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Multiple factors shape social contacts in dairy cows

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ABSTRACT

Cattle develop preferential relationships with other individuals in the herd. These social interactions between individuals have a significant impact on both animal welfare and production. Given the relevance of social behaviour in dairy cattle, scientific studies have focused on understanding social interactions among cattle. These may also be influenced by individual area preferences, particularly when animals are housed in confined spaces. Therefore, investigating the relationship between individual area preferences and social interactions is essential for understanding social behaviour in dairy cattle. Real-time location systems provide the opportunity to monitor individual area preferences and social contacts at the same time. This study aims to assess the impact of dairy cows' area preferences on their daily social contacts and to determine the potential implications of overlooking individual area preferences in social behaviour studies. The individual position of the lactating cows was automatically collected once per second for two months on a Swedish commercial farm housing dairy cows inside a free-stall barn. The location data of 243 lactating cows was used to construct the social networks and to estimate the similarity of the area utilisation distributions between these individuals. The effect of utilisation distribution similarity in social networks was investigated by applying separable temporal exponential random graph mixed models. The role of different cow characteristics in the similarity of the utilisation distributions was assessed through a linear mixed model. Our analyses stressed the importance of similarity of area preference, parity, kindergarten effect, and filial relatedness in shaping daily social contacts in dairy cattle. The kindergarten effect refers to the effect on cow behaviour of being grouped together in the early stages of their lives. Similarity of area preference was influenced by the kindergarten effect and relatedness by pedigree, which favoured interactions between these individuals. The described approach allowed to disassociate the area preference from the social contacts between cows, providing more accurate results of the importance of the cow's characteristics on their social behaviour.

1. Introduction

Cattle is a social species capable of developing preferential relationships with other individuals of the herd (Bouissou et al., 2001; Boyland et al., 2016). Affiliative social interactions reduce herd stress, thereby promoting animal welfare and health, while disturbances in social relationships between dairy cows could produce it, causing long-term effects on animal health (Bouissou et al., 2001; Boyland et al., 2016; Rocha et al., 2020). In addition, social behaviour is gaining recognition as a tool for the identification of sick animals (Weary et al., 2009). Animal sickness behaviour may include a decrease in general activity, food intake and social behaviour (Dantzer and Kelley, 2007). Given the importance of social behaviour in cattle, several scientific studies have focused on disentangling social interactions in dairy cattle through observational studies (e.g. Raussi et al., 2010; de Freslon et al., 2020; Pinheiro Machado et al., 2020). However, studies based on human

Abbreviations: Age_{cont}, contemporary age; DIM, days in milk; DIM_{cont}, contemporary DIM; REL, relationship matrix; RTLS, real-time locating systems; STERGM, separable temporal exponential random graph model; STERGMM, separable temporal exponential random graph mixed model; SNA, social network analysis; UD, utilisation distribution; UDsim, utilisation distribution similarity; VIF, variance inflation factors.

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visual observations were generally limited by the number of animals and the duration of the study. In this regard, real-time locating systems (**RTLS**) provide the opportunity to continuously monitor the position of individual cows and monitor their social contacts, overcoming the limitations of visual observational studies. Spatial proximity has been found to be positively correlated with affiliative interactions between dairy cows (Boyland et al., 2016). Accordingly, several studies have applied this technology to explore dyadic spatial interactions that occur in dairy farms (e.g. Chopra et al., 2020; Hansson et al., 2023; Vázquez-Diosdado et al., 2023). Hansson et al. (2023) described the effect of parity, lactation status, health status and barn area on the total number of social contacts in dairy cows. In addition, Marina et al. (2024) described the importance of different cow characteristics for the formation of social contacts and their persistence over time.

Spatial interactions may also be influenced by space utilisation preferences, particularly in the case of dairy cows, which are usually housed in free-stalls with limited space. Several factors may influence dairy cow area preferences, such as proximity to resources, stocking density or climatic conditions (e.g. temperature, relative humidity, and airflow) (Churakov et al., 2021; Seyfi, 2013). Churakov et al. (2021) described an age-related cubicle preference in dairy cows, which could favour the occurrence of spatial interactions between cows of similar age in the resting area. Hence, dairy cow area preferences may be partially involved in the results described in previous studies that identified preferential relationships among cows of similar age (Boyland et al., 2016; Marina et al., 2024). In addition, Marina et al. (2024) stressed a robust correlation between the total interaction time per cow and the amount of time they spent in different areas of the barn. This reinforces the idea that the time spent in certain areas increases the likelihood of establishing social contacts, supporting the rationale that animals' area preferences may shape their social interactions.

Position data from RTLS not only provides the possibility to continuously monitor spatial interactions but also to identify the area preferences of each individual in the herd. A recently described approach permits the estimation of the utilisation distribution of areas delimited by boundaries (Paterson, 2019). This approach, combined with social network analysis (**SNA**), which has been proposed as a useful method for understanding dyadic social interactions (Wey et al., 2008), could contribute to disentangling social relationships from spatial preferences in dairy cows. This article aims to determine the role of dairy cows' area preferences in shaping their daily social contacts by using RTLS information and to identify the potential implications for scientific studies based on this technology. The growing popularity of positioning systems to support farm management procedures has contributed to their increased use in scientific studies to understand the social behaviour of dairy cows, reinforcing the importance of integrating both approaches.

