Journal of Agricultural Engineering

Journal of Agricultural Engineering 2026; LVII:1897
doi:10.4081/jae.2025.1897

Precision monitoring of dry dairy cows herd: effects of environmental conditions, grazing availability and social network behavior

Eliseo Roma,[1] Lorenzo Leso,[1] Santo Orlando,[1] Mariangela Vallone,[1] Matteo Barbari[2]

[1]Department of Agricultural, Food and Forest Sciences, University of Palermo; [2]Department of Agriculture, Food, Environment and Forestry, University of Florence, Italy

Abstract

Access to outdoor space for dry cows is strongly influenced by environmental conditions, feed availability, and social dynamics within the barn. Understanding the interplay among these factors can support precision herd management strategies aimed at enhancing cow welfare and health. This study aimed to assess how environmental conditions, grazing forage availability and social dynamics influence the behavior of a dairy cow herd, based on their entry and exit from outdoor spaces monitored using the new technologies. The experiment was conducted for 154 days on a commercial dairy farm located in Mantua (Italy) with 35 Holstein cows during the dry period. The availability of outdoor forage was monitored by mowing on several test plots, while meteorological conditions were monitored using a weather station. The cows were equipped with radio frequency identification (RFID) tags to record their free access to the pasture. Social interactions were monitored based on the temporal association of cow passages through the gate. To identify a leader-follower relationship, a k-means algorithm was applied to log the frequency of time intervals between successive passages. Correlation analysis results between the number of daily passes and rumination and feeding time revealed strong correlations, with R^2 values of 0.71*** and 0.65***, respectively. Temperature-humidity index (THI) was the most influential parameter, while RH, solar radiation and rainfall appeared to have less significant impact. However, wind speed during the day and humidity at night have the greatest negative influence. The dynamic social network analysis (SNA) showed that the 42% of passages were associated with a leader-follower relationship and three key findings were observed: i) the cow established preferential relationships with specific members of the herd independently of animal's status (heifer or dry), age, and number of calvings; ii) some individuals are more skilled at establishing connections, while others tend to be more solitary; iii) when a significant bond is lost, it is often replaced by another.

Key words: animal behavior; precision livestock farming; free-choice pasture access.

Correspondence: Santo Orlando, Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze 4, 90128 Palermo, Italy. E-mail: santo.orlando@unipa.it

Introduction

In indoor production systems, providing cows with free access to pasture is a solution that allows them to express their preferences and benefit from various advantages (Charlton and Rutter, 2017). Providing access to pasture to dry cows and heifers can produce several health benefits and allow cows to exhibit natural behaviors (Arnott *et al*., 2017; Hernandez-Mendo *et al*., 2007). Arnott *et al.* (2017) observed that cows in pasture-based systems had lower levels of disease, mortality and injury, as well as behavioral improvements such as reduced aggression and increased resting times.

On the other hand, lack of control over feed composition during the dry period may increase the risk of metabolic disorders (Daros *et al*., 2022; Lanza *et al*., 2025), while during lactation it may not provide sufficient nutrients, potentially leading to reduced milk production (Bargo *et al*., 2003). Furthermore, to ensure optimal welfare conditions in pasture-based systems, management of outdoor space and climatic conditions plays a key role (Arnott *et al*., 2017; Charlton and Rutter, 2017; Di Grigoli *et al*., 2022). Pasture-based outdoor systems can expose animals to stressful conditions due to climate.

Scientific knowledge about the effects of grazing exclusively for dry cows remains limited, as most studies on pasture access in indoor systems have focused on lactating cows. Furthermore, the influence of forage availability and climatic conditions on grazing choices remains poorly understood (Charlton *et al*., 2011).

Another critical factor that has been attracting significant attention in recent years concerns the presence or absence of certain individuals who can positively influence the herd's movements to the outside areas. Social network analyses allow the study of herd organization, structure and social relationships (Krause *et al*., 2009). This approach has been applied in previous studies to identify social associations between individuals based on consecutive entries into automatic milking systems (Fadul-Pacheco *et al*., 2021; Marumo *et al*., 2022) or into outdoor areas (Nogues *et al*. 2024). Nogues et al. (2024) developed a methodology based on classification algorithms to determine leader-follower relationships and study in depth the social dynamics of the herd.

