Pigs, Production, & People: Utilizing Technology to Facilitate Biosecurity Monitoring in an Evolving Swine Production Industry

Dissertation

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By

Nicholas James Black, MPH-VPH
Graduate Program in Comparative Veterinary Medicine

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Dissertation Committee
Andreia Arruda, Advisor
Thomas Wittum, Advisor
Andrew Bowman
Jason Stull

Abstract

Swine production has evolved in recent years into capital intensive and specialized multi-site production systems, requiring greater emphasis on stringent biosecurity protocols and increasing the demand for a quality workforce. Furthermore, the industry faces labor-supply issues and is plagued by high turnover rates, which may impact production and overall animal health. The research objectives here were: (1) to investigate employee turnover in US swine farms and the impact on subsequent productivity and (2) to evaluate technological applications aimed at facilitating internal and external biosecurity monitoring. First, human resources and production data were collected from eleven farms belonging to two production systems in Ohio for 2019. Mixed effects models were fit to investigate the association between employee turnover (voluntary and involuntary) and subsequent monthly productivity (number pigs weaned per sow (PWS) and pre-weaning mortality (PWM)). Results showed high variability in turnover rates among swine farms, ranging from 8-217% for the year, and significant associations between the occurrence of an involuntary turnover event and improved PWS ($p = 0.01$) and PWM ($p = 0.02$) two-months later. In another study, an internal movement monitoring system was installed in three farrow-to-wean farms in Indiana (N=2) and Iowa (N=1) to investigate three within-farm movement types of workers thought to be important to internal biosecurity and disease transmission. Mixed effects models were fit to investigate the association between the weekly frequency of these movements and subsequent weekly productivity (PWS). Results indicated decreases in weekly PWS were associated with an increased frequency of worker movements between farrowing rooms the two-weeks prior ($p = 0.03$). In the final study, a mobile-based geofencing platform was evaluated under field conditions within two swine production systems. For one of the swine production systems (system 1), the accuracy of the platform's digital recording of site entries was estimated through a comparison with written manual logs maintained by company employees. This resulted in 95.23% (379/398) of the entries from the written manual logs that were also accurately captured by the geofencing platform. For the second system (system 2), social network analyses were performed utilizing indirect site connections established by employee movements between sites during one month. Results indicated that employees within administrative and support services roles were important increasing the indirect connections between sites of different production phases. Findings of these studies highlighted how innovative technological applications may be key to facilitate internal and external biosecurity monitoring among an evolving swine industry with an unstable labor force.

Dedication

Dedicated to my beloved wife, Laura, and my kids, Noah, Lillienne, & Roman

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Vita

2016…………………………………………B.S. Agriculture, The Ohio State University

2018…………………………………………M.P.H. – V.P.H., The Ohio State University

2018 to present………………………………Graduate Research Associate, Department of Veterinary Preventive Medicine, The Ohio State University

Publications

Black, N.J., Moraes, L.E., Arruda, A.G., 2020. Association between different types of within-farm worker movements and number of pigs weaned per sow in U.S. Swine farms. Prev. Vet. Med. 186. https://doi.org/10.1016/j.prevetmed.2020.105207

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Chapter 1. Literature Review

Swine industry overview and evolution

The U.S. swine industry ranks third among the largest pork producers in the world and first in pork exports (Giamalva, 2014). The industry grossed over $21 billion dollars in 2019 (USDA, 2020) and is a major source of employment for the U.S. workforce, with nearly 60,000 producers nationwide supplying approximately 550,000 jobs across the production chain (Work in Pork, 2021). In fact, the rate of employment grew 2.1% annually from 2001-2015 for the swine industry, which is three times faster than all U.S. industries (Boessen et al., 2018). The success of the industry has largely been the result of major improvements in production efficiency that have occurred over the past several decades. Through technological advancements in genetics and nutrition, along with the integration of pork production systems, the size of the U.S. breeding herd has steadily declined while maintaining an upward trend in overall pork production. For example, currently the industry requires 4% less feed for a market pig to produce a carcass that is 17% heavier than 25 years ago (Tokach et al., 2016).

Vertical integration now dominates the industry, where large production companies own the entire pork production chain from breeding herds to the processing facilities, most times utilizing contract farmers to care for pigs throughout the different stages. This has changed the swine production landscape from small diverse farms to large-scale systems with multiple specialized sites based on the stage of production (Key and McBride, 2007). This shift in how pigs are raised has allowed for a more controlled production environment, decrease in pork prices for the consumer and has hoisted the U.S. industry into a competitive position in the global market. However, with larger numbers of animals on a site and more farm workers to care for them, infectious diseases can potentially spread at a larger scale and persist in the production environment once introduced into the herd. As a drawback, the technological advances in swine production aimed at enhancing the health status of the herd have created a system that constantly produces naive pigs that may be susceptible to many swine pathogens (Amass and Clark, 1999).

Infectious diseases impacting the swine industry

Endemic diseases that impact the U.S. swine industry can result in major economic losses due to decrease in overall productivity, as well as excess costs incurred through treatment and enhancement of disease control measures. For example, porcine reproductive and respiratory syndrome (PRRS) is the most costly disease that the U.S. swine industry faces today, and despite decades of expansive research, it remains just as detrimental. Holtkamp et al. (2013) estimated the annual cost of PRRS to the U.S. industry to be upwards of $664 million dollars. PRRS is caused by the PRRS virus (PRRSv), with the key epidemiological feature of the ability to persist in a herd for long periods of time, often requiring extensive disease intervention strategies (Zimmerman et al., 2012). The PRRSv impacts production most notably among in breeding herds and is characterized by pre-term farrowing, late-term abortions, and litters consisting of a variable assortment of fresh stillborn, mummified, weak and low-viable, and normal liveborn piglets. Another important disease-causing virus that impacts the swine industry is the porcine epidemic disease virus (PEDv). PEDv first appeared in the U.S. in April 2013 and subsequently swept through the swine industry, causing high morbidity among all age groups, and being most fatal in pre-weaned pigs, resulting in a dramatic increase in pig losses in the U.S. breeding herd

(Schulz and Tonsor, 2015). Both of these important swine diseases exploit the vertically integrated structure of the industry that is highly interconnected (Arruda et al., 2017).

The movement of pigs between production sites is a known risk for the direct transmission of swine pathogens throughout the production system (Fèvre et al., 2006; VanderWaal et al., 2018). However, fomite transmission via personnel boots and clothing as well as vehicles and trailers is also a significant concern and has been documented for both the PRRSv (Otake et al., 2002; Dee et al., 2004; Pitkin et al., 2009) and PEDv (Lowe et al., 2014; Kim et al., 2017). Moreover, in a review of the transmission routes of 24 preventable infectious diseases of swine (Filippitzi et al., 2018), 19 (79%) were identified as transmissible by fomites. For this reason, the implementation of effective biosecurity protocols are an essential aspect of modern swine production in order to maintain herd health and successful levels of productivity.

The importance of biosecurity in swine production

Biosecurity refers to management strategies aimed at protecting herds from the introduction and spread of infectious agents (Amass and Clark, 1999). There are two main aspects of biosecurity; external biosecurity and internal biosecurity. External biosecurity is directed at preventing the introduction of new diseases into the herd and internal biosecurity focuses on controlling the spread of disease throughout the herd and facilitating elimination of disease from the herd after it has been introduced (Ramirez and Zaabel, 2012; Alarcón et al., 2021). Common external swine biosecurity protocols include ‘showering-in’ upon entering the farm, use of farm-designated clothing and tools, limiting farm access to unauthorized personnel, quarantining of incoming replacement animals, and more recently with respect to PRRS and breeding farms in pig-dense regions, the use of HEPA filtration on influent air (Dee et al., 2005; Otake et al., 2010). Internal biosecurity protocol is mostly oriented towards maintaining confined groups of animals based on similar age (production phase) and health status; and keeping a clear separation between these groups regarding both direct and indirect contact (McCaw, 2000). As such, common internal swine biosecurity management strategies include all-in-all-out flow of animal groupings with cleaning and decontamination and downtime between groups, limiting the movement of personnel and equipment between age groups, removal and isolation of sick pigs, and the use of footbaths (Lambert and D'Allaire, 2009; Alarcón et al., 2021). However, validation and quantification of benefits potentially brought by many of these protocols are lacking in the literature, likely due to the inherent difficulty in measuring their actual implementation under field conditions.

Established biosecurity management protocols have been shown to be associated with productive performance in farrow-to-finish farms in Europe (Laanen et al., 2013; Postma et al., 2016; Rodrigues da Costa et al., 2019) and Japan (Sasaki et al., 2020) as demonstrated through the use of biosecurity scoring systems, which quantify individual biosecurity levels through a series of survey questions pertaining to various aspects of external and internal biosecurity protocols used on farm. For example, in a study by Postma et al. (2016), they reported higher external biosecurity scores to be positively associated with the number of pigs weaned per sow per year using the Biocheck.UGent^{TM} biosecurity scoring system. Additionally, Sasaki et al. (2020) found higher biosecurity scores to be associated with improved number of pigs weaned per sow and pre-weaning mortality using the BioAsset scoring system. However, even though external and internal biosecurity protocols between farms can be very similar, farms show varying degrees of success in preventing and controlling diseases, indicating there is large variability in how these protocols are applied and implemented in the field. For example, Sanhueza et al. (2019), showed a notable difference in time to reach stability status following a PRRS outbreak among farms from the same production systems. This suggests that differences in the implementation of biosecurity practices between farms could be a reason for or, at least, contribute to the varied success in disease control and elimination. Therefore, the biosecurity protocol set as standard operating procedures by the producer is only successful at maintaining herd health and optimal levels of productivity if they are implemented appropriately and consistently at the farm-level. Success of biosecurity protocols are largely dependent on the persistent and continual compliance of farm employees and visitors (Lambert and D'Allaire, 2009), and thus are intertwined with human behavior, personalities and perceptions (Racicot et al., 2011a). While literature surrounding biosecurity compliance within swine production is scarce, lapses in biosecurity compliance in livestock production in general are common and have been previously documented in other industries (Vaillancourt and Carver, 1998; Racicot et al., 2011b). For example, Racicot et al. (2011c), investigated biosecurity compliance among poultry producers in Quebec after implementing video surveillance and audits and observed low biosecurity compliance six-months following these interventions. An example from outside of livestock production is the study by Manomenidis et al. (2019), which observed a reduction in hand hygiene compliance to be significantly associated with job burnout among a group of nurses. These examples demonstrate the importance of monitoring biosecurity compliance to ensure protocols are followed on farms on a consistent basis.

Biosecurity compliance and human behavior

Successful implementation of on-farm biosecurity protocols requires a shared responsibility across all aspects of the production system. This starts from the company administration, which decides system-wide biosecurity strategies through focusing on long-term objectives, and goes all the way to the localized operational level decisions of production workers to comply with biosecurity protocols on a consistent basis. Thus, biosecurity compliance is intertwined with human behavior, risk perception, and the pressure of performing efficiently. Indeed, human behavior influences biosecurity implementation at the operational level and has been identified as a critical factor for reducing the risk of an outbreak (Mankad, 2016). However, the ability to provide feedback of the performance of the implementation of biosecurity protocols at the operational level to the higher system wide administrative level is currently unavailable (Trinity et al., 2020).

The necessity for this feedback is underlined by the Merrill et al. (2019) study, which utilized an experimental disease simulation to find that an increased disease risk certainty increased biosecurity compliance at higher administrative levels, but actually decreased biosecurity compliance at the localized operational level within a production facility. Therefore, timely and precise feedback on biosecurity compliance at the operational level to the administrative levels, as well as effective communication on the risk of disease and the importance of compliance and implementation of biosecurity protocols from the administrative level to the operational, are essential factors in the biosecurity compliance decision-making processes of the production worker. Additionally, the swine industry is currently faced with high rates of employee turnover, making the feedback of biosecurity compliance and communication between the organizational levels of the production system even more important.

Turnover of swine caretakers

The ability to attract and retain quality animal caretaking personnel is one of the most pressing issues the U.S. swine industry faces today (Pork Priorities, 2018), with the annual turnover among animal caretakers in swine farms in the U.S. reported to be between 20 and 35%, depending on farm size (National Pork Board, 2017). Turnover among swine farms in neighboring Canada are estimated to be similar with an annual turnover of 39.6 % reported by the Ontario Pork Industry Council in 2008 (Marchand et al., 2008).

The industry's evolution in recent decades, shifting from smaller farms primarily dependent on family labor, to technological and capital-intensive systems, has drastically changed its labor needs. Not only did this shift create a demand for a greater number of employees but also a wider spectrum of skill levels needed on the farm. At the same time that the increase in production scale has created a higher job demand in the industry, the new skillset required from workers overlaps with skillsets required in other industries, creating more competition to fill the labor pool.

One major challenge to the farm's ability to procure suitable labor is the decreasing US unemployment rate over the past decade, which increased the competition in the labor market with other industries. Boessen et al. (2018) highlights that according to the U.S. Bureau of Labor Statistics, the national unemployment rate has dropped significantly from nearly 10% during the recession in 2009, to a low 4.1% in 2018. Furthermore, these unemployment rates are even lower at around 3% in the major hog producing states (e.g. Iowa, Minnesota, and Nebraska), compounding the issue of the availability of employees in such a tight labor force. Additionally, unemployment rate varies depending on educational attainment, with the rate among workers who have only acquired a high school degree being similar to the national average and decreasing significantly and becoming more stable as educational attainment increases.

Further exacerbating the strain on labor supply for the US swine industry is the decline of the population in local labor markets in rural America, where most food animal producers are located. Between 2010 and 2016, almost 70% of non-metro counties in the US had a declining population. This has resulted in an overall negative population growth in non-metro counties in the US over the past several years (Cromartie, 2017). Furthermore, this occurrence is disproportionately more dire in rural agricultural counties and skewed by influxes of other industries, such as oil, into other rural communities. This continuous shift of the population demographics in rural America is an indication that this trend is only going to accelerate in the years to come.