2. Materials and methods

2.1. Farm description

The present study was carried out on a Swedish commercial farm that houses around 210 dairy cows, in a non-insulated free-stall barn (Figure S1). The farm is divided into two management groups: early and late lactation. Lactating cows were routinely moved between groups at approximately 170 days in milk (**DIM**) upon confirmation of pregnancy or when destined for culling. Dry cows were housed in a separate building. Dairy cows were fed a total of 12 times a day ad libitum in an open bunk with a mixed ration. The cubicles in the resting area had rubber mattresses and sawdust as bedding material. Cows were milked twice a day in a milking parlour from GEA (2 × 12 GEA Euro class 800 with Dematron 75, GEA Farm Technologies, Bönen, Germany). Milking events occurred around 04:30 and 16:30 and lasted approximately 1.5 hours for each lactation group and event.

2.2. Position data

The position data of the lactating cows was automatically collected with a one-second fixed rate using a RTLS (CowView, GEA Farm Technologies, Bönen, Germany). Dairy cows were fitted with a tag attached to their collar, which transmitted ultra-wideband signals to anchors installed in the ceiling throughout the barn. Position data were recorded within the main barn area, including the feeding and resting areas (Figure S1). According to a previous study, the accuracy radius of this RTLS was 0.16 m for 95 % of the positions (Meunier et al., 2018). The accuracy of this system on this farm was evaluated by calculating the mean error distance for fixed performance tags, resulting in a mean error distance of 78 cm (Hansson et al., 2023). Positioning data were downloaded directly from GEA's server from 01 December 2020–31 January 2020; no RTLS outages were reported during this period. Data missing averaged 34.21 % (~8 h/d), with the most common scenario being a single second missing. Missing position information was interpolated using the Modified Akima Interpolation method (Akima, 1970; Ren et al., 2022), except for missing information at the beginning and end of a day, which was filled using the first posterior and anterior registered positions, respectively. The interpolation procedure was performed using MATLAB (MATLAB., 2020). Subsequently, R statistical software version 4.2.3 (R Core Team., 2023) was used for data pre-processing and statistical analyses.

2.3. Data collection

Individual cow information, regarding parity, calving date and tag-ID was provided by the farm whereas information about age and pedigree was extracted from the Swedish official milk recording scheme. Each cow included in this study was categorised to one of 3 parities (1, 2 or 3 +), and to one of 3 lactation stages; Early (<50 DIM), Mid (50 −179 DIM) or Late (≥180 DIM) lactation. A total of 243 lactating dairy cows with information on all characteristics were included in this study. The average age of the selected cows was approximately 4 years and ranged from 1 to 9 years. The pedigree information concerning the 243 cows comprised 9403 animals, with a pedigree completeness index of 0.75 and an average number of generations of 17.56. The pedigree completeness index represents the proportion of known ancestors in each ascending generation (Maccluer et al., 1983). The average number of generations was calculated as the mean of the maximum number of generations traced per individual. Among the lactating cows, there were 34 animals with a relationship coefficient over 0.5 and 108 animals with a relationship coefficient ranging between 0.25 and 0.50.

2.4. Estimating interactions using RTLS data

The position data were used to estimate the Euclidean distance between the tags attached to the collars of the 243 lactating cows included in this study. Meunier et al. (2018) reported an accuracy radius of 0.16 m for 95 % of the positions for this RTLS. The accuracy for this particular farm was estimated by computing the mean error distance for 13 fixed performance tags, reporting a mean error distance of 78 cm (Hansson et al., 2023). The amount of time each lactating cow spent with the rest of the herd was estimated per functional area using a tag radius threshold of 2.5 m (Hansson et al., 2023; Marina et al., 2024; Rocha et al., 2020). The rationale for this distance threshold is derived from the median cubicle width of 1.25 m in the resting area, where the maximum distance between two cows lying in consecutive cubicles would be approximately 2.5 m. Contact duration was aggregated independently for each functional area in the barn, feeding and resting (Figure S1). To exclude short contacts caused by the restricted space in the barn, we defined a cumulative time threshold of 600 s (10 min) per day to consider that a contact between lactating cows had occurred. Previous studies described no implications of varying the time and distance thresholds used in this study (Hansson et al., 2023; Marina et al., 2024). Contact matrices, known as adjacency matrices in graph theory terminology, were computed per functional area and day were coded in a binary format, with 1's indicating the occurrence of contacts and 0's indicating that no contacts longer than 10 min were reported during the day. Therefore, subsequent analyses did not investigate the total duration of social contact between cows, but the binary information from adjacency matrices summarising whether or not cows had social contact per day. Sociality in dairy cows can be described as a stable individual trait but dependent on the functional area (Rocha et al., 2020). Studying functional areas separately enables us to account for differences in social contacts between areas and the possibility of cows having different mates in different areas (Reinhardt and Reinhardt, 1981). Therefore, in this study, adjacency matrices were calculated separately for each functional area.