According to the few studies available in the literature, it appears that the social network of cows is characterized by distinct groups in which preferential rather than clear dominance relationships are established (Gygax *et* al., 2010; Rocha *et al*., 2020). Furthermore, the individual personality of cows can play a key role (Borbala Foris *et al*., 2019; Krause *et al.,* 2010). For example, Rocha *et al*. (2020) observed that the introduction of new cows into a herd does not produce strong bonds with resident cows. Moreover, cows that establish bonds tend to maintain them, contributing to the stability of the social network and promoting its gradual expansion. Preferential associations between individuals are often based on shared experiences during breeding, the dry period or family ties (Foris *et al*., 2021; Gutmann *et al*., 2015; Reinhardt and Reinhardt, 1981).

The spread of precision livestock farming (PLF) seamlessly integrates with the use of wearable technologies such as collars for monitoring animal activity (Lovarelli *et al*., 2024). These devices enable real-time data collection on cow behavior and health, in indoor and outdoor spaces. Collars allow for the monitoring of parameters such as resting times, activity periods, feeding time and movements toward grazing areas, providing valuable insights to optimize the management of livestock welfare and productivity, even in systems that promote pasture access. Emerging livestock monitoring technologies provide extensive data on animal activity and health status. Beyond information on feed availability and climatic conditions, recent studies have underscored the relevance of social interactions. However, to date, no studies have clearly applied these technologies to investigate how such factors may influence the behavioral choices of individual dairy cows during the dry period. Current evidence highlights the need for a more comprehensive understanding of the role of environmental, nutritional, and social determinants in regulating access to outdoor areas. Accordingly, the objective of the present study was to evaluate the influence of environmental conditions, grazing forage availability, and social dynamics on the behavior of a dairy cow herd, monitored through patterns of entry to and exit from outdoor areas using advanced technological systems.

Materials and Methods

The experimentation was conducted for 154 days, between the 81st day of the year (DOY) and the 235th DOY (when the last experimental cow was removed from the pen), on a commercial dairy farm located in Mantua, northern Italy (45°10'11.3" N, 10°45'01.7" E).

Animals, housing and management

Over the study period, a total of 35 Holstein cows were enrolled in the study using staggered enrolment (i.e., new cows added weekly). All adult cows (approx. 135 cows) and pregnant heifers present at the experimental farm during the study period were eligible for enrolment. As the study focused on providing pasture access during the dry period only, the remaining animals in the herd were excluded from the experiment. Once enrolled, the animals remained in the experiment until calving. All animals involved in the experiment had previous experience on pasture.

During the experiment, cows were housed in a strawyard pen. Fresh straw was added daily and the bedded pack was renovated monthly. Cows in had *ad libitum* access to grass hay (through a head-locking feed barrier with >1 feeding space per cow) and were fed 2.5 kg/cow*day of a commercial pelleted concentrate for dry cows (DM basis: 22.0% CP, 8.9% crude fiber, 2.9% crude fat, and 8.0% ash; as declared by the producer Maber Srl, Volta Mantovana, Italy). The concentrate was manually distributed to all cows in both pens. During the whole experimental period, the cows were allowed to freely access an exercise pasture. The pasture was accessible to the cows through a 12.5 m long and 4 m wide concrete-paved walkway. To access pasture (and return inside the barn) the cows had to pass through a 1-m wide gate.

Pasture

The pasture was established in 2019 and consisted mainly of perennial ryegrass and white clover. Although this pasture was intended mainly to provide cows with a comfortable outdoor area (exercise pasture), basic pasture management practices were employed to maintain a healthy grass sward. The pasture area (0.75 ha) was divided into 2 grazing paddocks (A and B) using an electric fence. A fresh paddock was offered to the cows on average (±SD) every 24±8 d, based on grass height availability. Compressed grass height was measured weekly with a rising plate meter (Grasshopper, True North Technologies, Ireland) in at least 20 locations evenly spread across every paddock. During the course of the study, the average (±SD) compressed sward height was 8.63±3.76 cm.

Weather data

Weather conditions were continuously measured during the experimental period using a data logging weather station (HOBO RX3000, Onset Computer Co., Bourne, MA, USA) located at the experimental site, near the pasture. The station was equipped with a signal repeater (HOBOnet Repeater, Onset Computer Co.) to enable the measurement of indoor conditions. Specifically, the following parameters were monitored: temperature (temp, °C), solar radiation (SR, W m^{-2}), relative humidity (RH, %), rainfall (Rain mm), wetness (W, %), wind speed (WS, m/s), gust speed (GS, m/s), wind direction (WD, °), dew point (DP, °C); while the temperature-humidity index (THI) was calculated as (National Oceanic and Atmospheric Administration, 1976):

$$THI = (1.8T + 32)\,[(0.55 - 0.0055RH) \times (1.8T - 26)] \quad \text{(Eq. 1)}$$

Monitoring of passages, feeding and ruminating time

The passages were recorded using a concrete-paved walkway RFID antenna (capable of individually detecting cows within a 1 m radius) placed on the paved walkway. The RFID gate automatically recorded the cow's ID, date and time of each passage. Presence of each cow inside and/or outside the barn was verified through manual sampling in order to correctly clean the pasture access data. Since the gate used was not able to identify whether it was an exit or an entry, once the data were cleaned, passages were categorized based on each cow and on a daily basis.

