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Roughage feeding patterns of dairy cows in a cow-calf contact system with automatic milking

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ABSTRACT

Dairy cows in contact with their calves can spend time engaging in maternal behaviors, which may affect their feeding patterns. This study aimed to evaluate the roughage feeding behavior patterns of dairy cows with minimum 12 weeks of full calf contact (**FC**) across the nursing (0–12 weeks in milk; **WIM**), gradual weaning (13–14 WIM) and post-separation periods (15–17 WIM), and compared with that of conventionally managed cows with no contact (**NC**) with their calves. Primiparous- and multiparous Swedish Holstein and Swedish Red cows were allocated to the FC (n = 18) or the NC (n = 20) treatment based on parity, dam breed, calf breed (dairy or beef mix), and calf sex. The NC cows were separated from their calves on average 13.5 h post-parturition. NC and FC cows shared roughage, lying (containing cubicles and concentrate feeders), and milking areas in the barn, whereas FC cows could additionally enter a contact area (containing cubicles and concentrate feeders) to be with their calves. All cows were milked in the same automatic milking unit and had ad libitum access to a partial mixed ration provided in 20 individual roughage bins with scales and automated individual visit registration. During the 0–12 WIM period, FC cows consumed more roughage per day than NC cows (40.2 vs. 36.2 kg/d, $P = 0.033$) and per meal (6.8 vs. 5.7 kg/meal, $P = 0.007$). During this period, number of daily meals, feeding rate, feeding duration per day and meal, number of feeder visits per day and per meal, and meal duration did not differ between treatment groups. Both FC and NC cows primarily visited the roughage bins directly following milking. However, during the 0–12 WIM period, FC cows more often returned directly to the area where the calves were housed than NC cows returned directly to their resting area (7.3 vs 3.2 % of occasions, $P < 0.001$). During the 13–14 WIM period, FC cows increased their feeding rate by 4 % ($P = 0.012$), while maintaining a similar roughage intake as NC cows. None other feeding pattern variables differed from NC cows. During the 15–17 WIM period, physical separation of the calves did not substantially alter the roughage feeding patterns in the dams. In conclusion, dairy cows with calf contact in the current system were able to maintain their roughage intake, while the use of functional areas of the barn differed slightly during the nursing period compared with conventional cows.

1. Introduction

Animal behavioral patterns are a result of an interplay between internal factors, such as motivation and physiology, and external factors, such as the housing design, presence of conspecifics and management practices (Kok et al., 2017). These behavioral patterns can change over time in reaction to internal and external factors without necessarily having negative impacts on animal welfare (Munksgaard et al., 2005). Some changes in behavioral patterns, however, have been related to animal welfare issues. For example, feeding patterns of dairy cows, encompassing variables such as daily feed intake, feeding rate, number and duration of meals and feeder visits, have been associated with health disorders such as ketosis, lameness and mastitis (González et al., 2008; Goldhawk et al., 2009; Llonch et al., 2018) and with stress (Schirmann

Abbreviations: CCC, cow-calf contact; DIM, days in milk; DM, dry matter; FC, Full Contact treatment group; NC, No Contact treatment group; MU, milking unit; PMR, partial mixed ration; SH, Swedish Holstein; SR, Swedish Red; WIM, weeks in milk.

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et al., 2011) in cows. In cow-calf contact (**CCC**) systems, where cows remain with their calves for an extended period of a few weeks up to several months (Sirovnik et al., 2020), it is not yet clear how management and housing factors inherent to these systems influence cow feeding patterns. Dairy cows are intrinsically motivated to be with their calf (Wenker et al., 2020) and, when given the opportunity, they establish a bond by performing maternal behaviors like licking, nursing and spending time with their calves (von Keyserlingk and Weary, 2007; Jensen, 2011; Wenker et al., 2021). Cows that spent part of their time on maternal behavior, including nursing of their calves, changed their daily behavior patterns and spent less time on feeding and socializing with other cows (Johansson et al., 2023). In general, studying behavior can provide indications of preferences and problems. In the current study, evaluating feeding patterns of CCC cows is more fundamentally informative, yet also relevant for dairy farmers, as CCC may influence feeding patterns that affect longer-term cow health (e.g., insufficient feed consumption or altered feeding frequency impacting herd resting behavior). It can be hypothesized that because of time allocated to performing maternal behaviors, dairy cows with CCC will exhibit different feeding patterns and different use of functional areas in the barn than conventional cows, as they might prioritize maternal behaviors over time spent feeding.

Besides maternal behaviors, also CCC-associated stressful events, such as the weaning and separation process, might compromise time allocated to other behaviors (Grant and Albright, 2001). Behavioral stress responses are often seen at these events (Weary et al., 2008; Johnsen et al., 2024) and may disrupt the feed intake of the cows (van Zyl et al., 2025a). Various approaches to decouple weaning and separation after CCC have been developed, attempting to reduce stress responses in both cow and calf (Bertelsen and Jensen, 2023; Sørby et al., 2024; Vogt et al., 2025). One such an approach is fence-line weaning, where weaning is decoupled from separation by placing calves behind a fence, which allows some physical contact between cow and calf but either limits or fully eliminates suckling possibilities (Wenker et al., 2022). It can, nevertheless, be hypothesized that stress-related responses to weaning and separation induce dairy cows with CCC to exhibit different feeding patterns during the nursing period, the fence-line period, and following separation from the calves.

The objective of the current study was to evaluate the roughage feeding behavior patterns of dairy cows in a CCC system with automatic milking. Behavior of CCC cows was evaluated longitudinally, across the nursing (0–12 weeks in milk (**WIM**)), gradual weaning (13–14 WIM) and post-separation (15–17 WIM) periods, and compared with that of conventionally managed cows in corresponding lactation weeks. These conventional cows were separated from their calves shortly after parturition. Roughage feeding patterns included both the behavior when feeding and the cow traffic towards different functional areas of the barn. In the current study, gradual weaning was established via a fence-line weaning strategy, reducing the possible daily suckling time by opening a semipermeable fence between cows and calves for gradually shorter durations over 10 days.

2. Material and methods

This study was approved by the Uppsala Ethics Committee for Animal Research, Uppsala, Sweden (diary number: 5.8.18–12179/2023), and conducted at the Swedish Livestock Research Centre of the Swedish University of Agricultural Sciences in Uppsala, Sweden. Details on the experimental design and animal management are reported in van Zyl et al. (2025b).

2.1. Animals and experimental design

Forty cows and their calves were enrolled in the study between October 1st and November 25th, 2023. Sample size determination was based on space availability in the contact area. Cows were included if not previously diagnosed with *Staphylococcus aureus* mastitis, not lame (based on Flower and Weary (2009)), and not aggressive towards humans in the calving pen when the calf was present. For the current study, specifically the cows were monitored. Cows were allocated to either no contact (**NC**; n = 20) or full contact with their calves (**FC**; n = 20). Treatment group allocation was balanced for cow breed (Swedish Holstein (**SH**) or Swedish Red (**SR**)), cow parity (1st through 7th parity), calf breed (purebred dairy or crossbred with Limousin or Angus beef breed), calving date and calf sex (heifer or bull). An average of seven non-experimental cows were also housed in the same pen as NC and FC cows during the study period, to maintain normal farm stocking rate of the automatic milking unit (**MU**).

Cows and calves of NC and FC groups were divided into two batches to prevent a large spread in calf age at weaning. The first batch of 10 NC and 10 FC cows calved between October 1st and 24th, 2023, and the second batch of 10 NC and 10 FC cows calved between October 24th and November 25th, 2023. For the current study, periods of interest were defined by the average WIM of NC and FC cows, namely the 0–12 WIM, 13–14 WIM and 15–17 WIM periods. For the FC cows, these periods respectively corresponded to: the nursing period, when FC cows were allowed full CCC throughout the whole day; the fence-line period, including 17 days of gradual fence-line weaning (described below); and the post-separation period, including the 3 weeks after FC calves were moved to a separate area. Daily milk yield to the MU during the 0–12 WIM period averaged (± SEM) 39.3 ± 0.3 kg/d for NC cows and 24.9 ± 0.2 kg/d for FC cows. During the 13–14 WIM period, daily milk yield to the MU of NC and FC cows was 39.0 ± 0.5 for NC and 35.4 ± 0.7 kg/d for FC cows, while during the 15–17 WIM period the corresponding numbers were 39.2 ± 0.2 and 36.8 ± 0.6 kg/d.

2.2. Housing and management

Cows calved in individual indoor calving pens of 3 × 4 m that were lined with rubber floors topped with sawdust. The NC cows and calves were separated on average 13.5 h (min: 12 h, max: 17 h) after birth, whereafter NC calves were housed in a separate area of the barn without cow contact. In the calving pens, all cows were milked twice daily by a mobile milking unit (BMS, DeLaval International AB, Tumba, Sweden), received ad libitum water, concentrates and partial mixed ration (**PMR**) consisting of grass-clover silage with 2 kg concentrates per cow per day (composition provided below). The NC cows remained in the calving pen for approximately 2 days after parturition before being moved to the indoor experimental area. The FC cows and calves were kept together in the calving pens for 2 – 3 days to strengthen the maternal bond before introduction to the same experimental area as the NC cows. In the experimental area, NC and FC cows shared the feeding, milking and general lying areas, while FC cows could additionally access the contact area where their calves were housed.

