4-21-2021

Effects of farrowing stall layout and number of heat lamps on sow and piglet behavior

Suzanne M. Leonard
Iowa State University, smleonar@iastate.edu

Hongwei Xin
Iowa State University, hxin2@utk.edu

Tami M. Brown-Brandl
University of Nebraska - Lincoln, tami.brownbrandl@unl.edu

Brett C. Ramirez
Iowa State University, bramirez@iastate.edu

Anna K. Johnson
Iowa State University, johnsona@iastate.edu

See next page for additional authors

Authors
Suzanne M. Leonard, Hongwei Xin, Tami M. Brown-Brandl, Brett C. Ramirez, Anna K. Johnson, Somak Dutta, and Gary A. Rohrer

Applied Animal Behaviour Science 239 (2021) 105334

Contents lists available at ScienceDirect

Applied Animal Behaviour Science

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

Effects of farrowing stall layout and number of heat lamps on sow and piglet behavior

Suzanne M. Leonard [a], Hongwei Xin [a,b,*], Tami M. Brown-Brandl [c,*], Brett C. Ramirez [a,*], Anna K. Johnson [d], Somak Dutta [e], Gary A. Rohrer [f]

[a] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA
[b] UT AgResearch, University of Tennessee, Knoxville, TN 37996, USA
[c] Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
[d] Department of Animal Science, Iowa State University, Ames, IA 50011, USA
[e] Department of Statistics, Iowa State University, Ames, IA 50011, USA
[f] USDA, ARS. U.S. Meat Animal Research Center, Clay Center, NE 68933, USA

ARTICLE INFO

Keywords:
Creep
Drinking
Feeding
Location
Posture
Microclimate

ABSTRACT

Farrowing stalls are used in the United States swine industry to reduce pre-weaning piglet mortality, enable efficient individual animal management, and decrease facility construction and operating costs. The quantity and quality of space provided for sows and piglets in farrowing stalls are important economic and welfare considerations. To further explore the impacts of farrowing stall space allocation, a large-scale field study was conducted to compare sow and piglet behavior when housed in three farrowing stall layouts (TSL – traditional stall layout, ECSL – expanded creep area stall layout, ESCSL – expanded sow and creep area stall layout) with either one or two heat lamps (1HL and 2HL, respectively). A computer vision system classified posture budgets and behaviors of 322 sows and piglet location for 324 litters. Linear mixed models were developed to compare behavior and piglet pre-weaning mortality metrics between experimental treatments. Results show sows in ESCSL spent more time lying compared to sows in ECSL ($p = 0.028$) and less time sitting compared to sows in TSL and ECSL ($p < 0.01$). Sows with the 2HL treatment had an increase in percentage lying ($p = 0.017$) and a decrease in percentage standing ($p = 0.045$) compared to sows with the 1HL treatment. Number of piglets, parity, and batch also influenced sow postural behavior ($p < 0.05$). Sow lying orientation was not impacted by HL treatment. Sow postures and behaviors were influenced by day of lactation ($p < 0.001$). Piglets with 2HL treatment spent more time in the heated region and less time in the creep and sow regions for all stall layouts on all days of lactation observed ($p < 0.001$). In the ESCSL, piglets had a greater percentage of time in the sow region compared to ECSL piglets ($p < 0.004$). Piglets did not spend equal percentages of time between the two creep or two HL regions ($p < 0.001$), and piglet location was correlated with sow lying orientation for most of the creep regions analyzed ($p < 0.01$). Increases in piglet pre-weaning mortality were correlated with increases in sow lying ($p = 0.027$) and decreases in standing ($p = 0.025$) and feeding ($p < 0.001$). However, correlations with sow posture were likely due to the impacts of day of lactation ($p < 0.001$). No correlations were found between piglet location and pre-weaning mortality ($p > 0.05$). Results can guide producers to consider wider sow areas in farrowing stalls to better meet sow behavioral needs and to include larger heated areas to meet piglet behavioral needs during lactation.

1. Introduction

The primary motivator for confining sows in stalls during farrowing and lactation is to decrease the relative risk of piglet pre-weaning mortality (Glencorse et al., 2019; Moustsen et al., 2013). Additionally, farrowing stalls can benefit sows, piglets, and caretakers by enabling easier and safer personnel interventions during farrowing (Edwards, 2002). Traditionally, farrowing stalls contain a centrally located sow

* Corresponding authors.
E-mail addresses: smleonar@iastate.edu (S.M. Leonard), hxin2@utk.edu (H. Xin), tami.brownbrandl@unl.edu (T.M. Brown-Brandl), bramirez@iastate.edu (B.C. Ramirez), johnsona@iastate.edu (A.K. Johnson), somakd@iastate.edu (S. Dutta), gary.rohrer@usda.gov (G.A. Rohrer).

https://doi.org/10.1016/j.applanim.2021.105334
Received 5 August 2020; Received in revised form 12 April 2021; Accepted 14 April 2021
Available online 21 April 2021

crate (nominally dimensioned 0.61 [W] × 2.13 [L] × 1.00 [H] m) with piglet creep area (0.46 [W] × 2.13 [L]) on both sides of the sow crate. Farrowing stalls allow for greater animal densities compared to open pens, thereby making stalls more cost effective by reducing facility construction and operating costs. With slatted floors and restricted dunging areas, farrowing stalls can streamline waste management and create a more hygienic environment for sows and piglets (Muehling and Stanislaw, 1977).

While farrowing stalls provide efficiency benefits, it is also important to consider how sow crate dimensions may impact sow movements and behaviors. Traditionally sized sow crates restrict sow movements; namely, the sow cannot turn around. It has also been suggested that crates may reduce the ability of sows to roll between sternal to recumbent lying (Weary et al., 1996). The time duration for sows to transition from standing to lying increased in crates compared to open pens, and this increased time was strongly correlated with increased body length (Marchant and Broom, 1996). These results indicate that sows, and in particular long sows, experience difficulty when changing postures in crates. Deep bodied sows may also be restricted when lying, as typical sow crates cannot accommodate the physical dimensions of these sows during late gestation (McGlone et al., 2004). Restrictions on space and movement could have negative physical implications, for example, decubital ulcer development, commonly called “shoulder sores.” Decubital ulcers form from prolonged lying on hard surfaces and forceful impacts with stall bars (Herskin et al., 2011). Sows with low body condition scores are more likely to form decubital ulcers (Roija-Lang et al., 2018). Therefore, the impact of sow crate size may be more pronounced in thin sows.

Van Beirendonck et al. (2014) reported an association between the behavior of sows and their piglets when housed in farrowing stalls. The allocation of space in farrowing stalls may impact the quality and frequency of the interactions between sows and piglets. Singh et al. (2017) found more frequent interactions between sows and piglets around the time of nursing when housed in farrowing pens compared to farrowing stalls. Authors attributed the increased interactions to the piglets having greater accessibility to the sow due to the open, greater floor area of the pen (Singh et al., 2017). Greater accessibility provided by increased sow crate floor area could encourage sow and piglet interaction, but piglets spending more time near the sow also puts them in greater danger of being stepped or laid on. Additionally, Rutherford et al. (2013) have documented steadily increasing litter sizes. Holding farrowing stall dimensions constant, when the number of piglets per stall increases, piglet stocking density and the potential for piglets to be in the more dangerous sow crate area also increase.

In addition to the quantity of space provided in farrowing stalls for both sows and piglets, the environmental conditions are also important for promoting positive animal welfare. Specifically, the microclimates for sows and piglets differ greatly with piglets requiring air temperatures from 32 °C to 35 °C while sows prefer 19 °C (PIC North America, 2017). In order to achieve these thermal conditions, a supplemental heat source is used to maintain thermoneutral conditions for piglets. Further, radiative heat can encourage piglets to spend more time resting in a safe area of the stall that can result in reduced crushing and decreased issues related to hypothermia (Baxter and Edwards, 2017; Edwards, 2002; Marchant et al., 2000). While supplemental radiative heat can improve the farrowing thermal environmental quality for piglets, in the USA, the national pre-weaning mortality rate was 17.8 % in 2017 (Stalder and National Pork Board, 2017). It is hypothesized that the pre-weaning mortality rate could be reduced by optimizing the farrowing stall environment. One potential solution is to increase the net heated area with an additional radiative heat source. However, scant information is available to determine how piglets utilize both heat lamps and how these heat lamps may impact the sow.

Literature has suggested that heat lamps influence sow behavior. Hrupka et al. (1998) reported sows decreased feed intake when heat lamps mounted above a plywood floor covering were placed beside the sow crate versus in the front of the farrowing stall during lactation. This could indicate that the additional heat radiated to the sow induced heat stress, thereby repressing feed intake. Lao et al. (2016) reported that sows oriented their udders away from the heat lamp for the first three days after farrowing, indicating a sow postural modification related to thermal discomfort.

Few other studies have targeted farrowing stall dimensions in conjunction with number of heat lamps. This large-scale field study compared three experimental farrowing stall layouts (traditional, expanded creep area, expanded sow and creep area) and the use of one or two heat lamps on sow and piglet behavior. The specific objectives were to evaluate the effects of farrowing stall layout and number of heat lamps on: (1) sow lying, sitting, standing, and kneeling, (2) sow postural shifts, (3) sow feeding and drinking, (4) sow udder orientation when lying, and (5) piglet location within the farrowing stall. Results can be used to better understand the implications of space allocation and number of heat lamps on sow and piglet welfare, as well as to guide farrowing stall designs.

2. Materials and methods

2.1. Data collection

This study was conducted at the United States Department of Agriculture - Agricultural Research Service U.S. Meat Animal Research Center (USMARC) in Clay Center, Nebraska, USA. All animal husbandry protocols were performed in compliance with federal and institutional regulations regarding proper animal care practices and were approved by the USMARC Institutional Animal Care and Use Committee (2015–21). The swine unit at USMARC is a farrow to finish production site that follows typical USA industry practices. Approximately 1040 litters are farrowed annually. Sows are from a Yorkshire-Landrace rotational cross where breed of sire alternates each year between Yorkshire and Landrace boars from commercial sources. Parities represented range from first to fourth. Sows that fail to wean a litter, fail to rebreed, or become lame are culled, and all sows are culled after weaning their fourth litter.