The feeding and ruminating behavior of dairy cows were automatically recorded using the collar-based sensor system (AfiCollar, Kibbutz Afikim, Afimilk, Israel). The collar uses a 3D accelerometer positioned on the left side of the cow's neck, inside a waterproof casing. To maintain the position sensor, a weight is placed at the bottom of the collar. The total weight of the device (including all components) was 922.4 g. Before the experiment, all cows had already been habituated to the device, having worn it for at least 14 days prior to the start of the observations. The raw accelerometer data collected by the sensor were processed using the AfiFarm V5.5 software (Kibbutz Afikim). The system returned individual hourly rumination and feeding times. The functioning and reliability of this system have already been evaluated in a previous study (Leso *et al*., 2021).

Statistical analysis

The different data sources were initially processed with Microsoft Excel 2016 (Microsoft Co., Redmond, WA, USA; 2018) to prepare the datasets. Statistical analysis and data visualization were performed with R version 4.2.0. (https://cran.r-project.org/), while the social-network analysis was performed including the Gephi software (Bastian *et al*., 2009).

Mixed linear models were used to analyze the effect of weather conditions and feed availability on the number of cow passages and rumination. For each response variable, a mixed-effects model was fitted using maximum likelihood with the cow as the experimental unit. Cow ID was included in the models as a random effect, and an unstructured covariance structure was chosen for all models based on the Akaike criterion. Satterthwaite's approximation was used to calculate degrees of freedom. Normality and homogeneity of variance were assessed visually or using the Shapiro-Wilk and Levene tests, respectively. Least squares means were computed, and multiple comparisons were performed with the Tukey procedure. Differences were declared significant at $p<0.05$. Data are presented as least squares means ±SE unless otherwise specified.

The proximity of a cow to the gate could result in an improper passage signal. Therefore, repeated measurements of the same individual's passage were cleaned where the interval was quick (<60 s), removing all events and keeping only the last event. The dataset was also cleaned from human interferences, e.g. cleaning of the pen, moving of the cows, passage of vehicles, *etc.* The final dataset consisted of 3,695 passages. Environmental data for each event were associated by approximating the time to the closest available environmental data, which were recorded on a 5 min frequency. To differentiate whether the passages occurred during the evening or the day, all weather conditions were classified as Night or Morning according to the time of sunrise and sunset depending on the day and the farm location.

The study of leader-follower relationships was conducted through dynamic social network analysis (DSNA) to examine interactions among individuals over time, as the copresence of all cows was not consistent during the experimental period. Prior to conducting the SNA, the interval between each event, along with the IDs of the two cows involved, was calculated. To determine if cows were following each other, k-means algorithm were applied of the time interval frequency distribution setting two groups, following a similar method by Nogues *et al*. (2024). The intersection of the two curves identified the threshold interval to consider two cows as moving in association rather than independently. When two cows were recorded within this threshold, the first recorded cow was designated as the "leader" and the other as the "follower."

Next steps we associated all passages to create a single leader-follower matrices. This matrix was used to construct social networks where each node represents a cow, the connection thickness indicates the number of interactions, while the flow direction represents the leader to follower path. Unlike what is shown in other social networks, the individuals did not remain in the barn for the same period of time. Instead, the size of each node was not related to centrality (the number of interactions) but to the frequency of interactions, normalizing the total interactions by the days spent in the barn. Dynamic SNA was conducted by measuring key social relationship parameters: centrality, betweenness centrality, eigenvector centrality, cluster modularity, and eigenvector-based centrality. Three types of centrality were identified and used: total centrality (considering all interactions), leader-only, and follower-only centralities. Betweenness centrality was applied to identify individuals acting as "bridges" in the network, influencing information flow among groups. Eigenvector centrality assessed the influence of each individual by considering both direct connections and the importance of linked nodes, highlighting network leaders. Cluster modularity measured the network's division into distinct subgroups, facilitating the identification of internal communities. Eigenvector centrality was also calculated over time to detect variations in individual importance within social dynamics. This dynamic approach provided a detailed view of interactions and hierarchies, enabling the identification of key roles and association patterns within the observed population, and allowed insight into how connections among individuals evolved in response to temporal and environmental variables.

