J. Dairy Sci. TBC
https://doi.org/10.3168/jds.2024-25209

Responses of dairy cows to weekly individualized feeding strategies for dairy cows regarding their metabolic status

C. Gaillard[1]* and J. Abarnou[1]
[1]Institut Agro, PEGASE, INRAE, 35590 Saint Gilles, France

ABSTRACT

In dairy farms, cows are commonly fed a mixture of forages and concentrates ad libitum. To improve the energetic status and productivity of dairy cows, individualized feeding strategies have been proposed. One of this strategy is providing supplemental concentrates to adjust the forage-to-concentrate ratio based on factors like individual milk yield or calculated energy balance. This strategy can affect milk production and cow health, though consistent rules for adjustment are lacking. The objectives of this study were to evaluate the effects of an individualized feeding strategy, adjusted weekly based on the body weight gain of dairy cows, on production performance; and to determine if the metabolic status of the cows could be predicted early in lactation to take it into account into the decisions rules of the strategy. A total of 40 multiparous Holstein cows were involved in a 4-mo trial. The cows entered the experiment individually after calving and were initially fed a standard ration with a fixed 3 kg of extra concentrate per day for the first 8 d (on average). The cows were then paired based on calving date, parity (2 or 3), and body weight gain over the initial week. One cow from each pair was assigned to the Standard Feeding (SF) strategy, which continued receiving the fixed ration, while the other was assigned to the Precision Feeding (PF) strategy, which received a variable amount of extra concentrate adjusted weekly based on body weight gain. Measurements included weekly body weight, daily milk yield, and daily intakes of concentrates and forages. Blood samples were collected to measure metabolites (glucose, BHB, NEFA) for metabolic profiling. The results showed no significant differences in overall body weight gain, milk yield, or intakes (concentrates and/or forages). Two metabolic clusters were identified based on blood metabolites (glucose, BHB, NEFA), predicting cows' metabolic status with 90% accuracy. The balanced cluster had higher milk production, feed intake, and lost more body weight than the imbalanced cluster. Alternative variables like body weight gain and total feed intake can be used to predict metabolic clusters, achieving up to 70% accuracy. To conclude, cows fed this precision feeding strategy had similar performances than those fed the standard feeding strategy. Long-term effect of this strategy should be studied. Metabolic profiling predicted cows' metabolic status suggesting its potential for enhancing individualized feeding decisions.
KEYWORDS: precision feeding, performance, clustering, Holstein, multiparous

INTRODUCTION

In dairy farms, the cows are usually fed a unique ration, ad libitum, which is a mixture of forages and concentrates. Several feeding strategies have been proposed to improve the energetic status of a dairy cow, and became more individualized to deal with the variability in requirements observed in a herd. Providing a supplemental concentrate, separated from the forage-based ration, is an attractive approach. In practice this strategy is possible if the farm is equipped with automatons or a milking system able to deliver feed, both allowing to adjust a part of the ration at an individual level. This option is interesting considering the huge individual variability of productivity and requirements between animals and during the lactation. André et al. (2010a,b) ran simulations to evaluate milk yield response to a linear increase in concentrate intake during early lactation, based on data collected over the 3 first weeks of lactations only, on 4 farms. Individual optimization of concentrate supply was compared with an average concentrate supply resulting in a potential economic gain ranging from 0.20 to 2.03 euros per cow per day.

Previous studies have started to work on the adjustment of the forage to concentrate ratio at the beginning of dairy cows' lactation (Bossen et al., 2009; Gaillard et al., 2016) and more frequent adjustments (i.e., weekly) have been tried (Maltz et al., 2013; Little et al., 2016; Purcell et al.,

Received May 23, 2024.
Accepted August 2, 2024.
*Corresponding author: Charlotte Gaillard. ORCID: 0000-0002-7896-2520. E-mail: charlotte.gaillard@inrae.fr

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

2016). However, there are no well-established-common rules of adjustment of the quantity to deliver this extra concentrate. Farmers can take decisions based on the cows productivity (i.e., milk yield), and other information collected on farm, combined with their experience and knowledge of their animals.

First, concerning the variable used for the adjustment of concentrate, Little et al. (2016) and Purcell et al. (2016) used milk yield to adjust weekly and individually concentrate supply but it did not improve milk compared with a flat rate group strategy in both cases. With a weekly adjustment based on calculated energy balance in early lactation, milk yield, and milk components increased without changing dry matter intake compared with a fixed concentrate to forage ratio strategy during the lactation (Maltz et al., 2013). However, this last strategy requires a high amount of data (dry matter intake, body weight, milk yield and components) to be able to calculate energy balance. Thorup et al. (2013) reported that energy balance of individual cows can be estimated in real-time on farm using frequent body weight measures, which represents a relevant and feasible approach in practice.

Second, knowledge is still required to deliver the right amount of concentrate when a change of energy balance is observed. Indeed, the cows may have different efficiencies and different ways to handle the extra energy provided (i.e., they can use it to build up body reserves, or to increase their milk production depending of their metabolism).

The first objective of this study was to evaluate the feasibility and interest of an individualized feeding strategy adjusted weekly and based on the body weight gain of dairy cows on production performance. The second objective was to determine if the metabolic status of the cows could be predicted early in lactation with production variables, if it was stable over time, and affected by the feeding strategy, to take it into account into the decisions rules of the quantity of concentrate to supply for each cow.

MATERIALS AND METHODS

The experiment was conducted from September 2021 to April 2022 at the Institut National de la Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE) experimental farm of Méjusseaume (Le Rheu, Brittany, France, https://doi.org/10.15454/yk9q-pf68). The procedures related to the care and management of the animals used in the experiment were approved by an animal care committee of the French Ministry of Agriculture, in accordance with French regulations (reference APAFIS #31836–2021053017181790 v3, approved on September 2021).

Animals and housing

A total of 40 multiparous Holstein cows (23 cows in their second lactation and 17 cows in their third lactation) entered the experiment from September to November 2021 at calving. They were kept in the trial for 4 mo before joining other trials. They were housed in a group pen with access to ad libitum water via 12 connected troughs (Blue Intelligence, La Buvette, France) and individual feed bins. The standard ration was an ad libitum mixture of forages and concentrates (composition in Table 1a) distributed in the individual feed bins by a unique robot circulating in front of the feed bins twice a day after milking. Extra concentrate (Table 1a) was also added to the ration, depending on the feeding strategy attributed to the cow. The cows were milked twice daily, starting at 07:00 and 16:00 in a rotary milking system.