At USMARC there were two farrowing units, each comprised of three farrowing rooms and a central corridor for air preconditioning. Each room contained twenty farrowing stalls and operated on a six-week cycle with sows arriving one week prior to farrowing, nursing for four weeks, and one-week downtime for cleaning. One group of all-in-all-out sows in a given room was referred to as a batch. One of the two farrowing units was utilized for data collection. The facility’s fluorescent lighting was automatically turned on at 05:30 and turned off at 19:00. For additional details on facilities and management practices refer to Leonard et al. (2020).

A Microsoft Kinect V2® (Microsoft, Redmond, WA, USA) was suspended 2.6 m above the floor and centered above each stall to capture image data. Once every 5 s, one digital and one depth image were captured and stored on external disk stations for later processing. Details regarding the image acquisition system can be found in Leonard et al. (2019). Images were collected for the entire farrowing cycle (32 d) for each batch. To streamline data analysis, a subset of these data was selected for analysis. That is, sow behavior was analyzed from three days prior to farrowing (day -3) to three days after farrowing (day 3) with farrowing designated as day 0, and subsequently, days 7, 14, and 21 of lactation. Piglet behavior was analyzed from days 0 to 3, as well as on days 7, 14, and 21. The days prior to farrowing were selected to establish sow baseline behavior prior to parturition. Days 0–3 were analyzed as more than half of pre-weaning piglet mortality occurs during this period (Hrupka et al., 1998). Days 7, 14, and 21 were selected to quantify sow and piglet behavior throughout the course of lactation. Piglets were weaned at 26.7 ± 1.9 d (average ± SD). Day of lactation was determined based on the farrowing date recorded by caretakers, as the exact farrowing time could not be determined for many litters due to dark nighttime images. The day of lactation for each sow was calculated based on that sow's farrowing date, rather than calendar date. Therefore, day 0 may not occur on the same calendar date for all sows in a batch. Each day of lactation was assumed to start at 00:00 and end at 23:59 for simplicity. Trained caretakers recorded parturition day, production performance, and mortality causes (Leonard et al., 2020). From the production data a binary variable of health status was created to distinguish sows that did or did not receive health interventions during the farrowing and lactation period. Data were collected from September 2017 to July 2018 on 19 batches of sows.

2.2. Experimental treatments

A thorough experimental design description can be found in Leonard et al. (2020). Briefly, the six experimental treatments consisted of three farrowing stall layouts tested in combination with one or two heat lamps (HLs; Fig. 1). Sow crate refers to the area that houses the sow, while farrowing stall refers to the collective unit of sow crate and adjoining piglet creep areas. The traditional farrowing stall layout (TSL) was based on common farrowing stall dimensions (Midwest Plan Service, 1983) and featured outer dimensions of 1.52 × 2.13 m with a centrally located 0.61 × 2.13 m sow crate. Expanded creep area stall layout (ECSL) provided additional creep area, with outer dimensions of 1.83 × 2.44 m and the same sow crate dimensions as the TSL. Expanded sow and creep area stall layout (ESCSL) had additional floor area allocated to the sow crate and creep areas compared to TSL, though the creep area in ESCSL was less than in ECSL. The ESCSL had outer dimensions of 1.83 × 2.44 m and sow crate dimensions of 0.71 × 2.13 m. In each stall layout, a stainless-steel bowl feeder was mounted in the front of the sow crate (Farrowing Sow Small Bowl Feeder, Hog Slat, Inc.; Newton Grove, NC, USA). Feeders had dimensions of (L × W × H) 0.35 × 0.34 × 0.39 m and protruded 0.23 m into the sow crate area. Water was provided *ad libitum* via sow and piglet nipple drinkers. Farrowing stall layouts were randomized by location within each room and remained constant for study duration.

Every farrowing stall featured a 175 W HL mounted 0.53 m above the creep area floor and centered front to back and left to right. A 0.30 × 1.22 m black rubber mat was placed below each HL and pre-experiment testing was conducted to evaluate the provided microenvironment and ensure that HLs did not impact adjacent farrowing stalls (Leonard et al., 2020). The experimental treatments with two HLs (2HL) had one HL suspended above the creep on both sides of the sow crate. Heat lamp treatments (1HL and 2HL) were randomized for each batch and balanced within room. Heat lamps were removed on day 21 of lactation. The HLs were operated by a room thermostat which turned them off when indoor dry-bulb air temperature exceeded 5.5 °C above room set point temperature.

2.3. Data processing

2.3.1. Sow postures and behavior

The percentage of time sows spent in each postural position (posture budgets) and sow behaviors were determined from depth images using a specialized algorithm developed in MATLAB (R2017a, The MathWorks, Inc., Natick, MA, USA; Leonard et al., 2019). In each image, the sow posture was classified as lying, sitting, standing, or kneeling. When sow posture classifications differed between two consecutive images, this indicated a posture shift. Each image was also classified with a behavioral attribute. If the sow was lying, the udder direction was used to determine lying orientation. Sitting, standing, and kneeling sows were assigned attributes of feeding behavior, drinking behavior, or other. However, it was not determined whether the behavior was completed. For example, a sow was classified with drinking behavior when her head was in the drinker area. The algorithm did not discern if direct contact was made with the drinker or if water was consumed. Classifications of feeding behavior included sows that were eating as well as sows with their heads over the feeder area.

The occurrence of each posture, behavior, and posture shifts were calculated as a percentage for each sow on each analyzed day of lactation. To do this, the number of images classified as each posture and behavior were counted and then divided by the total number of images taken that day to determine the percentage. For example, on day 1 for a given sow the number of images where the sow was standing was divided by the total number of images collected for that sow on day 1, then multiplied by 100 to determine the percentage standing for day 1.

The processing algorithm classified each sow posture with an accuracy >99.2 %, lying orientation with 96.2 % accuracy, and behavior attributes with >95.5 % accuracy (Leonard et al., 2019). Data outliers were classified based on a three standard deviation threshold limit, selected based on visual inspection of data distribution (see supplemental material). For each posture and behavior, on each day of lactation the average percentage ± three standard deviations was calculated as the daily threshold. The minimum and maximum of the daily threshold values were selected as the overall threshold for the posture/behavior and were applied to all days. When the threshold value exceeded the possible value range, the threshold was set at the maximum or minimum of the range. For lying the maximum threshold was set at 100 % while the minimum threshold for all other postures and behaviors was 0 %. Data days with less than 48.5 % lying, greater than 42.3 % standing, 17.4 % sitting, 4.6 % kneeling, 22.9 % feeding, or 7.4 %

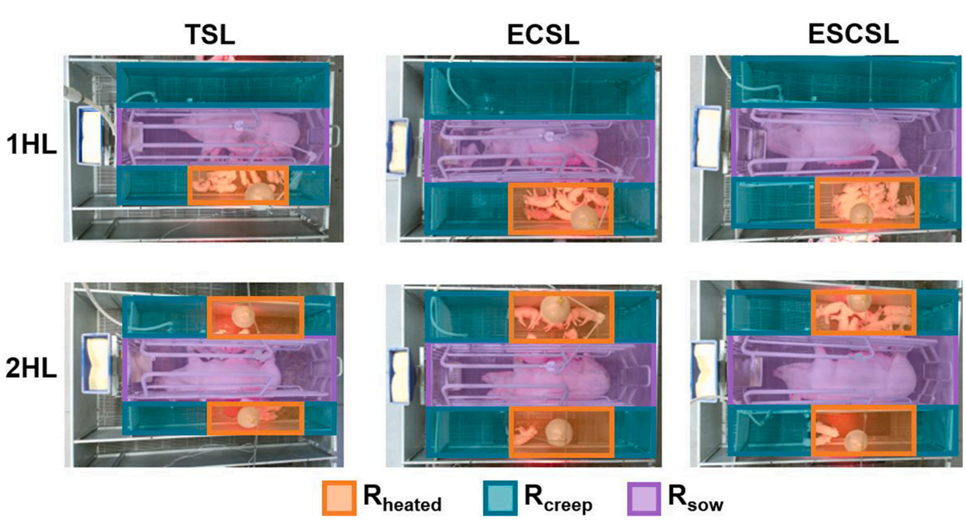

Fig. 1. A top-down view of regions used for piglet location analysis by treatment. Each farrowing stall was manually divided into three regions: R_{heated} under the heat lamp (HL), R_{creep} for all other creep areas, and R_{sow} for the sow crate area. In the one heat lamp (1HL) treatment, R_{creep} was divided into two sub-regions with $R_{creep\text{-}H}$ being on the same side of the sow crate as the HL and $R_{creep\text{-}U}$ being the opposite unheated creep (not labeled). For the two heat lamp (2HL) treatments, sub-regions were designated as being on the left side of the sow crate, $R_{creep\text{-}1}$ and $R_{heated\text{-}1}$, or the right side of the sow crate, $R_{creep\text{-}2}$ and $R_{heated\text{-}2}$ (not labeled). Farrowing stall layouts: TSL – traditional stall layout, ECSL – expanded creep area stall layout, ESCSL – expanded sow and creep area stall layout. 1HL – one heat lamp treatment, 2HL – two heat lamp treatment.

drinking were excluded as outliers. There were 4, 4, 8, 9, 6, and 11 data days that were outside the threshold values for each posture or behavior, respectively; however, some of these values coincided on the same data day, resulting in the removal of 32 data days from the data set.