On-farm animal caretaker labor is an important part of swine production (Boessen et al., 2018), with producers aiming to hire agriculturally-oriented labor in order to increase levels of retention and on-farm work compliance. These are especially necessary when considering the importance of biosecurity compliance among the swine production industry in maintaining optimal animal health and production (Laanen et al., 2013; Sasaki et al., 2019; Black et al., 2020). On-farm employee turnover can be costly and have an impact on productivity (Hinkin and Bruce Tracey, 2000; Park and Shaw, 2012; Boushey and Glynn, 2012), with the total cost incurred by a turnover event estimated to be from 30% of the employee's salary to up to 150% (Carroll, 2019). Turnover costs are incurred through a combination of recruiting, hiring, training costs, and disruptions to productivity (Boushey and Glynn, 2012; Moore, 2012).

The association between employee turnover and work-related performance (e.g. productivity) has been explored in other industries. For example, Kacmar et al. (2006) investigated this relationship within the food service industry, which have similarities with the swine industry including the issue of high employee turnover. They demonstrated that turnover events are associated with unit- and organizational-level performance on the long-term (years), but are mediated by the efficiency in the unit in a more immediate, short-term scale (months). The relationship between employee turnover and unit performance has not been investigated in depth in the swine industry. However, with high rates of employee turnover coupled with the high importance of the role of the employee in ensuring the implementation of the biosecurity standard operating procedures, monitoring the compliance of these procedures on farm may help mitigate persistent noncompliance, preventing disease occurrence and maintaining production.

Use of technology in swine production

Technological improvements and accessibility have dawned the age of precision livestock farming, aimed at improving production efficiency and animal welfare in an increasingly intensive production environment (Neethirajan, 2017; Benjamin and Yik, 2019; Ilyas and Ahmad, 2020). New technological applications for monitoring biosecurity compliance have been assessed in human healthcare settings using sensors to monitor handwashing hygiene of healthcare workers (Baslyman et al., 2015). Similar technologies could be highly valuable in helping monitor the biosecurity compliance of swine production workers. The capabilities of precision livestock farming from the ever-growing interconnectivity of individuals and entities through the "Internet of Things" and location monitoring from GPS utilization, have afforded producers more oversight among an expanding vertically integrated production landscape.

Such technologies, along with improvements in robust computational methods, have helped improve animal welfare in the swine industry through their application to different aspects of the swine production continuum. Various sensors such as cameras, microphones and accelerometers have been adapted and applied to the production environment to collect data, which is then analyzed through complex algorithms in computational software to provide meaningful information to farm staff (Benjamin and Yik, 2019). These innovative tools aid in precise real-time monitoring and timely notification, improving production efficiency and self-sufficiency, while also helping improve overall animal welfare. For example, the use of sensor technology for real-time monitoring of farm movements, may be utilized and paired with production parameters to improve internal biosecurity operating procedures, decreasing risk of disease and improving herd health and productivity (Piñeiro et al., 2019). Additionally, the application of geofencing technology in swine production could be a useful tool in facilitating the monitoring of biosecurity protocol with respect to direct or indirect connections between production sites and non-production facilities within a vertically integrated multi-site production system. In addition to facilitating biosecurity monitoring, geofencing technology could afford producers with actionable data pertaining to site connections and be accessible in a timely manner, affording the producer informed and directed disease mitigation efforts during an outbreak. However, technologies such as those mentioned here have not been validated and thoroughly investigated under field conditions and warrant further study for their utilization within the swine production industry.

The primary objectives for this dissertation therefore included: (1) to assess the amount employee turnover that swine producers can experience and investigate its impact on productivity; (2) to evaluate the application of a monitoring system of within farm movements of workers in farrow-to-wean farms under field conditions; and (3) to evaluate the utilization of geofencing technology to capture indirect connections of swine facilities through worker movements within a multisite production system under field conditions.

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Chapter 2. Turnover Events of Animal Caretakers and its Impact on Productivity in Swine Farms

Introduction

The ability to attract and retain quality animal caretaking personnel is one of the most pressing issues the U.S. swine industry faces today ("Pork Priorities," 2018), with turnover rates among animal caretakers in swine farms in the U.S. reported to be between 20 and 35%, depending on farm size (National Pork Board, 2017). Turnover rates among swine farms in neighboring Canada are estimated to be similar with a 39.6 % turnover rate reported by the Ontario Pork Industry Council in 2008 (Marchand et al., 2008).

The U.S. swine production industry has always been a major contributor to the U.S. workforce and economy. Standing as the third largest pork producer in the world and ranking first in pork exports (Giamalva, 2014), the industry grossed over 21 billion USD in 2018 (Meat Animals Production, Disposition, and Income 2018 Summary, 2019). With nearly 60,000 producers nationwide, the industry supplies approximately 550,000 jobs across the production chain (Work in Pork, 2021). In fact, employment in the industry grew by an annual rate of 2.1% from 2001 to 2015, which is three time faster than the growth of employment in all U.S. industries (Boessen et al., 2018).

Swine production has evolved over the past two decades, shifting from smaller farms primarily dependent on family labor, to technological and capital-intensive, integrated systems designed for large-scale production (Tokach et al., 2016). This shift in how pigs are produced has drastically changed the industry's labor needs, not only in regards to the number of employees, but also in regards to the spectrum of skill levels needed on farm. At the same time that the increase in production scale has created a higher job demand in the industry, the new skillset required from workers overlaps with skillsets required in other industries.

One major challenge to the farm's ability to procure suitable labor is the decreasing U.S. unemployment rate over the past decade, which increased the competition in the labor market with other industries. Boessen et al. (2018) highlights that according to the U.S. Bureau of Labor Statistics, the national unemployment rate has dropped significantly from nearly 10% during the recession in 2009, to a low 4.1% in 2018. Furthermore, these unemployment rates are even lower at around 3% in the major hog producing states (e.g. Iowa, Minnesota, and Nebraska), compounding the issue of the availability of employees in such a tight labor force. Additionally, unemployment rate varies depending on educational attainment, with the rate among workers who have only acquired a high school degree being similar to the national average and decreasing significantly and becoming more stable as educational attainment increases.

Further exacerbating the strain on labor supply for the U.S. swine industry is the decline of the population in local labor markets in rural America, where most food animal producers are located. Between 2010 and 2016, almost 70% of non-metro counties in the US had a declining population. This has resulted in an overall negative population growth in non-metro counties in the U.S. over the past several years (Cromartie, 2017). Furthermore, this occurrence is disproportionately more dire in rural agricultural counties and skewed by influxes of other industries, such as oil, into other rural communities. This continuous shift of the population demographics in rural America is an indication that this trend is only going to accelerate in the years to come.

On-farm animal caretaker labor is an important part of swine production (Boessen et al., 2018), with producers aiming to hire agriculturally-oriented labor in order to increase levels of retention and on-farm work compliance. These are especially necessary when considering the importance of biosecurity compliance among the swine production industry in maintaining optimal animal health and production (Laanen et al., 2013; Sasaki et al., 2019; Black et al., 2020). On-farm employee turnover can be costly and have an impact on productivity (Hinkin and Bruce Tracey, 2000; Boushey and Glynn, 2012; Park and Shaw, 2012), with the total cost incurred by a turnover event estimated to be from 30% of the employee's salary to as high as 150% (Carroll, 2019). Turnover costs are incurred through a combination of recruiting, hiring, training costs, and disruptions to productivity (Boushey and Glynn, 2012; Moore, 2012).

The association between employee turnover and work-related performance (e.g. productivity) has been explored in other industries. For example, Kacmar et al. (2006) investigated this relationship within the food service industry, which have similarities with the swine industry including the issue of high employee turnover. They demonstrated that turnover events are associated with unit- and organizational-level performance on the long-term (years), but are mediated by the efficiency in the unit in a more immediate, short-term scale (months). The relationship between employee turnover and unit performance has not been investigated in depth in the swine industry.

The primary objectives of this study were to describe the amount of animal caretaker turnover events that occurred in a single year in eleven swine farms in the state of Ohio, and to investigate associations between turnover events and subsequent swine-related production parameters of interest: number of pigs weaned per sow (PWS) and pre-weaning mortality (PWM).

Materials and Methods

Study population and data collection

A retrospective cohort study was conducted, with eleven commercial farrow-to-wean swine farms enrolled that belonged to two vertically integrated multi-site swine production systems in the state of Ohio. In this case, a production system was defined as two or more swine sites with a common owner or management structure (Arruda et al., 2017). Participants were identified through personal networking among veterinarians and stakeholders within the swine health and production industry and, as such, were selected based on convenience. Two of the participating farms were from one system, referred to as system 1 throughout the manuscript, and the remaining nine farms were from a second system, referred to as system 2. The two enrolled farms from system 1 were selected by the participating production company from the pool of breeding farms within the system (convenience sample), whereas the nine farms from system 2 were all of the breeding farms within that production system. These production systems were managed and operated under two different companies and had no connection of note, being separately recruited.

Human resources information and animal-related production data for the year of 2019 was obtained at the week level and collapsed at the month level for each farm. The human resources data obtained included information on farm location (county), the average number of full time employees working at the farm, herd size, and a list of all employee turnover events during that year, including whether they were voluntary and involuntary events. Voluntary turnover events were defined as the employee decided to leave the farm or quit employment and involuntary turnover events were defined as the employee was terminated by company decision. The production data was composed of standard herd performance parameters, including the number of pigs weaned per sow and pre-weaning mortality risk on a weekly basis. Lastly, monthly county-level unemployment rates were obtained from a public source; the Ohio Department of Job and Family Services website ("Ohio Labor Market Information"). Sample size was calculated considering number of pigs weaned per sow as our primary outcome and the occurrence of any turnover event as the main exposure of interest. Our calculations concluded that a minimum of ten turnover events would be needed to detect a difference in one piglet weaned per litter per sow (mean pigs weaned per sow of 10.4 (variance 0.2) for 'exposed' weeks versus mean 11.4 (variance 0.2) for 'unexposed weeks (Rocadembosch et al., 2016)) considering a conservative 20% turnover rate of workers on a farms with approximately 20 workers, a confidence level of 95% and 90% power. Therefore, our study required at least two participating farms with approximately 20 workers to share 52 weeks (one-year) worth of data.

Statistical Analysis

Primary outcomes of interest evaluated were the monthly herd average number of pigs weaned per sow (PWS) and pre-weaning mortality (PWM) risk following a turnover event (s). The two main predictors of interest for each outcome were the number of voluntary turnover events that occurred in a given month and whether an involuntary turnover event had occurred in a given month (measured as either yes or no). Individual linear mixed-effects models for the four main predictor and outcome of interest combinations were fit in STATA 15 (StataCorp, 2017) using maximum likelihood estimation within the "xtmixed" command (StataCorp, 2011). Since the time for a turnover event to potentially impact swine production parameters has not been previously published in the literature to the knowledge of the authors, turnover events were evaluated as predictors in separate models at one-, two-, three-, and six-months preceding the productivity outcome of interest.

Statistical model building followed the following steps: first, linearity between the monthly frequency of voluntary turnover events (continuous variable) and the outcomes of interest were assessed and the relationship was determined to be nonlinear. To address this issue, regression splines were utilized for the monthly frequency of voluntary turnover events with knots at one and three events, after evaluating the nonlinear relationship between the frequency of voluntary turnover events and subsequent productivity (Edwards et al., 2006). Random effects within the mixed model included farm, to account for the existence of multiple observations within farms, and system, to account for the occurrence of multiple farms within systems (Dohoo et al., 2003). To account for temporal trends in production, the number of pigs weaned per sow and pre-weaning mortality risk the month prior to the outcome were included in the models. Potential confounders considered in the analysis included the number of employees on the farm, herd size, season (defined as autumn, winter, spring, and summer), and monthly county-level unemployment rate. These were recognized a priori using a causal diagram, as well as during model building by monitoring the change in magnitude in the final model coefficients after the individual removal of variables. Variables were considered confounders and retained in the model regardless of statistical significance if their removal changed other coefficient's estimates by 20% or more. Univariable models were fit to screen for potential variables to be offered for final model selection, using a cutoff of $p < 0.2$.

The final models were selected through a backwards stepwise approach. A p-value < 0.05 was used to declare significance and $0.05 \leq p < 0.10$ was used to declare tendency. Likelihood ratio tests, along with the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were used for nested model comparisons. To estimate the amount of unexplained variability in the number of pigs weaned per sow and pre-weaning mortality risk attributable to the system and farm given the system (levels of clustering), the Intra-class Correlation Coefficient (ICC) was calculated. The final mixed model was evaluated through graphing of the best linear unbiased predictions (BLUPs) of the random effects, which should be normally distributed, and through the assessment of outliers from the estimated residuals, which should also reflect normality of errors.

Results

Descriptive statistics are displayed in Table 2.1. Average herd size among the farms ranged from 1,225 to 6,180 sows with a median of 2,500 sows and average number of full time employees ranged from 5 to 20 employees with a median of 12 employees. There were a total of 152 turnover events during the 52 weeks in 2019, with 4 and 148 total turnover events in systems 1 and 2, respectively. Of these, 75% (3/4) and 10% (15/148) of the turnover events were involuntary for systems 1 and 2, respectively. All participating farms experienced at least one involuntary turnover event during the year, with the exception of three of the nine farms from system 2. The frequency of turnover events among all the farms over the examined period ranged from one to 32 events, with five of the nine farms in system 2 having more than 20 turnover events in a single year. The percentage of total turnover experienced for the year of 2019 among the farms, calculated as the total number of all turnover events divided by the average number of fulltime employees, ranged from 8% (1/12) up to 217% (26/12) with an average of 92% (Table 2.1). Descriptive statistics including the mean, standard deviation, median, and range, for the monthly county-level unemployment rate and the two outcomes of interest, PWS and PWM, are available in Table 2.1.

Linear mixed effect univariable models for the pigs weaned per sow outcome yielded several variables that deserved to be further investigated and offered up for backwards selection for final models. These variables included the regression spline groupings for voluntary turnover events two months prior to the outcome (p = 0.0593) and three months prior to the outcome (p = 0.1573), as well as the occurrence of an involuntary event one month prior to the outcome (p = 0.121), two months prior to the outcome (p = 0.113), and three months prior to the outcome (p=0.128). The univariable models for the PWS outcome also yielded herd size (p = 0.196), season (p < 0.001), the PWS the month preceding the outcome (p < 0.001), and monthly county-level unemployment rate (p < 0.001) for backwards selection.