Feeding strategies

During "week 0," starting right after calving and lasting between 4 and 11 d - on average 8 d, all the cows were fed the standard ration ad libitum and 3 kg of extra concentrate per day. The cows were then paired based on calving date, parity (2 or 3), and body weight gain over the initial wk 0. One cow from each pair was assigned to the Standard Feeding (**SF**) strategy, which continued receiving the fixed ration, while the other was assigned to the Precision Feeding (**PF**) strategy, which received a variable amount of extra concentrate adjusted weekly based on body weight gain of the previous week. For the PF cows, the concentrate adjustment was done each Tuesday following wk 0. Therefore wk 1 to 16 are running from Tuesday to Monday, to cover each concentrate adjustment. Concerning the adjustment rules, first the extra concentrate range was defined between 0 and 6kg as it is generally recommended to maintain a forage-to-concentrate ratio where forage constitutes at least 40–60% of the diet on a dry matter basis to avoid health diseases and metabolic disorders, such as acidosis. Then, a cow losing body weight (**BW**) was considered in negative energy balance and supplied above the standard 3kg of extra concentrate received by the SF cows; while a cow gaining BW was considered in a positive energy balance and the extra concentrate part was reduced below 3kg. Second, farm historical data collected the year before the study from parity 2 cows, were used to define more precisely the adjustment rules, which are therefore, specific for this farm. Weekly body weight gain for each cow was calculated and used to establish the adjustment thresholds to obtain homogenous groups therefore containing 14 ± 3% of the data. It lead to the thresholds defined in Table 2 to cover the minimum weight losses and higher weight gain situations. It should be noted than from one week to

Table 1. Ration composition (a. ingredients and b. chemical composition) of the ad libitum part and extra concentrate adjusted part

Ingredients	INRAE Feed table code[1]	DM, %	DM, kg
Ad libitum part of the ration			
Maize silage	FE4720	76.1	14.2
Dried alfalfa	CD0030	5.60	1.04
Soybean meal 48	CX0240	18.3	3.42
Minerals and vitamins mix[2]	MP0100		0.20
Extra concentrate produced by Valorex (France)			
Wheat	CC0150	19.4	14.7
Maize	CC0020	9.9	7.40
Barley	CC0010	35.4	27.0
Cane molasses	CP0180	2.5	1.60
Dried alfalfa	CD0030	18.6	14.8
Canola meal	CX0200	14.2	11.1
Chemical composition (g/kgDM)			
Ash	68.1		
Crude protein	222		
Starch	188		
NDF	325		
Calcium (Ca)	8.13		
Phosphore (P)	3.84		

[1]French system (INRA, 2010).

[2]Kéomine Repro (Cooperl Hunaudaye, Lamballe, France): 55.7% calcium carbonate, 18.4% monocalcium phosphate, 10.0% magnesium phosphate, 9% cane molasses, 2.4% magnesium oxide, and 4.5% trace elements and vitamins.

DM: dry matter.

another a maximum change of 3 kg of extra concentrate was allowed to avoid too severe changes.

Measurements and calculations

Individual feed intake was recorded daily. Feed samples were taken daily for the wet ingredients (i.e., maize silage) and weekly for the dry ingredients. The samples were then dried at 60°C during 48h and stocked at ambient temperature in sealed bags. Samples pools were then realized and composition analyzed (Table 1b). Milk samples were taken once per week and analyzed for protein content, fat content, and cells.

Body weight was automatically recorded by a scale platform on the exit from milking every morning and evening. Data were cleaned to exclude artifacts because of the cow being only partly on the weighing platform as it entered and left the milking stall, and averaged over the day to run statistical analysis. During the experiment, to estimate weekly body weight for the ration adjustment, an individual and weekly regression model was applied to the morning and evening body weights. From this model, the body weight gain over the week was calculated and used to adjust the quantity of the extra concentrate individually following the rules given in Table 2.

Blood samples were taken every Tuesday morning after the morning milking and before the feed distribution. During wk 0, 3 blood samples were taken (at d 1, 3, and 5 after calving) from the tail caudal vein. For each sampling session, one sodium heparin tube of 9 mL was taken per cow and quickly centrifuged 4°C and 3000 g during 15 min. Plasma was then collected and stocked in 4 small tubes of 1 mL (including 2 labeled as "reserve") at −20°C before being analyzed for BHB, nonesterified fatty acids (NEFA), glucose, and urea.

Chemical analysis

Feed samples were ground with a 3-blade knife mill through a 0.8-mm screen. Feed samples were analyzed for dry matter (standard NF V18–109, October 1982), ash (incineration at 550°C for 5 h in a muffle furnace), and nitrogen (Dumas method, standard NF EN ISO 16634–1, 2008). NDF was determined according to the method

Table 2. Adjustment rules of the extra concentrates quantity to distribute based on individual body weight gain

Body weight over previous week	Concentrate to distribute[1]
If loss was …	
≥15 kg	6 kg
≥8 kg and <15 kg	5 kg
≥1 kg and <8 kg	4 kg
If loss or gain was ± 1 kg	3 kg
If gain was …	
≥1 kg and <8 kg	2 kg
≥8 kg and <15 kg	1 kg
≥15 kg	0 kg

[1]Exception to these rules: the variation of concentrate to distribute from one week to another cannot exceed 3 kg, even if the body weight change implies this change.

of Van Soest and Wine (1967). The dietary Ca content was measured by atomic absorption spectrophotometry (Spectra-AA20 Varian, Les Ulis, France) with the use of lanthanum chloride solution to dilute the sample and after calcination of the solid samples (500°C for 12 h). Dietary phosphorus content was determined by the Allen method using a KONE PRO multi-parameter analyzer (Thermo Fisher Scientific, Illkirch, France) (Standard NF EN 15621, 2017). Milk fat and protein contents were determined using mid-infrared analysis (Mylab, Châteaugiron, France). Plasma BHB, NEFA, glucose and urea were analyzed using an autoanalyzer.

Statistical analysis

The statistical analyses were carried out using R studio software (version 4.0.3, R Foundation, Vienna, Austria).