Results

The experiment aimed to investigate how environmental factors, food availability, and social relationships influence animal behavior, specifically access to outdoor areas. It was conducted on dairy cows during the dry period, which lasted an average of 56 days. The climatic conditions were characterized by an average temperature of 22.9°C and a THI of 69.9, gradually increasing as the season progressed.

Factors affecting preference to be inside or outside

From the experiment conducted it was possible to study how the exit of the animals depended on environmental factors, forage availability and also the social groups created. During the experiment, the cows exited an average of 24.4±18.4 times per day. The increase in the number of daily passages, can be attributed to a better welfare state of the animal as a clear increase in the rumination and feeding time of the cows was observed (Figure 1).

Correlation analysis between the number of daily passes and rumination and feeding time revealed strong correlations, with R^2 values of 0.71*** and 0.65***, respectively. A close relationship was also found between rumination time and feeding time, showing a correlation of R^2 0.86***, with no significant differences based on the animal's age or the length of the dry period. ANOVA analysis revealed a statistically significant difference in these two parameters at various levels of average grass height. These findings suggest that increased feed availability leads to higher feeding and rumination times, contributing to improved animal welfare. The effect of average grass height was found to vary between day and night: as average grass height increased, the number of passes decreased during the day ($p<0.05$), while it increased at night ($p<0.05$). The ANOVA analysis also revealed that the animal's status (heifer or dry), age, and number of calvings did not influence the number of passes to outdoor areas, although younger cows made more frequent exits. In general, the cows spent 1 h and 37 min in the outdoor paddock. However, this time was strongly influenced by several factors as: time of year, forage availability and by the cows' permanence. Throughout the trial, forage availability was associated with the conditions in the different paddocks. As shown in Figure 2, each time the paddock was changed, the improved quality of the fodder encouraged the animals to leave more frequently. The correlogram shown in Figure 3 illustrates that not all environmental parameters were able to influence the number of passes, rumination time, and feeding. The most influential parameter was the THI, followed by the mean temperature, while RH, solar radiation, wind speed, and rainfall appeared to have little significant impact. The factors with the greatest negative influence were wind speed during the day and humidity at night, respectively. THI showed higher correlation values with the number of passes during the evening than during the day. The greater tendency of cows to go outside during the evening compared to daytime, and the low impact of certain environmental factors such as rain, have also been observed in other studies (Charlton *et al*., 2011; Charlton and Rutter, 2017). During the day, THI was found to be most correlated with rumination time, indicating that cows prefer to ruminate during the day and go out during cooler hours with lower THI values (Legrand *et al*., 2009). From the two-way ANOVA analysis conducted using THI and mean grass height, it was found that the first factor (THI) did not have a significant impact, while grass height significantly influenced the number of passes (p<0.001). The interaction between the two factors was also significant (p<0.05).

Social network analysis

The effect of social relationships was examined to determine whether this factor also influences access to outdoor areas. By categorizing all passages, it was observed that 42% were associated with a leader-follower relationship. A strong relationship was therefore observed between social interactions within the barn and access to outdoor areas by the animals. The k-means algorithm applied to the frequency of log intervals between the passages of different cows identified two curves with a normal distribution intersecting at x = 3.39, corresponding to 30 seconds (*Figure S1*). This value was then used as a threshold to determine when the passage of first cow was associated with subsequent members in a leader-follower relationship.

The social structure of the herd was constructed based on the number of gate crossings between cows within the previously established threshold. However, the individual cows entered the barn at different times and remained there for a dry period ranging from 13 to 104 days. Consequently, not all cows were present in the same barn simultaneously (*Figure S2*). Nogues *et al*. (2024)