The experimental area was inside an insulated freestall barn with ridge and sidewall ventilation and an automatic milking system (Fig. 1). The feed alley had a rubber floor and twenty roughage feeding bins with weight scales (further described later) were present, as well as salt licks (Salinity AB, Göteborg, Sweden), six automatic water cups and two cow brushes (DeLaval swinging cow brush, DeLaval International AB, Tumba, Sweden).

In the milking area, cows were milked in an automatic MU (DeLaval VMS Classic, DeLaval International AB, Tumba, Sweden). The waiting area of the MU had a slatted floor. The NC cows were fetched for milking by barn staff 12 h after the previous milking, and FC cows after 18 h because of the additional milk removal by the calves.

The general lying area contained 31 cubicles lined with rubber mattresses (M40R, DeLaval International AB, Tumba, Sweden) that were automatically topped with a mix of peat and sawdust four to five times per day (JHminiStrø COW, MAFA i Ängelholm AB, Ängelholm, Sweden). Two automatic concentrate feeding stations (FSC400 DeLaval International AB, Tumba, Sweden) were present in the general lying area, and

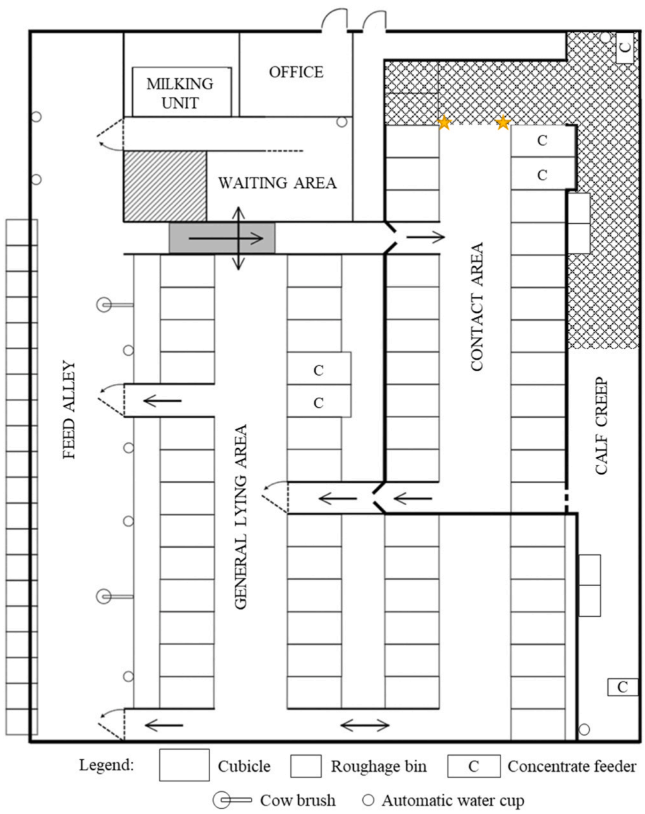

Fig. 1. Layout of experimental area in the barn. Cows had access to all roughage bins in the feeding alley. At the three-way selection gate (dark grey block), no-contact (NC) cows were directed to the automatic milking unit or general lying area, and full-contact (FC) cows to the automatic milking unit or to the contact area. The calf creep was only accessible to FC calves. Cow traffic from the general lying area and contact area to the feed alley was controlled through one-way gates (indicated by arrows). During weaning, the barn layout was adjusted by 1. dividing the calf creep into two sections: the upper section for the calves that were being weaned (crossed out section) and the lower section for the calves that were still allowed full contact; 2. placing a fence at the top of the alley (indicated by the yellow stars); and 3. allocating two cubicles in the contact area to calves being weaned while another served as passageway between the calf creep and contact area (indicated by dashed line). (Figure adapted from Wegner and Ternman 2023).

the alleys had grooved concrete floors. The feed alley and the alleys of the general lying area were equipped with mechanical manure scrapers that went every hour.

The contact area contained 24 lying cubicles identical to those in the general lying area, of which two were blocked off for calf use throughout the study, and two concentrate feeding stations similar to the ones in the general lying area. The manure scraper going through the contact area was run manually three to five times per day until the youngest calf was 5.9 weeks old, whereafter it went automatically in this area.

A calf creep for FC calves was present adjacent to the contact area in the experimental area. Here, only FC calves could obtain feed and water and spend time without the cows. The NC (and FC) cows in the cubicles were able to have auditory, visual, olfactory, and limited nose contact with the calves when lying in some of the cubicles in the general lying area (Fig. 1). Further management of NC and FC calves was reported in van Zyl et al. (2025b).

Cow traffic in the experimental area was a semi-controlled feed-first system: cows passed a three-way selection gate (DeLaval Smart Selection Gate SSG, DeLaval International AB, Tumba, Sweden) from the feed alley to either the MU (milking permission granted 6 h after previous milking), the general lying area (NC cows only) or the contact area where the calves were present (FC cows only). Cows were identified by this selection gate via their low-frequency (134.2 kHz) passive RFID ear tag (Combi E30 Rund or Flagg, OS ID Stallmästaren AB, Lidköping, Sweden). A spring-loaded one-way gate (FeedSelect, GEA Farm Technologies GmbH, Bönen, Germany) enabled FC cows to exit the contact area freely and enter the general lying area. From the general lying area, both NC and FC cows could access the feed alley via another one-way gate. Calves could not exit the contact area.

2.3. Weaning and separation

Nursing was allowed for a minimum of 12 weeks, in line with European Union regulations for organic farming (Commission Regulation (EC) 889/2008, Article 20.1). Weaning of batch 1 calves started on January 6th, 2024, and of batch 2 calves on February 3rd, 2024. The weaning process was initiated when the youngest FC calf of the respective batch was 10 weeks and 4 days old (on average, cows were in the 13th WIM (± 1.3, SD)). Weaning of FC calves was done by placing a fence at the top of the alley in the contact area and dividing the calf creep in two parts to separate calves being weaned from the younger calves that were still allowed full CCC. These younger calves could still access the contact area via the front of the lying cubicles and the bottom lying cubicle in the contact area was adapted for easier movement from the calf creep. The fence used for weaning enabled physical contact and suckling opportunities between FC calves and cows to be gradually reduced (see van Zyl et al. (2025b)). Directly after calves were placed behind the fence, cow-driven nursing was possible through the fence throughout the whole day. After 4 days, the nursing opportunity was gradually reduced by closing the fence for parts of the day: 6 h/d, between 00:00 and 06:00 h for 2 days; 12 h/d, between 18:00 and 06:00 h for 2 days; and for 18 h/d, between 12:00 and 06:00 h for 2 days. Thereafter, calves were fully weaned and remained behind the closed fence for 1 week. During this week, cows had partial CCC, including visual, auditory, olfactory and limited physical contact, but were unable to nurse the calves. After this week, FC cows and calves were permanently separated by removing the calves from the barn, whereby any further CCC was prevented. All cows remained in the experimental area with access to the same functional areas for at least 4 weeks after weaning of the second batch.

2.4. Feeding strategy and diet characteristics

All cows in the experimental area, thus NC and FC as well as non-experimental cows, had ad libitum access to all 20 roughage bins. Average stocking density at the roughage bins was 230 % during the study period, ranging from 170 % to 280 % (26 %, SD) during recruitment of experimental cows and from 225 % to 240 % (3 %, SD) after all experimental cows have been recruited. All roughage bins were filled automatically at 08:00, 11:00, 14:30 and 18:00 h by a rail-suspended distribution wagon (DeLaval FS1600, DeLaval International AB, Tumba, Sweden). Diets provided during the study period were calculated by the farm's regular extension nutritionist, according to the Nordic feed evaluation system (NorFor; Volden 2011). Cows of both treatments received the same PMR, which included 8 kg concentrates (EDEL Nova 190, AB Johan Hansson, Uppsala, Sweden) and 75 g minerals (Effekt Optimal Mineralfoder, Lantmännen, Stockholm, Sweden) per cow per day. For the total study time of batch 1 and until 13–14 WIM of batch 2, the roughage in the PMR consisted of 99 % grass-clover silage with an average dry matter (**DM**) content of 40 %, 151 g crude protein/kg DM, 402 g neutral detergent fiber/kg DM, 75 g ash/kg DM and 11.3 MJ metabolizable energy/kg DM, supplemented with 1 % wheat straw to increase fiber content (no analyses available). The same grass-clover silage was fed to all cows when they were housed in the calving pens, but during this period the roughage mix was supplemented with 2 % wheat straw. After 13–14 WIM of batch 2, the PMR changed to 90 % grass-clover silage and 10 % maize silage with a proportionally-derived DM content of 40 %, 148 g crude protein/kg DM, 402 g neutral detergent fiber/kg DM, 80 g ash/kg DM and 11.0 MJ metabolizable energy/kg DM. The inclusion of maize silage was then increased gradually to 40 % over the next week; grass-clover silage was now included at 59 % and wheat straw at 1 %, while the roughage mix had a proportionally-derived DM content of 38 %, 123 g crude protein/kg DM, 380 g neutral detergent fiber/kg DM, 67 g ash/kg DM and 10.6 MJ metabolizable energy/kg DM. Metabolizable energy of maize silage was estimated from NorFor (Volden, 2011).

Cows could obtain concentrates from the automatic feeding stations and in the MU when being milked (0.7 ± 0.29 kg (SD) per visit). All concentrates (EDEL Topp Single and EDEL Nova 190; AB Johan Hansson, Uppsala, Sweden) were provided according to the expected milk yield of the individual cow. For the NC cows, expected milk yield was based on the amount of milk delivered to the MU, while for the suckled FC cows it was based on herd milk yield averages adjusted to breed, lactation stage and parity.