Clustering. In the aim to predict the cows metabolic status, a k-means clustering method (packages factoextra and cluster, Maechler et al., 2016) was used integrating 3 blood variables (glucose, NEFA, and BHBA). These metabolites are known to reflect the "metabolic profile" of the animal (Ingvartsen, 2006; Foldager et al., 2020) referring to the analysis of blood biochemical parameters that are useful to assess and prevent metabolic and nutritional disorders in dairy herds (Puppel and Kuczyńska, 2016). Two clusters (k = 2) were constructed and renamed "IMBAL" and "BAL" for respectively the cows with metabolic imbalance and the balanced cows. These reference clusters were built up using the measurements taken at wk 0 (3 blood samples) from one side (Cluster_Ref_0), and the measurements taken from wk 1 to 16 (16 blood samples) from the other side (Cluster_Ref_16). Furthermore, the same clustering method was applied on different sets of variables (excluding glucose, BHB, and NEFA), measured at wk 0 or from wk 1 to 16. The different sets of variables were the following: all the production variables (milk yield, total feed intake, forages intake, total concentrate intake, extra concentrate intake, body weight gain), only 2 production variables (body weight gain and total feed intake), all the production variables plus urea in blood, or only 2 production variables (body weight gain and total feed intake) plus urea in blood. Moreover, from wk 1 to 16 supplementary data sets were evaluated using milk variables (fat, protein and cells in milk), milk variables plus 2 production variables (body weight gain and total feed intake), milk variables plus urea in blood, and milk variables plus 2 production variables (body weight gain and total feed intake) and urea in blood.

The similarity of prediction between Cluster_Ref_0 and Cluster_Ref_16 was evaluated comparing the proportion of cows classified in the same clusters, and used to evaluate the stability of the cluster of each cow over time. The same method was applied to compare reference clusters (Cluser_Ref_0 or Cluster_Ref_16) with clusters build from the different sets of variables described previously.

Linear mixed-effects models. Linear mixed-effects models were used with the "lme" function of the "nlme" package (Pinheiro et al., 2022). The models evaluated the effect of parity (2 vs. 3), the feeding strategy (SF vs. PF), the 2 ways interaction and the random effect of the cow, on the different production variables (daily average of body weight, milk yield, total feed intake, forages intake, total concentrates intake, extra concentrate intake) measured during wk 0. These production variables and the milk components (fat, protein and cells in milk) were also compared between weeks. In this case, the linear mixed-effects models evaluated the effects of parity (2 vs. 3), the feeding strategy (SF vs. PF), the challenge week (1 to 16), and the 2 ways interactions. These models also took into account the cow as random, and a temporal corAR1 function, representing an autocorrelation structure of order 1 (Pinheiro and Bates, 2000). Linear mixed-effects models were also used to evaluate the effect of parity (2 vs. 3), feeding strategy (SF vs. PF), and 2 ways interaction on the production variables summed over the 16 weeks of the trial (excluding wk 0). Similarly, linear models were used to evaluated the effect of cluster (BAL vs. IMBAL), feeding strategy (SF vs. PF), and 2 ways interaction on the total of each production variables.

RESULTS

Extra concentrate intake over challenge weeks

Based on the decision rules, the PF cows required more extra concentrate in the beginning of the lactation (from calving to wk 6) than the quantity usually offered (3 kg). From wk 8, the average extra concentrate intake was below the standard 3 kg, and kept decreasing thereafter (Figure 1). Figure 1 also shows a great individual variability of extra concentrate intake over the weeks (average standard deviation of 1.14 kg).

Production variables responses to challenges

At wk 0, all the cows received the same amount of the extra concentrate (3 kg/d). The groups SF and PF were well balanced regarding body weight, milk yield, and forage intake (Table 3), but the PF cows ate on average 1.2 kg more (distributed into +0.8 kg of forages – non-significant difference, and +0.4 kg of concentrates – significant difference) than the SF cows.

The feeding strategy had no effect on weekly body weight, body weight gain, milk yield, or fat in milk (Table 3). However, there was feeding strategy by parity

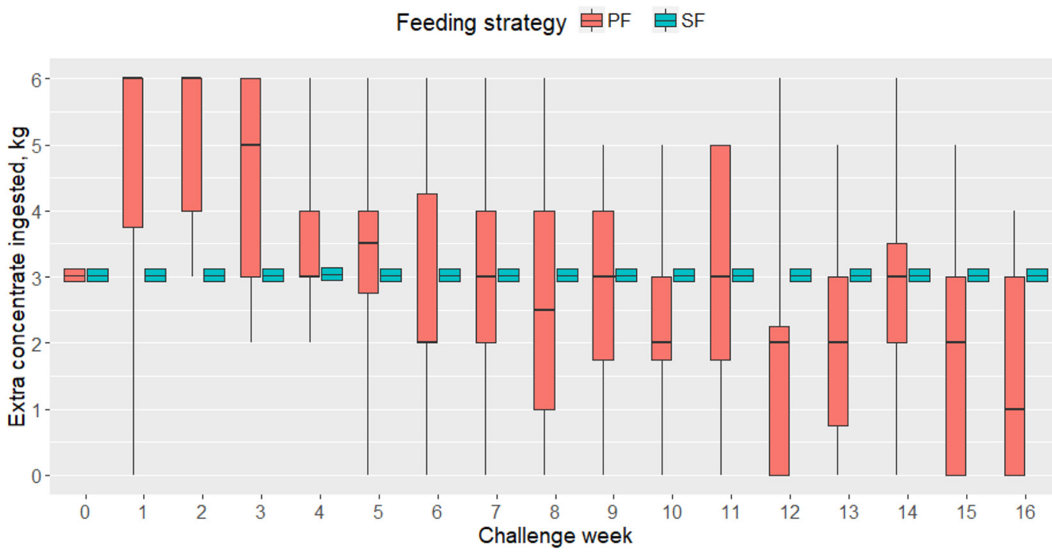


Figure 1. Average quantity of extra concentrate ingested over weeks of challenge, for the SF cows (standard feeding strategy) and the PF cows (precision feeding strategy, stable dotted line at 3 kg)

interactions for weekly total intake (*P* = 0.03) and for weekly forages intake (*P* = 0.01). For second parity cows the PF cows ate less than the SF cows (−0.71 kg/d of total feed intake driven by forages intake: −0.73 kg /d), while it was the opposite for third parity cows (+1.33 kg/d of total feed intake driven by forages intakes: +1.28 kg/d). Significant feeding strategy by week interaction (*P* < 0.01, Table 3) on protein in milk, cells in milk, total feed intake, total concentrate intake, and on the extra concentrate intake were also found. Pairwise comparisons indicated that the protein in milk of PF cows was higher than that of SF cows from wk 0 to 5 (*P* < 0.05) but there was no effect of the feeding strategy the following weeks. Total feed intake, total concentrate intake and extra concentrate intake (Figure 1) of PF cows were higher than those of SF cows from wk 0 to 4 (*P* < 0.05), and from wk 11 total concentrate intake and extra concentrate intake of PF cows were lower than those of SF cows. The number of cells in milk was higher for PF cows than SF cows only for wk 5, there was no other difference.