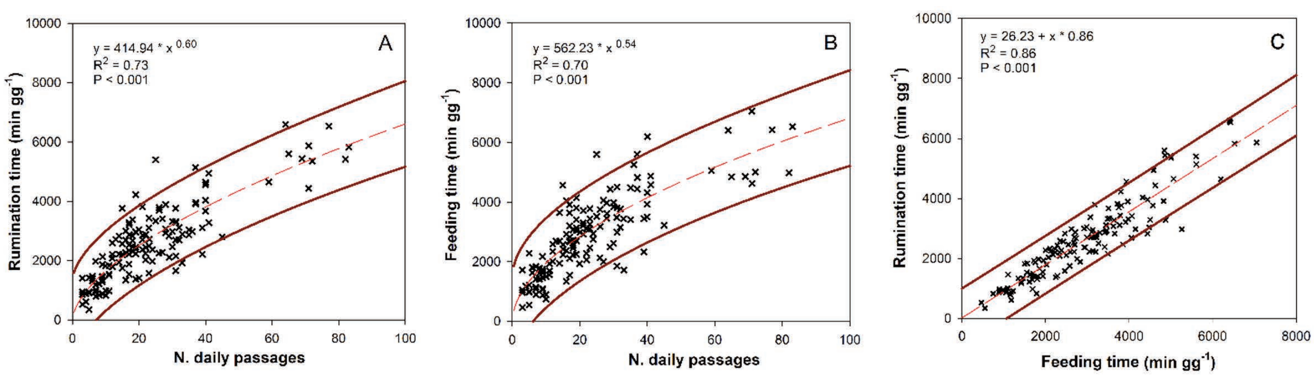


Figure 1. Statistical correlation between rumination time and number of passes (**A**), feeding time and number of passes (**B**), and rumination time and feeding time (**C**). The dark red curves indicate the 95% confidence limit, while the dashed red line indicates the regression curve.

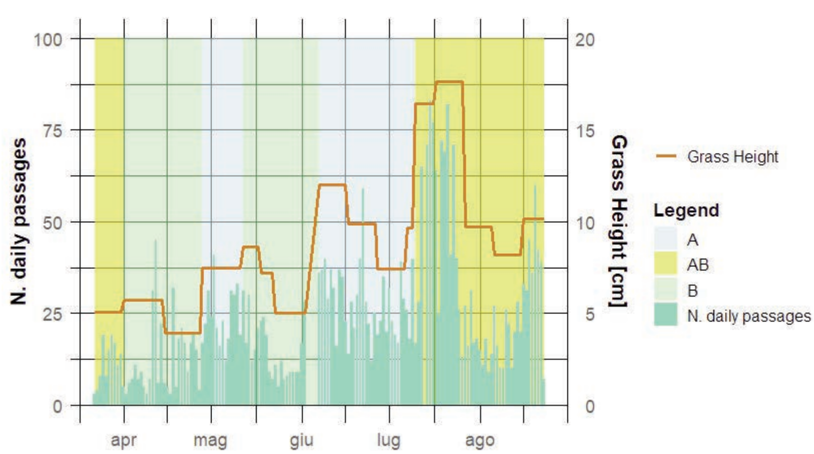


Figure 2. Grass height and number of daily passages made during the experiment. The background coloring indicates which paddock was available to the animals at various times.

OPEN ACCESS

studied social relationship using static approaches, but in our study, by adopting a dynamics approach over time, more precise information were obtained regarding the changes in leader-follower and group associations (Boyland *et al*., 2016).

The social dynamics within the herd varied depending on the presence or absence of other cows. No behavioral differences were identified based on cow age or other characteristics (heifer or dairy); moreover, since the cows are not family-linked to each other, it can be deduced that the links established are due to social dynamics. Overall, mutual relationships were predominantly observed (81.4%) where pairs of cows followed each other at least once; while only 19.6% were asymmetrical relationships, in which only one cow in the pair followed the other at least once. Only three cows did not show a relationship with other herd's animals.

The dynamic social network analysis (SNA) showed three key findings: i) the cow established preferential relationships with specific members of the herd rather than with the rest; ii) some individuals are more skilled at establishing connections, while others tend to be more solitary; iii) when a significant bond is lost, it is often replaced by another (Figure 4).

Modularity identified 4 different community groups within the whole herd by examining the temporal evolution of social relationships. Of these 4 groups, one group was associated with individuals that had no interaction with others.

The centrality of the various nodes depended on the number of total interactions they had; however, it was observed that the animals with the most interactions were also those that had a similar degree of centrality in (leader) and out (follower). This means that among the individuals who had the highest frequency of interaction, there was no real leader, but preferred groups of association in which the cows followed each other. Amongst the individuals that had higher leader and follower frequencies had low interaction frequencies. These results confirm that the cows has preferential relationships without clear-cut dominance links (Gygax *et al.,*