2.5. Data collection and collation

One FC cow (multiparous, SR) and her calf were moved to a sick pen at 14 days in milk (**DIM**) and removed from the study at 27 DIM, as the calf was weak and not suckling. One FC cow (multiparous, SR) was diagnosed with mastitis at 56 DIM and, together with her calf, was moved to a sick pen and subsequently removed from the study at 67 DIM when the cow was euthanized. Data from these cows were not used in the current study. One FC cow (multiparous, SH) was diagnosed with mastitis at 84 DIM (on the day that weaning was initiated) and moved to a sick pen, but was returned to the experimental area at 94 DIM; data collected before and after the period in the sick pen were included in the analyses as removing it did not affect the model outcomes in a preliminary analysis. For all cows, individual cow data from 3 days prior to being moved to a sick pen until 3 days after return to the experimental area were removed the analyses of feeding behaviors. Final composition of the NC treatment group (n = 20) was 5 primiparous (2 SH, 3 SR) and 15 multiparous cows (4 SH, 11 SR); the FC treatment group (n = 18) comprised 6 primiparous (2 SH, 4 SR) and 12 multiparous cows (4 SH, 8 SR).

2.5.1. Roughage bin data

Cows were identified by the roughage bins via their RFID ear tags. Throughout the study period, individual roughage intake per visit to the bin was measured by the weighing cells under each bin (CRFI, Biocontrol A/S, Rakkestad, Norway) and recorded in the management software (DelPro, DeLaval International AB, Tumba, Sweden). Duration of the individual visits was also recorded in the same software, whereafter the feeding rates per visit and the intervals between visits were calculated.

The roughage dataset was cleaned prior to analyses, based on the criteria used by Kok et al. (2017). Criteria for data to be removed included visits with a duration > 3 h (0 % of records), feeding rate > 2 kg/min (0.6 % of records) or feeding rate < 0.02 kg/min (0.2 % of records). Inspection of removed data showed that either the visit duration lasted so long because the end time of the visit was not registered correctly or that the roughage intake during these visits were impossibly large, likely caused by staff removing roughage from the bins without overriding the visit registration. Roughage bin registrations between 16:00 h on February 27 and 08:00 h the next day were removed (0.5 % of records), as the registration software of the feeding bins was updated and the scales were calibrated.

2.5.2. Meal criterion calculation

Feeding patterns of dairy cows included daily feed intake, the individual's visits to the roughage bins throughout the day, the intervals between these visits, duration of the visits, and the feeding rate. When analyzing feeding patterns, multiple individual feeding bouts divided by short intervals can be grouped into individual meals separated by longer intervals (Tolkamp et al., 1998). A meal criterion, defined as the minimum non-feeding interval accepted as interval between meals (Tolkamp et al., 2000), must be chosen to determine whether subsequent visits to the feeding bin are still part of the same meal or a new meal (Yeates et al., 2001; Tolkamp et al., 2002). For dairy cows, meal criteria are generally calculated by fitting a three-population model (Gaussian-Gaussian-Weibull) to the ln-transformed intervals between visits to the roughage bins. Hereby, short intervals between visits are described by the combination of the two Gaussian distributions and the longer intervals by the Weibull distribution (Yeates et al., 2001).

Before calculating meal criteria, roughage intake data on days expected to deviate from 'normal' feeding behavior for reasons not directly caused by the experimental treatments were removed. These included the first week in the experimental unit, as cows had to acclimatize to the new barn environment and roughage bins, and individual cow data from 3 days prior to being moved to a sick pen until 3 days after return to the experimental area. We applied the Gaussian-Gaussian-Weibull model (in Python, version 3.11) to the frequency distribution of the ln-transformed intervals between visits to the roughage bins of all cows, and subsequently determined the intersection of the second Gaussian and the Weibull distributions to determine the meal criterion in minutes.

Initially, one meal criterion was calculated per treatment group and per period. Preliminary results indicated no difference in meal criteria within treatment groups and across the 0–12 WIM, 13–14 WIM and 15–17 WIM periods: 48.6, 54.2 and 59.1 min for NC cows, and 47.5, 45.3 and 52.1 min for FC cows, respectively. When using meal criteria per period per treatment group, the number of meals per day for NC and FC cows were the same compared with when one meal criterion based on data from all cows was used. Therefore, the final meal criterion used, which was 55.4 min, was calculated from the pooled data of NC and FC cows throughout the study period. Using the same meal criterion across time and between treatment groups was done to be able to calculate meal-related variables the same way.

2.5.3. Feeding pattern variables calculation

The meal criterion was then used to cluster visits to the roughage bins into meals for all cows over all periods of interest. For the calculation of the number of daily meals, if a meal began before midnight, it was included in the meal count for that day. If a subsequent visit to the bin began after midnight, it was considered the start of a new meal for the following day, regardless of whether the interval between the two visits was shorter than the meal criterion (0.03 % of all meals). Thereafter, variables were calculated per day (daily roughage intake on fresh matter basis, daily feeding rate, daily feeding duration, number of feeder visits per day, and number of meals per day), or per meal (meal size, feeding duration per meal, number of feeder visits per meal, and meal duration). Definitions of feeding pattern variables are presented in Table 1. Daily means of feeding pattern variables were aggregated per cow and used in the statistical analyses.

2.5.4. Milking and cow traffic in the experimental area

The use of different functional areas in the barn was further explored by analyzing cow traffic, including visits to the roughage bins, the MU, and the general lying area (for NC cows) or alternatively the contact area (for FC cows only). Cows were individually registered via their RFID ear tags by the MU, roughage bins and a three-way selection gate (Fig. 1) and recorded in the management software. Passages through the passive one-way gates from the contact area to the general lying area and from the general lying area to the feed alley were not registered. Date-time registrations for end of milking, visits to roughage bins and cow presence at the selection gate were used to analyze the number of milkings a cow had per day and which route the cow took after milking. The first registration following end of milking being a visit to a roughage bin, was classified as 'to roughage bins', indicating the cow first went to eat after milking. The first registration following end of milking being a passage through the selection gate was classified as 'passing to lying area or contact area', indicating the cow returned to the general lying area (NC

Table 1
Variables calculated to describe the feeding patterns, based on Yeates et al. (2001), Tolkamp et al. (2002) and Abrahamse et al. (2008).

Variable	Description
Per day	
Daily roughage intake (kg/d)	Amount of roughage consumed per day
Feeding rate (g/(min feeding/d))	Amount of roughage consumed per minute spent feeding, averaged over all visits per day
Daily feeding duration (min/d)	Total time spent feeding per day. Calculated as the sum of the duration of visits to the roughage bin
Daily feeder visits (n)	Number of times a cow visited the roughage bins per day
Daily meals (n)	Number of meals, calculated based on a meal criterion (55.4 min in the current study), a cow had per day
Per meal	
Meal size (kg)	Amount of roughage consumed per meal
Feeding duration per meal (min/meal)	Total time spent feeding per meal. Calculated as the sum of the duration of visits to the roughage bin per meal
Feeder visits per meal (n)	Number of visits to the roughage bin per meal
Meal duration (min)	Total duration of a meal, i.e., time between the start of the first visit to the roughage bin until the end of the last visit including interval between individual visits in the same meal

cows) or to the contact area (FC cows) without visiting the roughage bins after milking. A cow that first arrived at the selection gate after end of milking but did not pass through once it opened, determined by the next registration which was a presence at a roughage bin, was classified as 'did not pass'.

Categorized cow traffic data were then used to calculate the number of occurrences of each route taken from the MU per individual cow and subsequently summed across weeks. The proportion of each route chosen per WIM was calculated for each cow by dividing the number of occurrences of a specific route by the total number of all recorded routes for that week. These individual weekly proportions were used to analyze cow traffic from the MU across the three periods of interest. Data on the daily individual cow traffic were visually inspected using directed weighted graphs, where nodes represent the relevant barn locations. In a complete daily path, the in- and outflows at each node should be equal, except for one node (current position of the cow) where this could differ by 1. Missing data would be indicated by discrepancies beyond this.

2.6. Statistical analyses

Data of feeding pattern variables at day and meal-level, as well as the number of daily milkings and cow traffic were analyzed across periods of interest. All statistical analyses were performed in SAS (version 9.4, SAS Institute, Cary NC, USA) and graphs were created in GraphPad Prism (version 10.0.0 for Windows, GraphPad Software, Boston, Massachusetts USA). The individual cow was regarded as the experimental unit for statistical models and visual inspection as well as statistical assessment of all model variables and residuals were conducted to evaluate normality. Differences were regarded as significant if $P < 0.05$ after Tukey-adjustment for multiple pairwise comparisons. Values are presented as LSM ± SEM unless stated otherwise. Preliminary visual inspection indicated no apparent effect of (the change in) ration composition on roughage intake, feeding rate, or daily feeding duration of the cows; therefore, it was not included in the statistical models. Preliminary analyses indicated no effect ($P > 0.05$) of weaning batch on the analyzed feeding pattern variables or daily milk yield, hence this variable was not included in any model.

