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Temporal stability of novel social network phenotypes in pigs from AI-assisted monitoring systems

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Introduction

Livestock species are typically housed in groups, where social interactions strongly influence productivity, welfare, and health (Wellock *et al.* 2003). Despite their importance, the integration of social behavior into breeding programs has been limited by insufficient data, labor-intensive, biased manual observations, and the lack of precise individual-level social phenotypes (Turner, 2010). In this context, social network analysis (SNA) has shown remarkable potential for quantifying group social structure and for providing individual-level phenotypes that describe each animal's role in social interactions (Farine *et al.* 2014). In pigs, SNA applied to manually extracted video-based data has shown that social centrality in aggression networks is associated with skin lesions (Foister *et al.* 2018). Moreover, studies have shown that individual SNA phenotypes, capturing individual centrality in aggressive interactions, are heritable and show favorable phenotypic and genetic correlations with economically important traits (Agha *et al.* 2020; 2022a; 2022b). However, manual video annotation is time-consuming and prone to observer bias.

Recently, automated monitoring systems incorporating advanced artificial intelligence (AI) technologies, such as deep learning (DL), have shown great potential for improving the efficiency of observing and detecting farm animals and their behaviors. Unlike traditional monitoring methods, AI approaches do not require manual feature extraction; instead, they largely rely on advanced learning models, e.g., convolutional neural networks (CNNs), to replace conventional image processing, achieving high accuracy across diverse farm conditions (Hollifield *et al.* 2024). Additionally, AI-assisted automated monitoring systems minimize observer bias and enhance data reliability, enabling more precise behavioral assessments.

In our previous study, we utilized data from AI-assisted automated monitoring systems relying on 2D video recordings of group-housed pigs (16–19 purebred animals per pen) at a PIC farm in the USA. The system captured each pig's position, posture (e.g., standing), and 2D XY coordinates. We further demonstrated that applying SNA to this AI-assisted monitoring data, based on proximity between animals, provides an efficient, real-time approach to identify SNA-derived phenotypes that quantify both direct and indirect roles of each individual and reveal novel insights into their social structures (Agha *et al.* 2025). Building on these results, the aim of this study was to assess the temporal stability of SNA-derived proximity phenotypes across developmental stages, a key step toward their integration into genomic prediction models.

Material & Methods

Data was collected using automated 2D camera systems of pigs at a PIC farm in the Midwest, USA (Figure 1). Video footage was processed using multi-object tracking and a customized DeepCut model for key-point detection and posture classification of individual pigs. The automated system integrates a tracking-by-detection approach using the Hungarian algorithm with a specialized ear tag reader to provide real-time pig identity and 2D XY coordinates. The system provides real-time data for ear tag IDs, elapsed time, positions, and postures for each pig. These automated data underwent extensive quality control to ensure accuracy and reliability (Hollifield *et al.* 2024; Agha *et al.* 2025).

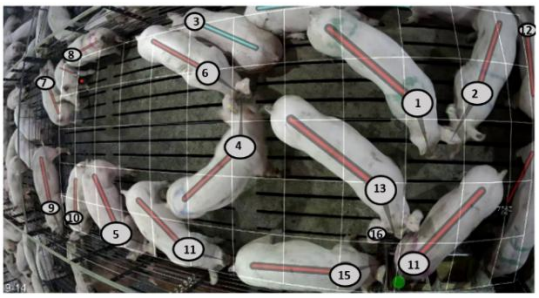

Figure 1. 2D camera image from the automated recording system showing ear tag, position, and posture (standing in red, sitting in blue) for each pig (Agha *et al.* 2025).

Social networks were constructed from the automated tracking data to describe contact patterns in the pens, using R packages including *spatsoc*, *asnipe*, *sna*, *vegan*, and *igraph*. Only "standing" pigs were included, capturing active social interactions in four pens, each containing 19 animals, across 30 consecutive days, over 12h/day (06:00–18:00) during the growing period. Interactions were defined by pigs being within 0.5 meters of each other's shoulders for longer than the daily average pen dyadic interaction time. The threshold of 0.5 meters was used to account for potential measurement errors in the XY coordinates (Agha *et al.* 2025) and is within the range of previously identified proximity distances between 0.3 and 1 meters defining interactions (Camerlink *et al.* 2022). Undirected weighted networks were constructed based on the duration of these proximity-based dyadic interactions, and individual SNA phenotypes were computed for each pig per day. Repeatability (Intra-class correlation coefficient, ICC) was estimated using linear mixed-effects models with individual pig as a random effect and day as a repeated measure to assess the proportion of variation attributable to differences between animals, indicating the temporal consistency of each SNA phenotype within pigs across days. Furthermore, to evaluate temporal stability, pigs were ranked daily for each trait and classified into the top 25%, middle 50%, and bottom 25%. Spearman's rank correlations between days were calculated to determine the consistency of social positions over time. Analyses were conducted in R (*version 4.3.2*) using *lme4* for mixed models.

Results

Table 1. Descriptive statistics for the individual SNA phenotypes of the four studied pens.