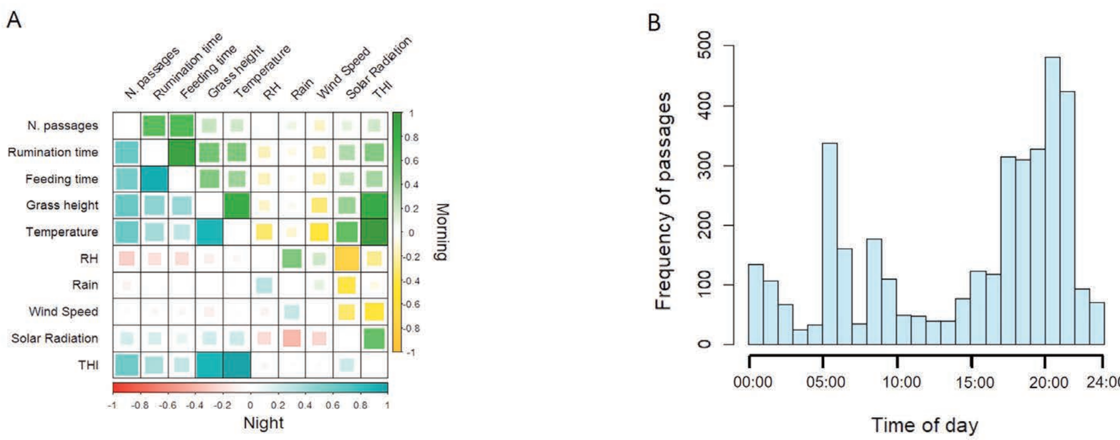
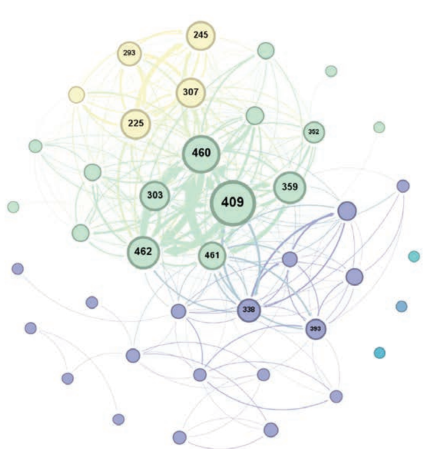


Figure 3. Correlation matrix between the main behavioral parameters of the animal (number of passes, rumination time and feeding), forage availability in outdoor areas (grass height) and weather conditions (temperature, RH, rain, wind speed, solar radiation and THI) (**A**). Frequency's histogram of passages observed during the experimental period (from 81st DOY to the 235th DOY) in the different time of the day (**B**).



https://youtu.be/kKULe3GRbhE

Figure 4. Social network of the experiment organized according to a dynamic Fruchterman-Reingold layout. Each node represents a cow and is characterized by a color indicating the social group (modularity), while the size indicates the overall interaction frequency (normalized total centrality unitless, based on the time spent in the barn). The numbers correspond to the identification codes assigned to the key experimental cows. The connections represent interactions between individuals, with thickness directly proportional to the number of interactions, while the direction indicates the connection from follower to leader. For more information reading the evolution of relationship over the time, scan the QRcode or use a link.

2010; Rocha *et al*., 2020). The highest betweenness centrality was observed in cows entering the barn that formed social bridges between groups with different modularity. These cows did not always have a high interaction frequency, but maintained a strong social network by establishing links with individuals who were not socially connected. The high variability of interaction of individuals in social behavior could be related to the individual personalities of cows (Foris *et al*., 2019; Krause *et al*., 2010).

The highest eigenvector centrality was observed for group 4, identifying it as a highly influential group within the social network as individuals in this group have many internal and direct connections with other network nodes.

Discussion

Experiments conducted during the dry period on dairy cows of different ages provided clear results of how weather conditions, food availability and social relationships within the herd influence free access to an outdoor area.

When given the opportunity, cows are naturally inclined to spend time in the pasture (Charlton and Rutter, 2017). Permitting dairy cows to graze outdoors is in fact considered a key factor in encouraging the expression of natural behavior and consequently increasing milk production in early lactation and the health condition (Leso *et al*., 2023). However, outdoor environmental conditions are always comfortable and it is important which factors can influence (Arnott *et al*., 2017; Charlton and Rutter, 2017; Di Grigoli *et al*., 2022). As also observed in other studies, pasture use varied considerably depending on the time of day (Charlton *et al*., 2011; Charlton and Rutter, 2017). The cows preferred to stay indoors during the day, while during the night the cows showed an almost exclusive preference for grazing and spent most of their resting time there. Some studies have observed a higher feeding time during the day than at night, whereas in our experiment, rumination and feeding time were correlated regardless of the time of day. It was also observed that THI is a stable parameter for evaluating outdoor environmental conditions and during the day, when THI was high, the cows spent more time indoors, probably to take advantage of the shade (Legrand *et al.*, 2009).

