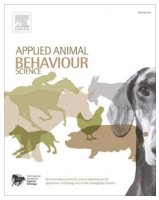
Applied Animal Behaviour Science 279 (2024) 106385

Contents lists available at ScienceDirect

Applied Animal Behaviour Science

journal homepage: www.elsevier.com/locate/applanim



Social interactions of dairy cows and their association with milk yield and somatic cell count

Helen R. Fielding [a,*,1], Matthew J. Silk [a], Trevelyan J. McKinley [b], Richard J. Delahay [c], Jared K. Wilson-Aggarwal [a], Laetitia Gauvin [d,g], Laura Ozella [e], Ciro Cattuto [d,f], Robbie A. McDonald [a]

[a] Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[b] College of Medicine and Health, University of Exeter, Exeter EX2 5DW, UK
[c] National Wildlife Management Centre, Animal and Plant Health Agency, Sand Hutton, York YO41 1LZ, UK
[d] ISI Foundation, Via Chisola 5, Torino 10126, Italy
[e] Department of Veterinary Sciences, University of Turin, Largo Braccini 2, TO, Grugliasco 10095, Italy
[f] Computer Science Department, University of Turin, Corso Svizzera 185, Torino 10149, Italy
[g] French National Research Institute for Sustainable Development, PRODIG, Aubervilliers, France

ARTICLE INFO

Keywords:
Cattle
Affiliative behaviour
Social network analysis
Proximity
Somatic cell count
milk production

ABSTRACT

The social environment experienced by livestock can have implications for their health, welfare, and subsequently, their productivity. Changes in the dairy industry have led to larger herd sizes and altered management of cows, which has impacted their social environment. Studies have shown that mixing of animals can lead to social instability of groups and expansion of herds can lead to high stocking densities resulting in social stress and negative effects on production. Yet few studies have assessed the putative impact of positive cow-cow interactions, such as proximity to preferred herd mates and engaging in grooming, on milk production and udder health. To address this, we used cattle proximity as a proxy for affiliative interactions between cows in three dairy herds in south-west England over one week study periods. We created proximity networks of dairy cows and measured cow-cow associations according to milk yield, somatic cell count (SCC; an indicator of mastitis), parity (number of lactations in the cow's lifetime), and lactation stage (grouped by days in milk for current lactation). We then assessed associations between social factors and production and health measures (milk yield and SCC). In all three herds, cows interacted more with cows in the same parity, suggesting early social bonding may be evident later in life and that grouping animals in terms of parity might encourage affiliative interactions. Cows did not associate according to milk yield, SCC, or lactation stage. There was no significant association between milk production or SCC and the total time spent in social contact with other cows, the mean time spent with the four closest herd mates, or the number of closest herd mates of the same parity. We suggest that further research on positive social environments for dairy cattle is warranted in the interests of improving welfare and enabling a more robust assessment of the putative effects on production and health parameters

1. Introduction

The social environment of animals impacts on their health and welfare (Mellor, 2015). For example, positive social experiences in livestock can reduce stress (Laister et al., 2011; Takeda et al., 2003) and animals with calm temperaments may have enhanced immunity (Dimitrov et al., 2005). Conversely, crowding, isolation, and social instability can precipitate stress and disease (Proudfoot and Habing, 2015; Proudfoot et al., 2012). Grouping of cows by their stage of lactation (number of days since calving) allows more precise feeding to meet nutritional requirements (Sowerby and Polan, 1978a), though moving animals between groups can be a source of social stress in dairy cows (Proudfoot and Habing, 2015). Industry-wide trends for larger herds (AHDB Dairy, 2019a) may exacerbate this problem as larger herds

* Corresponding author.
E-mail address: helen.fielding@ed.ac.uk (H.R. Fielding).
[1] Present address: The Royal (Dick) School of Veterinary Studies and The Roslin Institute, The University of Edinburgh, Easter Bush Campus, Midlothian, EH25 9RG, UK.

https://doi.org/10.1016/j.applanim.2024.106385
Received 20 December 2023; Received in revised form 23 August 2024; Accepted 29 August 2024
Available online 6 September 2024

usually require more management groups and the subsequent increased movement of cows between groups can cause social instability. The trend towards higher milk yields (AHDB Dairy, 2019b; Pryce and Veerkamp, 2001) has resulted in the need for more intensive management of cattle, often indoors, to meet their nutritional demands (Charlton et al., 2011). On some farms this might lead to overstocking (Krawczel et al., 2012) and concerns regarding their ability to perform natural behaviours (Arnott et al., 2016; Beaver et al., 2020).

Historically, animal welfare principles were aimed at avoiding negative states, i.e. the freedom from fear, distress and hunger (Farm Animal Welfare Council, 1979) and social stressors have been associated with reduced milk yield in cows, sheep and goats (Hasegawa et al., 1997; Miranda-de la Lama and Mattiello, 2010; Sevi et al., 2001) and reduced weight gain in pigs (Hyun et al., 1998). More recently, studies have focussed on measuring positive welfare outcomes (Boissy et al., 2007; Mellor and Beausoleil, 2015). Affiliative behaviours such as social licking in cattle have been shown to instil calmness (Laister et al., 2011) and to be positively correlated with the milk yield of the cow receiving the grooming (Sato et al., 1991; Wood, 1977). Being involved in grooming between cows (both receiving and performing) was associated with higher milk yields in one study (Sato et al., 1991), although no such relationship was found in a larger study (Wood, 1977). Milk yield was positively correlated with a principle component representing 24 % of the variance that included allogrooming and eating, suggesting that the two activities are correlated and may contribute to the mechanism increasing milk yield (Fukasawa and Tsukada, 2010). Two studies investigated the strength of social associations at automatic milking systems (AMS) (Marumo et al., 2022; Ozella et al., 2023). Neither showed a statistically significant association with milk yield, suggesting that observing interactions only at the AMS may not adequately represent the broader social environment of dairy cows. Yet Marumo et al. found a significant relationship with milk quality (protein and fat content). Additionally, milk quality has been shown to be better in calm sheep (Sart et al., 2004). Although the relationship between social factors and milk yield has been the subject of several studies (Table S1), few to date have investigated the impact of social factors on the somatic cell count of milk (SCC), which can be an indicator of infection in the mammary gland should counts exceed 200,000 cells/ml (Dohoo and Leslie, 1991). Regrouping of cows and transportation has also been associated with increased SCCs, possibly via a stress response and enhanced migration of peripheral blood leucocytes into the mammary duct vessels or movement into milk via leaky tight junctions (Kay et al., 1977; Yagi et al., 2004). However, the relationship between social interactions, stress and SCC is complex and two other studies found no relationship between SCC and dominance rank (Arave and Albright, 1976) or SCC and traditional cow regrouping (i.e. cows moved between groups based on their stage of lactation; Silva et al., 2013). We hypothesise that if negative social interactions putatively increase SCC, then more positive interactions may be associated with lower SCCs.