2.3.2. Piglet location

While images were collected from 00:00 to 23:59 each day, visibility was greatly reduced during nighttime hours when the overhead lights in the facility were turned off. Therefore, only daytime images from 05:30 to 19:00 were analyzed for piglet location. Piglet location within the farrowing stall was determined from digital images with an algorithm developed in Python (v3.6.1, Python Software Foundation, Wilmington, DE, USA). First, the farrowing stall floor area was manually labeled as regions (R), depicted in the top-down view (Fig. 1). There were three primary regions of interest. Region 1: R_{heated}, was the piglet creep area directly under the HL. Region 2: R_{creep}, was the creep area not directly under the HL. Region 3: R_{sow}, was the remainder of the stall and encompassed the sow crate area. For 1HL treatments, R_{creep} was divided into two sub-regions. The regions of R_{creep} that were on the same side of the sow crate as the HL were designated as $R_{creep\text{-}H}$ while the opposing unheated creep side was labeled $R_{creep\text{-}U}$. In the 2HL treatments, sub-regions were created based on the side of the sow crate. The regions on the left side of the sow were labeled $R_{creep\text{-}1}$ and $R_{heated\text{-}1}$, while the regions on the right side of the sow were labeled $R_{creep\text{-}2}$ and $R_{heated\text{-}2}$.

Next, the number of piglets in each region in each image was determined by the algorithm. The algorithm was trained with machine learning to automatically identify piglets and their location. Based on predetermined characteristics, the algorithm would identify areas of the image that "looked" like a piglet and assign a confidence prediction to how well the characteristics of the area matched the known piglet characteristics. The confidence predictions were enhanced by referencing the location of piglets in the previous image. For a simplified example, if two areas were identified as potential piglets with the same confidence prediction, one in $R_{creep\text{-}1}$ and one in $R_{creep\text{-}2}$, but the piglet was counted in $R_{creep\text{-}1}$ in the previous image, it is more likely that the piglet would still be in $R_{creep\text{-}1}$. Therefore, the area in $R_{creep\text{-}1}$ in the current image would be assigned a greater confidence prediction. In this manner, the program ranked all potential piglet areas. In order for the algorithm to know how many potential piglet areas were actually piglets, the number of expected piglets was input into the algorithm. The appropriate number of highest ranking potential piglet areas were then selected as piglet locations. Since the dates of piglet mortalities were known but not exact times, the number of expected piglets was the number of live piglets in each litter at the end of each workday (15:00). Utilization of the number of expected piglets compensated for scenarios when individual piglets were partially or fully obscured from the Kinect V2® line of sight when under the sow, HLs, or closely piled with other piglets.

On each day of the lactation cycle, the cumulative piglet counts in each region were summed and divided by the total number of images and number of piglets to determine the percentage of the day the piglets spent in each region (Eq. 1).

$$R_i = \frac{\sum_{j=1}^{N_{images}} N_{i,j}}{N_{images} \times N_{piglets}} \times 100 \tag{1}$$

Where R represented percentage of piglets, i represented a particular region, j was the individual image number, and N_i was the number of piglets counted in region i by the algorithm. N_{images} was the total number of images that were observed and $N_{piglets}$ was the total number of piglets in each image (i.e., litter size). Data outliers were determined based on a three standard deviation threshold limit following the procedure described in Section 2.3.1. (see supplemental material). The minimum threshold values for R_{creep} and R_{sow} were 0%, while the maximum threshold for R_{heated} was 100 %. Data days with less than 13.5 % R_{heated} or greater than 47.6 % R_{sow} or 72.0 % R_{creep} were discarded as outliers based on the threshold values. There were 6, 10, and 9 data days outside the threshold limits for R_{heated}, R_{sow}, and R_{creep}, respectively. The threshold values resulted in the removal of 20 data days as some of these values occurred on the same data day.

Algorithm results were compared to manual human observations on a data subset to determine location program accuracy. Human observers were first trained by an expert observer on a set of training images. The training images were 50 randomly selected daytime images from a randomly selected sow (ESCSL, 1HL, 11 piglets, day 7). Each of the eleven human observers (four female, seven male) labeled the training images independently and their piglet counts were compared to that of the expert observer. The expert observer was selected based on familiarity with farrowing environments, piglet behavior, and goals of the piglet location algorithm, but was not the creator of the location algorithm. Human observers were required to achieve greater than 85 % accuracy on the training set when compared to the expert observer before labeling the accuracy analysis data set.

For the accuracy analysis data set, 20 sows were randomly selected. To ensure even representation, 10 of the sows were selected from each HL treatment and were also balanced by stall layout (TSL: 7 sows, ECSL: 6 sows, ESCSL: 7 sows). One lactation day from the desired days to be analyzed was randomly selected from each sow (day 1: 4 sows, day 2: 4 sows, day 3: 5 sows, day 7: 5 sows, day 14: 1 sow, day 21: 1 sow). On the selected day, 100 images were randomly selected during daytime hours. Three different human observers were randomly assigned to each sow set and independently identified the number of piglets in each region in each image. If at least two of the three observers agreed on the piglet distribution between regions for an image, the piglet distribution was accepted. If two of the three did not agree, the expert observer determined the piglet distribution.

As piglets were not individually identifiable by the human observers or the algorithm, a distance formula (Eq. 2) was used to determine algorithm accuracy.

$$Distance = \frac{\sum_{i=1}^{m} \left| N_{R_i,A} - N_{R_i,H} \right|}{N_{images} \times N_{piglets}} \times 100 \tag{2}$$

Where Distance (%) was the metric of successful identifications, R_i represented a particular region, m was the total number of regions to be compared, $N_{Ri,A}$ was the number of piglets counted in the region by the algorithm, and $N_{Ri,H}$ was the number of piglets counted in the region by the human observer. N_{images} was the number of images that were observed and $N_{piglets}$ was the number of piglets in each image (i.e., litter size). When evaluating the regions of R_{creep}, R_{heated}, and R_{sow} the average distance was 0.42 for 1HL treatment and 0.56 for 2HL treatments. When calculating accuracy for sub-region identifications, the algorithm distance values increased slightly to 0.58 for the 1HL treatment and 0.76 for the 2HL treatment.

2.4. Statistical analysis

2.4.1. Sow postures and behavior

Statistical analyses were conducted using R statistical software with lmerTest and emmeans packages (Kuznetsova et al., 2017; Lenth, 2019; R Core Team, 2019). Sow behavior was compared using linear mixed models. Any zero percentage values were replaced with half of the lowest non-zero value for that classification and then a logit transform was applied to the percentage of day in each postural position or behavioral attribute as individual responses. For each posture and behavioral classification category, the model contained factors for the HL treatment, farrowing stall layout, day of lactation, number of piglets in the stall, sow parity, batch, and sow health status. Parity was included as a categorical variable and health status as a binary variable. While number of piglets in each litter per day of lactation ranged from 1 to 20 (average = 11.0, median = 11.0), no differences were found due to this covariate when treated as individual levels or grouped. Therefore, all litter sizes were analyzed concurrently. Random effects were specified for stall location within the room and sow. Models incorporated all two-way and three-way interactions among HL treatment, farrowing stall layout, and day of lactation.

Lying orientation was evaluated using separate paired contrasts for each stall layout, HL treatment, and day combination. Percentage of time lying with udder facing HL (1HL treatment) or lying on left side of body (2HL treatment) were compared to sow baseline behavior on day -3 to evaluate HL treatment impact. Comparisons were made with baseline behavior to account for individual sow lying orientation preferences which would inhibit conclusions regarding causation of significance. The p-values from these paired contrasts were adjusted using Bonferroni's correction for multiple comparisons.

2.4.2. Piglet behavior

Logit transformations were performed to normalize the piglet behavior data as well, with any zero percentage values being replaced with half of the lowest non-zero value for that region category. Linear mixed models were developed with the percentage of day in the desired region as the response and the interaction of stall layout, HL treatment, and day of lactation as factors. Number of piglets in the stall, sow parity, batch, and sow health status were covariates. Parity was included as a categorical variable and health status as a binary variable. Stall location within room and sow were specified as random effects, and random effect of sire was nested within sow. Data values are presented as average ± SE.

In the 2HL treatment, percentage of time in sub-regions $R_{heated\text{-}1}$ and $R_{heated\text{-}2}$ were compared with contrasts. These contrasts were conducted with the null hypothesis that the difference between the percentage of day spent under $R_{heated\text{-}1}$ and $R_{heated\text{-}2}$ was equal to zero. Data were compared separately for each stall layout on each day of lactation. Percentages of time spent in the creep sub-regions for 2HL treatments, $R_{creep\text{-}1}$ and $R_{creep\text{-}2}$, were also compared with contrasts. Sub-regions for the 1HL treatments, $R_{creep\text{-}U}$ and $R_{creep\text{-}H}$, were compared in a similar manner. For all paired contrasts, the p-values were adjusted using Bonferroni's correction for multiple comparisons.

2.4.3. Mortality and behaviors

Linear mixed models were developed with the logit transformed mortality data as the response. Models were fitted with percentage of time in each posture or behavior for sows or the percentage for each region for piglets. Day of lactation was also included as a factor, with the number of piglets in the stall, sow parity and health status, and batch as covariates. Parity was included as a categorical variable and health status as a binary variable. Stall location within room and sow were specified as random effects. The same procedures were followed to develop linear models with the logit transformed piglet overlay data as the response.

2.4.4. Sow lying orientation and piglet location

The full data set was divided into two groups based on HL treatment. For 1HL treatment, the regions investigated were $R_{creep\text{-}U}$, $R_{creep\text{-}H}$, and R_{heated}. Linear models were developed with the logit transformed region data as the response and variables included were stall layout, day, and their interaction. Number of piglets in the stall, sow parity, batch, sow health status, and percentage of time the sow was lying with her udder towards the HL were covariates. Parity was included as a categorical variable and health status as a binary variable. Stall location within room and sow were specified as random effects. Similar models were developed for the 2HL treatments, with the regions of interest being $R_{heated\text{-}1}$, $R_{heated\text{-}2}$, $R_{creep\text{-}1}$, and $R_{creep\text{-}2}$. As there were 2 HLs, the sow lying orientation was included in the models as percentage of day lying with udder towards side 1.