Experiments have shown that social interactions can play an essential role on the number of transitions to outdoor areas and consequently improve cow health. While previous studies have used variable ranges for the identification of leader-follower relationships (Sato, 1982), while the methodology proposed by Nogues *et al*. (2024) was found to be quite robust. Similar values (both less than 60 s) were obtained for the identification of leader-follower relationships. Compared to other studies analyzing social relationships in a static methodologies, while the dynamic analysis allowed for more precise information of changing social relationships within the herd, identifying how the different social roles played by individual cows may change (Boyland *et al*., 2016).

Detailed investigation of social networks has shown that the social network among cows is characterized by different groups in which preferential relationships are established and not by clear dominance links. (Gygax *et al*., 2010; Rocha *et al*., 2020). Our results are consistent with other social network analyses conducted on dairy cows, which show that mating is not random, but varies considerably in the degree of association (Boyland *et al*., 2016; Gygax *et al*., 2010). The high variability of interaction of individuals in social behavior could be related to the individual personalities of cows (Foris *et al*., 2019; Krause *et al*., 2010).

The SNA results are in line with other analyses of social networks in dairy cows, where animals have bonding preferences with other individuals (Boyland *et al*., 2016; Foris *et al*., 2019; Rocha *et al*., 2020). Rocha *et al*. (2020) observed that by introducing new cows into a herd, there is an absence of strong bonds between newcomers and resident cows and a weakening of bonds between resident cows. Our experimentation agrees with this result, however, it has also been observed that when strong bonds decay due to the exit of an animal, the remaining cow tends to establish a new bond within a short time. Moreover, the cows that establish bonds tend to preserve them, enhancing the stability of the social network while promoting its gradual expansion. As can be seen in the video associated with Figure 4, cow 338 is the socially central animal in the first part, establishing links with a larger number of individuals. When cow 338 leaves the barn, the links created with cows 409 and 461 allow them to assume new central roles within the social network. Studies have shown that preferential associations are established by cows with previous common experiences, either during rearing or during the dry period or family links (Foris *et al*., 2021; Gutmann *et al*., 2015; Reinhardt and Reinhardt, 1981). Unfortunately, past and future experiences were not observed in our study, so it was not possible to identify whether the observed preference relationships were the result of past events.

Conclusions

The results of this study highlight how environmental factors, forage availability, and social dynamics significantly influence cow behavior during the dry period, with direct implications for animal welfare management and access to outdoor areas. In particular, forage availability emerged as a key factor in influencing the number of passes cows make to outdoor areas, suggesting that optimal forage resource management can significantly improve animal welfare by increasing feeding and rumination times. The correlation between average grass height and the increase in passes during the evening, when climatic conditions are more comfortable, indicates the need to plan access to pasture areas based on environmental conditions, in order to optimize resource management. The analysis of environmental factors revealed that THI and average temperature are the most influential parameters on cow behavior, while factors such as solar radiation, wind speed, and precipitation had limited impact. These results suggest that monitoring climatic conditions, particularly THI, may be a useful tool for optimizing access to outdoor areas, especially in relation to the time of day. Finally, the role of social relationships within the herd showed that a significant portion of passes was associated with leadership dynamics and interactions between individuals, highlighting how social behavior influences access to outdoor areas. The social network analysis revealed the presence of preferential groups and individuals with higher centrality in interactions, suggesting that cows establish social links that influence their movement and access to the outdoor environment. These results provide useful insights for structuring spaces and social interactions in barns, with the goal of improving welfare and reducing stress while maintaining social cohesion within the group.

In summary, this study provides concrete guidelines for herd management, suggesting that integrating environmental, nutritional, and social factors into livestock management practices can enhance the quality of life for cows and optimize their productivity, thus contributing to a more sustainable approach to livestock management.

References

Arnott, G., Ferris, C., O'Connell, N. 2017. Welfare of dairy cows in continuously housed and pasture-based production systems. Animal 11:261-273.

Bargo, F., Muller, L.D., Kolver, E. S., Delahoy, J.E. 2003. Invited review: production and digestion of supplemented dairy cows on pasture. J. Dairy Sci. 86:1–42.

Bastian, M., Heymann, S., Jacomy, M. 2009. Gephi: an open source software for exploring and manipulating networks. Proc. Int. AAAI Conf. Weblogs Social Media 3:361-362.

Boyland, N.K., Mlynski, D.T., James, R., Brent, L.J., 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.

Charlton, G.L., Rutter, S.M. 2017. The behaviour of housed dairy cattle with and without pasture access: A review. Appl. Anim. Behav. Sci 192:2–9.