2.6.1. Feeding patterns

Data of each feeding pattern variable were analyzed with separate linear mixed models with repeated measures:

$$y_{ijklmn} = \mu + G_i + P_j + B_k + PC_l + (G \times P)_{ij} + (G \times B)_{ik} + (G \times PC)_{il} + (P \times B)_{jk} + (P \times PC)_{jl} + (B \times PC)_{kl} + \epsilon_{ijklmn}, \quad \textbf{[1]}$$

where y_{ij} is the dependent variable (daily roughage intake [kg/d], number of daily meals [n], number of daily feeder visits [n], daily feeding duration [min/d], daily feeding rate [g/(min/d)], individual meal size [kg], number of feeder visits per meal [n], feeding duration per meal [min/meal] or individual meal duration [min]), μ is the mean, G_i is the treatment group (i = NC or FC group), P_j is the period (j = 0–12 WIM, 13–14 WIM or 15–17 WIM period), B_k is the cow breed (k = SH or SR), PC_l is the parity class (l = primi- or multiparous cows). All two-way interactions of these fixed effects were also tested in these models. The backwards elimination procedure was subsequently followed for removing nonsignificant interactions ($P \geq 0.05$) from each model; the interaction between treatment group and period was always retained, as this was the focus of the analysis. The random residual term from a normal distribution is represented by ϵ_{ijklmn}. Repeated measurements within cows over time (DIM) were accounted for by modelling the correlation structure of observations within each cow using the compound symmetry covariance structure, as it provided the best model fit based on the Akaike Information Criterion.

2.6.2. Milkings and cow traffic in the experimental area

The number of milkings per day of NC and FC cows across periods (model 2) and the daily proportions of each of the three routes taken after end of milking across periods (model 3) were analyzed via generalized linear mixed models. These proportions entailed the number of times the specific route was taken after exiting the MU (to the roughage bins, to the general lying or the contact area, or did not pass the selection gate) out of the total number of times the cow was milked for the respective group and period. These models followed the same general structure of fixed effects as in model 1 above, while a Poisson distribution and a log link function was specified for model 2, and a binomial distribution and a logit link function was specified in model 3. All two-way interactions of the fixed effects were also tested in these models, but removed from the model via the backwards elimination procedure as all were nonsignificant ($P \geq 0.05$). The interaction between treatment group and period was retained, as this was the focus of the analysis. Repeated measurements and the correlation of observations within cows over time (DIM) were accounted for by specifying the residual covariance structure for each cow as random effect.

3. Results

Roughage feeding pattern variables of NC and FC cows across the three periods are presented in Table 2 and Fig. 2A – I depict the weekly progression of the feeding pattern variables from the start of lactation until the end of the study period. An interaction between treatment and cow breed was present for feeding rate. For SR cows, feeding rate of NC cows was lower than FC cows (258 ± 13 vs. 311 ± 14 g/(min/d); $P = 0.032$), while feeding rate of SH cows did not differ between treatments (283 ± 19 vs. 256 ± 19 g/(min/d), respectively; $P = 0.742$). An interaction between treatment and breed was present for the daily feeding duration, but post-hoc comparisons were nonsignificant (184 ± 11 vs. 204 ± 8 min/d, $P = 0.419$, for SH and SR cows in NC; 216 ± 11 vs. 183 ± 8 min/d, $P = 0.077$, for SH and SR cows in FC); the same was found for feeding duration per meal (26 ± 2 vs. 30 ± 1 min/meal, $P = 0.260$, for SH and SR cows in NC; 29 ± 2 vs. 26 ± 1 min/meal, $P = 0.617$, for SH and SR cows in FC). No effect of breed was present for the number of daily meals or the meal size. Exact values and trajectories of these interactions are included in Supplementary Materials S1.

3.1. The 0–12 WIM period

During the 0–12 WIM period (the nursing period for FC cows), daily roughage intake of NC cows was lower ($P = 0.033$) than that of FC cows,

Table 2
Feeding pattern variables (values represent least squares means and maximum SEM) during three periods (0–12 WIM[1], 13–14 WIM, 15–17 WIM) of cows that had no contact with their calves (NC) and cows that had minimum 12 weeks contact with their calves (FC).

	NC (n = 20)			FC (n = 18)			SEM	P-value[2]							
Variables	0–12 WIM	13–14 WIM	15–17 WIM	0–12 WIM	13–14 WIM	15–17 WIM		G × P	B × P	PC × P	G × B	G	P	B	PC
Per day															
Daily roughage intake (kg/d)	36.2^{b}	40.0^{a}	41.2^{a}	40.2^{y}*	42.5^{x}	42.0^{x}	1.1	< 0.001	< 0.001	0.005	-	0.069	< 0.001	0.847	< 0.001
Feeding rate (g/(min/d))	273^{a}	274^{ab}	264^{b}	283^{y}	295^{x}	273^{z}	12	0.030	0.028	< 0.001	0.019	0.430	< 0.001	0.375	< 0.001
Daily feeding duration (min/d)	179^{b}	201^{a}	202^{a}	188^{y}	207^{x}	204^{x}	7	0.049	-	< 0.001	0.007	0.538	< 0.001	0.484	0.081
Daily feeder visits (n)	28.1^{c}	35.4^{b}	37.9^{a}	29.2^{z}	36.0^{y}	37.9^{x}	1.6	0.170	< 0.001	< 0.001	-	0.770	< 0.001	0.147	< 0.001
Daily meals (n)	7.3^{a}	6.9^{b}	6.8^{b}	7.2	7.4	7.3	0.3	< 0.001	-	< 0.001	-	0.336	0.026	0.522	0.026
Per meal															
Meal size (kg)	5.7^{c}	6.8^{b}	7.4^{a}	6.8^{y}*	7.5^{x}	7.6^{x}	0.2	< 0.001	-	< 0.001	-	0.036	< 0.001	0.840	< 0.001
Feeding duration per meal (min)	25^{b}	29^{a}	30^{a}	26^{y}	28^{x}	28^{x}	1	< 0.001	0.029	< 0.001	0.036	0.713	< 0.001	0.667	0.773
Feeder visits per meal (n)	3.9^{c}	5.1^{b}	5.6^{a}	4.0^{z}	4.8^{y}	5.2^{x}	0.3	< 0.001	< 0.001	< 0.001	-	0.516	< 0.001	0.035	0.005
Meal duration (min)	183^{b}	208^{a}	206^{a}	184	189	184	8	< 0.001	-	< 0.001	-	0.154	< 0.001	0.197	0.059

[a-c] indicate difference between periods within NC treatment group.
[x-z] indicate difference between periods within FC treatment group.
[1] WIM = Weeks in milk; The 0–12 WIM period included the first average 12 weeks in milk (± 1.1), when FC cows could nurse their calves; 13–14 WIM period included the following 10 days when FC cows had only partial contact via a fence-line with nursing possible and 1 week of partial contact without nursing; 15–17 WIM period included the 3 weeks after FC cows were separated from their calves (who were moved to a separate barn).
[2] *P*-value considered significant when $P < 0.05$. G = treatment group (NC vs. FC); P = period (0–12 WIM vs. 13–14 WIM vs. 15–17 WIM); B = cow breed (Swedish Holstein or Swedish Red); PC = parity class (primiparous vs. multiparous); G × P = interaction between treatment group and period; B × P = interaction between cow breed and period; PC × P = interaction between parity class and period; and G × B = interaction between treatment group and breed.
[*] indicates difference between treatment groups within the specific period.

while feeding rate, number of daily feeder visits and daily feeding duration did not differ between treatments (all $P \geq 0.899$, Table 2). Meal size of NC cows was smaller ($P = 0.007$) than that of FC cows, while the number of feeder visits per meal, feeding duration per meal and meal duration did not differ between treatment groups (all $P \geq 0.940$).

During the 0–12 WIM period, feeding patterns did not differ between SH and SR cows, with cows having a daily roughage intake of 38.8 ± 1.2 and 37.6 ± 0.8 kg/d ($P = 0.954$), and a feeding rate of 273 ± 14 and 284 ± 10 g/(min/d) ($P = 0.984$), respectively. Breed also did not affect the number of times the cows visited the roughage bins ($P = 0.951$), with SH visiting 27.7 ± 1.8 and SR 29.6 ± 1.3 times per day. Number of visits per meal was 3.7 ± 0.3 for SH and 4.2 ± 0.2 times for SR ($P = 0.680$), each with an average feeding duration of 26 ± 1 min/meal.

Primiparous cows had a lower roughage intake (33.3 ± 1.2 vs. 43.1 ± 0.8 kg/d, $P < 0.001$) and feeding rate (253 ± 14 vs. 303 ± 10 g/(min/d), $P = 0.042$) than multiparous cows. Primiparous cows also had more feeder visits (32.0 ± 1.9 vs. 25.2 ± 1.3 visits/d, $P = 0.032$) and meals (7.8 ± 0.3 vs. 6.7 ± 0.2 meals/d, $P = 0.015$) than multiparous cows, while the number of feeder visits per meal did not differ between parity classes (4.1 ± 0.3 and 3.8 ± 0.2 visits/meal, $P = 0.908$). Meal size (5.1 ± 0.3 vs. 7.4 ± 0.2 kg/meal, $P < 0.001$) and meal duration (166 ± 9 vs. 201 ± 6 min, $P = 0.019$) were lower for primiparous than multiparous cows, but feeding duration (184 ± 8 min/d for both), and feeding duration per meal (24 ± 1 and 28 ± 1 min/meal, $P = 0.113$) did not differ between parity classes.