The results over the 16 experimental weeks indicated that the feeding strategy did not affect the overall body weight gain, or milk yield even though numerically, the PF cows produced more milk (4431 vs. 4419 kg respectively for PF and SF) and consumed less feed than the SF cows (total intake: 2772 vs. 2822 kg, forages intakes: 2061 vs. 2095 kg, total concentrates: 733 vs. 748 kg, respectively for PF and SF cows). There was a feeding strategy by parity interaction on the total feed intake (*P* = 0.02) and total forages intake (*P* = 0.01), with parity 2 cows fed with PF eating less than those fed with SF (−169 kg of total feed, −143 kg of forages); while it was the opposite for parity 3 cows (+132 kg of total feed, +133 kg of forages).

Cows' metabolic status based on glucose, BHB, and NEFA (reference clusters)

Two distinct clusters (Figure 2) were found when applying the clustering method on glucose, BHB, and NEFA, measured at wk 0 (3 measurements per cow) or from wk 1 to 16 (16 measurements per cow). Cluster 1 contained cows with higher plasmatic BHB and lower glucose than Cluster 2. Therefore, Cluster 1 represents the cow with a metabolic imbalanced (IMBAL) and Cluster 2 the balanced cows (BAL). When blood metabolites were measured in wk 0, the IMBAL cluster contained 14 cows and the BAL cluster 26, while when they were measured from wk 1 to 16, the clusters contained 16 and 24 cows respectively. Looking at each cow, 36 were sorted in the same cluster at wk 0 and from wk 1 to 16, so clustering based on metabolites data recorded during wk 0 could predict the cluster membership during the next 4 mo with an accuracy of 90%. Among the 4 cows changing cluster, 3 of them changed from the BAL cluster to the IMBAL cluster.

New trajectories regarding reference clusters

There was a balanced proportion of SF and PF cows among the clusters (BAL or IMBAL), and no significant effect of the cluster on the total extra concentrate part (*P* = 0.45, Table 4). There was no cluster by feeding strategy interaction on the production variables. The cluster had a significant effect on the total milk yield, total feed intake, total forage intakes and body weight gain over the 16 experimental weeks (Table 4). The cows belonging to the BAL cluster produced more milk, ate more *ad libitum* feed, and lost more body weight than the cows belonging to the IMBAL cluster (Figure 3).

New variables to establish these clusters

Different variables can be used instead of the usual blood variables (NEFA, BHB, glucose) to predict the clusters with different levels of accuracy (Figure 4). Based on body weight gain and total feed intake measured at wk 0, the clusters were predicted with an accuracy of 60% (compared with Cluster_Ref_0), while when more data were added (urea in blood, or/and more production variables), the accuracy increased up to 62.5%. Based on an average of weekly measurements taken from wk 1 to 16, clusters were predicted with an accuracy ranging from 50 to 70%, depending on the set of variables used. The highest accuracy was obtained using body weight gain, total feed intake and urea in blood (70%). Using only body weight gain and total feed intake decreased the accuracy (55%).

DISCUSSION

Production responses to the feeding strategy

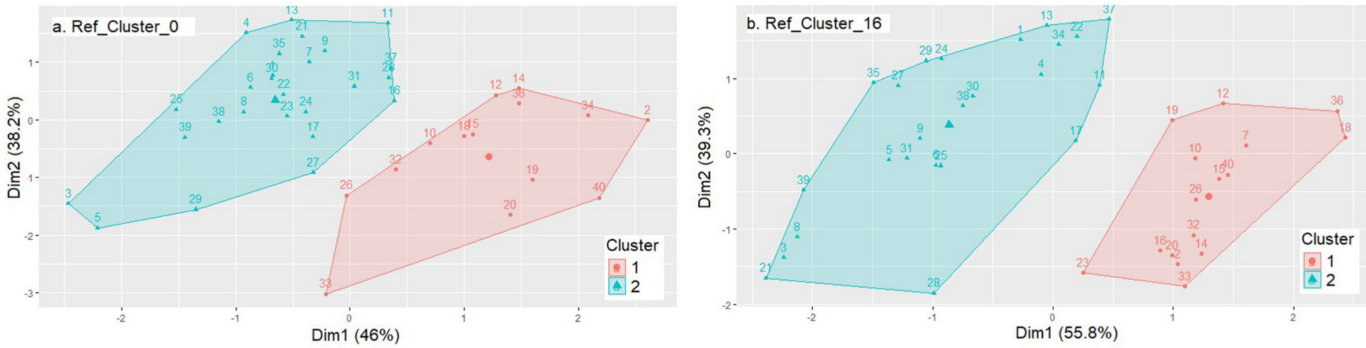
The high variability in cows' responses to the feeding strategy was also reported by André et al. (2010a,b) explaining that this variability could be exploited to improve economic results during early lactation. However, overall, the present individualized feeding strategy did not improve milk production nor decrease concentrate intake over the 4 experimental months, even though numerical improvements were observed.

First, it would be interesting to run (or simulate) this experiment over a full lactation to understand the long-term effects of such strategy and assess its economic impact. Nevertheless, at the end of the experiment (wk 16 postpartum), on average, PF cows consumed 1.5 kg less of extra concentrate than SF cows while producing 0.5 kg of milk more per day and consuming 0.27 kg less total feed per day. If this trend remains stable over the following weeks without affecting significantly milk production, the PF strategy could reduce farm costs. Maltz et al. (2013) also ran an experiment during 16 weeks (from wk 4 to wk 19 postpartum) involving a weekly concentrate adjustment based on calculated energy balance in early lactation. They found that, due to

Table 3. Effect of feeding strategy (Strategy: SF vs. PF), parity (2 vs.3) and week of challenge (1 to 16) on the different production variables of the Holstein dairy cows. Means and residual standard deviation (RSD) are presented for each variable at wk 0 (no feeding strategy), on weekly averages (from wk 1 to 16) and the total over the 4 mo of experiment (16 weeks)