3. Results

Detailed results of sow and piglet production performance are reported in Leonard et al. (2020). Briefly, no statistical evidence for differences were found between stall layouts or HL treatments for the percent pre-weaning mortality, overlay, number of piglets born alive, number of piglets weaned, piglet average daily weight gain, or litter uniformity ($p > 0.05$). Statistical differences were noted in percent stillborn between stall layouts ($p = 0.045$); however, the magnitude of the difference in means was not of practical significance.

A total of 2590 data days from 322 sows were analyzed for sow postures and behaviors, 1831 data days were analyzed from 324 litters for piglet location, and 1701 data days were analyzed for mortality and postures/behaviors/location. Due to data collection failures, not all allocated replicates had usable data on each analysis day. For example, 51 sows were assigned to the TSL and 1HL treatment group, but nine sows had incomplete image data on day -3, so data from 42 of the allocated sows were analyzed. Representation by analysis, treatment, and day of lactation are shown in the supplemental material. A summary of measured postures, behaviors, and piglet locations and significant factors are presented in Table 1. Overall, sow parity distribution was 40 % parity 1, 26 % parity 2, 15 % parity 3, and 19 % parity 4. One hundred seventy-five of the sows had a health intervention, reflected in the health status covariate.

3.1. Sow postures

Sows in ESCSL showed an increase in lying compared to ECSL (ESCSL = 86.8 ± 0.2 %, ECSL = 85.6 ± 0.2 %; $p = 0.028$). Sows housed in ESCSL also decreased sitting compared to ECSL ($p = 0.010$) and TSL ($p = 0.025$), with average values of 2.5 ± 0.1 %, 3.1 ± 0.1 %, and 3.0 ± 0.1 % for ESCSL, ECSL, and TSL, respectively. No evidence for differences between stall layouts were noted for standing ($p = 0.11$) or kneeling ($p = 0.40$).

Sows with 2HL increased lying ($p = 0.017$) compared to sows housed in farrowing stalls with 1HL. The difference in average lying between HL treatments varied by day of lactation, but the greatest difference was noted on day -1 (1HL = 79.3 ± 0.8 %, 2HL = 80.9 ± 0.8 %). Additionally, sows housed in farrowing stalls with 2HL decreased standing by an average of 0.8 % compared to 1HL treatment ($p = 0.045$). However, these standing differences may have little practical difference, as overall sows stood for an average of 11 % d^{-1}. Sitting ($p = 0.68$) and kneeling ($p = 0.74$) were not impacted by HL treatment.

Regardless of treatment, day of lactation impacted all postures (Fig. 2). The greatest percentages of sitting, kneeling, and standing occurred on days -1 and 0, corresponding with the lowest percentages of lying ($p < 0.001$). Batch also impacted lying ($p = 0.041$), standing ($p < 0.001$), sitting ($p < 0.01$), and kneeling ($p < 0.001$; supplemental material). Values and magnitudes of differences for kneeling were small, ranging from 0.8 % to 0.1 %. Lying varied from 83.0 % to 88.1 %, standing from 7.8 % to 13.6 %, and sitting ranged from 2.1 % to 4.2 %.

As the number of piglets increased, sow lying decreased ($p < 0.01$) while standing ($p < 0.001$) and kneeling ($p < 0.001$) increased. The magnitude of the differences in postures increased with duration of lactation. On day 3, sows with 10 piglets exhibited a 1.1 % increase in lying, 0.6 % decrease in standing, and 0.1 % decrease in kneeling compared to sows with 15 piglets. On day 21, sows with 10 piglets increased lying by 2.9 % compared to sows with 15 piglets, but decreased standing by 2.0 % and kneeling by 0.3 %. Sitting was unaffected by the number of piglets in the stall ($p = 0.21$).

Independent of stall layout and HL treatments, P1 sows laid more than P2 ($p = 0.012$), P3 ($p < 0.01$), and P4 ($p = 0.014$) sows (Table 2). Parity 1 sows decreased standing compared to P3 sows ($p = 0.015$), and decreased sitting compared to P2 ($p = 0.037$) and P4 sows ($p < 0.001$). Conversely, P1 sows increased kneeling compared to P2 ($p < 0.001$), P3 ($p < 0.001$), and P4 ($p < 0.001$) sows. Further, P2 sows spent more time

Table 1
A summary of p-values for sow postures, posture shifts, and behaviors and piglet location for three farrowing stall designs and two heat lamp (HL) configurations over farrowing and lactation. Significant values ($p < 0.05$) are shown in bold. Colons (:) indicate a model interaction term between factors.

	Sow[1] Postures[2]					Sow Behaviors[4]		Piglet Location[5]		
	Lying	Standing	Sitting	Kneeling	Posture Shifts[3]	Feeding	Drinking	R_{heated}	R_{creep}	R_{sow}
Stall Layout[6]	**0.034**	0.11	**<0.01**	0.40	**0.018**	**<0.01**	0.13	**<0.001**	**<0.001**	**<0.001**
HL Treatment[7]	**0.017**	**0.045**	0.68	0.74	0.90	0.15	0.25	**<0.001**	**<0.001**	**<0.001**
Day[8]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Number of Piglets	**<0.01**	**<0.001**	0.21	**<0.001**	**0.011**	**<0.001**	**<0.001**	0.23	0.73	0.85
Parity	**<0.001**	**0.022**	**<0.001**	**<0.001**	**0.020**	**0.015**	**<0.01**	0.41	**<0.001**	**<0.001**
Batch[9]	**0.041**	**<0.001**	**<0.01**	**<0.001**	**<0.001**	**<0.001**	0.62	**<0.001**	**<0.001**	0.92
Health Status	0.83	0.91	0.79	0.42	0.26	0.38	0.78	0.46	0.61	0.62
Stall Layout:HL	0.90	0.90	0.41	0.66	0.34	0.50	0.30	0.49	0.13	0.13
HL:Day	0.52	0.20	0.71	0.86	0.72	0.77	0.69	**<0.001**	**<0.001**	**<0.001**
Stall Layout:Day	0.80	0.088	0.16	0.23	**0.024**	0.28	0.61	**<0.001**	**<0.001**	**<0.001**
Stall Layout:HL:Day	0.94	0.84	0.99	0.72	0.96	0.80	0.91	0.81	0.84	0.79

[1] Sows were from a Yorkshire-Landrace rotational cross where breed of sire alternates each year between Yorkshire and Landrace boars from commercial sources. From the data, sow parity distribution was 40 % parity 1, 26 % parity 2, 15 % parity 3, and 19 % parity 4.
[2] Sow postures were classified by an image processing algorithm and refer to the percentage of day sows spent in each posture.
[3] Posture shifts were identified when the posture in an image differed from the preceding image postural classification (5 s interval) and were calculated as percentage of day.
[4] Sow behaviors of feeding and drinking were classified based on the position of the sow's head within the image and were also calculated as percentage of day.
[5] The percentage of piglets in each region within the farrowing stall were identified by an image processing algorithm, with R_{heated} being in the floor area under the HL, R_{creep} as all other creep floor areas, and R_{sow} as the sow crate area.
[6] Stall Layout indicated effects attributed to farrowing stall design (traditional stall layout, expanded creep area stall layout, or expanded sow and creep area stall layout).
[7] HL Treatment referred to the number of heat lamps (one heat lamp or two heat lamps).
[8] Batch was a group of all-in-all-out sows. Nineteen batches were recorded in the data set.
[9] Day of lactation was based on the day of farrowing as day 0 and was calculated from 00:00 to 23:59.

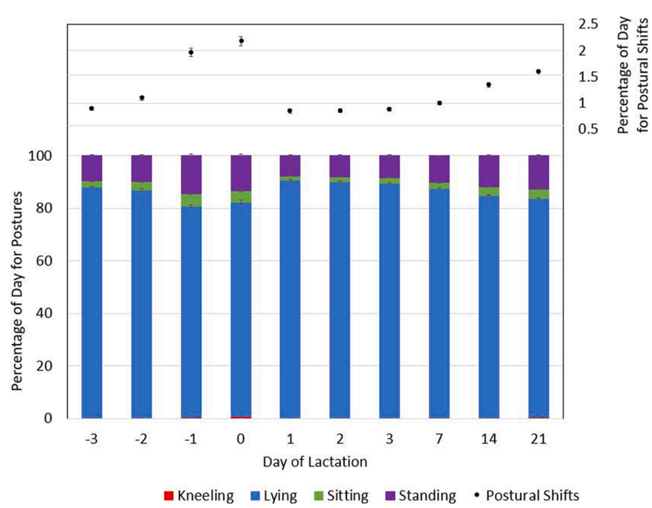

Fig. 2. Day of lactation significantly influenced the percentage of time sows spent kneeling, lying, sitting, and standing regardless of experimental treatment ($p < 0.001$). Day of farrowing is indicated as day 0 with each day including from 00:00 to 23:59. Postural shifts, identified when a sow's postural classification differed between consecutive (5 s interval) images, were also significantly influenced by day of lactation ($p < 0.001$). Error bars indicate SE.

kneeling than P4 sows ($p < 0.001$). On average per day, P3 sows spent an additional 1.7 % standing (17 % increase) compared to P1, but P1 sows spent 1.0 % less time sitting (11 % decrease) than P2 and 1.1 % less (10 % decrease) than P4.