Contacts amongst cattle recorded by proximity devices worn on neck collars have been shown to be a biologically and statistically significant predictor of affiliative rather than agonistic interactions (Boyland et al., 2016), perhaps due to the positioning of the sensor near the head and neck, where most grooming interactions occur (Tresoldi et al., 2015; Val-Laillet et al., 2009). Pairs of animals in close proximity were more likely to engage in allogrooming than agonistic interactions (Tresoldi et al., 2015) and proximity was positively correlated with licking behaviours (Pinheiro Machado et al., 2020). Proximity devices are able to monitor interactions continuously, generating near-complete data on cow-cow interactions (Chen et al., 2014), rather than short snapshots collected by direct observations or data gathered only at milking.

In this study, we used cattle proximity as a proxy for a positive social interaction and continuously recorded interactions among dairy cows for one week in three herds in south-west England. Through network analyses, we examined the social interactions of animals relative to their parity, lactation stage, milk yield, and SCC, whilst accounting for aspects of cow physiology and farm management that we also expect to influence these responses. We specifically tested if certain patterns of interactions were associated with milk yield and SCC. Better understanding of the social preferences of cows might inform cattle management and grouping structures that create a more positive social environment and allow animals to achieve their production potential (Rault, 2012).

2. Methods

2.1. Farm management

The milking groups of three commercial dairy herds (two Holstein-Friesian herds – 'HF1' and 'HF2', and one Ayrshire herd – 'Ayrshire') in Cornwall, England were studied for one week between August and November 2018 (Table 1). The spatial and temporal characteristics of the social networks of these herds during this period have been previously described (Fielding et al., 2021). All herds calved all year round, kept cows in separate milking and dry groups, and were milked twice daily in a parlour. Animals in HF1 were the low-yielding cows of that herd and were housed in cubicle stalls with a feed passage running along one side of the pen throughout the study period, owing to lack of grazing due to hot weather. Cows in HF2 and Ayrshire were on rotational grazing where the paddock was changed after every milking.

2.2. Equipment and proximity data

Nylon cattle collars with a plastic clasp (Suevia Haiges, Germany) were fitted with proximity devices based on a design by the OpenBeacon project (http://www.openbeacon.org/) and the SocioPatterns collaboration consortium (http://www.sociopatterns.org/). The devices use radio frequency identification detection (RFID) technology to exchange low-power radio packets in a peer-to-peer fashion, using the difference in signal strength as a proxy for distance between devices (Cattuto et al., 2010). We defined contacts based on a spatial threshold of 1–1.5 m to capture close contacts, assessed by validation analyses (Fielding et al., 2021). We only included contacts in our analysis that lasted over 20 seconds in duration, aiming to avoid detecting 'walk-by' type interactions and instead to record more significant behaviours such as allogrooming events, which are reported in observation studies to last 37–39 seconds on average (Sato, 1984; Tresoldi et al., 2015). Contacts are maintained if signals are transferred between devices at least once every 20 seconds, therefore contact time was measured in 20 second blocks. We removed contacts recorded during milking times reported by farmers as these represent times when animals were restricted in space and affiliative behaviours are less likely to occur during this period (Wood, 1977).

2.3. Social parameters

We constructed networks based on contact data described above, where cows were nodes and the edges were weighted according to the total duration of contact between them over the study period. We calculated the assortativity of cows by stage of lactation and parity (Ayrshire: $n = 44$, HF1: $n = 71$, HF2: $n = 95$), and SCC and milk yield (Ayrshire: $n = 39$, HF1: $n = 71$, HF2: $n = 87$) in the R (R Core Team Version 3.5.3, 2019a) package 'igraph' (Csardi and Nepusz, 2006). Assortativity measured the tendency of cows to interact more with similar cows based on a particular characteristic, with a value of $+1$ indicating preferential association between cows with similar characteristics, and -1 indicating preferential association between cows with different characteristics. As the networks were densely connected, we calculated assortativity on networks filtered by edge weights to focus on the effect of increasingly 'strong' ties. We achieved this by removing edges below the 50th, 75th and 90th percentiles of edge weights to create F50, F75 and F90 networks respectively. We constructed null

Table 1
Details of three study dairy farms and study periods providing information on farm management, group size and proximity data collected, including mean production indicators obtained from the nearest milk recording date to the study period. Proximity data includes the mean minutes in contact with other cows, mean minutes in contact with their top 4 contacts and the number of those cows with the same parity.

Group name/ breed	Group monitored	Housing/ Grazing	No. cows in group	Study Period (days)	Milk data recording date	Complete proximity data and cow lactation info	Complete milking and proximity data	Minutes in contact mean (SD)	Minutes in contact with top 4 mean (SD)	No. cows in top 4 contacts in same lactation (median)	Milk yield per day per cow (kg) mean (SD)	Median SCC (IQR)	Mean days in milk (SD)	Cows with SCC > 200,000 cells/ml
Ayrshire	Milking	Strip grazing	52	6.8	18/09/18	44	39	9.2 (4.4)	37.6 (18.9)	1	21.3 (7.5)	49 (27–126)	143 (102)	21 % (n = 11)
HF1 (Holstein Friesian)	Milking - low yield group	Indoor cubicles	111	6.8	18/09/18	71	71	14.2 (6.3)	74.6 (31.9)	1	21.0 (5.2)	128 (93–237)	244 (49)	31 % (n = 34)
HF2 (Holstein Friesian)	Milking	Rotational grazing	177	7.0	25/10/18	95	87	12.8 (7.1)	62.8 (33.2)	1	31.0 (7.7)	43 (27–105)	175 (99)	14 % (n = 25)

SD = standard deviation, IQR = interquartile range, SCC = somatic cell count.

graphs with the same number of nodes and edges as the observed network where each edge has an equal, fixed probability of being present or absent based on the Erdös-Rényi model (Erdös and Rényi, 1959). We randomly allocated observed edge weights to the edges of the new random networks (n = 4999). We removed edges from random graphs below filtering thresholds (F50, F75, and F90) after constructing the randomised graphs from the original networks. Assortativity values of our observed networks were deemed to be statistically significantly different to those on random networks when the observed value lay outside 95 % of randomised values.