				P-values					
	SF	PF	RSD	Strategy	Parity	Week	Treat * Parity	Treat * Week	Parity * Week
Number of cows	20	20							
Week 0									
Body weight, kg	668	677	0.07	0.39	<0.01	—	0.40	—	—
Milk yield, kg/d	29.7	30.4	0.15	0.60	0.29	—	0.98	—	—
Total intake, kg/d	17.3	18.5	0.10	0.04	0.40	—	0.29	—	—
Forages, kg/d	12.3	13.1	0.12	0.58	0.09	—	0.34	—	—
Total concentrate, kg/d	5.01	5.41	0.10	0.01	0.17	—	0.33	—	—
Extra concentrate, kg/d	3.00	3.00	0.00	—	—	—	—	—	—
Weekly averages									
Body weight, kg	659	665	0.07	0.44	<0.01	<0.01	0.10	0.28	<0.01
Body weight gain, kg	0.42	−0.18	98.1	0.51	0.16	<0.01	0.48	0.74	0.46
Milk yield, kg/d	37.9	38.8	0.13	0.38	0.18	<0.01	0.66	0.23	0.16
Fat in milk, %	41.7	40.2	0.12	0.14	0.72	<0.01	0.95	0.40	0.02
Protein in milk, %	30.1	30.3	0.08	0.76	0.66	0.04	0.08	<0.01	0.79
Cells (log10cell)	0.94	1.06	0.64	0.35	0.09	<0.01	0.74	<0.01	0.01
Total intake, kg/d	24.3	24.3	0.14	0.75	<0.01	<0.01	0.03	<0.01	<0.01
Forages, kg/d	17.9	18.0	0.16	0.78	<0.01	<0.01	0.01	0.71	<0.01
Total concentrate, kg/d	6.42	6.44	0.15	0.85	0.19	<0.01	0.74	<0.01	0.07
Extra concentrate, kg/d	3.00	2.96	0.43	0.67	0.10	<0.01	0.09	<0.01	0.80
Total (16 weeks)									
Body weight gain, kg	0.58	−4.40	16.4	0.64	0.09	—	0.26	—	—
Milk yield, kg	4419	4431	0.11	0.89	0.25	—	0.48	—	—
Total intake, kg	2823	2772	0.08	0.51	<0.01	—	0.02	—	—
Forages, kg	2095	2061	0.09	0.61	<0.01	—	0.01	—	—
Total concentrate, kg	748	733	0.07	0.41	0.33	—	0.48	—	—
Extra concentrate, kg	350	334	0.15	0.31	010		0.20		

SF: cows with the standard feeding strategy, PF: sows with the precision feeding strategy, RSD: residual standard deviation.



Ref_Cluster_0	Interpretation	Number of cows	Glucose	NEFA	BHB
Cluster 1	IMBAL	14	42.3	489	707
Cluster 2	BAL	26	67.8	908	661
RSD			0.24	0.51	0.23

Ref_Cluster_16	Interpretation	Number of cows	Glucose	NEFA	BHB
Cluster 1	IMBAL	16	54.3	211	863
Cluster 2	BAL	24	71.4	384	818
RSD			0.14	0.37	0.28

Figure 2. Reference clusters based on blood metabolites (glucose, BHB and NEFA) data collected at wk 0 (3 measurements per cows) and b) from wk 1 to 16 (16 measurements per cow). Means values are presented for each cluster and blood metabolite, as well as the residual standard deviation (RSD, unit of the variable).

an increase in concentrate intake (on average +0.86 kg/d) over the studied period, milk yield and milk components increased without affecting dry matter intake compared with a fixed concentrate-to-forage ratio strategy during lactation (Maltz et al., 2013). Although the study lasted 16 weeks, the authors reported that there was no indication that the response to the individualized feeding strategy declined over time. At wk 19 postpartum, the control cows were consuming 0.5 kg more concentrate than the cows fed with the adjusted strategy, despite having lower milk production.

Second, the variable of adjustment used in the present study (body weight gain) varied significantly over the day (high differences between morning and evening body weights) and between days. The data were cleaned and "milk free" as the cows were weighed just after milking but the gut content was not evaluated, which may explain the differences between morning and evening values. Thorup et al. (2013) proposed smoothing the body weight data using asymmetric double-exponential weighting and correcting them for the weight of milk produced, gut fill, and the growing conceptus. This method, though less straightforward on paper but functional on real-time, may provide more accurate estimations of energy balance.

Cows metabolic status

The present study reported that cows' metabolic profile can be identified easily during the first week of the lactation using 3 blood metabolites (glucose, NEFA, BHB). This is in agreement with previous studies reporting that elevated NEFA and BHB and decreased glucose and IGF-I are indicative of metabolically imbalanced cows, which are more at risk for an unsuccessful transition from the dry period to lactation (Ingvartsen et al., 2003; Puppel and Kuczynska, 2016). The same clusters composition (90% similarity) was found when using blood metabolites measured weekly from wk 0 to 16, so predicting the cluster membership at wk 0 is accurate, at least for the following 4 mo. As blood metabolites are not easy to obtain on farms and cannot be automatized, other biomarkers have been studied to try to predict these

Table 4. Effect of clusters (IMBAL or BAL, based on cluster reference from wk 1 to 16) on the production variables of Holstein cows

	Cluster 1 IMBAL	Cluster 2 BAL	RSD	P-value Cluster
Number of cows	16	24		
Number of PF cows	7	13		
Body weight at d 1 after calving, kg	680	704	0.07	0.35
Total Milk yield over 16 weeks, kg	4157	4605	0.11	<0.01
Total intake over 16 weeks, kg	2679	2876	0.08	0.01
Total forages over 16 weeks, kg	1984	2140	0.09	0.02
Total concentrate over 16 weeks, kg	716	757	0.07	0.06
Total adjusted concentrate over 16 weeks, kg	333	348	0.15	0.45
Body weight gain over 16 weeks, kg	10.8	−10.1	17.1	0.04