The density of the adjacency matrices was calculated as the total number of established social contacts divided by the total number of possible contacts. In this case, the occurrence of a social contact between two cows is represented in the social networks as an edge linking a specific pair of nodes. To assess the degree of similarity between the social networks constructed during the days included in the study, we estimated the pairwise Hamming distance independently by functional area. The Hamming distance is the sum of the simple differences between the adjacency matrices of two graphs (i.e. existing in one network and not the other, and vice versa) (Deza and Deza, 2014). This measure can be standardised by dividing it by the total number of possible edges in the networks, resulting in a measure that ranges between 0 and 1 and indicates the degree of dissimilarity between social networks.

2.5. Estimating utilisation distribution

The position information was also used to estimate the utilisation distribution (**UD**) of each dairy cow per day using the kernel-based utilisation distribution approach (Benhamou and Cornélis, 2010) implemented in the adehabitatHR package (Calenge, 2006). As the cows were housed in a free-stall barn, the external boundaries of both lactation groups were included in the analysis following Paterson (2019). Moreover, given that when a cow puts her head through the rails the tag could be outside the pen area, the boundaries were extended by 50 cm in all directions following Melzer et al. (2021). Having accounted for the boundaries, it is necessary to correct the overestimation bias of the unused area by setting the probability of quadrats outside the boundaries to zero and re-estimating quadrats inside the accessible area (Benhamou and Cornélis, 2010). The daily utilisation distributions will represent the area preference of the individuals during each day. The utilisation distribution similarity (**UDsim**) was obtained by estimating the pairwise Spearman correlation of the daily utilisation distribution between the dairy cows included in the study. In addition, to assess the degree of similarity between these daily UDsim matrices, which comprised the UDsim values between individuals, we computed the pairwise Pearson correlation of the UDsim matrices for each functional area, separately.

2.6. Statistical analysis

Social networks were visualized as sociograms using the igraph package (Csárdi and Nepusz, 2006). Marina et al. (2024) described how various cow characteristics differentially influenced the likelihood of formation and persistence of social contacts between dairy cows by applying the separable temporal exponential random graph model (**STERGM**) described by Krivitsky and Handcock (2010). STERGM models the probability of new contacts given no contacts on the previous day (referred to as formation) and the probability of contacts given existing contacts on the previous day (referred to as persistence). In the present study, we assessed how the consideration of UDsim influences the dynamics of social networks by applying a separable temporal exponential random graph mixed model (**STERGMM**), using our own R source code. The source code used is publicly available at github.com/CSI-DT/SNA.

The STERGMM was fitted as a mixed model separately for each functional area using the lme4 package (Bates et al., 2015). This approach consists of two different fitted logistic regressions for the formation and persistence part of the model. Social contact information, included as a response variable ($Y_{ij,t}$), was split into two subsets: one for formation ($y_{ij,t} = 0$), if there was no contact between nodes i and j at time t, and another for persistence ($y_{ij,t} = 1$), if there was contact between the nodes (Eq. 1).

$$\text{logitP}\left(Y_{ij,t+1} = 1 \middle| Y_{ij,t} = y_{ij,t}\right) = \mu + \beta_{x_{ij}} + \gamma_{x_{ij}} + \delta_{u_{ij}} + \omega_{a_{ij}} + \varepsilon \quad (1)$$

Therefore, the model was fitted twice, firstly for formation and secondly for persistence, in order to investigate how the effects included in the model independently influence the formation and persistence of network ties. Each model included an intercept term μ, and several node factor effects denoted by β, node match effects denoted by γ, edge covariates denoted by δ and random effects denoted by ω. The node factor and node match effects represent the combined information of the two individuals included in each pair, while the edge covariate represents a numerical value relative to the shared information of each pair. A more detailed description of the STERGM approach can be found in Marina et al. (2024). For instance, $\beta_{x_{ij}}$ was the node factor effect for the parity fixed effect, whose corresponding covariate value was equal to the number of cows of parity k (i.e., either 1, 2 or 3 +), connected to edge *ij*; while $\gamma_{x_{ij}}$ was the node match effect for parity, with corresponding covariate equal to 1, if the two cows i and j were the same parity, and 0 otherwise. The node factor and node match for lactation stage was defined similarly. Five additional variables were considered in the model as edge covariates (δ): contemporary age (**Age$_{\text{cont}}$**), contemporary DIM (**DIM$_{\text{cont}}$**), relationship matrix (**REL**), proportion of time spent in area and UDsim. The first two covariates, **Age$_{\text{cont}}$** and **DIM$_{\text{cont}}$**, represented pairs of cows born and calved within seven days, respectively, with a corresponding covariate equal to 1 if two cows were contemporary and 0 otherwise. These two covariates refer to the effect on cow behaviour of being grouped together during the early stages of life and during the last dried-off period, hereafter referred to as the kindergarten effect and the calving effect, respectively. Of the 31626 pairs of cows considered in this study, 158 and 1003 were born and calved within seven days, respectively. The relationship matrix (**REL**) was also fitted as an edge covariate, representing the additive relationship coefficient computed from the pedigree information. The proportion of time each animal spent in each functional area per day, hereafter referred to as time in area, was also included in the model to correct for the likelihood of establishing social contacts given the time spent in the area. Similarly, UDsim between dairy cows was fitted in the model to assess its effect on the formation and persistence of social contacts between individuals. Finally, the model included two random effects denoted by ω: date and edge, accounting for the total of days and cow pairs considered in this study. Both random effects were assumed to be normally distributed, (0, σ^2_{date}) and (0, σ^2_{edge}), where σ^2_{date} and σ^2_{edge} stand for the variance between dates and between edges, respectively. Recall that this procedure is fitted independently for formation and persistence part of the model, hence the variances of the distribution of the random effects (σ^2_{date} and σ^2_{edge}) were different for each model. Date and edge random effects were fitted in our model to adjust for variability between days and correct for overdispersion. The inclusion of the random effects could avoid the overestimation of the significance of the coefficients reported by the models. As the fitted STERGMM are two conditional logistic regressions, the estimated effects shall be interpreted as conditional log-odds ratios.