Linear mixed effect univariable models for the pre-weaning mortality risk outcome yielded the regression splines groupings for the number of voluntary turnover events two months prior to the outcome (p = 0.134), as well as the occurrence of an involuntary event two months prior to the outcome (p = 0. 072) and 3-months prior to the outcome (p = 0.002) to be offered for final model selection. Season (p < 0.001), the PWM the month preceding the outcome (p < 0.001), and monthly county-level unemployment rate (p = 0.0259), were also under the p < 0.2 cut-point and were offered for final model selection.

Following the backward stepwise selection for final model building, two significant final multivariable mixed effects models for the number of pigs weaned per sow outcome that included the predictors of interest remained (Table 2.2). This included a model for the association between the occurrence of an involuntary turnover event two months preceding the PWS outcome, and a model for the association between monthly pigs weaned per sows and the linear splines for voluntary turnover events two months prior to the outcome, with knots at one and three voluntary turnover events (Table 2.2).

For the involuntary turnover event model, there was a significant interaction between the occurrence of an involuntary turnover event and the monthly county-level unemployment rate in the negative direction (p = 0.02), indicating that the positive impact of an involuntary turnover on production (measured as number of pigs weaned per sow) two months later, may be diminished at higher rates of unemployment (Figure 2.1). This was after controlling for PWS in the previous month, season, production system, and farm. The ICC for farm within production system was 0.12 with a standard error of 0.13, while the system-level ICC was negligible. This farm-level ICC is indicative of fairly low correlation in monthly PWS between farms, given the production system, and is interpreted as the farm-level only accounting for 12% of the variability in the monthly pigs weaned per sow measure. According to the results for the model containing the linear spline segments for voluntary turnover events two months prior to the PWS outcome, the linear spline segments were indicative of a tendency of an increase in pigs weaned per sow moving from zero to one voluntary turnover event two months prior (p = 0.09); a decrease in pigs weaned per sow moving from one to three voluntary turnover events two months prior (p = 0.08), and an increase in pigs weaned per sow moving from three or more voluntary turnover events two months prior (p = 0.01). Both the system- and farm-level ICCs were negligible for this model. Full models with all retained variables are presented on Table 2.2.

For the pre-weaning mortality outcome, two significant final multivariable mixed effects models that included the predictors of interest remained (Table 2.3). These models were for the association between monthly PWM and the occurrence of an involuntary turnover event two and three months prior. The results for the final multivariable mixed effects model for the association between the occurrence of an involuntary turnover event two months preceding the PWM showed that an involuntary turnover event was significantly associated with a decrease in PWM two months later by 1.15% (p = 0.02), after controlling for PWM in the previous month, season, production system, and farm. Similar to the PWS outcome, this model is indicative of improved production two months following the occurrence of an involuntary turnover event. Furthermore, the ICC for farm within production system was 0.49 with a standard error of 0.17 with the system-level ICC being negligible. This farm-level ICC is indicative of moderate to high correlation in monthly PWM between farms, given the production system, and is interpreted as the farm-level accounting for nearly 50% of the variability in the monthly PWM measure. Finally, the results for the final multivariable mixed effects model for the association between monthly PWM and the occurrence of an involuntary event three months prior were similar to that of the two months prior model, with an estimated decrease in PWM by 1.31% ($p = 0.01$), after controlling for monthly PWM one month prior, season, production system, and farm (Table 3). The ICC for the production system-level was negligible for this model as well, with a farm-level within system ICC of 0.65. Diagnostic plots for the BLUPs and estimated residuals adequately reflected the normality assumption for all final models reported.

Discussion

The relationship between employee turnover and organizational performance has been investigated in many capacities in different industries (Park and Shaw, 2012), however to our knowledge, this is the first longitudinal study to investigate the association between turnover of animal caretakers on swine farms and production parameters of importance under field conditions in the US. While this study only included the evaluation of one part of the industry's work force; animal caretakers that work on the breeding farms, one could argue that this is one of the most important components within a swine production system.

Caretakers in breeding farms perform various tasks necessary to maintain the animals and their environment at conditions adequate for high levels of continuous piglet production. This is done with the expectation that work is conducted while adhering to strict biosecurity protocols that are commonly implemented on these farms for disease control and prevention purposes. Biosecurity protocols are important, especially among breeding farms (McCaw, 2000; Lambert and D'Allaire, 2009; Ramirez and Zaabel, 2012), as these employees may unknowingly transmit diseases to and throughout a farm (Otake et al., 2002; Pitkin et al., 2009; Kim et al., 2017), which can be costly for producers (Holtkamp et al., 2013; Schulz and Tonsor, 2015) and compromise the welfare of the animals. Furthermore, many of these workers operate the farrowing rooms, where variability in the day-to-day procedures can result in increased risks to the newborn piglets, who are at the most vulnerable stages of their life for the first several days post-farrowing (Tubbs et al., 1993; Bowman et al., 1996; Muns et al., 2016). For this reason, two frequently tracked metrics of productivity among swine producers are: (1) the number of pigs that make it through the roughly 3-week period in the farrowing room among all the sows that farrowed that same period (number pigs weaned per sow), and (2) the percentage of piglets born alive, out of all piglets born alive, that do not survive the farrowing stage during the farrowing period (pre-weaning mortality).

The dynamics of a swine caretaker's work results in products that can be assessed approximately every 3-4 weeks, creating a model that is suitable for assessing the effect of turnover on subsequent productivity on a relatively short time-scale (months). In the current study, the time for the effect of both voluntary and involuntary turnover to impact production was consistent at 2 months for both the monthly PWS and PWM outcomes, with the association remaining into 3 months for the PWM outcome. This is after accounting for important factors that are known to affect production and that may be related to turnover (confounders), including monthly trends in production, seasonality, production system, and farm. Interestingly, the occurrence of an involuntary turnover event in a given month had a much more statistically significant impact on subsequent productivity for both measured outcomes when compared to the number of employees that quit voluntarily in a given month. This might be explained by the theory that certain industries (e.g. service industry) may be impacted more by voluntary employee turnover than others (e.g. production, manufacturing, etc.) due to the higher degree of human capital (accumulated knowledge and skills (Strober, 1990)) needed to maintain successful levels of productivity. Additionally, organizations with high levels of employee turnover, as is the swine industry, may have workforces that lack accumulated human capital, therefore replacements can quickly gain similar levels of human capital to further negate losses (Shaw et al., 2005a, 2005b). It has also been argued that capital intensive industries tend to place greater emphasis on investments in technology, equipment, and physical resources, and less emphasis on developing human capital (Datta et al., 2005). These theories and examples from other industries could explain the weak association we found between voluntary turnover events and farm production. In contrast with voluntary turnover in the present study, the occurrence of an involuntary turnover event in a given month was associated with improved production two months later for both the PWS and PWM. This corroborates with the idea that involuntary turnover can be less harmful for an organization compared to a voluntary event, not only due to the planned nature of the decision that would be under the company's control, but also because it may serve functional purposes by eliminating poor performing employees (Abelson and Baysinger, 1984; Holtom et al., 2008). Moreover, under the assumption that the organization was able to adequately refill the poor performer's position with better performing employees, then it would be expected that there would be an association with improved productivity following the removal of a poor performer (Dalton et al., 1982; Hollenbeck and Williams, 1986). Interestingly, there was a significant interaction between the occurrence of an involuntary turnover event 2 months prior to the PWS outcome and the monthly county-level unemployment rate when examining monthly PWS. This interaction was indicative of improved performance (measured as PWS) following the occurrence of an involuntary event two months prior being most profound at the lowest levels of unemployment rate and diminishing at the highest levels. This could potentially be an indication of an effect of the local labor market conditions on the farm's ability to hire and retain adequate replacements following the termination of an employee (International Labour Office, 2019). For example, low unemployment could signal a surrounding labor market that is able to adequately supply quality employment to those actively seeking a job, whereas high unemployment could be an indication of a higher degree of unemployed in the surrounding market and lower quality job alternatives. Therefore, if unemployment is high following the termination of an employee, the chances of hiring a replacement that may not be as qualified is higher, because of the lack of competitive alternative employment options in the surrounding area. On the other hand, if unemployment is low, indicating more competitive job availability, then the chances of hiring someone actively seeking employment in the swine industry, and not just any job, may be more likely.

In contrast with the PWS model, the monthly county-level unemployment rate was not a significant contributing factor to the model with the PWM outcome. One reason for this could be due to the much higher variability in the monthly average PWM rate among the participating farms, as compared to the monthly average PWS, which was much more stable. This was underlined by the difference in model ICCs for the two models. The PWM model had a considerably high ICC of 0.49, with nearly half of the variability in this production measure attributable to farm differences given the production system. This is compared to the much lower

ICC or the PWS model, with only about 12% of the variability of the outcome attributable to the farm, given the production system.

Linear splines were utilized in the analysis of the association between the amount of voluntary turnover events in a given month and subsequent production, after observing a nonlinear trend in the association. A nonlinear relationship, as opposed to linear, between employee turnover and organizational performance has been suggested in some turnover literature (Park and Shaw, 2012), with the notion that low levels of turnover may be beneficial to the organization and increase performance, but at moderate to high levels may decrease performance (Dalton et al., 1982; Abelson and Baysinger, 1984). However, this study found a significant increasing trend of production (measured as pigs weaned per sow) indicated by the linear spline segment for three or more voluntary turnover events two months prior to the outcome. These results are similar to those observed by Glebbeek and Bax, (2004), which tested the inverted U-shape relationship between turnover and subsequent unit-level performance among temporary job agency offices, but observed a strong increase in performance at the highest levels of turnover. However, it is important to note that this observation in the current study is likely due to strong influences from outlying observations from a few farms that experienced higher than would be expected voluntary turnover events in a month, skewing the distribution and pulling this linear regression spline segment in the positive direction. To confirm this relationship, follow-up studies including a larger number of farms and months need to be conducted in the future.

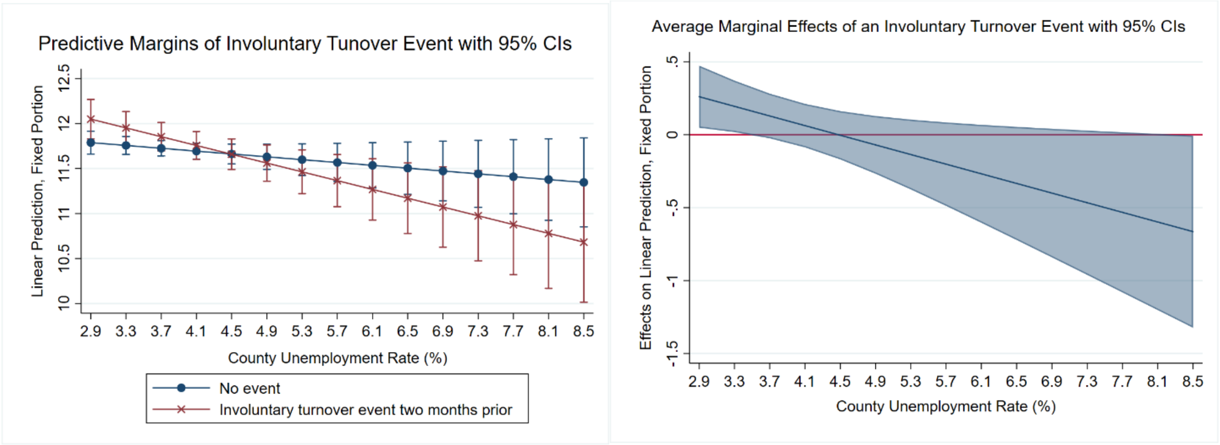
This study has limitations and is not without the potential influence of bias. One limitation was the inability to capture newly hired employees, as the human resources data provided did not include this information and therefore did not afford the ability to confirm the replacement of a former employee following a turnover event. The objectives of this study were however, focused on the disruptive nature of turnover as a whole, and as such, availability on information about new hires was not part of our inclusion criteria. Human resources-related data is notoriously difficult to obtain and capture in a standardized manner. Future studies should consider capturing new hires in addition to the data capturing herein in order to evaluate the effect of the replacement of a former employee.

Other limitations of the study are related to the sample of participants, which was based on convenience enrollment and restricted to the state of Ohio. This could have introduced selection bias and decreased generalizability of the study findings. However, the study population included multiple farms from two different production systems, encompassing a range of farm sizes that spread geographically throughout the state; and over the period of a full year. The enrollment of multiple farms within a production system improves the ability to address causality by minimizing certain threats to internal validity, holding production system factors constant among farms within the same system (Shadish et al., 2001). Additionally, the longitudinal data capture and inclusion of a temporal lag in the association, as well as the consideration of several confounding factors such as monthly and seasonal trends in production, and farm and production system differences, further improves the strength of evidence for the associations observed herein.

Lastly, another limitation of the study was the inability to identify and distinguish the specific jobs of the employees that were observed, which could make the observed associations less clear, due to the possibility of varying degrees of the impact the turnover event may have on production measures depending on the type of job performed by the employee (e.g. farrowing rooms versus gestation).

In conclusion, turnover of animal caretaking personnel in farrow-to-wean farms was confirmed to be highly variable and considerably high in the majority of farms in this study. Furthermore, animal caretaker turnover was associated with subsequent trends of production efficiency, warranting closer consideration of prioritizing managerial efforts in worker recruitment, training and retention.

Figure 2. 1 Graphical representations of the interaction between county-level unemployment rate on the occurrence of an involuntary turnover event two months prior to the outcome and the outcome pigs weaned per sow.



The figure on the left shows the different linear predictive margins with 95% confidence intervals for monthly pigs weaned per sow (y-axis) between the occurrence of an involuntary event two months prior (red line) and no involuntary turnover event two months prior (blue line) at increasing county-level unemployment rates(x-axis).

The figure on the right shows the difference in the linear predication (blue line) and 95% confidence interval band of the marginal average pigs weaned per sow (y-axis) between the occurrence of an involuntary event to months prior and no occurrence of an involuntary event two months prior at increasing county-level unemployment rates (x-axis). The red horizontal line represents no difference in the linear prediction between the occurrence and no occurrence of an involuntary event two months prior to the outcome.