Trait	Degree centrality	Closeness centrality	Betweenness centrality	Eigenvector centrality	Clustering coefficient
Mean	0.45	0.04	0.03	0.55	0.67
SD	0.21	0.02	0.04	0.27	0.22
Max	0.94	0.12	0.37	1.00	1.00
Min	0.06	0.01	0.001	0.003	0.001

The descriptive statistics for the individual SNA phenotypes of the studied pens are shown in Table 1. Low to moderate, but significant repeatability for several SNA phenotypes was observed, with higher consistency for degree (ICC = 0.38 ± 0.06) and eigenvector centrality (ICC = 0.37 ± 0.06), and lower repeatability for betweenness (ICC = 0.14 ± 0.07) (Table 2). These results indicate that certain pigs consistently occupy central positions in the social network, reflecting stable social roles within the group over time.

Table 2. Mean repeatability (ICC) of pig social network phenotypes for the four studied pens.

Trait	Repeatability (ICC)	SE
Degree centrality	0.38***	0.06
Closeness centrality	0.01	0.01
Betweenness centrality	0.14***	0.07
Eigenvector centrality	0.37***	0.06
Clustering coefficient	0.03*	0.001

Furthermore, pigs were ranked by their average social network phenotype scores and classified into the top 25%, middle 50%, and bottom 25% for each trait, allowing assessment of temporal stability and comparison between highly and lowly connected individuals. Spearman's rank correlations between days showed moderate temporal stability for degree, betweenness, and eigenvector centrality ($\rho > 0.71$, $p < 0.01$), indicating that pigs at the top and bottom of the social hierarchy tended to maintain their relative positions over time. As illustrated in Figure 1, the two animals with the highest degree, highlighted in red, consistently occupied central positions in the network and appeared in the top 5 across most days (73% and 80% of the observation period), providing a concrete example of this temporal stability.

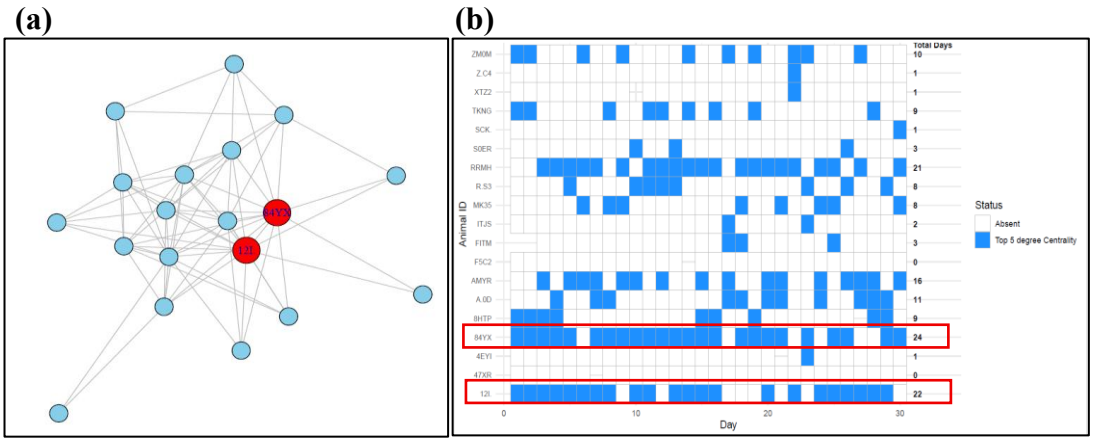

Figure 2. Temporal stability of social centrality in group-housed pigs; (a) Social network for a day with the top-degree centrality individuals highlighted in red. (b) Presence map showing the proportion of days each animal remained among the top five most central individuals. The top two animals, highlighted in red, ranked within the top five for 73% (22/30 days) and 80% (24/30 days) of the observation period, illustrating persistent social positions over time.

Discussion

AI-assisted automated monitoring systems provide continuous, high-resolution data on individual movement and behavioural activity, enabling precise phenotyping of animals. Previously, we demonstrated the feasibility of applying SNA to AI-assisted automated monitoring data to construct informative social networks that quantify the role of each animal in the social interaction (Agha *et al,* 2025). In the present study, automated tracking was employed to construct daily social networks, over 30 consecutive days, to assess the temporal stability of these novel SNA-derived phenotypes. The results of the repeatability analysis showed that certain pigs consistently occupy central positions in their social networks. Specifically, the top-degree individuals ranked among the top 5 most central animals for 73% and 80% of the observation period, respectively, illustrating persistence in social positions across time (Figure 2). Rank correlations between days further confirm moderate temporal stability for degree, betweenness, and eigenvector centrality ($\rho > 0.71$, $p < 0.01$), suggesting that highly connected and lowly connected individuals tend to maintain their relative positions within the group. These patterns indicate the presence of a stable social hierarchy, even in a system with relatively low to moderate overall repeatability. These stable social roles could reflect dominance, social influence, or affiliative tendencies, and can affect access to resources, performance, health, and welfare outcomes (Camerlink *et al.* 2022). Such patterns can be used to identify key individuals in the group to inform management strategies, e.g., group composition, resource allocation, and disease prevention, as well as smart breeding programs (Turner, 2010). The next step is to quantify the genetic and phenotypic associations between these stable SNA phenotypes and key performance and health traits, enabling their integration into genomic prediction models to improve breeding program efficiency.

Conclusion

This study demonstrates that AI-assisted monitoring combined with SNA can reliably identify individual social roles in group-housed pigs over time. Consistently central individuals exhibit stable social positions that influence group dynamics and access to resources. Integrating the stable SNA phenotypes into animal breeding and management strategies offers a promising approach to improve health, productivity, and welfare.

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