To assess the impact of including UDsim in the model results, we performed a supplementary analysis by re-running the model without

UDsim as a fixed effect, allowing us to assess its specific influence on the other factors considered in the model. To assess whether the inclusion of UDsim in the models provided the most parsimonious fit to the data, pairwise analyses of variance were performed for both the formation and persistence models in both functional areas. These analyses will indicate the importance of considering UDsim when studying social contacts in dairy cattle.

Variance inflation factors (**VIF**) were estimated to test for multicollinearity among the cow's characteristics considered in this study (parity, lactation stage, kindergarten and calving effect, relationship coefficient, UDsim and time in area) using the car package (Fox and Weisberg, 2018). VIF values were approximately 1, indicating no multicollinearity issues among the characteristics included in the model. Lactation group information was not considered as a fixed effect in the model due to collinearity issues with the lactation stage.

The effect of the different cow characteristics considered in this study on UDsim was estimated by applying a linear mixed model (Eq. 2) using the lme4 package (Bates et al., 2015).

$$Y_{ij,t} = \mu + \quad \beta_{x_{ij}} + \quad \gamma_{x_{ij}} + \quad \delta_{u_{ij}} + \quad \omega_{a_{ij}} + \varepsilon \tag{2}$$

where $Y_{ij,t}$ is the vector of UDsim for both the feeding and the resting area. Thus, this model was fitted separately for each functional area. The model includes the same information as described above (Eq. 1), except that UDsim is now included as the response variable. Briefly, the model included an intercept term μ, node factor and node match effects denoted by β and γ, respectively, edge covariates denoted by δ, and random effects by ω. Similarly, β and γ were the node factor and match effects for parity and lactation stage. Four further variables were fitted in the model as covariates (δ): the kindergarten effect (Age_{cont}), contemporary DIM (DIM_{cont}), relationship matrix (REL) and time in area. Likewise, the model included date and edge as random effects (ω), which were assumed to be normally distributed.

In addition, to confirm that the social contacts detected in this study were intentional and not the result of cows' strong area preferences, we performed an additional validation analysis. Only the first and last week of the two months were used in this analysis. The top 200 cow pairs with the highest number of interactions during this period were selected. The dates of the position data were randomly shuffled for one individual from each cow pair, hereafter referred to as the 'time-travelling' cow. This shuffled information was then used to estimate social contacts by calculating the Euclidean distance between one of the individuals remaining on the actual date and the other randomly 'time-travelling' to that date. Time travel social contacts were coded in a binary format, with 1's and 0's indicating the presence and absence of a contact, respectively, considering the 10 min threshold mentioned above. Subsequently, the correlation between the total duration of the observed and the time travel social contacts and the Hamming distance between the binary social contacts were estimated to compare these datasets. Similar reshuffling strategies have been applied to other species, such as broilers and bumblebees, to investigate spatial preferences further (Buijs et al., 2011; Jandt and Dornhaus, 2009). We hypothesise that if social contacts are the result of strict area preference, then these interactions will occur when combining position data from different dates, especially between pairs of cows that interact more frequently.

3. Results

The social networks analysed during the study period showed an average density of approximately 0.15 with a standard deviation of 0.01, both in the feeding and resting areas. The standardised pairwise Hamming distance between the daily social networks showed how different these networks were as the distance between days increased (Fig. 1). The average distance between all social networks was higher in the resting area (0.40) than in the feeding area (0.37), indicating that social networks vary more in the resting area. Sociograms illustrate the cumulative number of contacts between individuals over the study period considering both functional areas (Fig. 2). The sociograms distinctly illustrate the two lactation groups considered in this study connected by the cows that moved between groups during the two-month period analysed.

3.1. Social networks analyses

The following results reveal cows' preferences for establishing new contacts and for maintaining previous existing contacts, after correcting for cow area preferences in the model. Fig. 3 illustrates the individual coefficients interpreted as log-odds ratios estimated by STERGMM (Eq. 1). In the formation model, positive coefficients indicate a higher probability of contact formation in the network than expected by chance, whereas in the persistence model, positive coefficients indicate