Table 2. 1 Description of the predictors and outcomes of interest for the eleven participating farms in this study

ID[1]	N Employees[2]	Herd Size[3]	Total Turnover[4]	N Involuntary Events[5]	Turnover[6]	Unemployment Rate (%)[7]			N Wean/sow[8]			PWM (%)[9]		
						Mean (SD)	Median	Range	Mean (SD)	Median	Range	Mean (SD)	Median	Range
1 – 1	12	2500	1	1	0.08	3.83 (0.46)	3.8	3.0-4.6	11.32 (0.20)	11.34	11.0-11.6	17.32 (1.27)	17.27	14.4-18.9
1 – 2	10	2500	3	1	0.30	3.83 (0.46)	3.8	3.0-4.6	11.90 (0.34)	11.91	11.2-12.5	13.48 (2.08)	12.91	10.6-16.9
2 – 1	20	4173	32	3	1.60	3.43 (0.46)	3.4	2.9-4.5	11.65 (0.42)	11.61	10.9-12.3	15.69 (3.31)	15.15	9.3-20.1
2 – 2	12	2700	26	1	2.17	3.43 (0.46)	3.4	2.9-4.5	11.61 (0.33)	11.63	11.1-12.1	16.83 (1.92)	16.49	14.0-20.6
2 – 3	5	1309	2	0	0.40	3.72 (0.42)	3.7	3.1-4.7	11.45 (0.43)	11.51	10.8-12.0	16.82 (1.32)	16.45	15.2-19.4
2 – 4	20	4000	22	5	1.10	6.26 (0.93)	6.2	5.3-8.5	11.27 (0.36)	11.32	10.7-11.8	17.19 (1.58)	17.18	14.9-20.3
2 – 5	18	6180	21	2	1.17	3.43 (0.46)	3.4	2.9-4.5	11.91 (0.35)	11.91	11.2-12.6	17.20 (2.70)	16.96	11.5-21.4
2 – 6	12	2400	10	3	0.83	4.71 (0.64)	4.6	4.0-6.2	11.85 (0.21)	11.90	11.4-12.2	11.53 (4.04)	9.92	7.4-19.8
2 – 7	12	1300	6	0	0.50	3.68 (0.42)	3.65	3.1-4.6	11.38 (0.38)	11.44	10.7-11.9	17.08 (1.28)	17.29	15.2-19.2
2 – 8	6	1225	4	0	0.67	4.17 (0.52)	4.1	3.5-4.8	11.84 (0.20)	11.84	11.6-12.1	8.24 (2.15)	8.48	8.8-12.4
2 – 9	19	5500	25	1	1.32	3.43 (0.46)	3.4	2.9-4.5	11.95 (0.30)	11.96	11.4-12.4	11.75 (2.24)	11.2	9.2-15.2

[1] Identification, shown as System – Farm

[2] Average number of full time employees at the farm.

[3] Average herd size (number of sows) as reported by the farm manager.

[4] The total number of all turnover events (both voluntary and involuntary) that occurred on each farm in 2019.

[5] The total number of involuntary turnover events (employee was terminated by company decision) that occurred on each farm in 2019.

[6] Turnover rate for each farm for the year 2019, calculated as the total number of all turnover events over the number of full time employees at the farm at any given time in 2019.

[7] Monthly county-level unemployment rate.

[8] Monthly Number of pigs weaned per sow.

[9] Monthly pre-weaning mortality (percentage of piglets born alive that died prior to weaning out of all piglets born alive).

Table 2. 2 Results from the final linear mixed effects model investigating the association between the occurrence of an involuntary turnover event two months prior to the outcome and the outcome pigs weaned per sow, followed by the results for the final linear mixed effects model investigating the association between the occurrence of an involuntary turnover event two months prior to the outcome and the outcome pigs weaned per sow, followed by the results for the final linear mixed effects model investigating the association between linear spline segments for voluntary turnover events two months prior to the outcome and the outcome pigs weaned per sow [1].

Involuntary turnover event

Variable		Estimate (SE)	95% CI	P-value	F-test P-value
Involuntary turnover event (2 months prior to outcome) [2]		0.74 (0.30)	(0.16, 1.32)	0.01	
County unemployment rate (%)[3]		-0.08 (0.05)	(-0.18, 0.02)	0.14	
Involuntary event*unemployment rate product term[4]		-0.17 (0.07)	(-0.31, -0.02)	0.02	
PWS (1 month prior)[5]		0.37 (0.09)	(0.18, 0.56)	< 0.01	
Season	Autumn	Reference			0.20
	Winter	-0.11 (0.09)	(-0.28, 0.07)	0.24	
	Spring	-0.01 (0.07)	(-0.15, 0.14)	0.94	
	Summer	0.10 (0.07)	(-0.03, 0.23)	0.15	
Constant[6]		7.66 (1.19)	(5.34, 9.99)	< 0.01	

Voluntary turnover event

Variable		Estimate (SE)	95% CI	P-value	F-test P-value
Linear spline segments for voluntary turnover events (2 months prior to outcome)[7]	0-1[a]	0.11 (0.06)	(-0.02, 0.24)	0.09	
	1-3[b]	-0.09 (0.05)	(-0.20, 0.01)	0.08	
	3+ [c]	0.12 (0.05)	(0.03, 0.22)	0.01	
County unemployment rate (%)[3]		-0.06 (0.03)	(-0.13, 0.004)	0.07	
PWS (1 month prior)[5]		0.57 (0.08)	(0.40, 0.72)	< 0.01	
Season	Autumn	Reference			0.37
	Winter	-0.04 (0.09)	(-0.22, 0.15)	0.68	
	Spring	0.08 (0.07)	(-0.06, 0.22)	0.27	
	Summer	0.08 (0.07)	(-0.05, 0.21)	0.24	
Constant[6]		5.37 (1.02)	(3.38, 7.36)	< 0.01	

[1] Linear mixed effect model used production system and farm as random effects.

Continued

Table 2.2 footnote continued

[2] Indicator variable for whether an involuntary turnover event (employee was terminated by company decision) had occurred 2 months prior to the outcome monthly pigs weaned per sow.
[3] Monthly county-level unemployment rate.
[4] Product term for the statistical interaction between the occurrence of an involuntary turnover event 2 months prior to the outcome monthly pigs weaned per sow and the monthly county-level unemployment rate.
[5] Monthly number of pigs weaned per sow 1 month preceding the outcome.
[6] Linear mixed effects model constant term.
[7] Linear spline segments corresponding to the slopes of the segments of increasing number of voluntary turnover event (employee made decision to leave or quit) two months prior to the outcome pigs weaned per sow.
[a] Linear spline segment corresponding to the slope of the association between pigs weaned per sow and increasing from zero to one voluntary turnover event (employee made decision to leave or quit) two months prior to the outcome.
[b] Linear spline segment corresponding to the slope of the association between pigs weaned per sow and increasing from one to three voluntary turnover events (employee made decision to leave or quit) two months prior to the outcome.
[c] Linear spline segment corresponding to the slope of the association between pigs weaned per sow and increasing from three to the observed maximum (seven) voluntary turnover events (employee made decision to leave or quit) two months prior to the outcome.

Table 2. 3 Results from the final linear mixed effects models investigating the association between the occurrence of an involuntary turnover event two months and three months prior to the outcome and the outcome pre-weaning mortality[1]

Involuntary turnover event 2 months prior to outcome

Variable		Estimate (SE)	95% CI	P-value	F-test P-value
Involuntary Turnover Event (2 months prior to outcome)[2]		-1.15 (0.49)	(-2.11, -0.19)	0.02	
PWM (1 month prior)[3]		0.44 (0.07)	(0.30, 0.59)	<0.01	
Season	Autumn	Reference			0.29
	Winter	0.33 (0.57)	(-0.78, 1.44)	0.56	
	Spring	0.67 (0.43)	(-0.17, 1.51)	0.12	
	Summer	-0.10 (0.40)	(-0.88, 0.68)	0.79	
Model constant[4]		7.90 (1.19)	(5.57, 10.23)	<0.01	

Involuntary turnover event 3 months prior to outcome

Variable		Estimate (SE)	95% CI	P-value	F-test P-value
Involuntary Turnover Event (3 months prior to outcome)[5]		-1.31 (0.49)	(-2.27, -0.35)	0.02	
PWM (1 month prior)[3]		0.44 (0.07)	(0.30, 0.59)	<0.01	
	Autumn	Reference			0.41
	Winter	0.71 (0.55)	(-0.36, 1.78)	0.19	
	Spring	0.53 (0.46)	(-0.38, 1.43)	0.25	
	Summer	0.04 (0.39)	(-0.72, 0.79)	0.92	
Model constant[4]		9.77 (1.42)	(6.98, 12.56)	<0.01	

[1] Linear mixed effect model used production system and farm as random effects.

[2] Indicator variable for whether an involuntary turnover event (employee was terminated and company made the decision) had occurred 2 months prior to the outcome monthly pigs weaned per sow.

[3] Monthly pre-weaning mortality risk 1 month preceding the outcome.

[4] Linear mixed effects model constant term.

[5] Indicator variable for whether an involuntary turnover event (employee was terminated and company made the decision) had occurred 3 months prior to the outcome monthly pigs weaned per sow.

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Chapter 3. Association Between Different Types of Within-Farm Worker Movements and Number of Pigs Weaned per Sow in U.S. Swine Farms

Introduction

The U.S. swine industry ranks third among the largest pork producers in the world and first in pork exports (Giamalva, 2014). The industry grossed over $21 billion dollars in 2018 (USDA, 2019) and is a major source of employment for the U.S. workforce, with the rate of employment growing 2.1% annually from 2001-2015, three-times faster than all U.S. industries (Boessen et al., 2018). The success of the industry has largely been the result of major improvements in production efficiency that have occurred over the past two decades. Through technological advancements in genetics and nutrition, along with the integration of pork production systems, the size of the U.S. breeding herd has steadily declined while maintaining an upward trend in overall pork production (Tokach et al., 2016). Vertical integration now dominates the industry, where large production companies own the entire pork production chain from the breeding herd to the processing facility, utilizing contract farmers to care for pigs throughout the different stages. This has changed the swine production landscape from small diverse farms to large-scale systems with multiple specialized sites based on the stage of production. This shift in how pigs are raised has allowed for a more controlled production environment, decrease in pork prices for the consumer and has hoisted the U.S. industry into a competitive position in the global market. However, with larger numbers of animals on a site and more farm workers on site to care for them, infectious diseases could potentially spread at a larger scale and persist in the production environment once introduced into the herd. Many infectious diseases that impact the swine industry have high economic consequences due to decreased production and excess costs incurred from disease control and elimination efforts (Holtkamp et al., 2013; Shulz and Tonsor, 2015), thus strong biosecurity protocols are integral for maintaining successful levels of productivity.

Biosecurity refers to management strategies aimed at protecting herds from the introduction and spread of infectious agents (Amass and Clark, 1999). External biosecurity is directed at preventing the introduction of new diseases into the herd and internal biosecurity focuses on controlling the spread of disease throughout the herd and elimination of disease from the herd after it has been introduced (Ramirez et al., 2012). Even though external and internal biosecurity protocols between farms can be very similar, farms show varying degrees of success in preventing and controlling diseases, indicating there is large variability in how these protocols are applied and implemented in the field. For example, Sanhueza et al. (2019), showed a notable difference in time to reach stability status following a porcine reproductive and respiratory syndrome (PRRS) outbreak among farms from the same production systems. This suggests that differences in the implementation of internal biosecurity practices between farms could be a reason for or, at least, contribute to the varied success in disease control and elimination.

Fomite transmission plays a major role in the spread and persistence of pathogens causing disease in swine herds (Otake et al., 2002; Pitkin et al., 2009a; Kim et al., 2017), warranting internal biosecurity strategies that focus on limiting the movement of people and tools that could carry infectious pathogens through different areas on the farm. Specifically for sow farms, it is common that farms have internal biosecurity protocols including the use of all-in-all-out flow with decontamination of rooms between groups, the use of footbaths, and restriction of movement from areas that are considered high risk for pathogen contamination (e.g. movements from animal loading areas and on-site nurseries to farrowing rooms) (McCaw, 2000; Lambert and D'Allaire, 2009; Ramirez et al., 2012). However, validation and quantification of benefits potentially brought by these protocols are lacking in the literature, likely due to the inherent difficulty in measuring their actual implementation under field conditions.

Success of internal biosecurity protocols are largely dependent on the persistent and continual compliance of farm employees and visitors, and thus are intertwined with human behavior, personalities and perceptions (Racicot et al., 2011a). Lapses in biosecurity compliance in livestock production are common and have been previously documented (Vaillancourt & Carver, 1998). For example, Racicot et al. (2011b), investigated biosecurity compliance among poultry producers in Quebec after implementing video surveillance and audits and observed low biosecurity compliance six-months following these interventions. This demonstrates the importance of monitoring within-farm biosecurity compliance to ensure protocols are followed on farms on a consistent basis.

With technological capabilities continuously evolving, application of new technologies to animal production aimed at improving animal health may be key (Neethirajan, 2017; Benjamin and Yik, 2019). New technological applications for monitoring biosecurity compliance have been assessed in human healthcare settings using sensors to monitor handwashing hygiene of healthcare workers (Baslyman et al., 2015). Similar technologies could be highly valuable in helping monitor the internal biosecurity compliance of swine production workers.

The objectives of this study were to utilize an internal movement monitoring system (which is one component of PigChamp Pro Europa®) that uses beacon-sensor technology to describe the frequency of within-farm movements of workers in three U.S. swine breeding farms, and to investigate the association between the amount of within-farm movements and the number of pigs weaned per sow, an important production parameter in breeding herds.

Materials and Methods

Study population

Three commercial sow farms were enrolled into this observational study; two of the farms were located in the state of Indiana and one in Iowa. These farms were identified through the principal investigator's network of contacts with swine production veterinarians and stakeholders. The inclusion criteria were the existence of internet access throughout the farm, willingness to comply with the established monitoring system protocol, and a history of disease challenges (all enrolled farms had a history of PRRS outbreaks; which was a proxy for interest in learning more about potential biosecurity breaches and, therefore, increased compliance with the study project). Farm 1 was a 1,500-sow farrow-to-finish operation with no shower and no air filtration system. This site had a sow unit consisting of two gestation barns, nine farrowing rooms, two loadout areas, one office; and a wean-finish unit (four barns). The sow unit (including all rooms) and the wean-finish unit were separated by a road. For the remainder of the manuscript, the term loadout is synonymous of farm's shipping or animal loading points, where weaned piglets, cull sows and mortalities would be carried through in a regular basis. Farm 2 was a 4,500-sow farrow-to-wean operation consisting of three gestation barns, 21 farrowing rooms, one loadout area, one office, and an on-site staging nursery that would hold weaned pigs prior to shipment. This site had showers but no air filtration system. Lastly, farm 3 was a 4,400-sow farrow-to-wean operation consisting of two gestation barns, 16 farrowing rooms, two loadout areas, one office, and two 800-head on-site nurseries where pigs were held for three-weeks post-weaning. This site had showers and a high efficiency particulate air filtration system. Weekly production parameters were obtained for the three farms from March 2018 to April 2019 using the farm's standard production software and included number of pigs weaned per sow (PWS) and pre-weaning mortality (PWM).