3.2. The 13–14 WIM period

During the 13–14 WIM period (the fence-line period for FC cows), feeding pattern variables of NC and FC cows did not differ (Table 2). Compared with the 0–12 WIM period, daily roughage intake of all cows increased ($P < 0.001$), while feeding rate of only FC cows increased ($P = 0.004$). Additionally, daily feeding duration and number of daily feeder visits increased ($P < 0.001$) in both treatments, while the number of daily meals of only NC cows decreased ($P = 0.015$) from the 0–12 WIM to the 13–14 WIM period. Meal size, number of feeder visits per meal and feeding duration per meal increased ($P \leq 0.037$) in all cows, while meal duration increased ($P < 0.001$) only for NC cows.

From the 0–12 WIM to the 13–14 WIM period, daily roughage intake of SH cows increased by 7 % ($P = 0.001$) and that of SR cows by 9 % ($P < 0.001$), while both breeds had similar feeding rate as during the 0–12 WIM period. Number of feeder visits per day, feeder visits per meal and feeding duration per meal also increased, both for SH (by 22, 21 and 8 %, all $P < 0.001$) and SR cows (by 27, 28 and 14 %, all $P < 0.001$).

During the 13–14 WIM period, number of daily meals did not differ between parity classes ($P = 0.458$), while primiparous cows continued to have more feeder visits per day ($P < 0.001$). Compared with the 0–12 WIM period, daily roughage intake of primiparous cows increased by 15 % ($P < 0.001$), but intake still remained lower than multiparous cows ($P = 0.003$). At the same time, the feeding rate of multiparous cows increased by 4 % ($P < 0.001$), which still remained lower than primiparous cows ($P = 0.007$). Daily feeding duration also increased between periods, by 18 % ($P < 0.001$) in primiparous cows and by 4 %

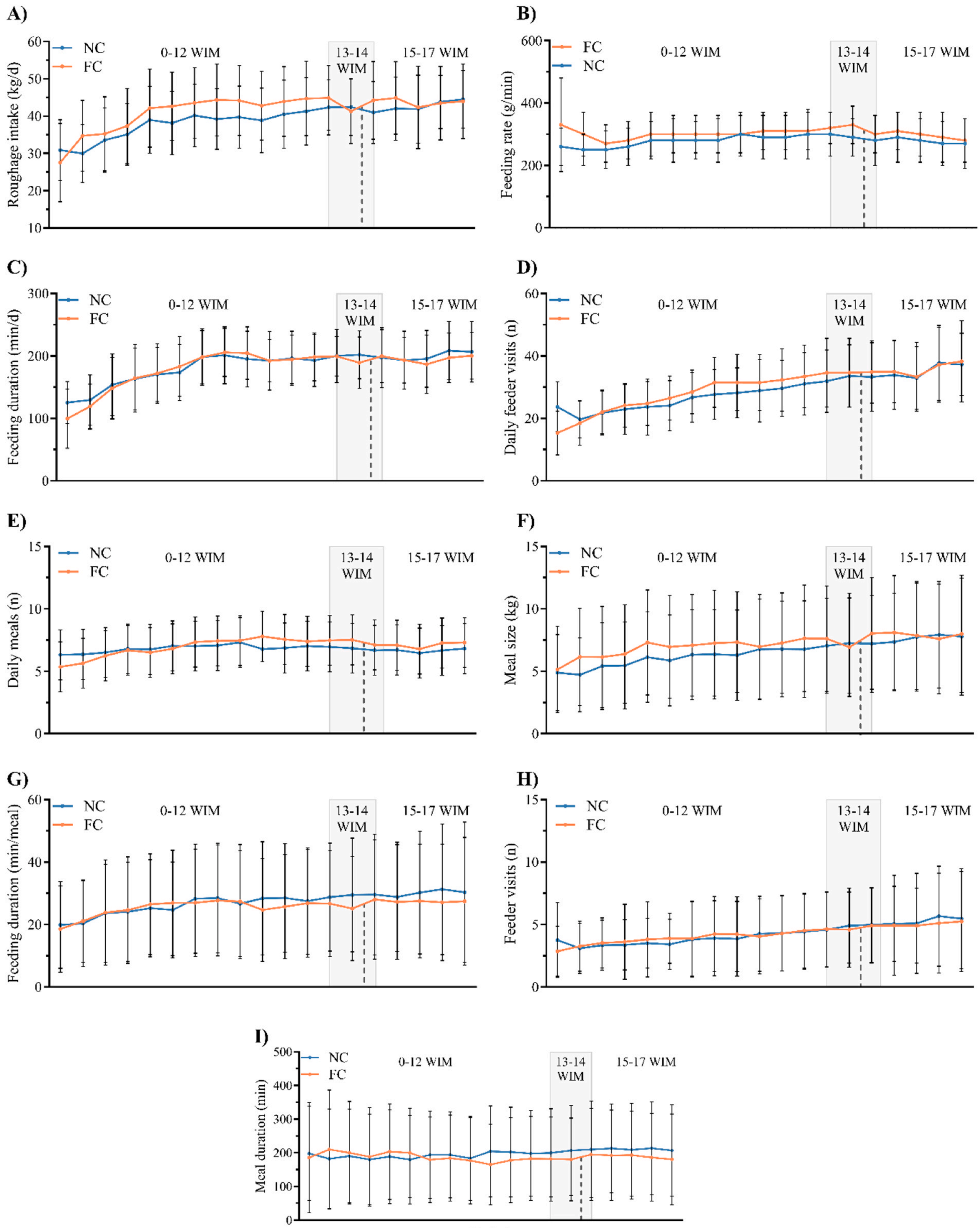

Fig. 2. Weekly progression of feeding pattern variables (A – I) of cows that had no contact with their calves (NC, n = 20) and cows that had minimum 12 weeks contact with their calves (FC, n = 18). The 0–12 WIM period included the first average 12 weeks in milk (± 1.1), when FC cows could nurse their calves; 13–14 WIM period included the following 10 days when FC cows had partial contact via a fence-line with nursing possible and 1 week of partial contact without nursing (starting at dashed line); 15–17 WIM period included the 3 weeks after FC cows were separated from their calves (who were moved to a separate barn). Values represent means ± SEM.

($P = 0.012$) in multiparous cows. However, during the 13–14 WIM period, daily feeding duration did not differ between parity classes ($P = 0.078$). The increase in number of feeder visits per day compared with the 0–12 WIM period was more pronounced in primiparous cows (29 %, $P < 0.001$) than in multiparous cows (19 %, $P < 0.001$). Meal size and number of feeder visits per meal of primiparous cows increased by 24 % and 34 % (all $P < 0.001$) and that of multiparous cows by 9 % and 15 %, respectively (all $P < 0.001$). Meal size of primiparous cows remained lower than multiparous cows ($P < 0.001$) and primiparous cows now had a greater number of feeder visits per meal ($P = 0.011$). For primiparous cows, feeding duration per meal increased by 23 % ($P < 0.001$) from the 0–12 WIM period, while their meal duration increased by 17 % ($P < 0.001$), reaching similar duration as the multiparous cows ($P = 0.925$).

3.3. The 15–17 WIM period

During the 15–17 WIM period (the post-separation period for FC cows), feeding pattern variables of NC and FC cows also did not differ (Table 2). Daily roughage intake of all cows remained similar to that of the 13–14 WIM period (all $P \geq 0.474$), while their feeding rate decreased ($P = 0.037$ for NC and $P < 0.001$ for FC). For all cows, daily feeding duration and number of meals per day remained similar to the 13–14 WIM period (all $P \geq 0.911$), while number of daily feeder visits increased ($P = 0.001$ for NC and $P = 0.028$ for FC). Meal size of NC cows increased ($P = 0.001$) compared with the 13–14 WIM, while that of FC cows remained similar ($P = 0.978$). For all cows, number of feeder visits per meal increased ($P < 0.001$) compared with the 13–14 WIM period, while feeding duration per meal (all $P \geq 0.606$) and meal duration (all $P \geq 0.813$) remained similar.

From the 13–14 WIM to the 15–17 WIM period, daily roughage intake and feeding duration per meal of SH and SR cows were similar (all $P \geq 0.156$), while feeding rate of SH cows decreased by 8 % ($P < 0.001$) and that of SR cows by 2 % ($P = 0.004$). The number of feeder visits per day of only SR cows increased (by 5 %, $P < 0.001$), and the increase in number of feeder visits per meal was more pronounced in SH (10 %, $P < 0.001$) than SR cows (7 %, $P < 0.001$), based on within-breed comparisons.

Compared with the 13–14 WIM period, daily roughage intake of primiparous and multiparous cows remained similar (all $P \geq 0.369$), while the feeding rate of primiparous cows decreased by 10 % ($P < 0.001$) and remained lower than that of multiparous cows ($P < 0.001$). Also the daily feeding duration and number of daily meals remained constant between periods in both parity classes (all $P \geq 0.915$). For primiparous cows, the number of daily feeder visits decreased by 7 % ($P = 0.002$) compared with the 13–14 WIM period, but still remained greater than that of multiparous cows ($P < 0.001$). Meal size of multiparous cows increased by 4 % ($P = 0.025$) from the 13–14 WIM and remained greater than that of primiparous cows ($P < 0.001$). Feeding duration per meal remained similar between periods and did not differ between parity classes (all $P \geq 0.487$) in the 15–17 WIM period, while the number of feeder visits per meal of primiparous cows increased by 10 % ($P < 0.001$) and that of multiparous cows by 7 % ($P = 0.004$) to the 15–17 WIM. Instead, meal duration remained similar between periods and did not differ between parity classes ($P = 0.692$) in the 15–17 WIM period.