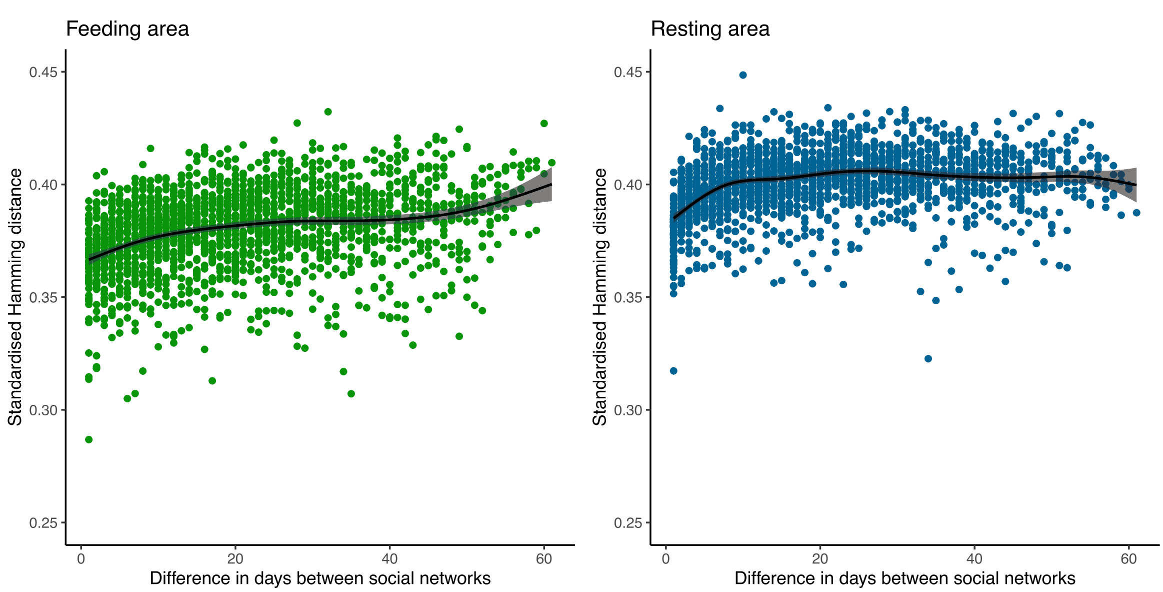

Fig. 1. Correlograms of the standardised Hamming distance results per functional area. The feeding and the resting area are shown in green and blue colour, respectively. Each plot includes a locally fitted polynomial regression curve (smoothed line), encapsulated by a shaded region representing the 95 % confidence interval.

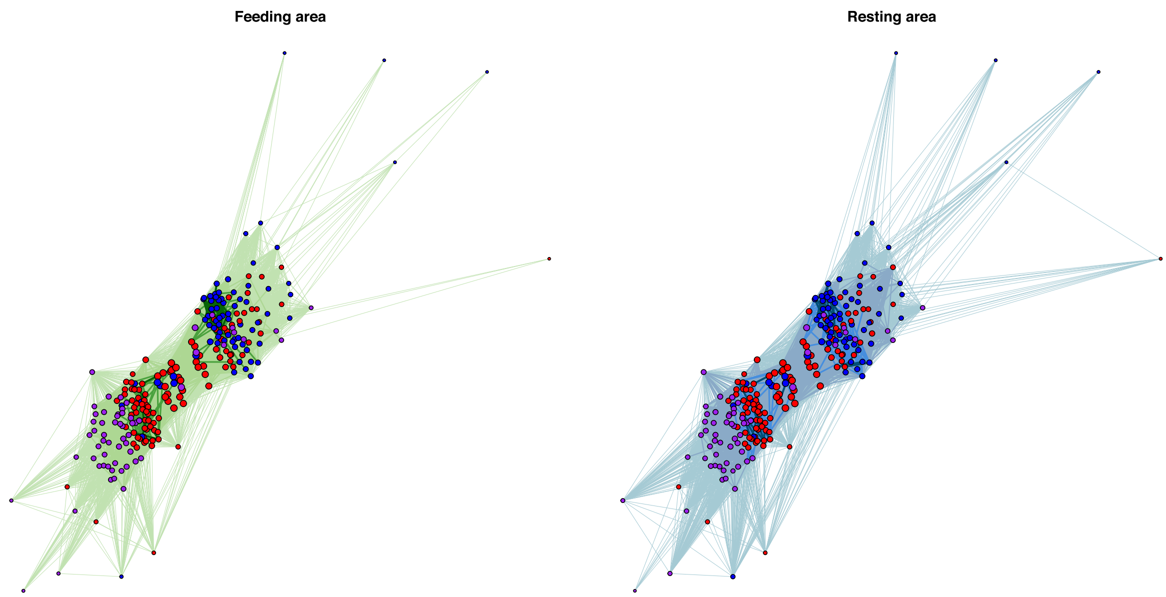

Fig. 2. Sociograms. The sociograms represent the social contacts observed in the feeding (green edges) and resting (blue edges) areas. Both networks were depicted using the same layout based on the force-directed layout algorithm described by Fruchterman and Reingold (1991). The thickness and darkness of the edges represent the cumulative number of social contacts over the days studied in the different functional areas. Only cumulative contacts over ten days are shown in this figure. The colours of the nodes represent the parity number: red (1), blue (2) and purple (3 +).