3.1.1. Posture shifts

There was an interaction between farrowing stall layout and day of lactation for sow postural shifts ($p = 0.024$). Specifically, on day 0 sows in ECSL changed postures more than sows in TSL or ESCSL (TSL = 2.0 ± 0.1 %, ECSL = 2.4 ± 0.2 %, ESCSL = 2.1 ± 0.2 %; $p = 0.024$). There was no effect from HL treatment on postural shifts ($p = 0.90$). Postural shifts were significantly impacted by day of lactation ($p < 0.001$), with the greatest percentage of posture shifts occurring on day 0, the day of farrowing, (2.2 ± 0.2 %) and the least occurring on day 1 (0.8 ± 0.1 %). Postural shifts were influenced by batch ($p < 0.001$). When averaged over batch, postural shifts varied from 1.0 ± 0.1 % to 1.7 ± 0.1 %. Postural shifts increased with increasing number of piglets ($p = 0.011$). When comparing sows with 10 and 15 piglets, the greatest difference in posture shifts was observed on day 14 (10 piglets: 1.2 ± 0.1 %, 15 piglets: 1.9 ± 0.1 %). Although the ANOVA analysis indicated significant parity effects ($p = 0.020$), the post hoc pairwise comparisons using Tukey's adjustment did not reveal any significant pairwise difference ($p > 0.10$).

3.1.2. Lying orientation

For sows housed in stalls with 1HL, time lying with udder facing the HL did not differ from baseline (day -3) on any subsequent day of lactation for any of the stall layouts ($p > 0.067$). For sows housed in stalls with 2HL, lying on their left side did not differ from lying on their right side when compared to baseline for any stall layout on any day of lactation ($p > 0.061$).

3.2. Sow behaviors

Stall layout influenced feeding behavior, with sows in ECSL having increased feeding compared to sows in TSL ($p = 0.024$) and ESCSL ($p = 0.012$), with average feeding time 7.1 ± 0.1 %, ECSL = 7.6 ± 0.1 %, ESCSL = 7.1 ± 0.1 %. Stall layout did not influence drinking behavior ($p = 0.13$). Experimental HL treatment did not significantly impact feeding ($p = 0.15$) or drinking ($p = 0.25$).

Day of lactation influenced both feeding and drinking behaviors ($p < 0.001$). The lowest proportion of time spent feeding occurred on day 1 (4.9 ± 0.1 %), while the greatest proportion occurred on day 21 (10.5 ± 0.2 %). For drinking behavior, the lowest proportion also occurred on day 1 (0.8 ± 0.0 %) but the greatest proportion occurred on day -1 (2.1 ± 0.1 %). Batch influenced feeding behavior ($p < 0.001$), with feeding varying from an average of 6.3 % (batch 4) to 8.3 % (batch 10). Batch did not influence drinking behavior ($p = 0.62$). As the number of piglets increased feeding ($p < 0.001$) and drinking ($p < 0.001$) behaviors also

Table 2
Mean ± SE percentage of day sows exhibited postures and feeding and drinking behaviors by parity. Values are averaged over experimental treatment. Sow postures were classified based on sow body position by an image processing algorithm and were mutually exclusive. Sow behaviors were identified for sows classified as standing, sitting, or kneeling. Behaviors were based on the location of the sow's head in the image.

		Parity			
		1	2	3	4
Number of Sows[1]		130	82	50	60
Postures[2], %	Lying[3]	87.3 ± 0.2[a]	85.4 ± 0.3[b]	85.5 ± 0.3[b]	85.7 ± 0.3[b]
	Standing[4]	10.0 ± 0.2[a]	11.0 ± 0.2[a,b]	11.6 ± 0.3[b]	10.6 ± 0.2[a,b]
	Sitting[5]	2.4 ± 0.1[a]	3.3 ± 0.1[b]	2.6 ± 0.1[a,b]	3.5 ± 0.1[b]
	Kneeling[5]	0.4 ± 0.0[a]	0.3 ± 0.0[b]	0.2 ± 0.0[b,c]	0.2 ± 0.0[c]
Behaviors[6], %	Feeding	6.8 ± 0.1[a]	7.6 ± 0.1[b]	7.8 ± 0.2[a,b]	7.4 ± 0. 2[a,b]
	Drinking	1.3 ± 0.0[a]	1.6 ± 0.0[a,b]	1.6 ± 0.1[b]	1.4 ± 0.0[a,b]

[a,b,c] Indicate statistical differences within row ($p < 0.05$).

[1] Sows were from a Yorkshire-Landrace rotational cross where breed of sire alternates each year between Yorkshire and Landrace boars from commercial sources.

[2] Sow postures were classified as lying, standing, sitting, or kneeling from depth images by a custom processing algorithm. The processing algorithm determined the average height of the complete sow, as well as average height of specific body segments, and utilized a series of logic statements to classify the sow's posture. Images were collected at 5 s intervals from 00:00 to 23:59, with the day of farrowing recorded as day 0. Days -3 to 3 and 7, 14, and 21 were analyzed for each sow.

[3] When the complete sow average height was less than a preset threshold, the sow was classified as lying. This position encompassed sternal as well as recumbent lying.

[4] Sows were classified as standing when the complete sow average height was greater than a preset threshold.

[5] If the complete sow average height was between the standing and lying threshold vales, sow segments were utilized to determine posture. When the height of the front section of the sow was greater than the back section, the sow was classified as sitting. When the height of the back section was greater than the front section, the sow was classified as kneeling.

[6] Sow behaviors were classified from depth images by a custom processing algorithm based on the location of the sow's head. A sow was classified as feeding when her head was over the feeder area and classified as drinking when her head was on or near the nipple drinker. Feeding and drinking classifications were only applicable to sows that were standing, sitting, or kneeling.

increased. On average, sows with 15 piglets spent an additional 14 min feeding and 3 min drinking each day compared to sows with 10 piglets. Feeding ($p = 0.015$) and drinking ($p < 0.01$) were both influenced by parity (Table 2). Parity 1 sows showed less feeding behavior compared to P2 sows ($p = 0.034$) and decreased drinking behavior compared to P3 sows ($p = 0.012$).

3.3. Piglet location

Interactions were observed between day of lactation and stall layout, and day of lactation and HL treatment for R_{heated}, R_{creep}, and R_{sow} ($p < 0.001$). Additionally, R_{heated} and R_{creep} were influenced by batch ($p < 0.001$). No differences were found in R_{heated} on day 0 between stall layouts, but on all other days piglets in TSL had decreased time in R_{heated} compared to piglets in ECSL ($p < 0.001$) and ESCSL ($p < 0.032$; Fig. 3). On average, piglets in TSL spent 2.8 h and 1.7 h less in the heated regions of the farrowing stall compared to piglets in ECSL and ESCSL, respectively (TSL = 68.5 ± 0.7 %, ECSL = 80.2 ± 0.6 %, ESCSL = 75.4 ± 0.6 %). On day 1, piglets in ECSL had a 5.7 % increase in R_{heated} compared to piglets in ESCSL ($p = 0.026$). Piglets in farrowing stalls with 2HL had increased time in R_{heated} compared to piglets in farrowing stalls with 1HL for all days of lactation ($p < 0.001$). On average, piglets with 2HL spent an additional 23 %, 21 %, and 14 % of day under the HLs on days 0–3, respectively, compared to piglets with 1HL.

Piglets in the TSL had increased time in R_{creep} compared to piglets in the ECSL on all days of lactation ($p < 0.033$, excluding day 0 when $p > 0.05$) and piglets in the ESCSL ($p < 0.001$). On days 0 and 1, piglets in the ECSL increased their time in R_{creep} compared to ESCSL piglets ($p < 0.001$). Piglets in farrowing stalls with 2HL exhibited decreased time in R_{creep} ($p < 0.001$) compared to piglets in farrowing stalls with 1HL on each day of lactation. On average, 2HL piglets spent 4 h less in R_{creep} than 1HL piglets.

On each day of lactation, piglets in ECSL spent less time in R_{sow} compared to ESCSL piglets ($p < 0.004$). Piglets in the TSL spent more time in R_{sow} compared to piglets in ECSL on most days (days 1, 2, 7, 14, 21) and less time compared to piglets in ESCSL on days 1, 7, 14, 21. On each day of lactation, piglets with 2HL had decreased time in R_{sow} ($p < 0.03$) compared to piglets with 1HL. Averaged across treatments, there was a decrease in R_{sow} values as the duration of lactation increased (day 1 = 13.1 ± 0.6 %, day 7 = 8.6 ± 0.4 %, day 21 = 7.2 ± 0.4 %). Additionally, parity was found to influence time in R_{sow}. Piglets with a P1 sow had increased time in R_{sow} compared to piglets with a P3 ($p = 0.005$) or P4 sow ($p < 0.001$). Piglets housed with a P2 sow had increased time in R_{sow} compared to piglets housed with a P4 sow ($p = 0.003$).

3.3.1. 1HL treatment sub-region comparisons

For each day of lactation, piglets with 1HL did not spend their time in the creep areas equally between $R_{creep\text{-}H}$ and $R_{creep\text{-}U}$ ($p < 0.001$ for each day of lactation; Table 3).

3.3.2. 2HL treatment sub-region comparisons

When compared within stall layout, piglets did not spend the same percentage of time in each creep area ($R_{creep\text{-}1}$ and $R_{creep\text{-}2}$) on any of the observed days of lactation ($p < 0.001$; Table 4). Similarly, piglets did not spend the same percentage of time under each heat lamp ($R_{heated\text{-}1}$ and $R_{heated\text{-}2}$) on any of the observed days ($p < 0.001$).

3.4. Mortality and behaviors

Piglet mortality increased as sow lying increased ($p = 0.027$), standing decreased ($p = 0.025$), and time spent feeding decreased ($p < 0.001$). Proportion of time sitting ($p = 0.46$), kneeling ($p = 0.62$), drinking ($p = 0.22$), and shifting postures ($p = 0.11$) were not statistically related to piglet mortality. Mortality was also statistically unaffected by piglet location, with neither R_{heated} ($p = 0.71$), R_{creep} ($p = 0.59$), nor R_{sow} ($p = 0.065$) having significant influence. Day of lactation influenced piglet mortality for all models ($p < 0.001$), while no other covariates were significant for any of the models ($p > 0.05$).