Internal Movement Monitoring System

Internet services were optimized throughout each farm and the PigChamp Pro Europa® internal movement monitoring system was installed. The monitoring system consisted of sensors that were placed in each farm room outlined above, which were able to detect Bluetooth-based beacon devices. Beacons were individually distributed to farm employees and movement data were collected for approximately one year, sent to a central database and collapsed weekly. A movement was recorded when an employee spent at least two minutes in one room after traveling from another room on the farm and as such, movements were always direct from one room to the other with no intermediate step in between. Farm managers were responsible for enforcing the use of the beacons on a daily basis. The research team conducted farm visits approximately every three months to check equipment and replace beacons as necessary.

The primary outcome assessed in this study was weekly average number of piglets weaned per sow. Weekly frequency of three within-farm movement types were assessed as primary predictors. These movements were selected because they are commonly considered to be important with respect to the facilitation of disease transmission and maintenance within the herd (McCaw, 2000; Pitkin et al., 2009b; Ramirez et al., 2012), and included movements from growing pig areas to farrowing rooms, movements from the loadout areas to farrowing rooms, and movements between farrowing rooms. The definition of the movement from growing pig areas to farrowing rooms differed slightly between the farms: for farm 1 this movement was defined as movements from the wean-to-finish unit (located across the road) to the farrowing rooms and for farms 2 and 3 this movement was defined as movements from the nursery rooms to the farrowing rooms. The frequency of these movements considering both one week prior to the outcome and two weeks prior to the outcome were investigated.

Statistical Analyses

Descriptive statistics including the mean, standard deviation, median, and range were calculated for PWS, PWM as well as for the three movement types by farm. A linear mixed-effects model was fit using STATA 15 (StataCorp., 2017) with farm included as a random effect to account for the clustering of observations at the farm-level (Dohoo et al., 2003, pp. 473-498). Linearity between continuous variables and the outcome of interest was evaluated. As the three movement types investigated in this study (main predictors of interest) did not meet the linearity assumption, they were categorized based on the tertile values of the frequency distribution of the movements for each individual farm (Table 3.1). The tertile categorization was chosen given the lack of previous information, and to assure similar sample size for the different categories while trying to have a higher degree of detail (three categories were kept instead of two). For the movement from the growing pig area to the farrowing rooms, the two upper tertiles were collapsed into one category due to the low frequency of these movements. Potential confounders considered in the analysis included PWM and season. These were recognized a priori using a causal diagram (Figure 3.1) as well as during model building by monitoring the change in magnitude in the final model coefficients after the individual removal of variables. Variables were considered confounders and retained in the model regardless of statistical significance if their removal changed the coefficient estimates by 20% or more. To account for temporal trends in productivity, PWS the week preceding the outcome and two weeks preceding the outcome were also considered.

Linear mixed-effects univariable models were utilized for screening potential variables to be offered for selection in the final multivariable model, using a cut-off of $P < 0.25$. A partial F-test was used for the screening of categorical variables. Correlation between predictor variables was assessed using the Spearman correlation coefficient and a cut-off value of 0.8.

The final multivariable model was built using a backwards stepwise approach and statistical significance was declared at $P < 0.05$ and tendency at $0.05 \leq P < 0.1$. The Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were used for nested model comparison. To estimate the amount of unexplained variability in the number of pigs weaned per sow attributable to the farm (level of clustering), the Intra-class Correlation Coefficient (ICC) was calculated. The final mixed model was evaluated through graphing of the best linear unbiased predictions (BLUPs) of the random effects, which should be normally distributed, as well as assessing outliers from the estimated residuals, which should also reflect normality of errors.

Results

The final dataset used for the model consisted of 147 observations, with farms 1, 2 and 3, contributing a total of 56, 39 and 52 observations, respectively. The approximate number of workers for each farm was 11, 18, and 26 for farms 1, 2, and 3, respectively. Descriptive statistics for production parameters and movements of interests are shown in Table 3.2. Farm 3 had the highest average PWS and the lowest average PWM with the lowest variability around the mean, followed by farms 1 and 2. The distribution of the weekly frequency of the within-farm movements of interest varied considerably between the three farms. The movement with the highest average frequency was the movement between farrowing rooms for all three farms. The second most frequent movement was from the loadout areas to farrowing rooms for farms 1 and

3, and from the growing pig areas to the farrowing rooms for farm 2. Farm 3 had the highest average weekly frequency and the widest range of values for all three movements of interest. Univariable analysis yielded five variables that were further offered for selection into the final model (Table 3.3). These included PWS one week prior to the outcome ($p < 0.01$), PWM ($p < 0.01$), season ($p < 0.01$), movements from growing pig rooms to farrowing rooms ("high" versus "low") for the same week as the outcome ($p = 0.18$), movements between farrowing rooms ("medium" versus "low" and "high" versus "low") for the two-weeks preceding the outcome ($p = 0.07$).

The final mixed-effects multivariable model included the predictor variables PWS the week preceding the outcome, PWM that same week (same group of weaned piglets), season, movements from the growing pigs rooms to the farrowing rooms the same week as the outcome, and movements between farrowing rooms the two weeks preceding the outcome (Table 3.4). The frequency of movements from the growing pigs to farrowing rooms was not significantly associated with PWS, but the high frequency of movements corresponded to a decrease of approximately one pig for every 10 sows, compared to the low frequency of movements ($p = 0.12$). For the movements between farrowing rooms, the medium frequency of movements the two weeks preceding the outcome was associated with a decrease in PWS by nearly one pig for every six sows (1.6 piglets for every 10 sows) compared to the low frequency of movements between farrowing rooms after controlling for farm, PWM, PWS the week prior, and season ($p = 0.03$). However, the high frequency of movements was not associated with PWS, compared to the low frequency.

The random effect variance estimate for the model was 0.21 with a standard error of 0.18. The ICC was 0.67 with a standard error of 0.19, indicating that 67% of the unexplained variability in PWS could be attributed to the farm level.

Discussion

This study was a proof-of-concept of the application of a sensor-based internal movement monitoring system in three commercial U.S. swine breeding farms under field conditions. The movement monitoring system was utilized to quantify the frequency of within-farm movements of workers and to investigate the association between the frequency of three movements commonly considered risky from the disease spread standpoint, and weekly number of pigs weaned per sow. To our knowledge, it is the first study to use such a system to quantify within-farm movements of workers and to investigate their association with productivity. We hypothesized that the number of pigs weaned per sow would be inversely associated with the frequency of all within-farm movements of interest. This finding remained significant after accounting for temporal production trends and other identified confounders, and the clustering of observations within farms. Although the highest level of this movement category was not found to be significantly associated with confidence limits on either side of the null, the direction of the estimate still showed a reduction in the PWS as the frequency of this movement increased compared to the lowest level (Table 3.4).

Movements between farrowing rooms is very common within sow production units due to the typical layout of farrowing rooms and flow of pigs through the barn, which was echoed here by the high frequency of these movements among all three farms in the study. However, as McCaw (2000) suggests in the “management changes to reduce exposure to bacteria to eliminate losses” (McREBEL) protocol, exposure between different farrowing rooms should be minimized to prevent the transmission of bacterial infections between groups. As such, decontamination measures between farrowing rooms, such as footbaths, are commonly suggested and utilized practices in large sow production units (Pitkin et al., 2009b). In this study, a medium frequency of movements between farrowing rooms during a two-week duration was significantly associated with a decrease in PWS the week following by approximately one pig for every six sows when compared to a low frequency of movements, even after controlling for PWM, which was used as a proxy for disease challenges that could also lead to an increase in this movement type. The association of this movement with the productivity parameter of interest (number of pigs weaned per sow) supports the importance of these practices, as well as warrant future studies investigating the frequency of these movements in association with the effectiveness of these measures in mitigating pathogen transmission between farrowing rooms. Two of the three farms enrolled in this study used footbaths when entering and exiting the farrowing rooms, however the maintenance of this procedure was not evaluated during the study, and it is important to note that the cleanliness of such footbaths commonly compromise efficacy of disinfection under field conditions (Amass et al., 2000). Additionally, a high frequency of movements from the growing pig areas to the farrowing rooms in one week corresponded to a decrease in PWS the same week by one pig for every ten sows. This movement from the growing pigs to the farrowing rooms was not statistically significant, but was maintained in the final model when considerable increases in AIC and BIC were observed upon removal, which is indicative of loss of information between the models (Buckland et. al., 1997).

The movements of interest selected for analysis were chosen to represent characteristics of internal biosecurity practices, as these movements are commonly thought to be risky with respect to transmission of swine pathogens within the herd. In that sense, the findings of this analysis agree with previous studies that found associations with biosecurity practices and key performance indicators (Lanaan et. al., 2013; Sasaki et al., 2019). Other variables retained in the final model included season and the PWS the week prior to the outcome. These were included in the model to account for weekly trends in production as well as seasonal effects on productivity. In the final model, a one piglet per sow increase the week prior corresponded to an increase in approximately one pig for every ten sows the following week. For season, comparing to autumn there was a decrease in one pig for every 20 sows in the winter, an increase of approximately one pig for every eight sows in the spring, and an increase in the summer by approximately one pig for every seventeen sows, after accounting for all other variables. These results agree with productivity analyses that indicate a general seasonal trend in productivity, with productivity decreasing through the winter months and then steadily improving through late spring (Stalder, 2017). Finally, PWM was used in the model as a proxy for a possible indication for disease challenges and possible treatment interventions, which would confound the relationship between internal movement frequency of workers and productivity, as it would be expected that more movements between areas may occur during treatment (particularly between farrowing rooms) and would also trend with a decrease in PWS. This was also the case in our model, with every one percent increase in PWM being significantly associated with a decrease of approximately one pig for every seventeen sows. We have also added this variable in the model because it is being used as a proxy for treatments and/ or disease challenges, for which information was not available to the research team, which is a limitation of our study.

Potential sources of bias may be present in the study, which includes the occurrence of periodic sensor inoperability. This was assumed to have occurred independently of our outcome and main exposure of interest; which is plausible but could not be confirmed. This, combined with a lack of direct oversight of compliance to the internal movement monitoring system from the investigators could also potentially introduce misclassification bias; which we expect to be non-differential. Additionally, the movement data were aggregated at the week level due to the weekly nature of capture of the outcome (weekly average number of pigs weaned per sow), which could have resulted in information loss and decrease of the power in the analysis. For example, due to variability in the number of days from farrowing to weaning between litters, we were unable to ensure that all the litters that were included in the weekly PWS outcome were also encompassed in the prior weekly movement predictors. We further acknowledge that, due to the modest sample size, we were not able to investigate all types of movements occurring in a given farm (e.g. movements to/ from gestation room, office, etc.) with respect to the outcome of interest or other outcomes. This information could had been informative from the internal biosecurity standpoint and should be considered in future studies that extends for longer periods of time.

Furthermore, the fact that only three farms were included in the study limits the generalizability of study findings to overall swine industry. However it is important to note that the three farms that participated in the study differed with respect to herd size, design, management styles, etc., encompassing a variety of sow production units seen in the U.S. industry, affording a more representative sample of data. This was underlined by the ICC value of 0.67, indicating that 67% of the unknown variability in PWS can be attributable to farm differences, which are likely a combination of management style, facility type and age, geographical location, occurrence of diseases and other unmeasured factors.

Technological and computational advancements have dawned the movement of precision livestock farming by applying new technologies to aid in the improvement of animal health through real-time monitoring (Benjamin and Yik, 2019; Piñeiro et al., 2019). Technological applications to monitoring trends of within farm movements of farm personnel, such as the system used here, have the potential to identify specific movements related to farm-specific biosecurity protocol allowing corrective measures and facilitating focused efforts on disease control and mitigation; in turn maintaining productivity and improving overall animal health.

In conclusion, this proof-of-concept study showed that internal movement monitoring technologies can be successfully applied in the field, even in on-farm conditions within relatively remote rural areas. Movements of swine workers throughout the farm has long been hypothesized to be directly related to on-farm internal biosecurity; thus potentially having an effect on measures of productivity. We have shown that this could be the case based on the conditions of our study. However, more extensive longitudinal studies including a larger sample size, detailed level of data and the inclusion of specific measures of disease challenges may offer a more vivid picture of the complex dynamic between internal biosecurity, worker movements and productivity.