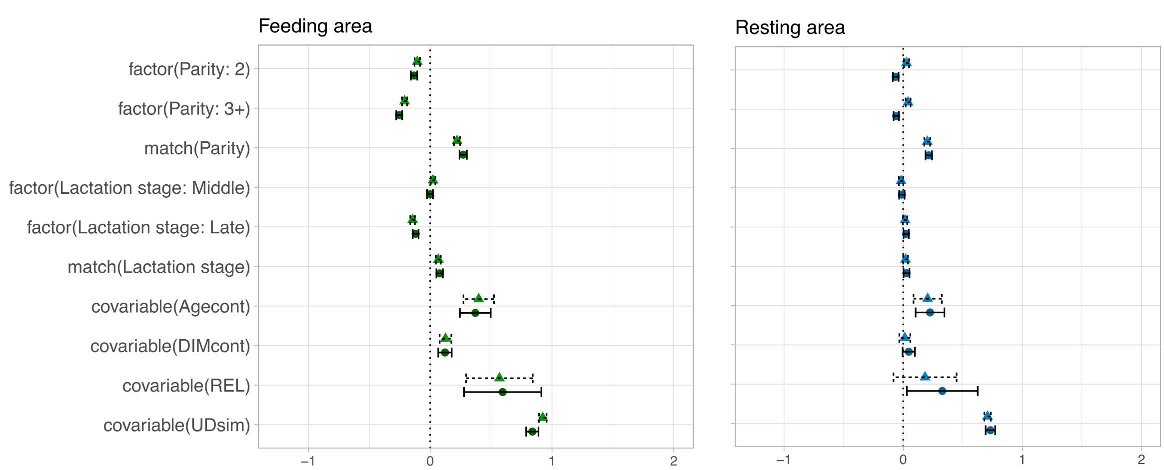

Fig. 3. Formation and persistence log-odds ratios estimated using separable temporal exponential random graph mixed model (STERGMM). Formation estimates are represented by light green and blue triangles for the feeding and resting areas, respectively. Persistence estimates are represented by dark green and blue circles for the feeding and resting areas, respectively. Error bars represent the 95 % confidence intervals of the estimates. The model included the following terms: i) *factor*: sum of the node values for all existing edges in the network; ii) *match*: number of edges in which the value between the nodes (*i*, *j*) is the equivalent; iii) *covariable*: value for each edge appearing in the network. Age_{cont} and DIM_{cont} represent pairs of animals born and calved within 7 days of each other. REL stands for the additive relationship coefficient calculated from the pedigree information, and UDsim is the utilisation distribution similarity.

a higher probability of contact persistence, and vice versa.

Estimates of the UDsim variable revealed the most significant and strongest effect of the fixed factors included in the model, influencing both the formation and persistence of social contacts across functional areas. The estimated coefficients ranged from 0.71 to 0.92 (P-values<0.001). Hence, animals whose utilisation distribution correlated on 0.50 had 52–75 % higher odds of either establishing a new contact or maintaining them, depending on the functional area.

The formation and persistence coefficients for parity match were positive in both functional areas, ranging from 0.20 to 0.27 (P-values<0.001). This consistent result across areas indicated that cows of the same parity were more likely to establish a social contact with each other, whether or not they had been in contact the day before (odds increased from 22 % to 31 %), compared to cows of different parities. Additionally, first parity cows showed greater contact formation and persistence odds in the feeding area compared to cows with a higher number of parities. Likewise, Age_{cont} showed a strong positive effect on the formation and persistence of social contacts in both functional areas. The estimated Age_{cont} coefficients ranged from 0.21 to 0.40 (P-values<0.001), with greater values in the feeding area. Hence, cows born within seven days of each other on the same farm were 23–49 % more likely to initiate a new contact or maintain an existing one, compared to cows born more than seven days apart or at different farms.

Closely related individuals showed an increased likelihood of social contact compared to distantly related individuals in the feeding area (P-values <0.001). Estimates of the REL effect in this area ranged from 0.57 to 0.60, suggesting that, for example, parent-offspring relationships were associated with 38–41 % higher odds of social contact compared to non-related animals. Estimates of REL for the resting area suggested a positive effect, although in general there were no significant differences

(P-values ranged from 0.03 to 0.17). Lactation stage match had a positive effect on contact formation and persistence in both functional areas (P values <0.001). Lactation stage match estimates ranged from 0.02 in the resting area to 0.07 in the feeding area, suggesting that cows in the same lactation stage were 2–7 % more likely to establish social contact with each other than with cows in different lactation stages. Similarly, DIM_{cont} showed a stronger positive effect on the feeding area, estimates were 0.12 approximately (P-values <0.001), compared to the resting area, where the results were not significant. Hence, cows calved within seven days of each other were 13 % more likely to initiate a new contact or maintain an existing one in the feeding area, regardless of their contact status the previous day, compared to cows calved more than seven days apart.

3.2. Area utilisation distribution

The Pearson correlations between the UDsim daily matrices showed that the UDsim decreased over time (Fig. 4). The correlation between feeding and resting areas showed a pronounced decline when the interval between days was less than 10, and a more progressive decrease when the interval between days exceeded this threshold. The average correlation between all UDsim daily matrices was higher in the feeding area (0.35) than in the resting area (0.27), indicating that the common area used by dairy cows is more constant in the feeding area.