Increases from mortalities specifically from overlays were correlated with a decrease in standing ($p = 0.047$) and feeding ($p < 0.01$), but no correlation was found with lying ($p = 0.078$), sitting ($p = 0.90$), kneeling ($p = 0.93$), drinking ($p = 0.48$), or shifting ($p = 0.17$). An increase in overlays was correlated with an increase in R_{sow} ($p = 0.013$) but not with R_{heated} ($p = 0.42$) or R_{creep} ($p = 0.70$). For all models, day of lactation was a significant factor ($p < 0.001$) while all other covariates were not ($p > 0.05$).

3.5. Sow lying orientation and piglet location

In the 1HL treatment data subset, $R_{creep\text{-}U}$ decreased when the sow increased proportion of lying time with udder towards the HL ($p < 0.001$). No significant correlations were found between sow udder orientation and $R_{creep\text{-}H}$ ($p = 0.55$) or R_{heated} ($p = 0.50$). Day of lactation ($p < 0.001$) and stall layout ($p < 0.01$) were significant for $R_{creep\text{-}U}$, $R_{creep\text{-}H}$, and R_{heated}, while the interaction of day and stall layout was

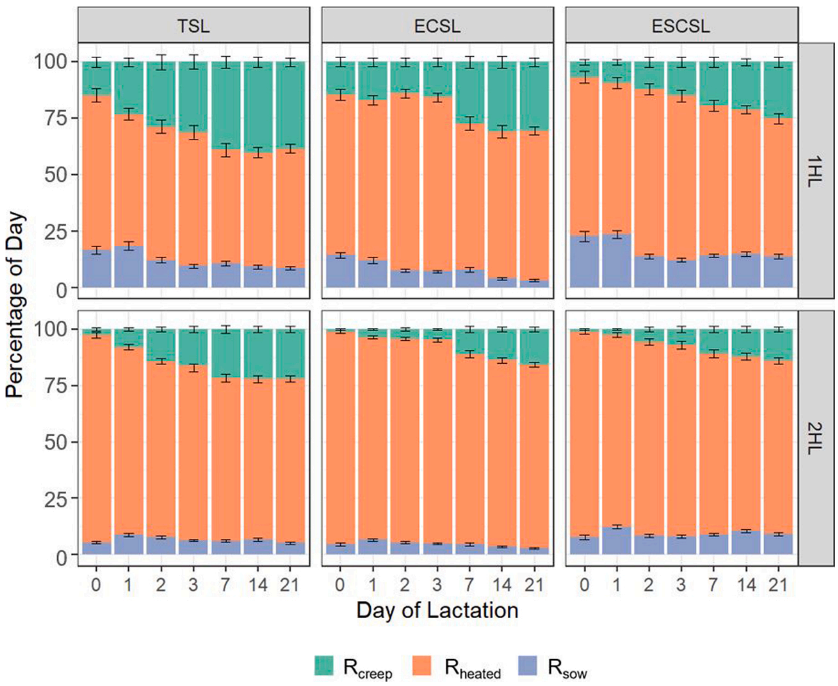

Fig. 3. Percentage of time on each day of lactation piglets spent in each region of the farrowing stall by experimental treatment. Piglet location was identified as R_{creep} when in the creep area, R_{heated} when directly under the heat lamp, or R_{sow} when in the sow crate region. Day of farrowing is indicated as Day of Lactation 0 and was designated from 00:00 to 23:59. Error bars indicate SE. Farrowing stall layouts: TSL – traditional stall layout, ECSL – expanded creep area stall layout, ESCSL – expanded sow and creep area stall layout. 1HL – one heat lamp treatment, 2HL – two heat lamp treatment.

Table 3
Average ± SE percentage of each day of lactation piglets spent in the creep area on the side with the heat lamp ($R_{creep\text{-}H}$) and the opposing side creep area ($R_{creep\text{-}U}$) by experimental stall layout. The values for $R_{creep\text{-}U}$ and $R_{creep\text{-}H}$ were compared within a stall layout for each day of lactation and were found to be statistically different.

Stall Layout[2]	Sub-region[3]	Day of Lactation[1] 0	1	2	3	7	14	21
TSL	$R_{creep\text{-}H}$	5.8 ± 1.1[a]	12.8 ± 1.9 [a]	22.2 ± 3.2 [a]	24.6 ± 3.1 [a]	29.8 ± 2.5 [a]	25.4 ± 1.8 [a]	24.1 ± 1.5 [a]
	$R_{creep\text{-}U}$	8.9 ± 1.9 [b]	10.2 ± 1.2 [b]	6.4 ± 1.4 [b]	6.7 ± 1.0 [b]	9.1 ± 1.3 [b]	14.6 ± 2.0 [b]	14.1 ± 1.4 [b]
ECSL	$R_{creep\text{-}H}$	4.1 ± 1.4 [a]	5.5 ± 1.2 [a]	8.2 ± 1.6 [a]	8.7 ± 1.5 [a]	15.1 ± 2.0 [a]	13.5 ± 1.6 [a]	11.8 ± 1.1 [a]
	$R_{creep\text{-}U}$	10.2 ± 1.5 [b]	11.3 ± 1.4 [b]	5.8 ± 0.6 [b]	7.0 ± 0.9 [b]	12.0 ± 1.2 [b]	17.3 ± 2.1 [b]	18.6 ± 1.6 [b]
ESCSL	$R_{creep\text{-}H}$	1.9 ± 0.3 [a]	3.6 ± 0.6 [a]	6.3 ± 1.0 [a]	9.3 ± 1.7 [a]	11.6 ± 1.3 [a]	11.5 ± 1.0 [a]	12.2 ± 1.2 [a]
	$R_{creep\text{-}U}$	4.8 ± 1.0 [b]	5.7 ± 0.9 [b]	5.8 ± 1.8 [b]	5.6 ± 1.7 [b]	7.6 ± 1.6 [b]	9.7 ± 1.4 [b]	12.8 ± 2.0 [b]

[a,b] Indicate statistically different values within a stall layout for each day of lactation.
[1] Day of lactation was designated as 00:00 to 23:59 for each day based on day of farrowing, day 0. Sows were from a Yorkshire-Landrace rotational cross where breed of sire alternates each year between Yorkshire and Landrace boars from commercial sources.
[2] Three experimental farrowing stall layouts were used. The traditional farrowing stall layout, TSL, had the dimensions of a typical commercial farrowing stall. The expanded creep area stall layout, ECSL, provided the piglets greater area while maintaining the same sized sow crate as the TSL. The expanded sow and creep area stall layout, ESCSL, gave the piglets more area than in TSL but less than in ECSL. The sow crate in the ESCSL was wider than in the TSL and ECSL.
[3] Color images collected at a 5 s interval were processed with a custom computer program to count the percentage of piglets in each sub-region. Sub-region boundaries were manually selected.

only significant for R_{heated} ($p = 0.023$). Batch was found to impact $R_{creep\text{-}H}$ ($p < 0.01$) and R_{heated} ($p < 0.01$).

The lying orientation of the sow in the 2HL treatments were significantly correlated with $R_{heated\text{-}1}$ ($p < 0.001$), $R_{heated\text{-}2}$ ($p < 0.001$), $R_{creep\text{-}1}$ ($p < 0.001$), and $R_{creep\text{-}2}$ ($p < 0.01$). As time the sow udder faced side 1 of the creep increased, $R_{heated\text{-}1}$ and $R_{creep\text{-}1}$ increased while $R_{heated\text{-}2}$ and $R_{creep\text{-}2}$ decreased. Stall layout ($p < 0.01$) and day ($p < 0.001$) significantly influenced all models, with the interaction between stall layout and day being significant for $R_{creep\text{-}1}$ ($p = 0.011$) and $R_{heated\text{-}2}$ ($p = 0.017$). Batch impacted $R_{creep\text{-}1}$ ($p < 0.01$) and $R_{creep\text{-}2}$ ($p < 0.001$) and parity impacted $R_{creep\text{-}1}$ ($p = 0.014$).

4. Discussion

The farrowing environment presents competing requirements for sows and piglets. Newborn piglets need air temperatures of 32 °C to 35 °C while sows are thermoneutral around 19 °C (PIC North America, 2017). Piglets often lay near sows, especially in early days of life, but being near the sows also presents danger with an increased risk of being laid or stepped on (Berg et al., 2006). Therefore, when considering animal needs and welfare in the farrowing environment, it is necessary to consider sows and piglets simultaneously.

Results of the present study suggest that placing two HLs in farrowing stalls can improve piglet thermal comfort. When piglets were provided a second HL, daily usage of the heated areas increased by 20 %. This may be attributed to piglets having twice the floor area in R_{heated} for those with 2HL. Regardless, the additional time in R_{heated} could reduce piglet energy requirements for thermoregulation; however, no correlation between R_{heated} and pre-weaning mortality were found in this study.

For sows, the 2HL treatment increased lying and decreased standing compared to the 1HL treatment. These postural differences were small in magnitude, indicating a minor positive change in sow welfare. No differences in sow lying orientation compared to baseline behavior were found for either HL treatment, suggesting that HLs placed in these configurations do not impact sow lying orientation. This is contrary to results reported by Lao et al. (2016), which stated that sows in stalls with a single 175W HL preferred to lay with udders facing away from the heat source for the first three days after farrowing. However, Lao et al. (2016)

Table 4
Average ± SE percentage of each day of lactation piglets spent in the creep area on the left side of the sow crate ($R_{creep-1}$), the creep area on the right side of the sow crate ($R_{creep-2}$), and the heated creep areas on the left and right side of the sow crate ($R_{heated-1}$ and $R_{heated-2}$, respectively) by experimental stall layout. The values for $R_{creep-1}$ and $R_{creep-2}$ were compared within a stall layout for each day of lactation and were found to be statistically different. The values for $R_{heated-1}$ and $R_{heated-2}$ were compared in the same manner and found to be statistically different.