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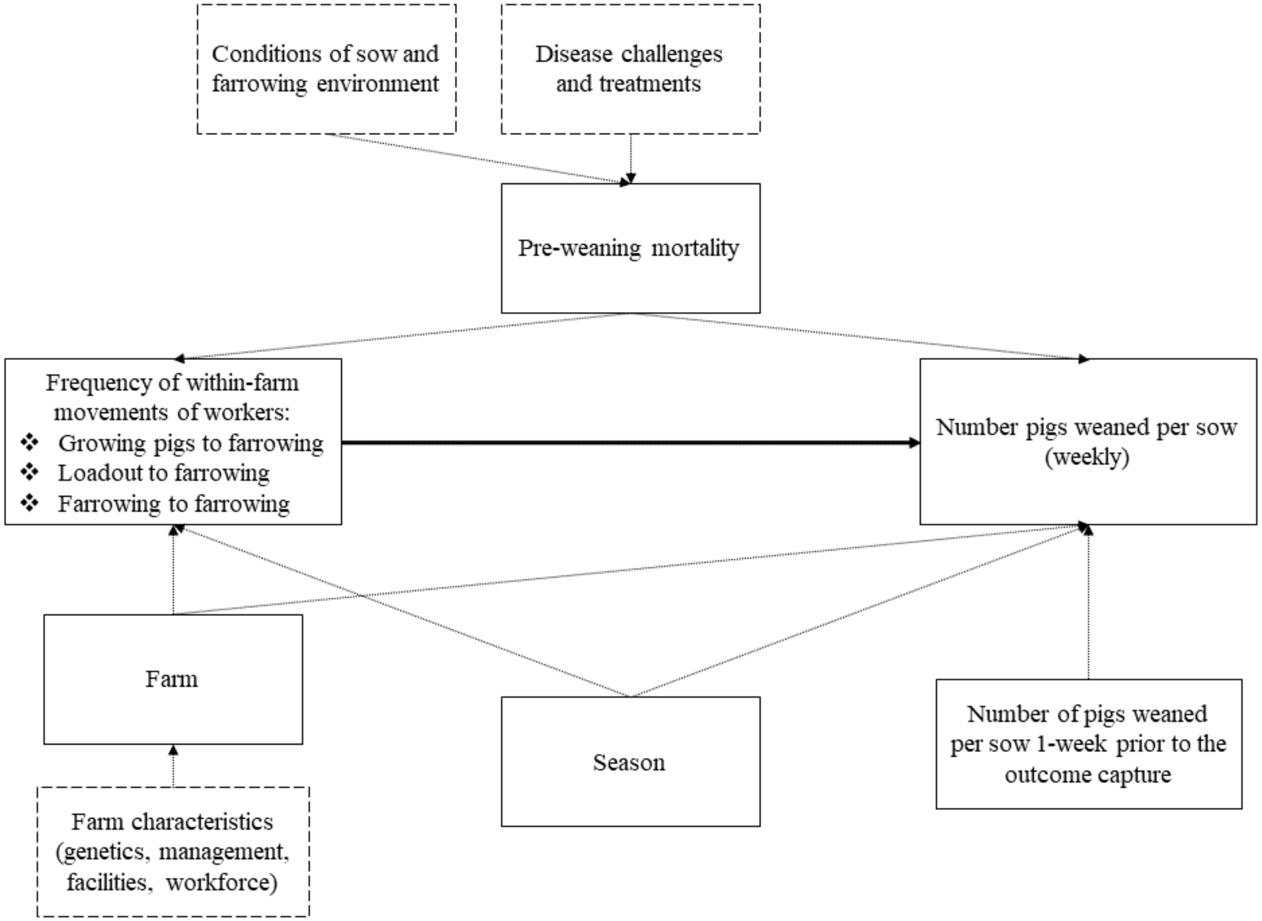
Figure 3. 1 Causal diagram depicting the relationship between the variables taken into account in this study



The main outcome for analysis was "number of pigs weaned per sow" (far right), and the main predictors of interest included three within-farm movement types (far left). Important variables that could not be captured are shown in dashed boxes, and their proxy variables by their directly connected arrow. Hypothesized associations between variables are shown by the solid arrows.

Table 3. 1 Frequency (number) of weekly movements included within each movement category for each farm participating in this study, which explored the use of an internal movement monitoring system in three sow farms under field conditions in the U.S.

Movement type	Week[1]	Level[2]	Farm 1	Farm 2	Farm 3
Growing pigs to Farrowing[3]	Same week	Low	none	2 or less	4 or less
		High	1 or more	>2	>4
	2-weeks prior	Low	1 or less	7 or less	10 or less
		High	>1	>7	>10
Shipping Point to Farrowing[4]	Same week	Low	26 or less	1 or less	61 or less
		Medium	27 – 44	2 – 5	62 – 124
		High	>44	>5	>124
	2-weeks prior	Low	69 or less	4 or less	135 or less
		Medium	70 – 88	5 – 13	136 – 231
		High	>88	>13	>231
Farrowing to Farrowing[5]	Same week	Low	34 or less	54 or less	315 or less
		Medium	35 – 60	55 – 90	316 – 454
		High	>60	>90	>454
	2-weeks prior	Low	86 or less	115 or less	656 or less
		Medium	87 – 112	116 – 195	657 – 902
		High	>112	>195	>902

[1] The week the movements occurred and were captured with respect to the outcome (weekly number of pigs weaned per sow).

[2] Categories determined by tertile values for each individual farm. The medium and high categories for the growing pigs to farrowing movement were collapsed to make the high category due to low cell counts in this movement.

[3] Total weekly movements from the growing pig areas to the farrowing rooms the same week as the outcome. The definition of the movement from growing pig areas to farrowing rooms differed slightly between the farms: For farm 1, this movement was defined as movements from the wean-to-finish unit (located across the road) to the farrowing rooms, and for farms 2 and 3 this movement was defined as movements from the nursery rooms to the farrowing rooms.

[4] Total weekly movements from the loadout area to any farrowing rooms the two weeks prior to the outcome.

[5] Total weekly movements between farrowing rooms the two weeks preceding the outcome.

Table 3. 2 Description of predictors and outcome of interest for the three farms participating in this study, which explored the use of an internal movement monitoring system in three sow farms under field conditions in the U.S. Columns for which the number of weeks is lower than the farm total represent system inoperability

	Farm 1 (N = 56)				Farm 2 (N = 39)				Farm 3 (N = 52)			
Variable	N weeks	Mean (SD)	Median	Range	N weeks	Mean (SD)	Median	Range	N weeks	Mean (SD)	Median	Range
Production Parameters												
PWS[1]	56	11.68 (0.52)	11.70	10.40-12.70	39	10.98 (0.48)	10.86	10-12.20	52	12.39 (0.31)	12.41	11.70-13.20
PWM[2]	56	13.80 (2.81)	13.17	9.50-21.30	39	15.15 (4.82)	15.25	4.70-23.10	52	10.91 (2.24)	10.96	5.38-16.0
Movement Types												
Growing pigs to farrowing[3]	42	1.31 (1.89)	0	0-7	36	7.75 (7.98)	5.5	0-31	52	8.23 (9.82)	6	2-69
Loadout to farrowing[4]	48	41.90 (27.16)	38.50	5-112	34	4.76 (4.61)	3.5	0-16	52	103.83 (79.41)	81	1-299
Farrowing to farrowing[5]	54	48.44 (25.0)	45.50	1-111	39	82.64 (51.37)	73	6-204	52	384.54 (141.35)	358.50	121-716

[1] Weekly number of pigs weaned per sow.

[2] Weekly pre-weaning mortality (percentage of piglets born alive that died prior to weaning out of all piglets born alive).

Continued

Table 3.2 footnote continued

[3] Total number weekly movements from the growing pigs area to the farrowing rooms the same week as outcome. The definition of the movement from growing pig areas to farrowing rooms differed slightly between the farms: For farm 1, this movement was defined as movements from the wean-to-finish unit (located across the road) to farrowing rooms, and for farms 2 and 3 this movement was defined as movements from the nursery rooms to the farrowing rooms.

[4] Total number of weekly movements from the loadout area to the farrowing rooms.

[5] Total number of weekly movements between farrowing rooms.

Table 3. 3 Results from linear mixed effects univariable models[1] investigating the association between movement types and the outcome pigs weaned per sow. This study explored the use of an internal movement monitoring system in three sow farms under field conditions in the U.S.

Variable	Week[2]	Level[3]	Estimate (SE)	95% CI	P-value	F-test p-value
PWS 1-week prior[4]			0.32 (0.08)	(0.17, 0.48)	<0.01	NA
PWM[5]			-0.07 (0.01)	(-0.09, -0.05)	<0.01	NA
Season		Autumn	Reference			<0.01
		Winter	-0.07 (0.17)	(-0.42, 0.27)	0.67	
		Spring	0.14 (0.16)	(-0.18, 0.46)	0.38	
		Summer	-0.07 (0.16)	(-0.39, 0.25)	0.68	
Growing pigs to farrowing[6]	Same week	Low	Reference			
		High	-0.10 (0.07)	(-0.24, 0.05)	0.18	
	2 weeks prior	Low	Reference			
		High	-0.0075 (0.08)	(-0.16, 0.15)	0.92	
Loadout to farrowing[7]	Same week	Low	Reference			0.37
		Medium	-0.11 (0.09)	(-0.29, 0.06)	0.19	
		High	-0.01 (0.09)	(-0.19, 0.16)	0.87	
	2 weeks prior	Low	Reference			0.51
		Medium	-0.098 (0.09)	(-0.27, 0.08)	0.27	
		High	-0.020 (0.09)	(-0.19, 0.15)	0.82	
Farrowing to farrowing[8]	Same week	Low	Reference			0.26
		Medium	0.067 (0.09)	(-0.11, 0.24)	0.45	
		High	-0.08 (0.09)	(-0.25, 0.09)	0.37	
	2 weeks prior	Low	Reference			0.07
		Medium	-0.14 (0.09)	(-0.31, 0.03)	0.10	
		High	0.05 (0.09)	(-0.12, 0.22)	0.55	

[1] Linear mixed effects models were used for univariable analyses with weekly number of pigs weaned per sow as the outcome and farm as a random effect for all models. Variables with a p-value < 0.25 were offered in the original mixed model for selection.

[2] The week the movements occurred with respect to the outcome.

[3] Categories for the movements were determined by tertile values for each individual farm. The medium and high categories for the growing pigs to farrowing movement were collapsed to make the high category due to low cell counts. Please refer to Table 1 for further details.

[4] Weekly number of pigs weaned per sow the week preceding the outcome.

[5] Pre-weaning mortality (percentage of piglets born alive that died prior to weaning out of all piglets born alive) the same week as the outcome.

[6] Total weekly movements from the growing pigs area to the farrowing rooms the same week as outcome. For farm 1 this corresponded to movements from finishing barns to farrowing rooms, gestation rooms, or loadout areas. For farms 2 and 3, this corresponded to movements from the on-site nurseries to the farrowing rooms.

Continued

Table 3.3 footnotes continued

[7] Total weekly movements from loadout areas to any farrowing rooms

[8] Total weekly movements between farrowing rooms

Table 3. 4 Results from the final multivariable linear mixed effects model investigating the association between movement types and the outcome pigs weaned per sow1. This study explored the use of an internal movement monitoring system in three sow farms under field conditions in the U.S.

Variable		Estimate (SE)	95% CI	P-value
PWS 1-week prior[2]		0.09 (0.08)	(-0.06, 0.24)	0.26
PWM[3]		-0.06 (0.01)	(-0.07, -0.04)	<0.01
Season				
	Autumn	Reference		
	Winter	-0.05 (0.09)	(-0.22, 0.12)	0.57
	Spring	0.12 (0.09)	(-0.05, 0.30)	0.17
	Summer	0.06 (0.08)	(-0.10, 0.22)	0.48
Growing pigs to Farrowing[4]; same week				
	Low	Reference		
	High	-0.10 (0.06)	(-0.22, 0.03)	0.12
Farrowing to farrowing[5]; 2 weeks prior				
	Low	Reference		
	Medium	-0.16 (0.07)	(-0.30, -0.02)	0.03
	High	-0.003 (0.08)	(-0.15, 0.14)	0.97

[1] Linear mixed effects model used farm as a random effect.

[2] Pigs weaned per sow the week preceding the outcome.

[3] Pre-weaning mortality (percentage of piglets born alive that died prior to weaning out of all piglets born alive) the same week as the outcome.

[4] Total weekly movements from the growing pig areas to the farrowing rooms the same week as outcome. For farm 1 this corresponded to movements from finishing barns to farrowing rooms, gestation rooms, or loadout areas. For farms 2 and 3, this corresponded to movements from the on-site nurseries to the farrowing rooms.

[5] Total weekly movements between farrowing rooms the two weeks preceding to the outcome combined.

Chapter 4. Evaluating the uses of Geofencing to Characterize Networks of Swine Facilities within Production Systems under Field Conditions

Introduction

The importance of biosecurity in swine production has increased over the past few decades and is now an integral part of maintaining successful levels of production in the industry. Biosecurity refers to protocols and management strategies aimed at preventing the introduction and spread of disease-causing pathogens within pig production sites. The industry has undergone an evolutionary transition over past decades and is now dominated by vertically integrated multisite production systems designed for efficiency and large-scale production (McBride and Key, 2013). The intensification in how pigs are produced has improved efficiency of the process, but has also created an environment that facilitates the introduction and spread of swine diseases between and throughout production sites. This is due not only to the increase in the number of animals and workers on a single production site, but also the interconnectedness of sites within and between production systems. The importance of indirect transmission of swine disease-causing pathogens via fomites is well documented (Otake et al., 2002; Pitkin et al., 2009; Arruda et al., 2017; Kim et al., 2017). Moreover, diseases such as porcine reproductive and respiratory syndrome (PRRS) (Holtkamp et al., 2013) and porcine epidemic diarrhea (PED) (Schulz and Tonsor, 2015) are costly and result in economic losses to producers from decreased production and excess costs incurred from disease control and elimination efforts.

Biosecurity can be broken into two main categories, internal biosecurity or biocontainment, which refers to efforts to contain the further spread of a disease after it has already been introduced into the herd; and external biosecurity or bioexclusion, which refers to efforts to prevent entry of the disease into the production environment (Ramirez and Zaabel, 2012). The success of biosecurity protocols in any operation is highly dependent on the compliance of its employees and outside visitors; and non-compliance in biosecurity practices among livestock production has been previously reported to be a common issue (Racicot et al., 2011a), even though these reports are scarce given the challenges in capturing biosecurity compliance. Furthermore, even farms within the same production system that have a similar biosecurity protocol (e.g. farms that belong to the same production system with consistent standard operating procedures, veterinarians, etc.) can have varying degrees of success in preventing and controlling disease outbreaks, indicating a large variability in the implementation of these protocol in the field (Sanhueza et al., 2019).

One of the most challenging areas for external biosecurity is timely trace back of indirect connections between swine sites, which is especially necessary when such introduction is of an exotic pathogen. This becomes even more important in a highly connected industry such as the North American swine industry. Increasing threats of foreign animal diseases (e.g. African Swine Fever) impacting U.S. swine production has highlighted the importance of stringent external biosecurity protocols along with the necessity of maintaining accurate and accessible site-connection information to facilitate directed and timely mitigation efforts in the face of an outbreak.