C 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.

Daros, R.R., Weary, D.M., von Keyserlingk, M.A.G. 2022. Invited review: Risk factors for transition period disease in intensive grazing and housed dairy cattle. J. Dairy Sci. 105:4734-4748.

Di Grigoli, A., Ponte, M., Bonanno, A., Maniaci, G., Alabiso, M. 202). Effects of grazing season on physico-chemical characteristics and fatty acids of nutritional interest of Caciocavallo Palermitano cheese. Animals 12:544.

Fadul-Pacheco, L., Liou, M., Reinemann, D.J., Cabrera, V.E. 2021. A preliminary investigation of social network analysis applied to dairy cow behavior in automatic milking system environments. Animals 11:1229.

Foris, B., Haas, H.-G., Langbein, J., Melzer, N. 2021. Familiarity influences social networks in dairy cows after regrouping. J. Dairy Sci. 104:3485–3494.

Foris, B., Zebunke, M., Langbein, J., Melzer, N. 2019. Comprehensive analysis of affiliative and agonistic social networks in lactating dairy cattle groups. Appl. Anim. Behav. Sci. 210:60–67.

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.

Gygax, L., Neisen, G., Wechsler, B. 2010. Socio-spatial relationships in dairy cows. Ethology 116: 10–23.

Hernandez-Mendo, O., Von Keyserlingk, M., Veira, D., Weary, D. 2007. Effects of pasture on lameness in dairy cows. J. Dairy Sci. 90:1209-1214.

Krause, J., James, R., Croft, D. 2010. Personality in the context of social networks. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365:4099-4106.

Lanza, M., Ponte, M., Pipi, M., Bonanno, A., Di Grigoli, A., Avondo, M., Tumino, S. 2025. Milk performance and grazing behaviour of Cinisara cows supplemented with low-and high-polyphenols faba bean varieties. Animals 15:335.

Legrand, A., Von Keyserlingk, M., Weary, D. 2009. Preference and usage of pasture versus free-stall housing by lactating dairy cattle. J. Dairy Sci. 92:3651-3658.

Leso, L., Becciolini, V., Rossi, G., Camiciottoli, S., Barbari, M. 2021. Validation of a commercial collar-based sensor for monitoring eating and ruminating behaviour of dairy cows. Animals (Basel) 11:2852.

Leso, L., Andrade, R.R., Bambi, G., Becciolini, V., Barbari, M. 2023. Free-choice pasture access for dry cows: Effects on health, behavior, and milk production. J. Dairy Sci. 106:7954–7964.

Lovarelli, D., Bovo, M., Giannone, C., Santolini, E., Tassinari, P., Guarino, M. 2024. Reducing life cycle environmental impacts of milk production through precision livestock farming. Sustain. Prod. Consum. 51:303–314.

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.

National Oceanic and Atmospheric Administration, 1976. Livestock hot weather stress. Regional Operations Manual Letter C-31–76. Kansas City, U.S .Dep. Commerce, Natl. Oceanic and Atmospheric, Weather Service Central Region.

Nogues, E., Weary, D.M., von Keyserlingk, M.A. 2024. Effect of social relationships on dairy cows' decision to move to and from an outdoor area. Appl. Anim. Behav. Sci. 272:106200.

Reinhardt, V., Reinhardt, A. 1981. Cohesive relationships in a cattle herd (Bos indicus). Behaviour 77:121-150.

Rocha, L.E., Terenius, O., Veissier, I., Meunier, B., Nielsen, P.P. 2020. Persistence of sociality in group dynamics of dairy cattle. Appl. Anim. Behav. Sci. 223:104921.

Sato, S. 1982. Leadership during actual grazing in a small herd of cattle. Appl. Anim. Ethol. 8:53-65.

Online Supplementary Material

Figure S1. K-means algorithm results.

Figure S2. Overlap of individual cows.

Received: 24 June 2025; Accepted: 10 October 2025.

Contributions: Eliseo Roma, Lorenzo Leso, Matteo Barbari: contribution to conceptualization and contribution to experiment software; Eliseo Roma, Lorenzo Leso, Santo Orlando, Mariangela Vallone, validation; Eliseo Roma, Lorenzo Leso, Santo Orlando, Mariangela Vallone, Matteo Barbari: data curation, writing - original draft preparation; Lorenzo Leso, Santo Orlando, writing- reviewing and editing, project administration, funding acquisition. All authors read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of interest: the author declares no known competitive economic interests or personal relationships that affect the work reported in this article.

Availability of data and materials: all data generated or analyzed during this study are included in this published article.