We calculated the mean association strength, i.e. the time each cow spent with all other cows in the network divided by the number of cows it could have potentially contacted (n-1). Individuals that spend longer amounts of time in contact with other cows may be considered to be more gregarious, however the definition of social bonds is complex and this metric does not reveal whether this time is distributed equally among many herd mates, or whether an individual has just a few partners with which they spend a lot of time (Shultz and Dunbar, 2010). It has been estimated that cows might be most comfortable with two to four individuals (Takeda et al., 2000); therefore, to estimate a cow's tendency to form stronger social bonds, we took the mean of the time each cow spent with its longest four contacts (mean top four contacts) and in order to explore the effect of a cow spending time with more familiar cows, we recorded the number of top four contacts in the same parity as the selected cow.

2.4. Statistical modelling

We assessed the relationship between the previously described social factors and milk yield and SCC using two similar Bayesian mixed effects models with daily milk yield (measured by kg weight; Model 1) and SCC (thousand cells per ml; Model 2) as response variables. Farm was included as a random effect in both models to account for farm-level differences in nutrition, husbandry, and breed. Mean association strength, 'mean top 4 contacts', and the number of top 4 contacts in the same parity, parity (categorical), stage of lactation (categorical), and SCC (in Model 1 only) and milk yield (in Model 2 only) were included as fixed covariates (Table S2). We accessed the last calving date and parity of all cows in HF1 and a subset of cows in Ayrshire and HF2 from the National Milk Records and Cattle Information Service databases. Milk yields and SCCs are recorded monthly and the nearest recorded values were used for the study (HF1 = 7 days after study period, HF2 = 1 day before study period, and Ayrshire = 11 days after study period; Table 1). To check if this single value would approximate to values over the study period, we additionally obtained daily milk yields during the study period for HF1, and milk yield and SCC data from a second recording 16 days before the study period for the Ayrshire group. Mean daily milk yield in HF1 was highly correlated with the single milk recording value ($r = 0.9$, $P < 0.001$; Fig. S1). For the Ayrshire group, the two values for milk yield and SCC from milk recording days were moderately correlated ($r = 0.59$, $P < 0.001$ and $r = 0.67$, $P < 0.001$ respectively; Fig. S1). Correlations were based on Pearson's product moment correlation coefficient in R. We also ran a model similar to Model 1 using HF1 average daily milk yields as a response variable instead of the single milk yield value, and outcomes were similar to those identified in Model 1.

Parity represents the number of full-term pregnancies a cow has had, and therefore typically correlates with age. On our study farms, animals were home-bred, and therefore parity might also be a proxy for time spent together as calves and time spent in the milking herd. This was classed as a categorical variable with the final level corresponding to 5 or more. Parity has a non-linear relationship with milk yield, which is lowest in a heifer's first lactation, rising in the 2nd and 3rd lactation and then decreasing as cows mature (Vijayakumar et al., 2017). Parity also mediates the relationships between stage of lactation and milk yield (cows in their 2nd and 3rd lactations tend to reach peak yield more quickly (Vijayakumar et al., 2017), and SCC and milk yield, where

higher milk losses occur in older cows (Hand et al., 2012).

Days in milk was the number of days between the most recent calving date and the milk recording date when SCC and milk yield were measured. Multiparous cows (two or more lactations) with a similar number of days in milk are likely to have been re-introduced back into the milking group at a similar time and grouped together in the preceding dry period. The relationship between days in milk and milk yield is described by the lactation curve, the profile of which changes with parity. Therefore, we grouped this variable into four stages of lactation; 1–70 days, 71–170 days, 171–270 days and >271 days in milk (Vijayakumar et al., 2017) to allow for variation in the relationship.

To acknowledge these effects, we ran Model 1 with an interaction between parity and lactation stage, and between parity and SCC. We tested Model 2 with an interaction between parity and milk yield. Including the interaction terms in either model did not appreciably alter model fit (measured by the leave-one-out cross-validation information criterion 'LOOIC'; (Vehtari et al., 2017) and did not alter the interpretation of our social variables, therefore we present the models without interactions. To reduce bias, we did not perform variable selection except for the interaction terms (Harrell, 2001). Regression parameters of fixed effects were given improper flat priors and random effects were given non-standardised half Student-t priors based on the standard deviation of the random effect with 3 degrees of freedom and a scale parameter (Carpenter et al., 2017). Predictive posterior distributions showed good model fit (Figs. S2 and S3) and good model convergence is demonstrated by Gelman-Rubin $\widehat{R}$ values of 1.00 and large effective sample sizes (Table S2). Effect sizes of continuous variables were scaled by the 10th and 90th percentiles of raw data so that they could be interpreted relative to the spread of raw data values (Fig. 2 and Table S2). The effect size thus represents the change in the response variable associated with an increase in the explanatory variable from the 10th percentile of the data to the 90th percentile. All data analysis was performed in R (R Core Team Version 3.5.3, 2019b), with models constructed in 'brms' (Bürkner, 2017) and networks constructed in 'igraph' (Csardi and Nepusz, 2006).

3. Results

After accounting for hardware and software performance of the proximity devices, data on contacts, parity and lactation stage were available for 85 % (Ayrshire = 44/52), 64 % (HF1 = 71/111), and 54 % (HF2 = 95/177) of animals in the study herds (Table 1) for use in calculating network parameters. Milk yield and SCC data were available for all 71 cows in HF1 and for only a subset of the Ayrshire (n = 39/44) and HF2 (n = 87/95) herds and were used in our statistical models (total n = 197; Table S2). Over all groups, the mean total contact time per pair of cows was 12.6 minutes per week-long study period (standard deviation (SD) = 6.6 minutes). The cumulative mean time spent by a cow with any one of their top four longest contacts was 62.0 minutes (SD = 33.0 minutes). For 73.6 % of cows, at least one individual in their top four contacts was of the same parity but only 2.0 % of cows shared the same parity with all four (Table S2). There were similar numbers of cows in each parity (mean = 39, SD = 5) and the largest proportion of cows (40.1 %) were between 171 and 270 days in milk (Table S2). The overall mean milk yield per cow was 25.6 kg per day over two milkings (SD = 8.4 kg). SCCs were low for most cows, but 20 % had cell counts above