		Day of Lactation[1]						
Stall Layout[2]	Sub-Region[3]	0	1	2	3	7	14	21
TSL	$R_{creep-1}$	1.1 ± 0.4[a]	3.7 ± 0.6 [a]	8.3 ± 1.0 [a]	9.3 ± 1.1 [a]	13.4 ± 1.4 [a]	12.9 ± 1.1 [a]	12.1 ± 1.1 [a]
	$R_{creep-2}$	1.5 ± 0.4 [b]	4.1 ± 0.5 [b]	5.8 ± 0.7 [b]	6.4 ± 0.6 [b]	8.2 ± 0.8 [b]	9.2 ± 1.1 [b]	10.0 ± 1.0 [b]
ECSL	$R_{creep-1}$	0.5 ± 0.1 [a]	1.7 ± 0.2 [a]	2.5 ± 0.4 [a]	2.9 ± 0.4 [a]	7.3 ± 1.1 [a]	8.6 ± 1.0 [a]	9.5 ± 0.9 [a]
	$R_{creep-2}$	0.5 ± 0.1 [b]	1.8 ± 0.2 [b]	1.8 ± 0.3 [b]	1.8 ± 0.3 [b]	3.8 ± 0.6 [b]	5.1 ± 0.4 [b]	6.3 ± 0.6 [b]
ESCSL	$R_{creep-1}$	0.4 ± 0.1 [a]	1.4 ± 0.3 [a]	3.7 ± 1.1 [a]	4.9 ± 1.2 [a]	7.2 ± 1.2 [a]	8.6 ± 1.1 [a]	8.4 ± 1.0 [a]
	$R_{creep-2}$	0.6 ± 0.2 [b]	1.2 ± 0.3 [b]	1.8 ± 0.5 [b]	2.1 ± 0.4 [b]	3.6 ± 0.5 [b]	3.4 ± 0.3 [b]	5.4 ± 0.7 [b]
TSL	$R_{heated-1}$	40.6 ± 1.8 [c]	32.8 ± 1.8 [c]	37.5 ± 2.3 [c]	36.0 ± 2.1 [c]	34.2 ± 1.8 [c]	33.8 ± 1.8 [c]	34.3 ± 1.6 [c]
	$R_{heated-2}$	51.4 ± 1.7 [d]	50.4 ± 2.5 [d]	40.7 ± 2.5 [d]	40.7 ± 2.3 [d]	38.1 ± 1.7 [d]	37.3 ± 1.7 [d]	38.4 ± 1.9 [d]
ECSL	$R_{heated-1}$	45.0 ± 2.0 [c]	42.8 ± 2.1 [c]	51.2 ± 2.8 [c]	56.8 ± 2.7 [c]	49.0 ± 2.3 [c]	47.7 ± 1.7 [c]	45.0 ± 1.9 [c]
	$R_{heated-2}$	49.3 ± 1.9 [d]	47.2 ± 2.2 [d]	39.2 ± 2.9 [d]	33.6 ± 2.8 [d]	35.4 ± 2.4 [d]	35.0 ± 1.9 [d]	36.4 ± 2.1 [d]
ESCSL	$R_{heated-1}$	41.8 ± 2.4 [c]	44.2 ± 2.2 [c]	53.3 ± 3.8 [c]	52.5 ± 3.1 [c]	45.3 ± 2.0 [c]	46.6 ± 1.7 [c]	41.4 ± 2.0 [c]
	$R_{heated-2}$	49.5 ± 2.5 [d]	40.8 ± 2.3 [d]	32.7 ± 3.3 [d]	32.3 ± 3.0 [d]	35.1 ± 1.9 [d]	30.9 ± 1.7 [d]	35.6 ± 2.4 [d]

[a,b] Indicate statistically different values of $R_{creep-1}$ and $R_{creep-2}$ within a stall layout for each day of lactation.
[1] Day of lactation was designated as 00:00 to 23:59 for each day based on day of farrowing, day 0. Sows were from a Yorkshire-Landrace rotational cross where breed of sire alternates each year between Yorkshire and Landrace boars from commercial sources.
[2] Three experimental farrowing stall layouts were used. The traditional farrowing stall layout, TSL, had the dimensions of a typical commercial farrowing stall. The expanded creep area stall layout, ECSL, provided the piglets greater area while maintaining the same sized sow crate as the TSL. The expanded sow and creep area stall layout, ESCSL, gave the piglets more area than in TSL but less than in ECSL. The sow crate in the ESCSL was wider than in the TSL and ECSL.
[3] Color images collected at a 5 s interval were processed with a custom computer program to count the percentage of piglets in each sub-region. Sub-region boundaries were manually selected.

was conducted with 15 sows, with the HL suspended at an unspecified height. The present study had a greater sample size of 162 sows in the 1HL treatment group (by stall layout, TSL = 51 sows, ECSL = 51, ESCSL = 57). Placing a second HL in the farrowing stall could improve piglet comfort without negatively influencing sows.

When comparing farrowing stall layouts, ESCSL increased lying compared to sows in the TSL and decreased time sitting compared to sows in the TSL and ECSL. Andersen et al. (2014) reported that sows spent more time sitting when housed in farrowing stalls compared to farrowing pens, confirming that the provision of more sow space can encourage sows to decrease sitting. Baxter and Edwards (2017) suggested that sows in crates sit to mitigate interactions with their piglets. Therefore, a wider sow crate may provide the sow greater control with regards to piglet interactions and reducing the time she spends sitting. This hypothesis is further supported as lying decreased with increasing number of piglets while standing, kneeling, and number of posture shifts increased. Fraser (1975) reported that the frequency of fighting among piglets increased with increasing litter size. Frequent piglet fighting could further motivate sows to manage interactions with larger litters. Anil et al. (2002) reported that shorter, more narrow sows require less time to transition between lying and standing when housed in crates. Therefore, another potential reason for the decrease in time sitting in wider crates in the present study is that sows can transition between lying and standing with less restriction, and thus, are able to change posture more quickly and decrease sitting as a transitional posture. Sow structural shape may also influence postures and behaviors in crates. Nordbø et al. (2018) reported that sow scapular shape was moderately correlated with sow body condition score (BCS) and shoulder lesion occurrence. A sow with a wide scapula and low BCS is more likely to develop shoulder sores; therefore, a wider crate may be of increased importance for accommodating these body types comfortably. As individual sow BCS and shapes were outside the scope of this study, these metrics could be investigated in future works to further understand crate influences on sow behavior.

For piglets housed in the ESCSL, there was generally a greater percentage of time in R_{sow} compared to TSL and ECSL. This is undesirable, as more piglets in the sow area increase the potential for overlay. However, piglets in the ECSL consistently had the lowest average percentage of time in R_{sow}. This indicates that the additional 0.21 m^2 creep area in the ECSL, as compared to ESCSL, was successful in encouraging piglets to spend more time away from the sow. Therefore, further expanding the creep area in the ESCSL layout could encourage piglets to decrease time in R_{sow}.

In 2HL stalls, $R_{heated-1}$ and $R_{heated-2}$ were used unequally, as were $R_{creep-1}$ and $R_{creep-2}$. After day 1, piglets in all three stall layouts preferred $R_{creep-1}$. Generally, the preferred creep side was also the preferred heated side (i.e., when $R_{heated-1}$ was preferred corresponded to when $R_{creep-1}$ was preferred), with the exceptions being TSL heated regions on days 2, 3, 7, 14, and 21. This result suggests the differences in region usage could be a result of piglet preference to pile together under a HL. An alternative explanation could be that piglets spend more time on the side of the creep the sow's udder is facing, as seen in the 2HL treatment. This pattern was also noted in the 1HL treatment, as when sows increased time with udder facing the HL the piglets spent less time in $R_{creep-U}$. The uneven division of time between the similar regions within the stalls could be an indication that piglets perceived difference in the quality of areas within the farrowing stall. For example, the piglets may have spent less time on one side of the farrowing crate if the area became soiled or was drafty. Additional evidence is needed before definitive conclusions can be deduced.

For all treatments, the creep regions that were preferred on day 2 remained the preferred regions for the remainder of the lactation period. The only consistent preference seen on all days of lactation was for $R_{heated-2}$ in the TSL. Less consistent preferences were seen in the 1HL stalls between $R_{creep-H}$ and $R_{creep-U}$. Piglets in all three stall layouts preferred $R_{creep-U}$ on day 0 and $R_{creep-H}$ for days 2, 3, and 7, but preferences on other days varied by layout.

Results regarding sow parity can be used to refine management strategies. Parity influenced feeding and drinking behaviors, with P1 sows devoting less time to feeding compared to P2 sows, and spent less time drinking compared to P3 sows. Primiparous sows have lower feed intake than multiparous sows, which aligns with these results (Biensen et al., 1996).

Trends in sow and piglet behavior with respect to day of lactation were similar to those reported in other studies (Andersen et al., 2014; Baxter et al., 2011; Lao et al., 2016; Ostović et al., 2012; Pedersen et al., 2013). While these are not novel results, they do further validate the present study and highlight that behavior and sow and piglet comfort needs are dynamic throughout lactation. Investigations into correlations between pre-weaning piglet mortality and behavior observations further highlighted the importance of day of lactation, as day was a highly significant factor for all models. Results also showed that mortalities increased when lying increased, standing decreased, and feeding decreased. These results are likely related to the influence of day on posture behavior, as lying is greatest and standing and feeding lowest in the early days of lactation when pre-wean mortality is the highest. It is important to note that since mortality and behavior information were observed concurrently, direct causation cannot be determined.

Similar results were obtained when investigating overlays and behaviors, with day of lactation being significant for all models and an increase in overlays associated with a decrease in standing and feeding. These correlations can also likely be attributed sow behavior patterns with regards to day of lactation. An increase in overlay was correlated with an increase in R_{sow}. A piglet must be near the sow in order to be overlaid, and piglets tend to spend more time in R_{sow} in the early days of lactation; therefore, it is logical that there would be a correlation.