Figure S2 illustrates the individual coefficients estimated by the STERGMM, disregarding the area preferences of the individuals. Fitting UDsim into the model resulted in decreased estimates for parity match, Age_{cont}, and REL in both functional areas. The parameter most affected was REL, with odds ratio differences ranging from 0.17 to 0.24. This translates to a 9–12 % increase in the likelihood of parent-offspring interactions compared to when UDsim was included in the model. The increase in REL estimates was more pronounced in the resting area than in the feeding area. The results for parity match and Age_{cont} were also affected by fitting UDsim into the model, although to a lesser extent. The pairwise analyses of variance comparing models including and excluding UDsim revealed that the incorporation of this variable significantly improved the fit of the model in both functional areas (P-value < 0.001).

To determine whether the cow characteristics considered in this study were related to the utilisation distribution similarity, we performed a linear mixed model with UDsim as the response variable. Figure S3 illustrates the estimates of fixed effects from this linear mixed model. The linear regression indicated a significant effect of REL and Age_{cont} on UDsim in both functional areas. This finding suggests that cows born within seven days of each other or related by pedigree tend to occupy similar areas in the barn. Moreover, the effect of REL was more pronounced in the resting area, which explains the reason behind REL being the parameter most affected by the inclusion of UDsim in the STERGMM approach (Figure S2).

3.3. Validation analysis

The top 200 cow pairs selected for the validation analyses had an average of more than eight social contacts during the first and last week of the whole period studied in each functional area. These 200 cow pairs comprised a total of 88 individuals. Out of the 200 pairs selected, 135 were composed of cows of the same parity. These individuals also exhibited moderately higher UDsim values compared to the population averages described above. Apart from that, these pairs did not show any major differences in other characteristics compared to the rest of the population. After the data was randomly shuffled, the number of social contacts between time-travelling cows was halved in both functional areas. The correlation between the total contacted time during the observed and the time travel social contacts was 0.10 in the feeding area and 0.13 in the resting area. In addition, the global Hamming distance between these datasets was 0.48 in the feeding area and 0.45 in the resting area. The time travel social contacts were analysed using the STERGMM approach, but due to the limited number of pairs, the model reports non-significant differences between the observed and simulated datasets.

4. Discussion

In this study, we investigated the role of area preferences in shaping daily social contacts between dairy cows using RTLS information. We approached this in two different ways, firstly by applying social network analysis accounting for the utilisation distribution in the models, and secondly by comparing social contacts between dairy cows in a validation study. Our results indicate that area preference may shape social contacts in dairy cows and that not accounting for it in the model may

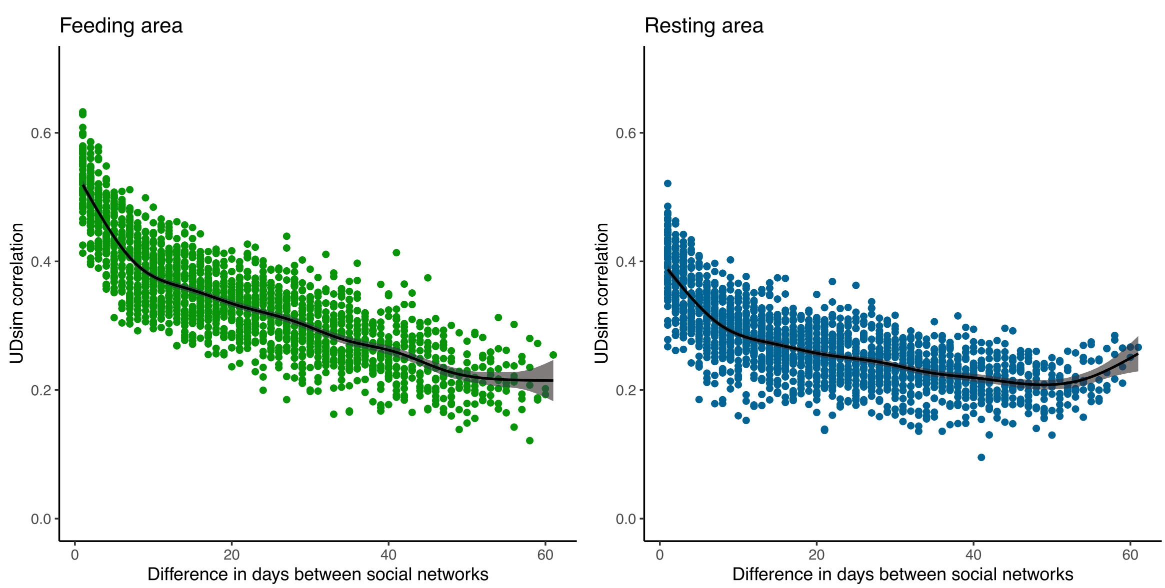

Fig. 4. Correlograms of the utilisation distribution similarity results per functional area. The feeding and the resting area are shown in green and blue colour, respectively. Each plot includes a locally fitted polynomial regression curve (smoothed line), encapsulated by a shaded region representing the 95 % confidence interval.

bias the results of social behaviour studies in dairy cows.

4.1. Factors influencing area preference in dairy cattle

Several studies have focused on the area preferences of dairy cattle, comparing indoor and outdoor systems due to their importance for animal welfare, production, and the development of efficient management strategies (Charlton et al., 2011; Falk et al., 2012). As indoor housing is a common practice in dairy cattle, previous studies focused specifically on investigating area preferences in free-stall barns (Churakov et al., 2021; Seyfi, 2013). Our results revealed a significant effect of contemporary age (Age_{cont}) and filial relationship on the similarity of area preference (here referred to as UDsim). These results were consistent with previous studies describing higher synchrony in area utilisation between cows that grew up together and higher contact duration and frequency between cows related by pedigree (Gygax et al., 2010; Marina et al., 2024; Swain and Bishop-Hurley, 2007).