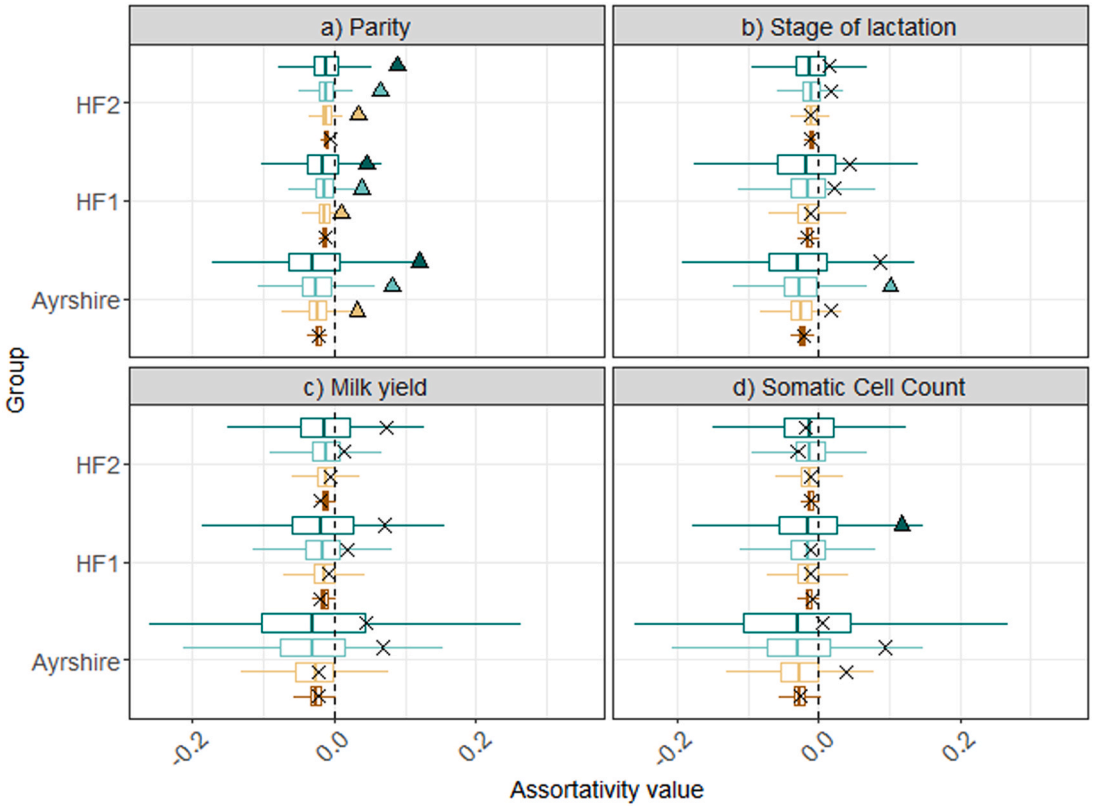


Fig. 1. Assortativity values from observed and random networks of cattle from three study groups (n = 193). Triangles represent observed assortativity values outside 95 % of random network values, crosses represent observed values within 95 % of random network values, and boxplots represent the distribution of random values. Assortativity indicates the tendency of cows to interact preferentially, based on similarities in a) parity and b) stage of lactation (Ayrshire n = 44, HF1 n = 71, HF2 n = 95), c) milk yield and d) SCC (Ayrshire n = 39, HF1 n = 71, HF2 n = 87). Assortativity was calculated on undirected, weighted networks that were not-filtered (NT – brown), and networks with 50th (F50 – gold), 75th (F75 – light blue), and 90th (F90 – dark green) percentiles of edge weights removed. The dashed line at zero represents the assortativity value where interactions are unrelated to characteristics of each cow. Cows tend to interact preferentially with cows of a similar parity (a), but they did not tend to interact preferentially based on their stage of lactation (b), milk yield (c) or SCC (d).

200,000 cells/ml, suggestive of mastitis (Dohoo and Leslie, 1991).

Cows in all groups showed a statistically significant tendency to associate preferentially with others of the same parity on all filtered networks compared to random networks (Fig. 1), though not to a great extent (<0.15). For other measures, assortativity was no different to that expected on random networks in all cases apart from on the F75 network for stage of lactation (Fig. 1d), though due to the lack of other statistically significant effects in other herd's networks for this variable, we expect this may be a Type I error.

We detected no statistically significant associations between mean association strength, spending longer times with certain cows and those cows being in the same lactation and either milk yield or SCC (Fig. 2 and Table S2). As expected, there was a statistically significant relationship between parity and milk yield in Model 1, with the lowest yields in first lactation heifers and higher milk yield thereafter (Fig. 2 and Table S2). There was a positive relationship between milk yield and lactation stage in the first 70 days of lactation in Model 1 and then this decreased through all subsequent stages of lactation, demonstrating the expected long tail of the lactation curve. In Model 1, there was no statistically significant association between SCC and milk yield, or vice versa in Model 2 (Fig. 2 and Table S2). Model 2 demonstrated increasing SCC with the number of days in milk and a higher SCC was associated with cows in their 5th or higher lactation (Fig. 2).

4. Discussion

In this study we showed that in multiple herds, cows preferentially associate with animals in the same parity. Similar parity in the herds where animals are home-bred (as in this study), is likely to mean that cows may have been reared as calves in the same cohort, entered the milking herd at a similar time and are of a similar age. By recording proximity among cattle in a commercial dairy herd, Boyland et al. (Boyland et al., 2016) also found that UK cows preferred to interact more with cows with the same parity and Marina et al. (Marina et al., 2023) found interactions were greater and more consistent between Swedish cows of the same parity and those that were born within 7 days on the same farm. By recording grooming behaviour between a herd made up of twin cows grouped since they were 4–7 days old, Wood (1977) found that cows preferred grooming other cows in their own age group. These findings reinforce the theory that early bonding is influential in the formation and maintenance of social bonds, even later in life (Reinhardt and Reinhardt, 1975), although this has not been seen in all studies (Chopra et al., 2020). In contrast, the lactation *stage* of cows (i.e. number of days in milk) represented shorter-term familiarity (i.e., being more recently in a group of dry cows together) and was not associated with preferred associations in the present study, similar to previous findings (Gutmann et al., 2015; Marina et al., 2023).