Improvements in technological and computational capabilities, as well as increases in the accessibility of these technologies, has led to investigations of applying such technologies to the production environment with the goal of improving production and overall animal health. Monitoring internal biosecurity compliance of workers is one technological application that has been recently investigated within the swine industry (Black et al., 2020). Additionally, monitoring of external biosecurity compliance of workers in the poultry industry has been investigated using video cameras and audits (Racicot et al., 2011b; Racicot et al., 2011c) Geofencing technology, which is the creation of virtual barriers around global positioning system (GPS)-specified locations, may be a technological application in swine production to improve the ability to monitor external biosecurity compliance. Application of geofencing technology could benefit the swine industry by allowing swine producers, veterinarians, and animal health officials to have accessible and actionable, real-time farm contact tracing information. This has the potential to not only facilitate timely and directed disease mitigation efforts in the face of an emerging disease outbreak, but also to afford producers and veterinarians the ability of direct oversight of external biosecurity compliance in regards to employee movements between swine facilities. Furthermore, the information collected through the utilization of geofencing technology could be used to perform social network analyses, which is an analytical approach to study relationships among entities (i.e. farms), and to evaluate patterns and implications of these relationships. This analytical tool has gained attention in veterinary epidemiology to improve knowledge of potential disease risks and support decision-making regarding disease mitigation and control strategies.

The primary goal of this project was to evaluate the accuracy, usefulness and practicality of a mobile application-based geofencing platform under field conditions. The objectives to address this primary goal included: (1) to validate the geofencing platform by estimating its accuracy to detect movement of people/ vehicles between both animal sites and non-animal facilities in a multi-site production systems under field conditions; (2) to describe the social network of movements between sites in a vertically-integrated production system and investigate differences in site connectivity patterns according to the employees' roles; and (3) to identify and quantify movements between sites that are potential breaches to standard biosecurity protocols of swine production systems, bringing focused ideas to improve external biosecurity.

Materials & Methods

A collaborating technology company that had developed and implemented a mobile application-based geofencing technology platform for the past five years (BarnTools, 2020) and two participating swine production companies (referred to here as System 1 and System 2) were identified and requested to participate in this study through the professional network of study investigators. Both production companies were large multisite production systems with over 200 sites. System 1 was located in the state of Ohio and System 2 in Iowa.

Geofencing Technology

The installation of the geofencing technology was coordinated and implemented with participants by the collaborating technology company using the company's standard procedures. This technology was a mobile application-based platform that utilizes GPS coordinates to establish virtual barriers around individual sites within a larger production system. Individual employees working for the participating production companies were invited to participate in the project by the companies and participants were asked to download the application on their cell phones. For participants that did not own a company-specific device or did not feel comfortable downloading the app on their personal devices, a cell phone was provided by their companies. Company personnel selected for this project included a combination of animal health-related personnel (veterinarians, caretakers, etc.), and industry service providers (e.g., truck drivers, maintenance team members, etc.).

All observations collected by the system were de-identified, and the final dataset included the date and time of site entry, person involved (non-identifiable identification number), person's role in the production system (e.g. truck driver, service provider, service technician, herd veterinarian, etc.), site visited (non-identifiable identification number or code), and site type (e.g. breeding site, finisher site, feed mill, office, slaughter plant, etc.).

System accuracy assessment

Self-reported accuracy of the digital site entry recording by the technology company was 98-99% (unpublished data). To objectively and independently assess the geofencing technology platform, the accuracy of the digital recording of site premise entries was estimated under field conditions. To achieve this, several employees from System 1 were asked to manually record each site entry for approximately one month on a physical (paper-based) logging sheet, while also maintaining use of the geofencing application. The "gold standard", defined as the user-recorded physical logs, were compared to the "new system", defined as the digitally recorded site entries from the geofencing system. Estimation of the system accuracy was calculated from the formula: true positive divided by total number of observations, which measures the proportion of the observations in which the geofencing technology was correct as compared to the gold standard written logs. The number of true positives was defined as the number of site entries detected by the system that were also recorded by the gold standard. A priori sample size calculations determined that a minimum number of 381 observations were required for the accuracy estimation considering an accuracy of 99% with a ± 1% precision (defined as the allowable or acceptable error in the estimate) and 95% confidence level (Sergeant, 2018).

Social network analysis

To illustrate the application of social network analysis in geofencing, employee site entries within System 2 were recorded prospectively for one month between November 22 and December 19, 2020. Consecutive site entries from an individual employee that occurred within a single day were used to obtain indirect movements between sites. Site movements were categorized according to the department within the company corresponding to the role of the employee that made the movement. The departmental categories included "Communications and Information Systems", "Maintenance", "Gilt Developing Unit (GDU)", "Sow" operations, "Wean to Finish" operations, and "Other" (encompassed "Health Services", "Nutrient Management", "Production Well Being", and "Ventilation and Filtration", which were combined given the low sample sizes of employees in with these roles). A non-reflexive (source site could not also be destination site), directed multiplex network structure (Kinsley et al., 2020) was built in R (R Core Team, 2020) using the *igraph* (Gabor Csardi and Tamas Nepusz, 2006) and *multinet* (Matteo Magnani et al., 2021) packages.

The multiplex network was constructed to represent a whole-system network of site connections that occurred over the entire month of data capture and was comprised of all of the department categories as multiplex layers. A multiplex network was utilized in this study as it affords the ability to create multiple layers of networks among the same set of actors or nodes (i.e. sites). Each layer represents a different type of interaction between the nodes (edge or site connection type), which in this case corresponds to the different employee roles within the production system. Furthermore, these multiplex layers can be stacked to represent the entire system as a whole, as well as assessed individually to compare each department's role in forming the whole-system network (De Domenico et al., 2013; Díaz-Guilera et al., 2013). In the network structure, individual sites within System 2 were represented by unique nodes and employee movements from one site to another were represented by weighted directed edges, with the arrow of the edges indicating the direction of the movement. Edges were weighted according to the number of occurrences of the same individual edge by the same department category.

Centrality measures of individual nodes, including total degree, in-degree and out-degree, were estimated for the whole-system network with all of the company departments included, and then separately for each departmental network. Degree was defined as the total number of unique connections an individual site had to other sites regardless of directionally of the employee movement. In-degree was defined as the number of site connections of an individual site that was the destination of an employee coming from another site. Out-degree was defined as the number of site connections of an individual site that was the source of an employee moving to another location (Wasserman and Faust, 1994).

Global network metrics were estimated for the whole-system network and each department category separately, and included the number of strongly connected components, size or number of sites within the largest strong component, density, transitivity or clustering coefficient, average path length, and network diameter. A strongly connected component was defined as a subset of sites in the network in which any two sites in that subset were reachable along a directed path. The size of the largest strongly connected component is also known as the giant strongly connected component and is an estimate of the lower bound of a maximum potential size of an outbreak, given pathogen introduction into one of the sites in the component (Kao et al., 2006; Kiss et al., 2006; Kinsley et al., 2019). Global network density was defined as the proportion of site connections that were observed in the network out of all possible site connections (Wasserman and Faust, 1994; Schaeffer, 2007; Dubé et al., 2011). Transitivity (also referred in the literature as clustering coefficient) was defined as the probability that two sites were connected, given they both shared a connection with another site (Wasserman and Faust, 1994; Kinsley et al., 2019; Makau et al., 2021). Average path length was defined as the shortest path (or geodesic) among two sites averaged over all of the site pairs present in the network (Watts and Strogatz, 1998; Dubé et al., 2011). Finally, network diameter was defined as the longest length among any of the shortest paths connecting any two sites within the network (Wasserman and Faust, 1994; Lee et al., 2017).

Identification of Biosecurity Breaches

To identify employee movements that were potential breaches when considering between-site biosecurity protocol, system 2-specific "nights down" rules were discussed with the industry partner. The term "nights down" refers to the number of nights that are required for an employee to wait before entering a production site higher on the herd's health pyramid (i.e. sow or breeding sites) after visiting a site lower on the health pyramid (i.e. finishing site). The nights down protocols assessed here were solely based on a site's production type and did not take into account the health status of the site. This information was used following the collection of employee movement data to quantify and highlight the number and types of occurrence of biosecurity protocol breaches that had occurred during the study. A breach to the biosecurity protocol was defined as an instance when an employee entered a site premises of a site type after previously visiting a site of a different production type within a shorter duration of time than what was required by the company's protocol. The nights down protocols included the requirement of two nights prior to entering a GDU and one night prior to entering a sow farm after previously entering nursery or finishing site, as well as one night prior to entering a sow farm after previously entering a GDU. The occurrence of biosecurity breaches was also investigated and described by company department category.

Results

For the accuracy estimate, five employees from System 1 kept manual written site entry logs while also maintaining the use of the geofencing application for a period ranging between one to six weeks. This resulted in 398 observations from the written logs (range 9-190 observations per person; median = 63). Of these 398 observations, 379 were also digitally recorded by the geofencing mobile application, resulting in a proportion of 95.23% that the geofencing platform accurately captured the manually recorded site entries. Description of the frequency of site entries and the number of unique nodes included in the multiplex network by site type are included in Table 4.1.

Table 4. 1 Description of the frequency of site entries and unique nodes included in the network by site type from System 2

Site type[1]	Number of sites with at least one entry[2]	Total number of entries[3]	Number of sites (nodes) with at least one indirect connection within the whole network[4]
Boar Studs	2	3	0
GDU[5]	46	149	38
Sows	48	420	42
Nurseries	20	81	19
Wean to Finish	404	1026	366
Finishers	111	256	100
Total	631	1935	565

[1] The type of the site refers to the phase of production it specializes in.

[2] Total number of sites that had at least one recorded entry (employee passes through a geofence) during the study period by site type.

[3] Total number of site entries (employee passes through geofence) that had occurred during the study period by site type.

[4] Total number of unique sites that had at least one connection to another site within the same day during the study period by site type.

[5] Acronym for "Gilt Developing Unit".

Description of the System 2 department categories including the number of employees represented, the total number of site connections during the study period, as well as the number of non-reflexive weighted arcs included in the network analysis by department category is included in Table 4.2.

Table 4. 2 Description of the System 2 department categories and site connections during study period

Department Category	Number of employees	Total number of site entries	Total number of directed site connections	Number of directed non-reflexive site connections[1]
Communications & Information Systems	11	190	99	89
Maintenance	22	446	231	156
GDU[2]	5	69	14	13
Sow	8	123	31	8
Wean to Finish	30	1009	541	532
Other	14	100	17	13
Total	90	1937	933	811

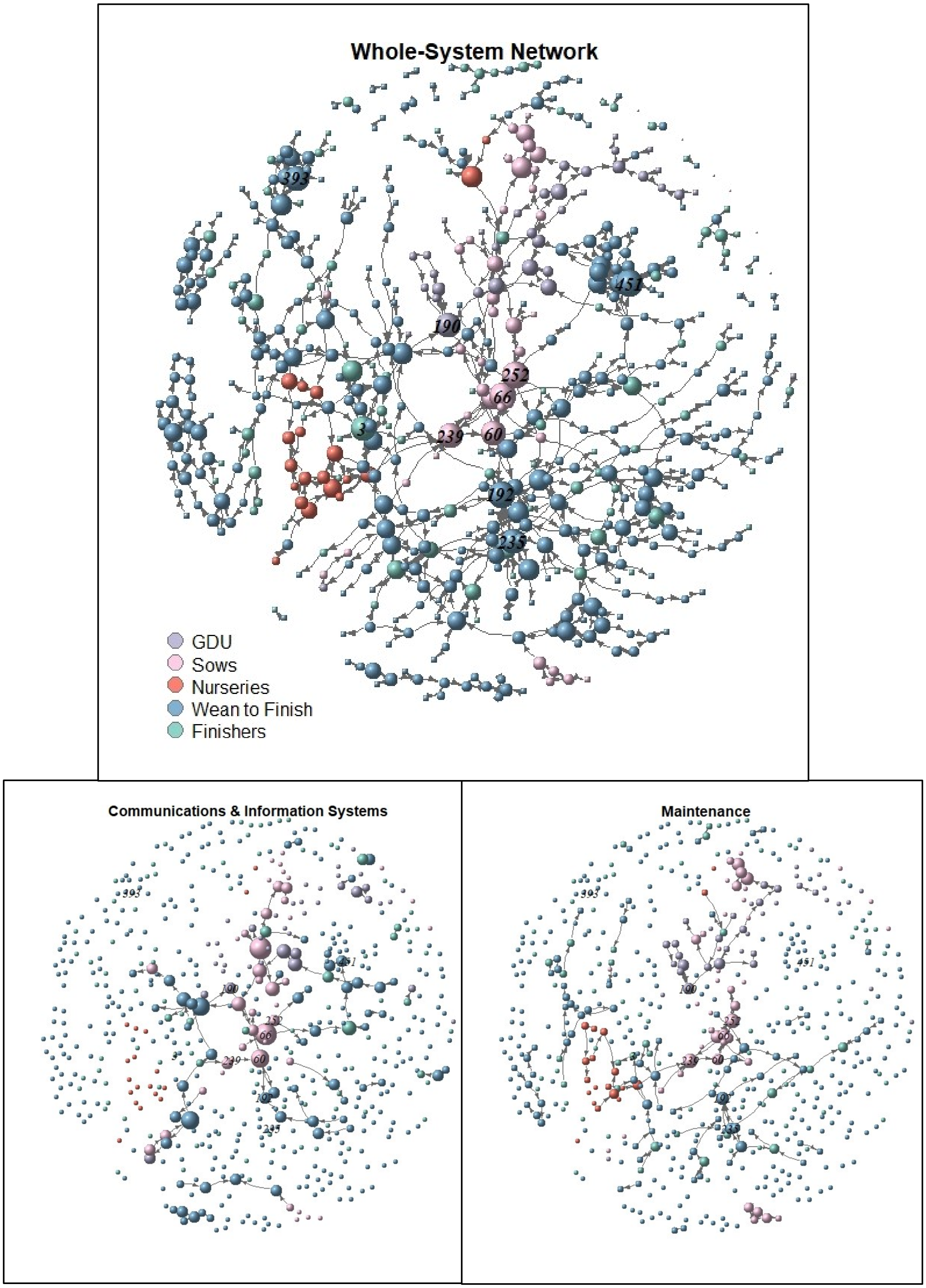
[1] Total number of site connections established by a directed employee movement in which the source site was also not the destination site.

[2] Acronym for "Gilt Developing Unit".

Graphical representation of the social network of site connections that occurred during the study period for the entire system, as well as for each department category are displayed in Figure 4.1. In this figure, nodes (sites) are sized according to the number of total degree (unique site connections to other sites either outgoing or incoming) for that site and node color corresponds to the production type of the site. The site ID is displayed in black on the ten sites with the highest total degrees.