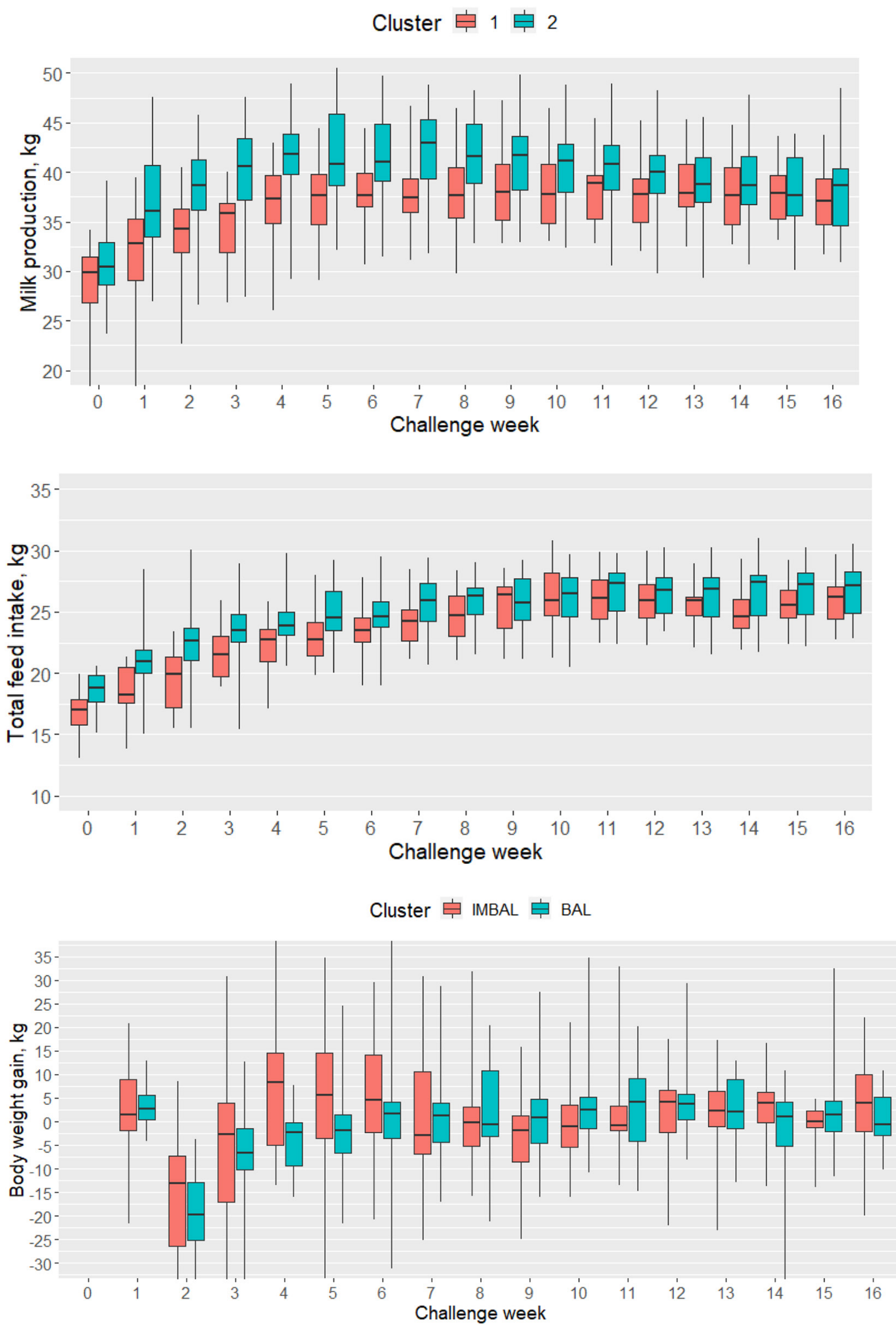


Figure 3. Effect of clusters (1 = IMBAL, 2 = BAL) on average daily milk yield, feed intake and body weight gain of Holstein cows over the experimental weeks

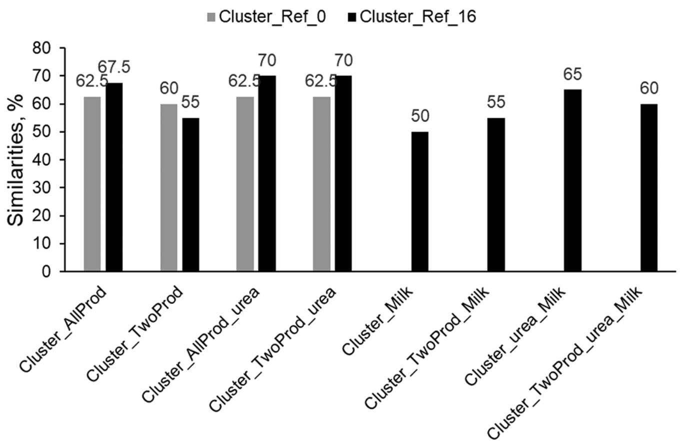


Figure 4. Similarities (%) between the prediction of reference clusters (Ref_0 or Ref_16) using blood variables (NEFA, BHB, glucose) and clusters predicted using a set of other variables (production variables, milk components and urea in blood). Cluster_AllProd: clustering using all the production variables (milk yield, total feed intake, forages intake, total concentrate intake, adjusted concentrate intake, body weight gain); Cluster_TwoProd: clustering using only 2 production variables (body weight gain and total feed intake); Cluster_AllProd_urea: clustering using all the production variables plus urea in blood; Cluster_TwoProd_urea: clustering using only 2 production variables (body weight gain and total feed intake) plus urea in blood; Cluster_Milk: clustering using milk variables (fat, protein and cells in milk); Cluster_TwoProd_Milk: clustering using milk variables plus body weight gain and total feed intake; Cluster_urea_Milk: clustering using milk variables plus urea in blood; Cluster_TwoProd_urea_Milk: clustering using milk variables plus 2 production variables (body weight gain and total feed intake) and urea in blood

metabolic clusters. The present results showed that using production (body weight gain and total feed intake only) or milk data available on farm gives an accurate estimation of the metabolic status from 60 to 70%, depending on the variable chosen and the number of measurements. Even though these values are a bit lower than those found in literature, they are consistent with previous studies. Indeed, previous studies reported that using milk metabolites and enzymes (i.e., glucose, glucose-6-phosphate, BHB, lactate dehydrogenase, N-acetyl-β-d-glucosaminidase, isocitrate) combined with days in milk and parity could predict metabolic status with an accuracy of 80% (de Koster et al., 2019). The Fourier transform mid-IR (FT-MIR) spectra of milk can also predict metabolic cluster accurately (79% accuracy in de Koster et al., 2019; 74% accuracy in Grelet et al., 2019), and this is a fast and cost-effective technology currently available in many countries. The results of the present study have the advantage of being available during the first 7 d of the lactation without supplementary measurements or costs while previously reported studies required up to 5 weeks of measurements and analysis costs. To go further and improve the present methodology, using values over the first 2 or 3 weeks instead of just the first week after calving may help to increase the accuracy of the prediction.

Metabolic status and trajectories

The metabolic status had an effect on the production variables of the cows, which is in accordance with previous studies. Cows with a balanced metabolic status (BAL) tend to have a higher dry matter intake, milk production, and energy balance than the imbalanced cows (IMBAL) (de Koster et al., 2019). The relationship between dry matter intake and metabolic status may be explained by the fact that certain metabolites (i.e., NEFA) may regulate feed intake in ruminants by the hepatic oxidation of these metabolites, thereby causing a satiety signal and depressing feed intake (Ingvartsen and Andersen, 2000; Allen et al., 2009). Knowing the metabolic status of the cows should help to improve the decisions taken to select the best feeding strategy for each cow or group of cows. By identifying metabolic profiles early in lactation, we can tailor the feeding strategy to meet the specific energy and nutrient requirements of different cows. For instance, cows identified with an imbalanced metabolic profile may benefit from targeted nutritional interventions such as supplemental feeding with glycerol or propylene glycol. Indeed, as demonstrated by Lomander et al. (2012) glycerol supplementation during the first 3 weeks of lactation increased milk yield without adversely affecting metabolic status. This targeted approach ensures that each cow's specific metabolic needs are met, potentially improving overall herd productivity and health. Therefore, integrating metabolic profiling into the precision feeding framework allows for more precise and individualized feeding strategies. This integration helps to address the variability in metabolic responses among cows, leading to better management decisions that enhance both productivity and metabolic health over the lactation period.