Although we found that cows preferred to interact with others of the same parity, we found no evidence that having more cows of the same parity in their top four closest contacts, time spent with other cows, or closeness of relationship with certain cows (the time spent with their top four contacts) was associated with a statistically or biologically significant change in milk yields or SCC. This is similar to results of some previous studies where milk yield and social associations at automatic milking systems were investigated and no relationship was found (Marumo et al., 2022; Ozella et al., 2023), but contrasts with other studies which found significant relationships between affiliative behaviours and milk yield in both indoor and outdoor housed cows (Fukasawa and Tsukada, 2010; Sato et al., 1991; Wood, 1977). Studies that identified a positive significant relationship with milk yield directly measured allogrooming behaviours over short time periods, whereas studies using proximity as a proxy measure for affiliative behaviour did not. Proximity is typically measured continuously, and whilst being correlated with affiliative behaviours (Boyland et al., 2016), this measure may also include other behaviours that dilute the relationship between solely affiliative behaviours and production parameters, making it more difficult to identify. In more extensive systems, such as rotational grazing, we expected proximity to be governed largely by preference, however, in the indoor group (HF1) and groups with restricted grazing (Ayrshire) proximity may be less tied to cow choice and better understood by competition for resources. Future studies could examine spatio-temporal proximity in relation to food provision, where that data is available. HF1 cows were low yielding cows likely to have a lower feed intake than comparable higher yielding cows, which may reduce the

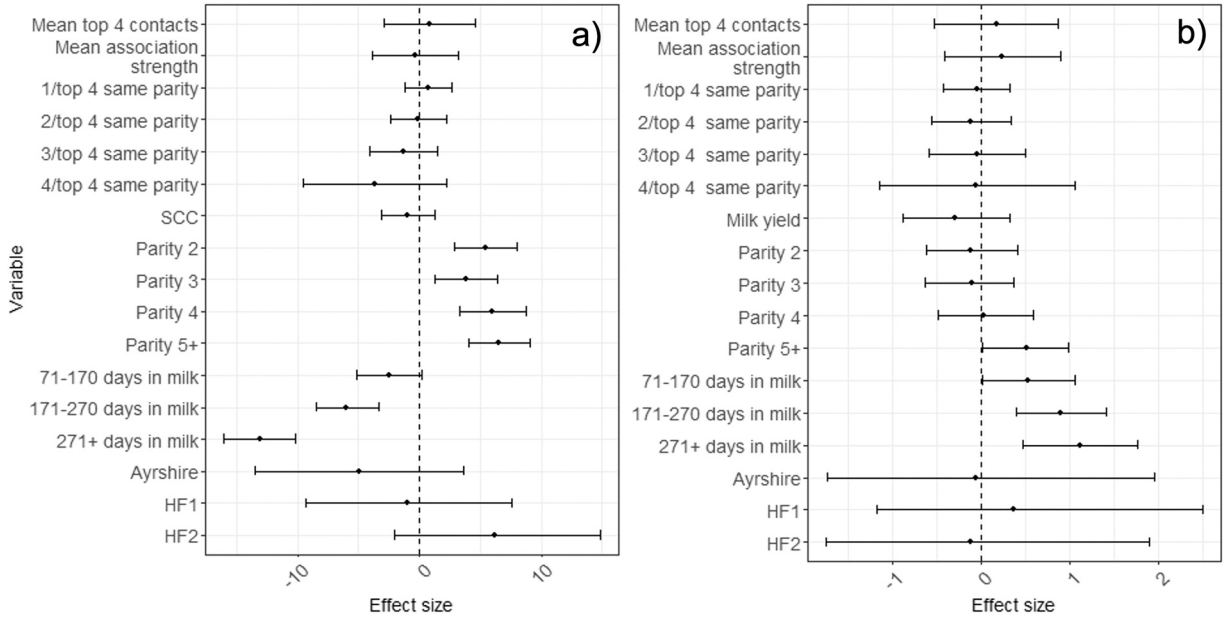


Fig. 2. Results of Bayesian mixed effects models with the response variables of (a) Model 1: milk yield and (b) Model 2: SCC showing effect sizes and 95 % credible intervals. Studies included 193 cattle from three Cornish dairy herds. Fixed effects in the models were mean association strength, mean time spent with four closest herd mates, number of those closest herd mates of the same parity, parity, stage of lactation, and SCC (Model 1) and milk yield (Model 2). Farm is included as a random effect in both models. Continuous variables are scaled to represent the effect size associated with a change in the explanatory variable from the 10th to the 90th percentile of the raw data. Points show effect sizes and whiskers represent 95 % credible intervals (see Table S2 for values).

impact of any competition for resources. There were significant management differences between our groups and whilst this reduces the ability to compare between the groups, it does suggest the findings of our study are applicable to a wide range of commercial dairy herds.

The baseline milk yield of each cow is likely to influence the magnitude of any association with social parameters (Jezierski and Podluzny, 1984). Cows already achieving close to their physiological potential are likely to have less opportunity for further increases in production as a result of positive social experiences, whilst being more susceptible to decreases in yield due to negative experiences. Negative social experiences may be therefore more easily detected and perhaps contributes to why studies have previously been more focussed on negative, rather than positive social experiences (Ellen et al., 2014).

Introduction of new animals and regrouping animals is a common management practice in modern dairy herds, and occurred on all farms in our study, mainly due to cows that had recently calved entering the lactating group, cows entering the low-lactation group or leaving the group at the end of a lactation. Negative associations between regrouping and milk production have been identified in the short (1–5 days after regrouping; (Brakel and Leis, 1976; Jezierski and Podluzny, 1984; von Keyserlingk et al., 2008) and longer-term (7–14 days after regrouping; (Arave and Albright, 1976; Hasegawa et al., 1997; Phillips and Rind, 2002). Removal of cows that contribute positively to the group (e.g. 'social groomers') might be particularly detrimental to herd milk yield (Wood, 1977) and the magnitude of the impact of removing animals from the group may depend on the sociality of the cow (Jezierski and Podluzny, 1984). It has also been suggested that such social stresses of group mixing may decrease with age and experience within the herd and may affect younger cows to a greater degree (Sowerby and Polan, 1978b). These additional factors may contribute to some other studies not recognising a significant relationship between regrouping and milk yield (Clark et al., 1977; Collis et al., 1979; Silva et al., 2013; Sowerby and Polan, 1978b; Zwald and Shaver, 2012). Cow movements may have affected the social environment and thus milk yield of cows in the present study, however these were not recorded, which would be beneficial in future studies.

We found no significant relationship between the tested social factors and SCC, consistent with two larger studies (n = 103 and 567) that showed no SCC difference between control (stable groups) and treatment (new animals introduced) groups (Clark et al., 1977; Silva et al., 2013). SCC may either be unrelated to social interactions or primarily influenced by negative social factors (Kay et al., 1977; Yagi et al., 2004) rather than the positive interactions tested here.