3.4. Milkings and cow traffic in the experimental area

Number of milkings per day did not differ between NC and FC cows during any of the periods (all $P \geq 0.661$). During the 0–12 WIM period, NC cows were milked 2.2 ± 0.1 times per day in the automatic MU and FC cows 2.1 ± 0.1 times per day. During the 13–14 WIM period, the number of milkings per day of all cows increased, with 8 % for NC cows to 2.4 ± 0.1 milkings/d ($P < 0.001$) and with 13 % for FC cows to 2.4 ± 0.1 milkings/d ($P < 0.001$). The number of milkings per day of all cows then remained similar in the 15–17 WIM period, at 2.5 ± 0.1 milkings/d for NC cows and 2.4 ± 0.1 milkings/d for FC cows.

Routes of NC and FC cows taken after exiting the MU are presented in Fig. 3 and individual routes of all cows are presented in Supplementary Material S2. During the 0–12 WIM period, it was less common for FC cows than for NC cows ($P = 0.025$) to not pass the selection gate when they chose to go there first after exiting the MU. During the 0–12 WIM period, NC cows first visited the roughage feeder bins after 64.8 ± 1.0 % of MU exits, which increased to 76.6 ± 1.6 % during the 13–14 WIM period ($P < 0.001$) and did not differ during the 15–17 WIM period (71.1 ± 1.6 %; $P = 0.133$). The NC cows passed the selection gate to the general lying area directly after 3.2 ± 0.3 % of the MU exits during the 0–12 WIM period, and never during the 13–14 WIM and 15–17 WIM periods.

During the 0–12 WIM period (the nursing period), FC cows first visited the roughage feeder bins after 62.6 ± 1.0 % of MU exits, which increased to 80.2 ± 1.7 % during the 13–14 WIM period (the fence-line period; $P < 0.001$) and decreased to 73.2 ± 1.6 % during the 15–17 WIM period (the post-separation period; $P = 0.036$). The FC cows passed the selection gate to the contact area where their calves were present directly after 7.3 ± 0.5 % of the MU exits during the 0–12 WIM period, which never happened during the 13–14 WIM and 15–17 WIM periods. On the remainder of occasions, NC and FC cows first arrived at the selection gate but did not pass through directly once it opened.

Independent of treatment and period, primiparous cows first visited the roughage feeder bins after exiting the MU 5 % more frequently than multiparous cows ($P = 0.001$) and passed the selection gate to the general lying or the contact area 66 % less frequently than multiparous cows ($P < 0.001$). Independent of treatment and period, SH cows first visited the roughage feeder bins after exiting the MU 4 % less frequently than SR cows ($P = 0.008$), and directly passed the selection gate to the general lying or the contact area 57 % less frequently than SR cows ($P < 0.001$).

4. Discussion

During the first 12 WIM, when FC cows could nurse their calves, they consumed on average more roughage per day and meal than NC cows, while their number of daily meals and other feeding pattern variables did not differ. This contradicted our expectations, as we predicted daily roughage intake of cows with CCC to be similar to those without CCC (Johansson et al., 2023; van Zyl et al., 2025a), or even slightly decreased due to time spent on maternal behaviors (Johnsen et al., 2021). Given Fig. 2, showing daily roughage intake per WIM, it seems likely that the greater daily roughage intake of FC cows during the 0–12 WIM period was a result of both an earlier and more pronounced increase in roughage intake compared with NC cows. The earlier increase in roughage intake might indicate a higher energy demand due to being suckled and milked or that CCC stimulated roughage consumption in cows earlier post-partum than conventionally managed cows, with a feeding bout perhaps following a suckling bout, but these warrant further research. All cows consumed less roughage during the 0–12 WIM period than during the later periods, presumably because roughage intake generally increases during early lactation (Leduc et al., 2021), in line with the increasing milk production during this period.

It was most common for all cows to first visit the roughage feeding bins upon exiting the MU. The barn layout of the current study meant that cows passed some of the roughage bins when exiting the MU, likely influencing their choice of whether to first eat or go to the selection gate leading to the general lying area or the contact area. During the 0–12 WIM period, FC cows appeared to hesitate less than NC cows before passing the selection gate, perhaps due to their motivation to return to their calves in the contact area. This was, however, only the case when FC cows had unrestricted, full-day, contact with their calves. This aligns with previous findings demonstrating that when cows were unable to access full calf contact due to increased resistance of weighted gates,

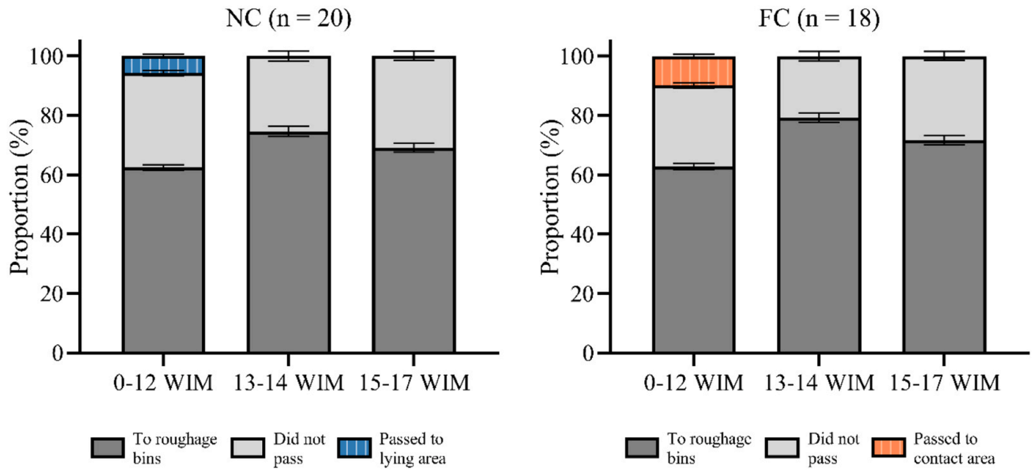

Fig. 3. Proportion of different routes taken to functional units of the barn by cows that had no contact with their calves (NC) and cows that had a minimum of 12 weeks contact with their calves (FC) when exiting the milking unit across the periods of interest (0–12 weeks in milk (WIM), 13–14 WIM and 15–17 WIM). Three post-milking routes were considered: 1) 'to roughage bins' when end of milking was directly followed by a registration at a roughage bin; 2) 'did not pass' when end of milking was directly followed by a registration at the selection gate but the cow did not pass through once it opened, but consumed roughage from the roughage bins; and 3) 'passing to lying area or contact area' when end of milking was directly followed by a registration of passing the selection gate to the general lying area (NC cows) or contact area where calves were (FC cows) once it opened. Values represent least squares means ± SEM.

they preferred to remain in a pen without calves than settle for partial contact with their calves (Jensen et al., 2024).

During the period when the contact between FC cows and their calves was restricted (13–14 WIM period), daily roughage intake no longer differed between the groups and FC cows responded by increasing their feeding rate, which was not seen for NC cows. Therefore, it seems cows make selective trade-offs for their calves and, in the current study, chose to increase their feeding rate instead of reducing their roughage intake. The FC cows also had shorter and more frequent roughage bin visits than during the 0–12 WIM period, resulting in a greater daily feeding duration. The increase in daily feeding duration and meal duration of FC cows mirrored that of NC cows in our study, consistent with findings by Nielsen et al. (2000) and DeVries et al. (2003) as lactation progressed. However, the shorter and more frequent visits to the roughage bins of FC cows might indicate increased restlessness when contact with the calves was restricted. More specifically, FC cows tended to increase their daily feeding rate to 359 g/min on the second day of having only fence-line contact with the calves, compared with the feeding rate of 310 g/min on the last day of having full CCC. This was perhaps due to stress experienced during the weaning period, to return to their calves as soon as possible after milking or to spend time seeking opportunities to physically reunite with their calves, who were often observed vocalizing from behind the fence (undocumented observations).

In the current study, however, all cows stopped directly passing the selection gate to the general lying area or the contact area after exiting the MU without first visiting the roughage bins in the week of the recruitment period that the stocking density at the roughage bins peaked at average 245 % (daily range: 215–280 %). Concomitantly, all cows started going to the roughage bins more often upon exiting the MU than in the weeks leading up to this peak in stocking density. Stocking density at the roughage bins or feed bunk has been reported to affect the feeding behavior of dairy cows (DeVries et al., 2004; Huzzey et al., 2006; Reyes et al., 2024). It might thus be that with the increasing stocking density, and thus increased competition for roughage bin access, cows preferred first visiting the roughage bins present in the feed alley upon exiting the MU than to pass the selection gate to the general lying area or contact area. Additionally, the motivation of the FC cows to initiate contact with their calves after exiting the MU might have decreased over time, as contact initiation usually shifts from the cow to the calf during the first week or two after calving (Jensen, 2011; Wenker et al., 2021).

Separation of cow and calf during the weaning period had subtle but measurable effects on the roughage feeding patterns of the FC cows, though none of the feeding pattern variables were significantly different between treatment groups during the 15–17 WIM period. Both FC and NC cows visited the roughage bins more frequently during the 15–17 WIM period than during previous periods. Further behavioral studies are warranted, as separation-related movement of FC cows might affect their and NC cows' resting behavior. Additionally, daily roughage intake of FC cows did not drop during the 15–17 WIM period, despite cows being physically separated from their calves. This contrasts the findings of van Zyl et al. (2025a), who reported that, after 4 months of full CCC, cow roughage intake decreased when their calves were abruptly weaned and simultaneously separated. The set-up of the current study, which gradually reduced nursing opportunities and allowed for partial CCC before permanent separation, likely aided in alleviating the behavioral responses of cows to separation from their calves (Johnsen et al., 2015; Bertelsen and Jensen, 2023; Vogt et al., 2025).