Feeding strategy, energy balance and metabolic status

The lack of improvement in energy balance or metabolic status with the present precision feeding strategy (PF) can be attributed to several factors. Individual variability among cows, influenced by genetics, health status, and previous nutrition, likely diluted the PF strategy's overall effect. Furthermore, if feed intake patterns remained unchanged, the overall nutrient intake might not have differed significantly between groups, limiting the impact on energy balance. The thresholds for concentrate adjustment, derived from historical data, might not have been optimal for all cows. Additionally, energy balance and metabolic status are complex traits affected by numerous factors beyond feed intake, such as stress and lactation stage, which this body weight based PF strategy may not have fully addressed. Body weight sensitivity as an indicator of energy balance can also be questioned. Even if it is practical to record, it is influenced by several factors such gut fill and water retention. Therefore, weekly body weight measurements may not capture rapid metabolic fluctuations effectively. However, in González et al. (2014), BW and daily BW changes are used to predict energy balance of grazing animals through a model-data fusion approach. Body weight data are collected remotely from individual animals using a weighing station placed to monitor frequently and consistently each animal's weight changes on a daily basis. The collected BW data is used to calculate the daily change in BW, providing an ongoing assessment of the animals' growth rates. The daily BW change data is used to predict the animals' feed intake over a 342-d grazing period. This prediction is crucial for understanding the animals' nutritional needs and managing their diets accordingly. The required amount of supplementary feed to maintain body weight varied daily, depending on the observed weight loss, which reflects the quality and quantity of grass available in the paddock. This real-time data can more precisely define the timing and quantity of feed supplementation needed for grazing animals, ensuring daily feed requirements are met to achieve target production levels based on observed BW trends. This approach can reduce feeding costs, lower the environmental footprint, and enhance animal health and welfare.

Precision feeding strategy

In this study, the precision feeding strategy was based on the same concentrate distributed in varying quantities. While this approach provides valuable insights, it has limitations compared with using differently formulated concentrates tailored to the individual nutritional needs of cows. Ideally, precision feeding would involve not only adjusting the amount of concentrate but also its composition, to better match the specific dietary requirements of each cow as done for gestating and lactating sows (Gaillard et al., 2022; Gauthier et al., 2019). With such a strategy, each cow might benefit from tailored nutrient profiles that address their unique energy, protein, and micronutrient needs.

The way of distributing the concentrate, whether in individual feeder or separately in an automaton, should also be considered. Based on current literature, with a concentrate adjustment in the total mixed ration (TMR, as done in the present study) milk yield generally increased on short (Gaillard et al., 2016) or long-term (Bossen et al., 2009; Maltz et al., 2013), whereas when concentrates were offered separately from silage at an automaton milk yield was not affected (Little et al., 2016; Purcell et al., 2016). The basic diet, such as a partial mixed ration (PMR), plays a crucial role in the overall nutritional strategy. Adjusting the PMR for the group can help ensure a balanced baseline diet, but individual supplementation should be fine-tuned to optimize performance and health. Furthermore, the interaction between the PMR and the supplemental concentrates must be carefully managed. Different cows may respond differently to the same supplement depending on their base diet composition. Incorporating a variety of concentrates formulated for specific purposes (e.g., high-energy, high-protein, or fortified with specific vitamins and minerals) can make precision feeding more effective in addressing the diverse needs of a herd. However, practical challenges such as cost, storage, and management complexity need to be considered. Implementing a more nuanced supplementation strategy requires robust management practices and possibly advanced feeding technologies. Future research should explore the benefits of using differently formulated concentrates in precision feeding and develop guidelines for integrating these with PMR adjustments.

CONCLUSION

Adjusting weekly and individually the concentrate part of the ration represents an opportunity to take into account the huge variability of nutrient requirements and production responses among dairy cows. However, the present feeding strategy using body weight gain to adjust weekly and individually the concentrate part of the ration does not seem to affect the performances of the animals, at least during the first 4 mo of the lactation. More work is needed to define the decision rules of concentrate distribution. Further analysis indicated that the metabolic status of the cows can represent relevant information to integrate in the decision rules of concentrate distribution as it affects cows' performances. It can be predicted during the first days of lactation based on 3 blood metabolites (glucose, BHB, NEFA) or a combination of 2 to 3 variables (intake, body weight, etc.) but with a lower accuracy.

ACKNOWLEDGMENTS

This project has received funding from the department of Animal Physiology and Livestock Systems (PHASE) of INRAE. The authors gratefully acknowledge all the staff at the experimental farm who participated in this project, especially Ophélie Dhumez for her precious help and constant presence throughout the project. The authors also wish to thank Thibaud Le Mouël for analyzing the blood samples.

CONFLICT OF INTEREST The authors declare no real or perceived conflicts of interest.

REFERENCES

Allen, M. S., B. J. Bradford, and M. Oba. 2009. BOARD-INVITED REVIEW: The hepatic oxidation theory of the control of feed intake and its application to ruminants. J. Anim. Sci. 87:3317–3334. https://doi.org/10.2527/jas.2009-1779.

André, G., P. B. Berentsen, B. Engel, C. J. de Koning, and A. G. Oude Lansink. 2010b. Increasing the revenues from automatic milking by using individual variation in milking characteristics. J. Dairy Sci. 93:942–953. https://doi.org/10.3168/jds.2009-2373.

André, G., P. B. M. Berentsen, G. Van Duinkerken, B. Engel, and A. G. J. M. O. Lansink. 2010a. Economic potential of individual variation in milk yield response to concentrate intake of dairy cows. J. Agric. Sci. 148:263–276. https://doi.org/10.1017/S0021859610000134.

Bossen, D., and M. R. Weisbjerg. 2009. Allocation of feed based on individual dairy cow live weight changes. Effect on milk production. Livest. Sci. 126:273–285. https://doi.org/10.1016/j.livsci.2009.07.011.