Both milk yield and SCC vary widely amongst individual cows, within a lactation and over the lifetime of an individual, yet due to technological limitations, the present study only collected data for one week. Detecting impacts of positive social experiences in future studies would benefit from longer and multiple observations of the same cows over several lactations to better understand patterns of variation in physiology and social behaviour over time. Larger sample sizes are preferred to have sufficient power to detect small effects, as even modest changes in daily milk yields could have large financial impacts when scaled up over several herd years.

5. Conclusions

In the three herds we studied, we identified a preference for cows to interact with conspecifics of the same parity, consistent with evidence for social preference according to long-standing familiarity in cattle. The sociality of cows was not significantly associated with milk yield or SCC and we detected no production or health benefit to cows being closely associated with those of the same parity. Previous literature suggests that the social environment of cattle at least partly influences cattle welfare and production, therefore with technological advances that facilitate longer periods of study, further research on this topic may elucidate a better understanding of this complex relationship, beneficial to cow welfare and farm finances.

Ethics

All fieldwork was approved by the University of Exeter College of Life and Environmental Sciences (Penryn Campus) animal ethics committee (Reference eCORN000087 v4.6).

Funding

HRF was funded by an iCASE studentship from the BBSRC [Grant reference: BB/M015874/1] in partnership with the Animal and Plant Health Agency. LO, LG, CC acknowledge partial support from the Lagrange Project of ISI Foundation funded by CRT Foundation.

CRediT authorship contribution statement

Laura Ozella: Writing – review & editing, Validation, Software, Resources, Methodology, Data curation. **Laetitia Gauvin:** Writing – review & editing, Validation, Software, Resources, Methodology, Data curation. **Robbie A. McDonald:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ciro Cattuto:** Writing – review & editing, Software, Resources, Methodology, Data curation. **Matthew J. Silk:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Helen Rebecca Fielding:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard J. Delahay:** Writing – review & editing, Supervision, Funding acquisition. **Trevelyan J. McKinley:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Jared K. Wilson-Aggarwal:** Writing – review & editing, Resources, Methodology, Data curation.

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

During the preparation of this work the author(s) used ChatGPT-4 in order to reduce the characters in the Highlights and reduce the length of one paragraph. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) 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.

Acknowledgements

Thank you to all the dairy farmers that assisted with the study and allowing us access to milk records. Thanks to Edward Firth, Kelly Astley, Madeleine Green and Charlotte Epps for assisting with field data collection and to Darren Croft for sharing his proximity sensor validation studies.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2024.106385.

References

AHDB Dairy, 2019a. Average Herd Size, in: Agriculture and Horticulture Development Board. https://dairy.ahdb.org.uk/resources-library/market-information/farming-data/average-herd-size/#.XTINSPJKiUm. Accessed on 28th July 2019.

AHDB Dairy, 2019b. Average UK milk yield, in: Agriculture and Horticulture Development Board. https://dairy.ahdb.org.uk/resources-library/market-information/farming-data/average-milk-yield/#.XT2Qt_JKiUk Accessed on 28th July 2019.

Arave, C.W., Albright, J.L., 1976. Social rank and physiological traits of dairy cows as influenced by changing group membership. J. Dairy Sci. 59, 974–981. https://doi.org/10.3168/jds.S0022-0302(76)84306-8.

Arnott, G., Ferris, C.P., O'Connell, N.E., 2016. Review: welfare of dairy cows in continuously housed and pasture-based production systems. Animal 11, 261–273. https://doi.org/10.1017/S1751731116001336.

Beaver, A., Proudfoot, K.L., von Keyserlingk, M.A.G., 2020. Symposium review: Considerations for the future of dairy cattle housing: An animal welfare perspective. J. Dairy Sci. 103, 5746–5758. https://doi.org/10.3168/jds.2019-17804.

Boissy, A., Manteuffel, G., Jensen, M.B., Moe, R.O., Spruijt, B., Keeling, L.J., Winckler, C., Forkman, B., Dimitrov, I., Langbein, J., Bakken, M., Veissier, I., Aubert, A., 2007. Assessment of positive emotions in animals to improve their welfare. Physiol. Behav. 92, 375–397. https://doi.org/10.1016/j.physbeh.2007.02.003.

Boyland, N.K., Mlynski, D.T., James, R., Brent, L.J.N., Croft, D.P., 2016. The social network structure of a dynamic group of dairy cows: from individual to group level patterns. Appl. Anim. Behav. Sci. 174, 1–10. https://doi.org/10.1016/j.applanim.2015.11.016.

Brakel, W.J., Leis, R.A., 1976. Impact of Social Disorganization on Behavior, Milk Yield, and Body Weight of Dairy Cows. J. Dairy Sci. 59, 716–721. https://doi.org/10.3168/jds.s0022-0302(76)84263-4.

Bürkner, P.-C., 2017. brms: An R Package for Bayesian Multilevel Models Using Stan. J. Stat. Softw. 80 https://doi.org/10.18637/jss.v080.i01.

Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M.A., Guo, J., Li, P., Riddell, A., 2017. Stan: A probabilistic programming language. J. Stat. Softw. 76, 1–32. https://doi.org/10.18637/jss.v076.i01.

Cattuto, C., van den Broeck, W., Barrat, A., Colizza, V., Pinton, J.F., Vespignani, A., 2010. Dynamics of person-to-person interactions from distributed RFID sensor networks. PLoS One 5, e11596. https://doi.org/10.1371/journal.pone.0011596.

Charlton, G.L., Rutter, S.M., East, M., Sinclair, L.A., 2011. Effects of providing total mixed rations indoors and on pasture on the behavior of lactating dairy cattle and their preference to be indoors or on pasture. J. Dairy Sci. 94, 3875–3884. https://doi.org/10.3168/jds.2011-4172.

Chen, S., White, B.J., Sanderson, M.W., Amrine, D.E., Ilany, A., Lanzas, C., 2014. Highly dynamic animal contact network and implications on disease transmission. Sci. Rep. 4, 4472. https://doi.org/10.1038/srep04472.

Chopra, K., Hodges, H.R., Barker, Z.E., Vázquez Diosdado, J.A., Amory, J.R., Cameron, T. C., Croft, D.P., Bell, N.J., Codling, E.A., 2020. Proximity Interactions in a Permanently Housed Dairy Herd: Network Structure, Consistency, and Individual Differences. Front Vet. Sci. 7 https://doi.org/10.3389/fvets.2020.583715.

Clark, P.W., Ricketts, R.E., Krause, G.F., 1977. Effect on Milk Yield of Moving Cows from Group to Group. J. Dairy Sci. 60, 769–772. https://doi.org/10.3168/jds.S0022-0302(77)83933-7.

