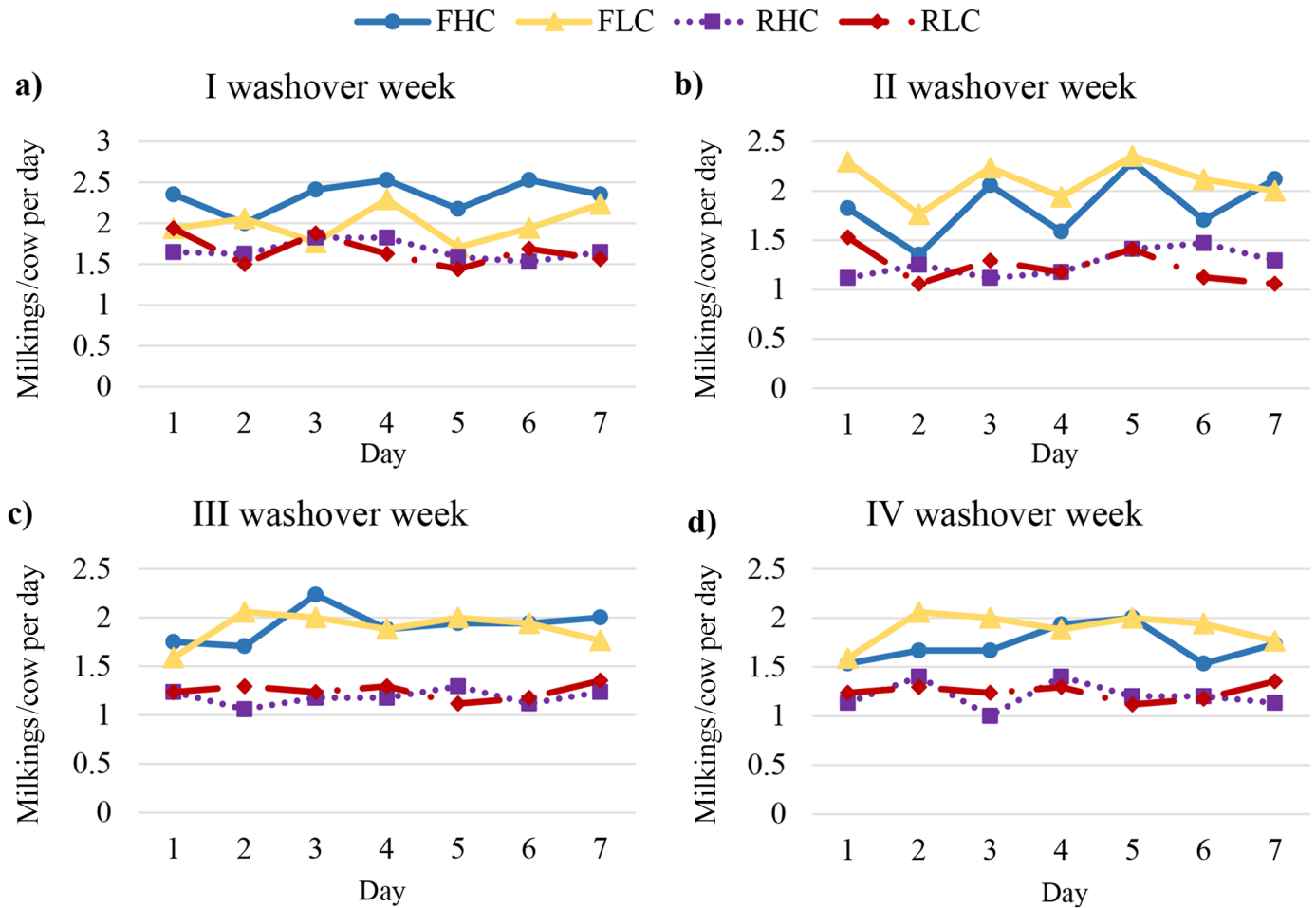


Figure A2. Number of milkings per cow per day for each washover week for each treatment. Washover week: (a) washover wk 1 = from May 2, 2022, to May 8, 2022; (b) washover wk 2 = from June 6, 2022, to June 12, 2022; (c) washover wk 3 = from July 11, 2022, to July 17, 2022; (d) washover wk 4 = from August 15, 2022, to August 21, 2022. Treatment: FHC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), high concentrate supplementation (3.5 kg/d); FLC = frequent milking permission (permission to milk after 6 to 8 h of previous milking), low concentrate supplementation (0.5 kg/d); RHC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), high concentrate supplementation (3.5 kg/d); RLC = restricted milking permission (permission to milk after 9.6 to 14 h of previous milking), low concentrate supplementation (0.5 kg/d).