5. Conclusions

A computer vision system was used to compare sow postures and behaviors and piglet location between three farrowing designs (TSL – traditional stall layout, ECSL – expanded creep area stall layout, ESCSL – expanded sow and creep area stall layout) and the use of one (1HL) or two heat lamps (2HL). Providing a second HL (2HL) increased the amount of time piglets were in the heated area and decreased sow standing compared to 1HL. Sows in ESCSL increased lying and decreased sitting compared to TSL and ECSL. More piglets resulted in sows spending less time lying and more time standing, kneeling, feeding, drinking, and increased postural shifts. Day of lactation, parity, and batch effects influenced sow postural budgets and piglet location behavior. Sow lying orientation did not deviate from baseline behavior for 1HL or 2HL treatments, but piglet location was generally correlated with sow lying orientation. Piglets did not equally divide time between the two creep regions (1HL and 2HL treatments) or between each of the heat lamps (2HL treatment). Generally, piglets in ECSL and ESCSL spent more time under the HLs and less time in the creep area than piglets in TSL. Piglets in ESCSL had more time in R_{sow} compared to ECSL piglets. Piglet pre-weaning mortality was correlated with sow lying, standing, and feeding, but mortality was more strongly correlated with day of lactation. Results can guide producers to build wider farrowing stalls to better meet sow behavioral needs and to include larger heated areas to meet piglet behavioral needs during lactation.

Funding

This work was supported by the USDA, Agricultural Research Service, USDA NIFA Grant [award number 2016-67015-24]; and HATCH project [grant number IOW03617].

Declaration of Competing Interest

None.

Acknowledgements

This research was funded in part by USDA, Agricultural Research Service and USDA NIFA Award No. 2016-67015-24. This work is a product of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Project No. IOW03617 (Somak Dutta) and No. IOW04100 (Brett Ramirez) are sponsored by the Hatch Act and State of Iowa funds. The content of this article is however solely the responsibility of the authors and does not represent the official views of the USDA. USDA is an equal opportunity provider and employer. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Authors would like to acknowledge the swine personnel at USDA ARS USMARC for their animal husbandry and data collection. The authors would also like to thank John Holman for equipment installation and aiding in experimental management as well as Troy Gramke for aiding in experimental management. Authors would like to thank Jeffrey Kinard for developing the piglet location algorithm and the many undergraduate research assistants (Ashley, Becca, Brad, Clara, Emma, Felipe, Jack, Jonny, Josh, Kevin, Sam) for their multitudinous hours of counting piglets.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.applanim.2021.105334.

References

Andersen, I.L., Vasdal, G., Pedersen, L.J., 2014. Nest building and posture changes and activity budget of gilts housed in pens and crates. Appl. Anim. Behav. Sci. 159, 29–33. https://doi.org/10.1016/j.applanim.2014.07.002.

Anil, L., Anil, S.S., Deen, J., 2002. Relationship between postural behaviour and gestation stall dimensions in relation to sow size. Appl. Anim. Behav. Sci. 77, 173–181. https://10.1016/S0168-1591(02)00048-5.

Baxter, E.M., Edwards, S.A., 2017. Piglet mortality and morbidity: inevitable or unacceptable? In: Spinka, M. (Ed.), Advances in Pig Welfare. Woodhead Publishing, Duxford, UK, pp. 73–100.

Baxter, E.M., Lawrence, A.B., Edwards, S.A., 2011. Alternative farrowing systems: design criteria for farrowing systems based on the biological needs of sows and piglets. Animal 5, 580–600. https://doi.org/10.1017/S1751731110002272.

Berg, S., Andersen, I.L., Tajet, G.M., Haukvik, I.A., Kongsrud, S., Bøe, K.E., 2006. Piglet use of the creep area and piglet mortality - Effects of closing the piglets inside the creep area during sow feeding time in pens for individually loose-housed sows. Anim. Sci. 82, 277–281. https://doi.org/10.1079/ASC200633.

Biensen, N.J., Von Borell, E.H., Ford, S.P., 1996. Effects of space allocation and temperature on periparturient maternal behaviors, steroid concentrations, and piglet growth rates. J. Anim. Sci. 74, 2641–2648. https://doi.org/10.2527/1996.74112641x.

Edwards, S.A., 2002. Perinatal mortality in the pig: environmental or physiological solutions? Livest. Prod. Sci. 78, 3–12. https://doi.org/10.1016/S0301-6226(02)00180-X.

Fraser, D., 1975. The 'teat order' of suckling pigs, part II: fighting during suckling and the effects of clipping the eye teeth. J. Ag. Sci. 84 (3), 393–400.

Glencorse, D., Plush, K., Hazel, S., D'souza, D., Hebart, M., 2019. Impact of non-confinement accommodation on farrowing performance: a systematic review and meta-analysis of farrowing crates versus pens. Animals 9. https://doi.org/10.3390/ani9110957.

Herskin, M.S., Bonde, M.K., Jørgensen, E., Jensen, K.H., 2011. Decubital shoulder ulcers in sows: a review of classification, pain and welfare consequences. Animal 5, 757–766. https://doi.org/10.1017/S175173111000203X.

Hrupka, B.J., Leibbrandt, V.D., Crenshaw, T.D., Benevenga, N.J., 1998. The effect of farrowing crate heat lamp location on sow and pig patterns of lying and pig survival. J. Anim. Sci. 76, 2995–3002. https://doi.org/10.2527/1998.76122995x.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 82, 1–26.

Lao, F., Brown-Brandl, T.M., Stinn, J.P., Teng, G., Liu, K., Xin, H., 2016. Sow lying behaviors before, during, and after farrowing. In: ASABE Annual International Meeting. Orlando, FL, USA.

Lenth, R.V., 2019. Emmeans: Estimated Marginal Means, Aka Least-squares Means. R Package Version 1.4.3. https://CRAN.R-project.org/package=emmeans.

Leonard, S.M., Xin, H., Brown-Brandl, T.M., Ramirez, B.C., 2019. Development and application of an image acquisition system for characterizing sow behaviors in farrowing stalls. Comput. Electron. Agric. 163 https://doi.org/10.1016/j.compag.2019.104866.

Leonard, S.M., Xin, H., Brown-Brandl, T.M., Ramirez, B.C., Dutta, S., Rohrer, G.A., 2020. Effects of farrowing stall layout and number of heat lamps on sow and piglet production performance. Animals 10, 1–18.

Marchant, J.N., Broom, D.M., 1996. Factors affecting posture-changing in loose-housed and confined gestating sows. Anim. Sci. 63, 477–485. https://doi.org/10.1017/S135772980001537X.

Marchant, J.N., Rudd, A.R., Mendl, M.T., Broom, D.M., Meredith, M.J., Corning, S., Simmins, P.H., 2000. Timing and causes of piglet mortality in alternative and conventional farrowing systems. Vet. Rec. 147, 209–214. https://doi.org/10.1136/vr.147.8.209.

McGlone, J.J., Vines, B., Rudine, A.C., Dubois, P., 2004. The physical size of gestating sows. J. Anim. Sci. 82, 2421–2427.

Midwest Plan Service, 1983. Swine Housing and Equipment Handbook.

Moustsen, V.A., Hales, J., Lahrmann, H.P., Weber, P.M., Hansen, C.F., 2013. Confinement of lactating sows in crates for 4 days after farrowing reduces piglet mortality. Animal 7, 648–654. https://doi.org/10.1017/S1751731112002170.

Muehling, A.J., Stanislaw, C.M., 1977. Pork Industry Handbook: Swine Farrowing Units. Washington State University Cooperative Extension Service.

Nordbø, Gangsei, L.E., Aasmundstad, T., Grindflek, E., Kongsro, J., 2018. The genetic correlation between scapula shape and shoulder lesions in sows. J. Anim. Sci. 96, 1237–1245. https://doi.org/10.1093/jas/sky051.

Ostović, M., Pavičić, Ž., Tofant, A., Kabalin, A.E., Menčik, S., Potočnjak, D., Antunović, B., 2012. Sow parity, body length, postural changes and piglet crushing. Vet. Arh. 82, 319–326.

Pedersen, L.J., Malmkvist, J., Andersen, H.M.L., 2013. Housing of sows during farrowing: a review on pen design, welfare and productivity. Livestock Housing: Modern Management to Ensure Optimal Health and Welfare of Farm Animals. Wageningen Academic Publishers, pp. 93–112. https://doi.org/10.3920/978-90-8686-771-4.

PIC North America, 2017. Gilt and Sow Management Guidelines. Hendersonville, TN, USA.

R Core Team, 2019. R: a Language and Environment for Statistical Computing. URL:. R Foundation for Statistical Computing, Vienna, Austria https://r-project.org/.

Roija-Lang, F.C., Seddon, Y.M., Brown, J.A., 2018. Shoulder lesions in sows: a review of their causes, prevention, and treatment. J Swine Health Prod. 26 (2), 101–107.

Rutherford, K.M.D., Baxter, E.M., D'Eath, R.B., Turner, S.P., Arnott, G., Roehe, R., Ask, B., Sandoe, P., Moustsen, V.A., Thorup, F., Edwards, S.A., Berg, P., Lawrence, A. B., 2013. The welfare implications of large litter size in the domestic pig I: biological factors. Anim. Welf. 22, 199–218. https://doi.org/10.7120/09627286.22.2.199.

Singh, C., Cronin, G.M., Hemsworth, P.H., 2017. The behavior and welfare of sows and piglets in farrowing crates or lactation pens. Anim. 11 (7), 1210–1221. https://doi.org/10.1017/S1751731116002573.

Stalder, K.J., National Pork Board, 2017. 2017 Pork Industry Productivity Analysis. Ames, Iowa, USA.

Van Beirendonck, S., Van Thielen, J., Verbeke, G., Driessen, B., 2014. The association between sow and piglet behavior. J. Vet. Behav. 9, 107–113. https://doi.org/10.1016/j.jveb.2014.01.005.

Weary, D.M., Pajor, E.A., Fraser, D., Honkanen, A., 1996. Sow body movements that crush piglets: a comparison between two types of farrowing accommodation. Appl. Anim. Behav. Sci. 49, 149–158. https://doi.org/10.1016/0168-1591(96)01042-8.