Collis, K.A., Kay, S.J., Grant, A.J., Quick, A.J., 1979. The effect on social organization and milk production of minor group alterations in dairy cattle. Appl. Anim. Ethol. 5, 103–111. https://doi.org/10.1016/0304-3762(79)90082-8.

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJournal, Complex Systems, Version 1.2.2.

Dimitrov, I., Djorbineva, M., Sotirov, L., Tanchev, S., 2005. Influence of fearfulness on lysozyme and complement concentrations in dairy sheep. Rev. Med Vet. (Toulouse) 156, 445–448.

Dohoo, I.R., Leslie, K.E., 1991. Evaluation of changes in somatic cell counts as indicators of new intramammary infections. Prev. Vet. Med 10, 225–237. https://doi.org/10.1016/0167-5877(91)90006-N.

Ellen, E.D., Bas Rodenburg, T., Albers, G.A.A., Elizabeth Bolhuis, J., Camerlink, I., Duijvesteijn, N., Knol, E.F., Muir, W.M., Peeters, K., Reimert, I., Sell-Kubiak, E., van Arendonk, J.A.M., Visscher, J., Bijma, P., 2014. The prospects of selection for social genetic effects to improve welfare and productivity in livestock. Front Genet 5, 377. https://doi.org/10.3389/fgene.2014.00377.

Erdös, P., Rényi, A., 1959. On random graphs. Publicationes Mathematicae 6, 290–297. https://doi.org/10.2307/1999405.

Farm Animal Welfare Council, 1979. FAWC Press Statement [WWW Document]. URL https://webarchive.nationalarchives.gov.uk/ukgwa/20110618120810/http:/www.fawc.org.uk/freedoms.htm Accessed on 10th June 2024.

Fielding, H.R., Silk, M.J., McKinley, T.J., Delahay, R.J., Wilson-Aggarwal, J.K., Gauvin, L., Ozella, L., Cattuto, C., McDonald, R.A., 2021. Spatial and temporal variation in proximity networks of commercial dairy cattle in Great Britain. Prev. Vet. Med 194, 105443. https://doi.org/10.1016/j.prevetmed.2021.105443.

Fukasawa, M., Tsukada, H., 2010. Relationship between milk cortisol concentration and the behavioral characteristics of postpartum cows introduced to a new group. Anim. Sci. J. 81, 612–617. https://doi.org/10.1111/j.1740-0929.2010.00770.x.

Gutmann, A.K., Špinka, M., Winckler, C., 2015. Long-term familiarity creates preferred social partners in dairy cows. Appl. Anim. Behav. Sci. 169, 1–8. https://doi.org/10.1016/j.applanim.2015.05.007.

Hand, K.J., Godkin, A., Kelton, D.F., 2012. Milk production and somatic cell counts: A cow-level analysis. J. Dairy Sci. 95, 1358–1362. https://doi.org/10.3168/jds.2011-4927.

Harrell, F., 2001. Regression Modeling Strategies. Springer-Verlag, New York. https://doi.org/10.1007/978-1-4757-3462-1.

Hasegawa, N., Nishiwaki, A., Sugawara, K., Iwao, I., 1997. The effects of social exchange between two groups of lactating primiparous heifers on milk production, dominance order, behavior and adrenocortical response. Appl. Anim. Behav. Sci. 51, 15–27. https://doi.org/10.1016/S0168-1591(96)01082-9.

Hyun, Y., Ellis, M., Johnson, R.W., 1998. Effects of Feeder Type, Space Allowance, and Mixing on the Growth Performance and Feed Intake Pattern of Growing Pigs. J. Anim. Sci. 76, 2771–2778. https://doi.org/10.2527/1998.76112771x.

Jezierski, T.A., Podluzny, M., 1984. A quantitative analysis of social behaviour of different crossbreds of dairy cattle kept in loose housing and its relationship to productivity. Appl. Anim. Behav. Sci. 13, 31–40.

Kay, S.J., Collis, K.A., Anderson, J.C., Grant, A.J., 1977. The effect of intergroup movement of dairy cows on bulk-milk somatic cell numbers. J. Dairy Res. 44, 589–593. https://doi.org/10.1017/S0022029900020549.

Krawczel, P.D., Klaiber, L.B., Butzler, R.E., Klaiber, L.M., Dann, H.M., Mooney, C.S., Grant, R.J., 2012. Short-term increases in stocking density affect the lying and social behavior, but not the productivity, of lactating Holstein dairy cows. J. Dairy Sci. 95, 4298–4308. https://doi.org/10.3168/jds.2011-4687.

Laister, S., Stockinger, B., Regner, A.M., Zenger, K., Knierim, U., Winckler, C., 2011. Social licking in dairy cattle-Effects on heart rate in performers and receivers. Appl. Anim. Behav. Sci. 130, 81–90. https://doi.org/10.1016/j.applanim.2010.12.003.

Marina, H., Ren, K., Hansson, I., Fikse, F., Nielsen, P.P., Rönnegård, L., 2023. New insight into social relationships in dairy cows, and how time of birth, parity and relatedness affect spatial interactions later in life. J. Dairy Sci. https://doi.org/10.3168/jds.2023-23483.

Marumo, J.L., Fisher, D.N., Lusseau, D., Mackie, M., Speakman, J.R., Hambly, C., 2022. Social associations in lactating dairy cows housed in a robotic milking system. Appl. Anim. Behav. Sci. 249, 105589 https://doi.org/10.1016/j.applanim.2022.105589.

Mellor, D.J., 2015. Positive animal welfare states and encouraging environment-focused and animal-to-animal interactive behaviours. N. Z. Vet. J. 63, 9–16. https://doi.org/10.1080/00480169.2014.926800.

Mellor, D.J., Beausoleil, N.J., 2015. Extending the "Five Domains" model for animal welfare assessment to incorporate positive welfare states. Anim. Welf. 24, 241–253. https://doi.org/10.7120/09627286.24.3.241.

Miranda-de la Lama, G.C., Mattiello, S., 2010. The importance of social behaviour for goat welfare in livestock farming. Small Rumin. Res. 90, 1–10. https://doi.org/10.1016/j.smallrumres.2010.01.006.

Ozella, L., Giacobini, M., Diaz, E.V., Schiavone, A., Forte, C., 2023. A Comparative Study of Social Behavior in Primiparous and Multiparous Dairy Cows During Automatic Milking. Appl. Anim. Behav. Sci. 268, 106065 https://doi.org/10.1016/j.applanim.2023.106065.