The stability of the similarity of area preference and social networks was investigated by performing a daily basis pairwise comparison. The similarity of area preference revealed a higher similarity between consecutive days, followed by a rapid decline in correlation after the 10 days, whereas social networks showed a higher variability, reaching a plateau after 10 days. These findings indicate that social networks and area preferences change at different paces over time. While social networks are more dynamic and variable, there is some stability in the similarity of area preferences between consecutive days, suggesting that area preferences between individuals vary more slowly. In the present study, the similarity of area preference was analysed considering two functional areas. Further studies are needed to understand the basis of these similarities by considering additional functional areas.

4.2. Effect of area preference on social contacts

Despite the observed effect of area preference, to our knowledge, area preference information has not been integrated with social network studies focused on understanding social behaviour in dairy cattle. Previous studies have described how cow interactions were more likely to involve individuals with similar characteristics (Boyland et al., 2016; Marina et al., 2024). Marina et al. (2024) described a strong homophily effect of parity, kindergarten effect (also referred to as Age_{cont}) and filial relationship on the formation and persistence of social contacts between dairy cows. Although the present study confirmed the positive effect of those characteristics on the social behaviour of dairy cattle, we also described how omitting area preference from the model resulted in larger effect estimates. The similarity in area preference between dairy cows (UDsim) showed a strong positive effect on the formation and persistence of social contacts in both functional areas. The higher the similarity, the greater the likelihood of social contact between cows. Moreover, cows in the same parity, Age_{cont}, or related by pedigree were more likely to establish social contacts, even after the area preference effect was adjusted by the model.

Boyland et al. (2016) observed a positive correlation between spatial contacts of dairy cows and affiliative social interactions, whereas no correlation was observed between spatial contacts and agonistic interactions. Moreover, Ben-Meir et al. (2023) found that agonistic interactions were associated with short encounters (shorter than ~ 120 s), whereas affiliative interactions were associated with long encounters (longer than ~ 600 s). Hence, given the filters applied in this study, our results could be mainly based on affiliative social contacts between dairy cows. This would explain the observed results since cows in the same parity, that share life experiences (Age_{cont} and DIM_{cont}) or that are related by pedigree would be more likely to express affiliative interactions among themselves than with the rest of the herd.

The complexity of social contacts between dairy cattle, due to their variability across multiple days (Chen et al., 2014; Rocha et al., 2020), reinforces the importance of adopting specific approaches, such as the STERGMM, described in this work, to assess the effect of area preference on the social contacts in dairy cattle. Our approach allowed us to dissociate similarities in area preference from social contacts in cattle, stressing the importance of accounting for both when investigating social contacts in dairy cattle. Consequently, we can confidently recommend the use of this approach in future studies aimed at understanding social behaviour using RTLS information.

4.3. Validation analysis

The Hamming distances between the observed and the time-travelling social contacts indicate that, although the contacts detected by the positioning system and the contacts simulated by time travel differed, some of the social contacts still occurred in the latter scenario. This could be explained by the fact that the 200 cow pairs were composed of a high number of cows of the same parity and had moderately higher UDsim values compared to the population averages. The low correlation between the total time in contact comparing these scenarios indicates that the social contacts established in the simulated scenario occurred mainly by chance, as both cows utilised the same area at the same time on different days. The rationale behind the inclusion of the first and last week in the validation study was to avoid the use of consecutive days with high similarity in cow area preference. However, the use of specific areas after timed events in the farm management, such as specific parts of the feeding table or water troughs after milking, could facilitate the occurrence of these contacts, especially in free-stall barns where the space is limited. Similarly, the lack of social contact during a cow's time travel may be attributed to insufficient UDsim to facilitate spurious contacts.

These findings confirm that social contacts can be influenced by the genuine intention to interact and by the similarity in area preference in the barn. This validation analysis illustrates the importance of considering the similarity between the area preferences of the individuals as it can lead to the establishment of spurious social contacts even when comparing data from completely different dates. Further studies should explore this validation method to determine the impact of utilisation distribution on the establishment of spurious social contacts in dairy cattle.

5. Conclusions

The present study applied RTLS information to describe the association between area preference and the establishment of social contacts in dairy cows. Our method highlights the relevance of considering area preference when exploring social contacts between dairy cows. The approach described here allows to dissociate area preferences from social contacts between cows. Our analyses stress the importance of similarity of area preference, parity, contemporary age, and filial relatedness between individuals for daily social contacts in dairy cattle. The similarity of area preference was influenced by the kindergarten effect and sharing filial relatedness between cows, favouring the interaction between these individuals on a more constant basis. Future studies aimed at exploring social contacts in dairy cattle should consider individual area preferences to obtain more accurate results on the importance of cow characteristics on their social behaviour.

CRediT authorship contribution statement

H. Marina: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualizatio**P. Nielsen:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition. **W.F. Fikse:** Writing – review & editing, Supervision, Resources, Investigation, Data curation. **L. Rönnegård:** Writing – review & editing, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.2024.106366.

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