De Koster, J., M. Salavati, C. Grelet, M. A. Crowe, E. Matthews, R. O'Flaherty, G. Opsomer, L. Foldager, and M. Hostens. 2019. Prediction of metabolic clusters in early-lactation dairy cows using models based on milk biomarkers. J. Dairy Sci. 102:2631–2644. https://doi.org/10.3168/jds.2018-15533.

Foldager, L., C. Gaillard, M. T. Sorensen, T. Larsen, E. Matthew, R. O'Flaherty, F. Carter, M. A. Crowe, C. Grelete, M. Salavatif, M. Hostensg, and E. Gplus. 2020. Predicting physiological imbalance in Holstein dairy cows by three different sets of milk biomarkers. Prev. Vet. Med. 179:105006. https://doi.org/10.1016/j.prevetmed.2020.105006.

Gaillard, C., and J. Y. Dourmad. 2022. Application of a precision feeding strategy for gestating sows. Anim. Feed Sci. Technol. 287:115280. https://doi.org/10.1016/j.anifeedsci.2022.115280.

Gaillard, C., N. C. Friggens, M. Taghipoor, M. R. Weisbjerg, J. O. Lehmann, and J. Sehested. 2016. Effects of an individual weight-adjusted feeding strategy in early lactation on milk production of Holstein cows during extended lactation. J. Dairy Sci. 99:2221–2236. https://doi.org/10.3168/jds.2015-10359.

Gauthier, R., C. Largouët, C. Gaillard, L. Cloutier, F. Guay, and J. Y. Dourmad. 2019. Dynamic modeling of nutrient use and individual requirements of lactating sows. J. Anim. Sci. 97:2822–2836. https://doi.org/10.1093/jas/skz167.

González, L. A., E. Charmley, and B. K. Henry. 2014. Modelling methane emissions from remotely collected liveweight data and faecal near-infrared spectroscopy in beef cattle. Anim. Prod. Sci. 54:1980–1987. https://doi.org/10.1071/AN14615.

Grelet, C., A. Vanlierde, M. Hostens, L. Foldager, M. Salavati, K. L. Ingvartsen, M. Crowe, M. T. Sorensen, E. Froidmont, C. P. Ferris, C. Marchitelli, F. Becker, T. Larsen, F. Carter, and E. Gplus. 2019. Potential of milk mid-IR spectra to predict metabolic status of cows through blood components and an innovative clustering approach. Animal 13:649–658. https://doi.org/10.1017/S1751731118001751.

Ingvartsen, K. L. 2006. Feeding- and management-related diseases in the transition cow: physiological adaptations around calving and strategies to reduce feeding-related diseases. Anim. Feed Sci. Technol. 126:175–213. https://doi.org/10.1016/j.anifeedsci.2005.08.003.

Ingvartsen, K. L., and J. B. Andersen. 2000. Integration of Metabolism and Intake Regulation: A Review Focusing on Periparturient Animals. J. Dairy Sci. 83:1573–1597. https://doi.org/10.3168/jds.S0022-0302(00)75029-6.

Ingvartsen, K. L., R. J. Dewhurst, and N. C. Friggens. 2003. On the relationship between lactational performance and health: is it yield or metabolic imbalance that cause production diseases in dairy cattle? A position paper. Livest. Prod. Sci. 83:277–308. https://doi.org/10.1016/S0301-6226(03)00110-6.

Jensen, L. M., B. Markussen, N. I. Nielsen, E. Nadeau, M. R. Weisbjerg, and P. Norgaard. 2016. Description and evaluation of a net energy intake model as a function of dietary chewing index. J. Dairy Sci. 99:8699–8715. https://doi.org/10.3168/jds.2015-10389.

Little, M. W., N. E. O'Connell, and C. P. Ferris. 2016. A comparison of individual cow versus group concentrate allocation strategies on dry matter intake, milk production, tissue changes, and fertility of Holstein-Friesian cows offered a grass silage diet. J. Dairy Sci. 99:4360–4373. https://doi.org/10.3168/jds.2015-10441.

Lomander, H., J. Frössling, K. L. Ingvartsen, H. Gustafsson, and C. Svensson. 2012. Supplemental feeding with glycerol or propylene glycol of dairy cows in early lactation—Effects on metabolic status, body condition, and milk yield. J. Dairy Sci. 95:2397–2408. https://doi.org/10.3168/jds.2011-4535.

Maechler, M., P. Rousseeuw, A. Struyf, M. Hubert, and K. Hornik. 2016. Cluster: Cluster Analysis Basics and Extensions. R package version 2.0.5.

Maltz, E., L. F. Barbosa, P. Bueno, L. Scagion, K. Kaniyamattam, L. F. Greco, A. De Vries, and J. E. Santos. 2013. Effect of feeding according to energy balance on performance, nutrient excretion, and feeding behavior of early lactation dairy cows. J. Dairy Sci. 96:5249–5266. https://doi.org/10.3168/jds.2013-6549.

Pinheiro, J., and D. Bates. R Core Team. 2022. Nlme: Linear and Nonlinear Mixed Effects Models. R. Package Version 3, 1–158. https://CRAN.R-project.org/package=nlme

Pinheiro, J. C., and D. M. Bates. 2000. Mixed-effects models in S and S-PLUS. USA: Springer, esp; p. 235, 397.

Puppel, K., and B. Kuczyńska. 2016. Metabolic profiles of cow's blood; a review. J. Sci. Food Agric. 96:4321–4328. https://doi.org/10.1002/jsfa.7779.

Purcell, P. J., R. A. Law, A. W. Gordon, S. A. McGettrick, and C. P. Ferris. 2016. Effect of concentrate feeding method on the performance of dairy cows in early to mid lactation. J. Dairy Sci. 99:2811–2824. https://doi.org/10.3168/jds.2015-9988.

Rinne, M., S. Jaakkola, K. Kaustell, T. Heikkila, and P. Huhtanen. 1999. Silages harvested at different stages of grass growth v. concentrate foods as energy and protein sources in milk production. Anim. Sci. 69:251–263. https://doi.org/10.1017/S1357729800051286.

Thorup, V. M., S. Højsgaard, M. R. Weisbjerg, and N. C. Friggens. 2013. Energy balance of individual cows can be estimated in real-time on farm using frequent live weight measures even in the absence of body condition score. Animal 7:1631–1639. https://doi.org/10.1017/S1751731113001237.

Van Soest, P. J., and R. H. Wine. 1967. Use of detergent in the analysis of fibrous feed. IV—Determination of plant cell walls constituents. J. Assoc. Off. Anal. Chem. 50:50–55. https://doi.org/10.1093/jaoac/50.1.50.

ORCIDS

C. Gaillard https://orcid.org/0000-0002-7896-2520