Phillips, C.J.C., Rind, M.I., 2002. The effects of social dominance on the production and behavior of grazing dairy cows offered forage supplements. J. Dairy Sci. 85, 51–59. https://doi.org/10.3168/jds.S0022-0302(02)74052-6.

Pinheiro Machado, T.M., Machado Filho, L.C.P., Daros, R.R., Pinheiro Machado, G.T.B., Hötzel, M.J., 2020. Licking and agonistic interactions in grazing dairy cows as indicators of preferential companies. Appl. Anim. Behav. Sci. 227, 104994 https://doi.org/10.1016/j.applanim.2020.104994.

Proudfoot, K., Habing, G., 2015. Social stress as a cause of diseases in farm animals: Current knowledge and future directions. Vet. J. 206, 15–21. https://doi.org/10.1016/j.tvjl.2015.05.024.

Proudfoot, K.L., Weary, D.M., von Keyserlingk, M.A.G., 2012. Linking the social environment to illness in farm animals. Appl. Anim. Behav. Sci. 138, 203–215. https://doi.org/10.1016/j.applanim.2012.02.008.

Pryce, J., Veerkamp, R.F., 2001. The incorporation of fertility indices in genetic improvement programmes. : Fertil. High. Prod. Dairy Cow. BNAS Occas. Publ. BNAS 237–250. https://doi.org/10.1017/S0263967X00033711.

R Core Team Version 3.5.3, 2019a. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

R Core Team Version 3.5.3, 2019b. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rault, J.L., 2012. Friends with benefits: Social support and its relevance for farm animal welfare. Appl. Anim. Behav. Sci. 136, 1–14. https://doi.org/10.1016/j.applanim.2011.10.002.

Reinhardt, V., Reinhardt, A., 1975. Dynamics of Social Hierarchy in a Dairy Herd. Z. Tierpsychol. 38, 315–323. https://doi.org/10.1111/j.1439-0310.1975.tb02007.x.

Sart, S., Bencini, R., Blache, D., Martin, G., 2004. Calm Ewes Produce Milk With More Protein Than Nervous Ewes. Animal Production in Australia 25, 307.

Sato, S., 1984. Social licking pattern and its relationships to social dominance and live weight gain in weaned calves. Appl. Anim. Behav. Sci. 12, 25–32. https://doi.org/10.1016/0168-1591(84)90093-5.

Sato, S., Tarmuizu, K., Sonoda, T., 1991. Social, behavioural and physiological functions of allo-grooming in cattle, in: Applied Animal Behaviour: Past, Present and Future. Proceedings of the international congress Edinburgh, pp. 77–78.

Sevi, A., Taibi, L., Albenzio, M., Muscio, A., Dell'Aquila, S., Napolitano, F., 2001. Behavioral, adrenal, immune, and productive responses of lactating ewes to regrouping and relocation. J. Anim. Sci. 79, 1457–1465. https://doi.org/10.2527/2001.7961457x.

Shultz, S., Dunbar, R., 2010. Bondedness and sociality. Behaviour 147, 775–803. https://doi.org/10.1163/000579510x501151.

Silva, P.R.B., Moraes, J.G.N., Mendonça, L.G.D., Scanavez, A.A., Nakagawa, G., Fetrow, J., Endres, M.I., Chebel, R.C., 2013. Effects of weekly regrouping of prepartum dairy cows on metabolic, health, reproductive, and productive parameters. J. Dairy Sci. 96, 4436–4446. https://doi.org/10.3168/jds.2012-6464.

Sowerby, M., Polan, C., 1978a. Milk Production Response to Shifting Cows Between Intraherd Groups. J. Dairy Sci. 61, 455–460. https://doi.org/10.3168/jds.S0022-0302(78)83620-0.

Sowerby, M., Polan, C., 1978b. Milk Production Response to Shifting Cows Between Intraherd Groups. J. Dairy Sci. 61, 455–460. https://doi.org/10.3168/jds.S0022-0302(78)83620-0.

Takeda, K., Sato, S., Kazuo, S., 2000. The number of farm mates influences social and maintenance behaviours of Japanese Black cows in a communal pasture. Appl. Anim. Behav. Sci. 67, 181–192. https://doi.org/10.1016/S0168-1591(99)00124-0.

Takeda, K.I., Sato, S., Sugawara, K., 2003. Familiarity and group size affect emotional stress in Japanese Black heifers. Appl. Anim. Behav. Sci. 82, 1–11. https://doi.org/10.1016/S0168-1591(03)00039-X.

Tresoldi, G., Weary, D.M., Filho, L.C.P.M., von Keyserlingk, M.A.G., 2015. Social licking in pregnant dairy heifers. Animals 5, 1169–1179. https://doi.org/10.3390/ani5040404.

Val-Laillet, D., Guesdon, V., von Keyserlingk, M.A.G., de Passillé, A.M., Rushen, J., 2009. Allogrooming in cattle: Relationships between social preferences, feeding displacements and social dominance. Appl. Anim. Behav. Sci. 116, 141–149. https://doi.org/10.1016/j.applanim.2008.08.005.

Vehtari, A., Gelman, A., Gabry, J., 2017. Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Stat. Comput. 27, 1413–1432. https://doi.org/10.1007/s11222-016-9696-4.

Vijayakumar, M., Park, J.H., Ki, K.S., Lim, D.H., Kim, S.B., Park, S.M., Jeong, H.Y., Park, B.Y., Kim, T.Il, 2017. The effect of lactation number, stage, length, and milking frequency on milk yield in Korean Holstein dairy cows using automatic milking system. Asian-Austral J. Anim. Sci. 30, 1093–1098. https://doi.org/10.5713/ajas.16.0882.

von Keyserlingk, M.A.G., Olenick, D., Weary, D.M., 2008. Acute Behavioral Effects of Regrouping Dairy Cows. J. Dairy Sci. 91, 1011–1016. https://doi.org/10.3168/jds.2007-0532.

Wood, M.T., 1977. Social grooming patterns in two herds of monozygotic twin dairy cows. Anim. Behav. 25, 635–642. https://doi.org/10.1016/0003-3472(77)90114-2.

Yagi, Y., Shiono, H., Chikayama, Y., Ohnuma, A., Nakamura, I., Yayou, K.I., 2004. Transport stress increases somatic cell counts in milk, and enhances the migration capacity of peripheral blood neutrophils of dairy cows. J. Vet. Med. Sci. 66, 381–387. https://doi.org/10.1292/jvms.66.381.

Zwald, A., Shaver, R., 2012. Effect of pen change on milk yield by dairy cows in 2 commercial herds. Prof. Anim. Sci. 28, 569–572.