Cow breed and parity affected the feeding patterns of the cows across periods, but their responses to CCC aligned closely with the treatment groups. While feeding patterns were largely comparable between SH and SR cows during the 0–12 WIM period, SH cows had a smaller increase in roughage intake to the 13–14 WIM period and a greater decline in feeding rate to the 15–17 WIM period. These differences may reflect breed characteristics, such as milk production potential, metabolic load, or temperament (Loberg and Lidfors, 2001; Bieber et al., 2020). Throughout the study, multiparous cows had a greater daily roughage intake, daily feeding rate and meal size compared with primiparous cows, while primiparous cows visited the roughage feeding bins more frequently per day and per meal. These parity differences in feeding patterns were similar to that found by Neave et al. (2017), and while some of these findings might be partially attributed to differences in body weight and milk production between primi- and multiparous cows (Proudfoot and Huzzey, 2022), they could also be related to lack of experience or lower social dominance rankings of primiparous cows (Val-Laillet et al., 2008).

Earlier research has shown that feeding patterns of cows can be affected by external factors like their physical and social environment or management practices (Nielsen, 1999; González et al., 2008; Gomez and Cook, 2010), potentially also influencing the calculated meal criterion. Additionally, the findings of the current study could have been affected by data processing, among which meal criterion calculation. The determined meal criterion directly affects the calculated number of meals per day and all other feeding patterns variables expressed per meal (i.e. meal size, feeder visits per meal, feeding duration per meal and meal duration), complicating direct comparisons across studies (Dado and Allen, 1994). In the present study, the meal criterion of 55.4 min was higher than in most previous studies and was more comparable to the 40 min calculated by Melin et al. (2005) than the 24–28 min calculated by Yeates et al. (2001) or Tolkamp et al. (2002). External factors in our study set-up differing from previous studies that might have affected the meal criterion calculated include, amongst others, the prolonged CCC allowed, the cows being milked in an automatic MU, the stocking density at the roughage bins, barn layout with three-way selection gate, and the automatic concentrate feeding stations present in the general lying area and in the contact area. As the concentrate feeding stations were located outside the feed alley, the cows' motivation to return to the roughage bins soon after arriving in the general lying or the contact area might have been reduced, ultimately affecting the feeding patterns and meal criterion.

The current study shows that cows in this CCC system were able to maintain adequate roughage intake despite having prolonged calf contact. This suggests that such a CCC system does not necessarily compromise the cows' nutritional needs – an important consideration for the cow and also farmers considering this approach. Future research is needed to address the effects of different management strategies for enabling CCC in terms of the type and duration of physical contact, the possibility to choose physical contact (cow- vs. calf-driven), and cow traffic between functional areas in the barn, as well as different weaning and separation strategies. Additionally, research into the effects of stocking density at the roughage bins on the feeding patterns of cows with CCC is warranted.

5. Conclusion

Dairy cows that were allowed full contact with their calves (FC cows) had a greater daily roughage intake and meal size during the 12-week nursing period than cows separated from their calves shortly after birth (NC cows). During the nursing period, however, daily feeding rate, daily feeding duration, number of visits to the roughage bins per day and per meal, number of meals per day, feeding duration per meal and the meal duration did not differ among treatments, and all cows mostly visited the roughage bins directly after exiting the milking unit. Additionally, FC cows more often returned directly to the area where the calves were housed during the nursing period than NC cows returned directly to their resting area. During the fence-line contact period, when calves were gradually weaned, FC cows increased their feeding rate, but otherwise had similar roughage feeding patterns and intake as NC cows. After the fence-line period, upon physical separation of the calves, roughage feeding patterns of FC cows remained largely unchanged and did not differ from those of NC cows. Cows with calf contact were thus able to maintain their roughage intake, while the use of functional areas of the barn differed slightly during the nursing period compared with conventional cows.

CRediT authorship contribution statement

Bus Jacinta: Writing – review & editing, Software. **Bas Kemp:** Writing – review & editing, Supervision, Methodology. **Aarts Yannick:** Writing – review & editing, Software, Formal analysis. **van Zyl Coenraad Lodewyk:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bokkers Eddie:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Hanna Eriksson:** Writing – review & editing, Methodology, Investigation, Conceptualization. **van Knegsel Ariëtte T.M.:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to revise parts of the script for Python and statistical analyses in SAS. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2025.106902.

References

Abrahamse, P.A., Vlaeminck, B., Tamminga, S., Dijkstra, J., 2008. The effect of silage and concentrate type on intake behavior, rumen function, and milk production in dairy cows in early and late lactation. J. Dairy Sci. 91 (12), 4778–4792. https://doi.org/10.3168/jds.2008-1350.

Bertelsen, M., Jensen, M.B., 2023. Comparing weaning methods in dairy calves with different dam-contact levels, 961 J. Dairy Sci. 106 (12), 9598. https://doi.org/10.3168/jds.2023-23393.

Bieber, A., Wallenbeck, A., Spengler Neff, A., Leiber, F., Simantke, C., Knierim, U., Ivemeyer, S., 2020. Comparison of performance and fitness traits in German Angler, Swedish Red and Swedish Polled with Holstein dairy cattle breeds under organic production. Animal 14 (3), 609–616. https://doi.org/10.1017/S1751731119001964.

Commission Regulation (EC) No 889/2008 of 5 September 2008 laying down detailed rules for the Implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control. ⟨https://eur-lex.europa.eu/eli/reg/2008/889/oj⟩.

Dado, R.G., Allen, M.S., 1994. Variation in and relationships among feeding, chewing, and drinking variables for lactating dairy cows. J. Dairy Sci. 77 (1), 132–144. https://doi.org/10.3168/jds.S0022-0302(94)76936-8.

DeVries, T.J., von Keyserlingk, M.A.G., Weary, D.M., 2004. Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. J. Dairy Sci. 87 (5), 1432–1438. https://doi.org/10.3168/jds.S0022-0302(04)73293-2.

DeVries, T.J., von Keyserlingk, M.A.G., Weary, D.M., Beauchemin, K.A., 2003. Measuring the feeding behavior of lactating dairy cows in early to peak lactation. J. Dairy Sci. 86 (10), 3354–3361. https://doi.org/10.3168/jds.S0022-0302(03)73938-1.

Flower, F.C., Weary, D.M., 2009. Gait assessment in dairy cattle. animal 3, 87–95. https://doi.org/10.1017/S1751731108003194.

Goldhawk, C., Chapinal, N., Veira, D.M., Weary, D.M., von Keyserlingk, M.A., 2009. Prepartum feeding behavior is an early indicator of subclinical ketosis. J. Dairy Sci. 92 (10), 4971–4977. https://doi.org/10.3168/jds.2009-2242.

Gomez, A., Cook, N.B., 2010. Time budgets of lactating dairy cattle in commercial freestall herds. J. Dairy Sci. 93 (12), 5772–5781. https://doi.org/10.3168/jds.2010-3436.

González, L.A., Tolkamp, B.J., Coffey, M.P., Ferret, A., Kyriazakis, I., 2008. Changes in feeding behavior as possible indicators for the automatic monitoring of health disorders in dairy cows. J. Dairy Sci. 91 (3), 1017–1028. https://doi.org/10.3168/jds.2007-0530.

Grant, R.J., Albright, J.L., 2001. Effect of Animal Grouping on Feeding Behavior and Intake of Dairy Cattle. J. Dairy Sci. 84, E156–E163. https://doi.org/10.3168/jds.S0022-0302(01)70210-X.

Huzzey, J.M., DeVries, T.J., Valois, P., von Keyserlingk, M.A.G., 2006. Stocking Density and Feed Barrier Design Affect the Feeding and Social Behavior of Dairy Cattle. J. Dairy Sci. 89 (1), 126–133. https://doi.org/10.3168/jds.S0022-0302(06)72075-6.

Jensen, M.B., 2011. The early behaviour of cow and calf in an individual calving pen. Appl. Anim. Behav. Sci. 134 (3), 92–99. https://doi.org/10.1016/j.applanim.2011.06.017.

Jensen, E.H., Bateson, M., Neave, H.W., Rault, J.-L., Jensen, M.B., 2024. Dairy cows' motivation to nurse their calves. Sci. Rep. 14 (1), 13728. https://doi.org/10.1038/s41598-024-64038-z.

Johansson, T., Agenäs, S., Lindberg, M., 2023. Time budgets of dairy cows in a cow-calf contact system with automatic milking. JDS Comm. https://doi.org/10.3168/jdsc.2023-0401.

Johnsen, J.F., Ellingsen, K., Grøndahl, A.M., Bøe, K.E., Lidfors, L., Mejdell, C.M., 2015. The effect of physical contact between dairy cows and calves during separation on their post-separation behavioural response. Appl. Anim. Behav. Sci. 166, 11–19. https://doi.org/10.1016/j.applanim.2015.03.002.

Johnsen, J.F., Johanssen, J.R.E., Aaby, A.V., Kischel, S.G., Ruud, L.E., Soki-Makilutila, A., Kristiansen, T.B., Wibe, A.G., Bøe, K.E., Ferneborg, S., 2021. Investigating cow− calf contact in cow-driven systems: behaviour of the dairy cow and calf. J. Dairy Res. 88 (1), 52–55. https://doi.org/10.1017/S0022029921000194.

Johnsen, J.F., Sørby, J., Ferneborg, S., Kischel, S.G., 2024. Effect of debonding on stress indicators in cow and calf in a cow-calf contact system. JDS Comm. 5 (5), 426–430. https://doi.org/10.3168/jdsc.2023-0468.

Kok, A., van Hoeij, R.J., Tolkamp, B.J., Haskell, M.J., van Knegsel, A.T.M., de Boer, I.J.M., Bokkers, E.A.M., 2017. Behavioural adaptation to a short or no dry period with associated management in dairy cows. Appl. Anim. Behav. Sci. 186, 7–15. https://doi.org/10.1016/j.applanim.2016.10.017.

Leduc, A., Souchet, S., Gelé, M., Le Provost, F., Boutinaud, M., 2021. Effect of feed restriction on dairy cow milk production: a review. J. Anim. Sci. 99 (7). https://doi.org/10.1093/jas/skab130.

Llonch, P., Mainau, E., Ipharraguerre, I.R., Bargo, F., Tedó, G., Blanch, M., Manteca, X., 2018. Chicken or the egg: the reciprocal association between feeding behavior and animal welfare and their impact on productivity in dairy cows. Front. Vet. Sci. 5, 305. https://doi.org/10.3389/fvets.2018.00305.

Loberg, J., Lidfors, L., 2001. Effect of stage of lactation and breed on dairy cows' acceptance of foster calves. Appl. Anim. Behav. Sci. 74 (2), 97–108. https://doi.org/10.1016/S0168-1591(01)00157-5.

Melin, M., Wiktorsson, H., Norell, L., 2005. Analysis of Feeding and Drinking Patterns of Dairy Cows in Two Cow Traffic Situations in Automatic Milking Systems. J. Dairy Sci. 88 (1), 71–85. https://doi.org/10.3168/jds.S0022-0302(05)72664-3.

Munksgaard, L., Jensen, M.B., Pedersen, L.J., Hansen, S.W., Matthews, L., 2005. Quantifying behavioural priorities—effects of time constraints on behaviour of dairy cows, Bos taurus. Appl. Anim. Behav. Sci. 92 (1), 3–14. https://doi.org/10.1016/j.applanim.2004.11.005.

Neave, H.W., Lomb, J., von Keyserlingk, M.A.G., Behnam-Shabahang, A., Weary, D.M., 2017. Parity differences in the behavior of transition dairy cows. J. Dairy Sci. 100 (1), 548–561. https://doi.org/10.3168/jds.2016-10987.

Nielsen, B.L., 1999. On the interpretation of feeding behaviour measures and the use of feeding rate as an indicator of social constraint. Appl. Anim. Behav. Sci. 63 (1), 79–91. https://doi.org/10.1016/S0168-1591(99)00003-9.

Nielsen, B.L., F., V. R, Lawrence, A.B., 2000. Effects of Genotype, Feed Type and Lactational Stage on the Time Budget of Dairy Cows. Acta Agric. Scandi. A Anim. Sci. 50 (4), 272–278. https://doi.org/10.1080/090647000750069467.

Proudfoot, K.L., Huzzey, J.M., 2022. A first time for everything: The influence of parity on the behavior of transition dairy cows*. JDS Comm. 3 (6), 467–471. https://doi.org/10.3168/jdsc.2022-0290.

Reyes, F.S., White, H.M., Weigel, K.A., Van Os, J.M., 2024. Behavioral consistency of competitive behaviors and feeding patterns in lactating dairy cows across stocking densities at the feed bunk. Front. Vet. Sci. 11, 1302573. https://doi.org/10.3389/fvets.2024.1302573.

Schirmann, K., Chapinal, N., Weary, D.M., Heuwieser, W., von Keyserlingk, M.A.G., 2011. Short-term effects of regrouping on behavior of prepartum dairy cows. J. Dairy Sci. 94 (5), 2312–2319. https://doi.org/10.3168/jds.2010-3639.

Sirovnik, J., Barth, K., de Oliveira, D., Ferneborg, S., Haskell, M.J., Hillmann, E., Jensen, M.B., Mejdell, C.M., Napolitano, F., Vaarst, M., Verwer, C.M., Waiblinger, S., Zipp, K.A., Johnsen, J.F., 2020. Methodological terminology and definitions for research and discussion of cow-calf contact systems. J. Dairy Res. 87 (S1), 108–114. https://doi.org/10.1017/S0022029920000564.

Sørby, J., Johnsen, J.F., Kischel, S.G., Ferneborg, S., 2024. Effects of 2 gradual debonding strategies on machine milk yield, flow and composition in a cow-driven cow-calf contact system. J. Dairy Sci. 107 (2), 944–955. https://doi.org/10.3168/jds.2022-23117.

Tolkamp, B.J., Allcroft, D.J., Austin, E.J., Nielsen, B.L., Kyriazakis, I.I., 1998. Satiety splits feeding behaviour into bouts. J. Theor. Biol. 194 (2), 235–250. https://doi.org/10.1006/jtbi.1998.0759.

Tolkamp, B.J., Friggens, N.C., Emmans, G.C., Kyriazakis, I., Oldham, J.D., 2002. Meal patterns of dairy cows consuming mixed foods with a high or a low ratio of concentrate to grass silage. Anim. Sci. 74 (2), 369–382. https://doi.org/10.1017/S1357729800052528.

Tolkamp, B.J., Schweitzer, D.P., Kyriazakis, I., 2000. The biologically relevant unit for the analysis of short-term feeding behavior of dairy cows. J. Dairy Sci. 83 (9), 2057–2068. https://doi.org/10.3168/jds.S0022-0302(00)75087-9.

Val-Laillet, D., Passillé, A.M. d, Rushen, J., von Keyserlingk, M.A.G., 2008. The concept of social dominance and the social distribution of feeding-related displacements between cows. Appl. Anim. Behav. Sci. 111 (1), 158–172. https://doi.org/10.1016/j.applanim.2007.06.001.

van Zyl, C.L., Bokkers, E.A.M., Kemp, B., Agenäs, S., Van Knegsel, A.T.M., 2025b. Growth and metabolism of calves in a dairy cow-calf contact system with gradual weaning and separation. J. Dairy Sci. 108, 11103–11118. https://doi.org/10.3168/JDS.2025-26619.

van Zyl, C.L., Eriksson, H.K., Bokkers, E.A.M., Kemp, B., Van Knegsel, A.T.M., Agenäs, S., 2025a. Consequences of weaning and separation for feed intake and milking characteristics of dairy cows in a cow-calf contact system. J. Dairy Sci. 108 (3), 2820–2838. https://doi.org/10.3168/jds.2024-25202.

Vogt, A., Waiblinger, S., Palme, R., König von Borstel, U., Barth, K., 2025. Dairy cows' responses to 2 separation methods after 3 months of cow-calf contact. J. Dairy Sci. 108 (2), 1940–1963. https://doi.org/10.3168/jds.2024-25293.

Volden, H., 2011. *NorFor*-The Nordic feed evaluation. system. Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-718-9.

von Keyserlingk, M.A.G., Weary, D.M., 2007. Maternal behavior in cattle. Horm. Behav. 52 (1), 106–113. https://doi.org/10.1016/j.yhbeh.2007.03.015.

Weary, D.M., Jasper, J., Hötzel, M.J., 2008. Understanding weaning distress. Appl. Anim. Behav. Sci. 110 (1), 24–41. https://doi.org/10.1016/j.applanim.2007.03.025.

Wegner, C.S., Ternman, E., 2023. Lying behaviour of lactating dairy cows in a cow-calf contact freestall system. Appl. Anim. Behav. Sci. 259, 105851. https://doi.org/10.1016/j.applanim.2023.105851.

Wenker, M.L., Bokkers, E.A.M., Lecorps, B., von Keyserlingk, M.A.G., van Reenen, C.G., Verwer, C.M., Weary, D.M., 2020. Effect of cow-calf contact on cow motivation to reunite with their calf. Sci. Rep. 10 (1), 14233. https://doi.org/10.1038/s41598-020-70927-w.

Wenker, M.L., van Reenen, C.G., Bokkers, E.A.M., McCrea, K., de Oliveira, D., Sørheim, K., Cao, Y., Bruckmaier, R.M., Gross, J.J., Gort, G., Verwer, C.M., 2022. Comparing gradual debonding strategies after prolonged cow-calf contact: stress responses, performance, and health of dairy cow and calf. Appl. Anim. Behav. Sci. 253, 105694. https://doi.org/10.1016/j.applanim.2022.105694.

Wenker, M.L., van Reenen, C.G., de Oliveira, D., McCrea, K., Verwer, C.M., Bokkers, E.A.M., 2021. Calf-directed affiliative behaviour of dairy cows in two types of cow-calf contact systems. Appl. Anim. Behav. Sci. 243, 105461. https://doi.org/10.1016/j.applanim.2021.105461.

Yeates, M.P., Tolkamp, B.J., Allcroft, D.J., Kyriazakis, I., 2001. The use of mixed distribution models to determine bout criteria for analysis of animal behaviour. J. Theor. Biol. 213 (3), 413–425. https://doi.org/10.1006/jtbi.2001.2425.