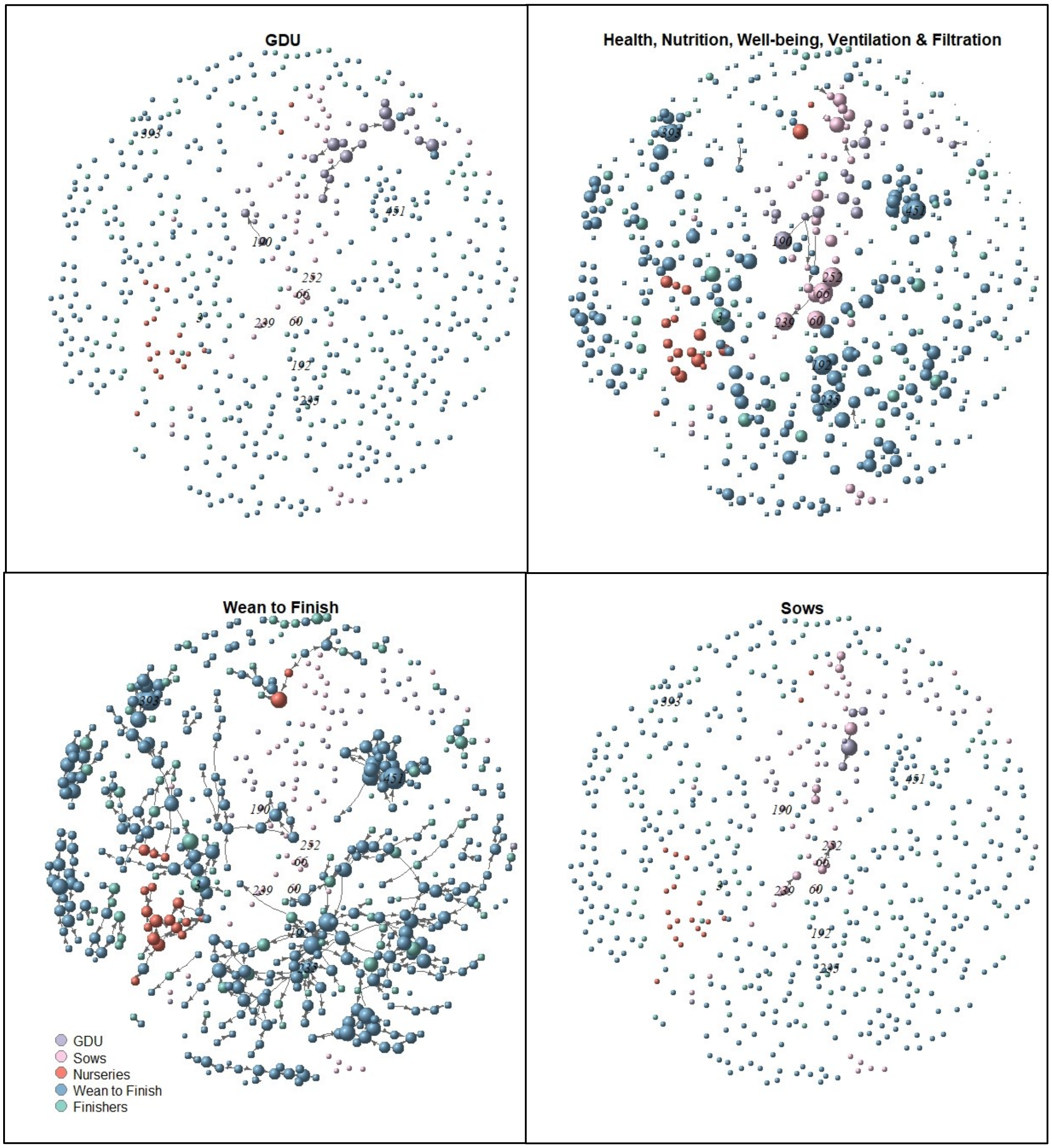
Description of node centrality in terms of total degree, in-degree, and out-degree for the top ten sites with the highest total degree in the whole-system network as well as by each department category multiplex layer are displayed in Table 4.3. Global descriptive statistics including number of nodes, number of edges, number of connected strong components, size (number of sites) of the largest strong component, density, transitivity, average path length, and the network diameter, for the whole-system multiplex network and each department category multiplex layer are displayed in table 4.4. The total number of movements during the study period that were breaches to the nights-down biosecurity protocol established by System 2 by movement type and department category are displayed in Table 4.5. There were a total of 1861 connections between sites when also considering consecutive employee site entries that did not occur on the same day. Of these, 0.64% (12/1861) were identified as breaches to the company's standard nights-down biosecurity protocol. When broken down by department category, 75% (9/12) of the breaches were from an employee that worked within the "Communications and Information Systems" department, which included two movements from a GDU to a sow farm, two from a finishing site to a GDU, and five from a finishing site to a sow farm.

Figure 4. 1 Graphical representation of the whole-system network and by department category



Continued

Figure 4.1 continued



In this figure the site type of the nodes (sites) are indicated by color as shown in legend in the bottom left corner. The nodes are sized according to the degree of the node corresponding to each multiplex layer (department category) and are labeled according to site ID number in black writing. The arcs (directed site connections) are indicated by the grey arrow pointing in the direction of the movement and are weighted by multiple occurrences of the same movement by department category, which is represented by arrow thickness. Node placement is the same for each multiplex layer.

Table 4. 3 Node centrality measures of degree, in-degree and out-degree for the top ten sites with the highest degree in the whole-system network and comparison by department category

		Top ten sites with highest degree in the whole-system network									
Department Category	Site ID[1]	192	252	66	451	190	235	239	3	60	393
	Site type[2]	Wean to Finish	Sow	Sow	Wean to Finish	GDU[3]	Wean to Finish	Sow	Finisher	Sow	Wean to Finish
Whole-System	Degree[4]	9	9	9	9	8	8	8	8	8	8
	In-degree[5]	5	6	4	5	3	4	4	5	3	4
	Out-degree[6]	4	3	5	4	5	4	4	3	5	4
Communications & Information Systems	Degree	2	2	5	0	2	0	0	0	4	0
	In-degree	1	1	2	0	1	0	0	0	2	0
	Out-degree	1	1	3	0	1	0	0	0	2	0
Maintenance	Degree	5	6	4	0	4	4	6	2	4	0
	In-degree	3	4	2	0	2	2	3	1	1	0
	Out-degree	2	2	2	0	2	2	3	1	3	0
GDU	Degree	0	0	0	0	1	0	0	0	0	0
	In-degree	0	0	0	0	0	0	0	0	0	0
	Out-degree	0	0	0	0	1	0	0	0	0	0
Sow	Degree	0	1	0	0	0	0	1	0	0	0
	In-degree	0	1	0	0	0	0	0	0	0	0
	Out-degree	0	0	0	0	0	0	1	0	0	0
Wean to Finish	Degree	2	0	0	9	0	4	0	6	0	8
	In-degree	1	0	0	5	0	2	0	4	0	4
	Out-degree	1	0	0	4	0	2	0	2	0	4
Other[7]	Degree	0	0	0	0	1	0	1	0	0	0
	In-degree	0	0	0	0	0	0	1	0	0	0
	Out-degree	0	0	0	0	1	0	0	0	0	0

[1] Arbitrary numerical identification number assigned to an individual site.

[2] The type of the site refers to the phase of production it specializes in.

[3] Acronym for “Gilt Developing Unit”.

[4] Total number of unique connections an individual site has to other sites regardless of directionally of the employee movement.

Continued

Table 4.3 footnote continued

[5] Number of site connections of an individual site that was the destination of an employee coming from another site.
[6] Number of site connections of an individual site that was the source of an employee moving to another location.
[7] Encompassed the departments of Health Services, Nutrient Management, Production Well Being, and Ventilation and filtration.

Table 4. 4 Global descriptive statistic for the whole-system multiplex network and each department category multiplex layer

Network layer	Number of nodes	Number of directed non-reflexive weighted edges[1]	Number of strongly connected components[2]	Size of the largest strong component[3]	Density[4]	Transitivity[5]	Average path length[6]	Network diameter[7]
Whole-system	565	775	19	484	0.002432	0.106239	12.00264	30
Communications & Information Systems	105	89	20	28	0.00815	0.031579	3.240469	11
Maintenance	159	149	29	20	0.005931	0.089286	3.083183	12
GDU[8]	19	12	7	4	0.035088	0	1.266667	3
Sow	13	8	6	3	0.051282	0	1.111111	2
Wean to Finish	429	504	48	55	0.002745	0.136653	3.07212	12
Other[9]	24	13	12	2	0.023551	NA	1	1

[1] Number of edges established by a directed employee movement in which the source site was also not the destination site. Edges were weighted according to multiple occurrences of the same individual edge by the same department category.

[2] A subset of sites in the network in which any two sites in that subset are reachable along a directed path.

[3] The number of nodes (unique sites) within the largest strongly connected component. Also known as a giant strongly connected component.

[4] The proportion of site connections that are observed in the network out of all possible site connections.

[5] The probability that two sites are connected, given they both share a connection with another site. Also known as the clustering coefficient.

[6] The shortest path (or geodesic) among two sites averaged over all of the site pairs present in the network.

[7] The longest length among any of the shortest paths connecting any two sites within the network

[8] Acronym for “Gilt Developing Unit”.

[9] Encompassed the departments of Health Services, Nutrient Management, Production Well Being, and Ventilation and filtration.

Table 4. 5 Number of nights down protocol breaches by movement type and department category

Department category	Movement type[1]				Total (%)
	GDU[2] to sow farm	Finisher to GDU[2]	Finisher to sow farm	Nursery to sow farm	
Communications & Information Systems	2	2	5	0	9 (75%)
Maintenance	0	0	0	1	1 (8.3%)
GDU[2]	0	0	0	0	0
Sow	1	0	0	0	1 (8.3%)
Wean to Finish	0	0	0	0	0
Other[3]	0	0	1	0	1 (8.3%)
Total (%)	3 (25%)	2 (16.7%)	6 (50%)	1 (8.3%)	12

[1] The type of movement from one site to another identified as a breach to System 2's standard operating nights down protocols.

[2] Acronym for "Gilt Developing Unit".

[3] Encompassed the departments of Health Services, Nutrient Management, Production Well Being, and Ventilation and filtration.

[4] A gilt developing unit

Discussion

This study evaluated the application of a geofencing technology to record indirect site connections based on employee movements in vertically integrated multisite swine production systems under field conditions. The geofencing technology platform utilized in the study was a mobile application and it was assessed through an accuracy estimation comparing the current industry standard of written site entry logs to the digital record of the geofencing platform. Furthermore, the data collected during the field application was used to perform social network analyses with the goal of describing site connectivity patterns of employee movements between sites and to investigate the potential of biosecurity monitoring through the identification of breaches to the production company's standard operating nights down procedures.

The capabilities of precision livestock farming from the ever-growing interconnectivity of individuals and entities through the "Internet of Things" and location monitoring from GPS utilization, have afforded producers more oversight among an expanding vertically integrated production landscape. Within the swine industry, the threat of costly endemic diseases, such as the porcine reproductive and respiratory syndrome virus, along with foreign animal diseases such as the African swine fever have underlined the necessary prioritization of biosecurity as part of standard operating procedures. Additionally, faced with ongoing labor-supply issues (Black and Arruda, 2021) and difficulty with biosecurity compliance among agricultural workers (Racicot et al., 2011b; Backhans et al., 2015), monitoring of biosecurity protocol is an important aspect of maintaining successful levels of production in the swine industry. This study supports the feasibility of applying geofencing technology, such as the one used here, under field conditions in commercial swine production.

Assessment of the geofencing mobile application used in this study was completed through estimating the proportion of digital site entry records the mobile platform correctly recorded out of the site entries that were manually recorded on paper sheets from five employees within System 1. This resulted with the mobile geofencing platform recording 95.23% (379/398) of the observations as recorded in the manual written logs. This percentage of digitally recorded site entries seems to be representative of a fairly high level of accuracy of the mobile geofencing application as compared to the written manual logs. While there are no similar technology evaluations in the literature with respect to the use of geofencing in livestock production, a study by Nguyen et al. (2017) that evaluated the use of mobile geofencing to ascertain hospitalizations reported that the geofencing system recorded 17 out of a total of 22 hospitalizations during the study. This resulted in a sensitivity of 77%. It is important to note however, that the estimation in the current study relies entirely on the complete and consistent cooperation of the participating employees, as they were not directly observed while completing the study and as such is subject to information bias introduced through human error.

Social network analyses is an analytical tool growing in popularity and its application in the field of veterinary epidemiology has increased in recent years. It has been utilized to evaluate the network of animal movements in particular throughout swine production systems or regions and to investigate the epidemic potential of disease transmission between production sites from direct contact between animals (Lee et al., 2017; Kinsley et al., 2019; Passafaro et al., 2020; Makau et al., 2021). However, few studies have evaluated social networks of the contact patterns of swine production systems through indirect site connections, such as those created by employee or vehicle movements between sites (VanderWaal et al., 2018). This remains an important epidemiological aspect of disease transmission within a swine production system, as the role of fomites in the transmission of important swine diseases between sites is well documented in the literature (Dee et al., 2004; Otake et al., 2002; Pitkin et al., 2009). Furthermore, given the difficulty to adequately capture employee movements throughout a production system, the geofencing platform used in this study provided the data necessary to perform such an analysis.

The whole-system social network in this study was predominately comprised of movements by employees within the departments of “Wean to Finish”, “Maintenance”, and “Communications & Information Services”; with the “Wean to Finish”, and “Maintenance” departments also having the greatest number of employees, with 30 and 22 employees, respectively (Table 4.2). This is reasonable for the “Wean to Finish” category when considering the largest number of sites in the production system are going to be designated for growing pigs with fewer specialized sites for breeding and multiplication. Furthermore, with the large number of sites within this production system, it is understandable that “Maintenance” is the second largest department category. Maintenance employees service all the different types of sites within the system and therefore a large production system such as the one in this study would require a considerable number of employees in this department.

When evaluating the top ten most connected sites with respect to degree centrality, the production-based departments (i.e. “GDU”, “Sow”, and “Wean to Finish”) were only represented (i.e. at least one site connection) within their respective site-types (e.g. sow workers for sow sites, etc.). In contrast, the “Communications & Information Services” department were represented in half of the sites (two sow farms, two GDU’s, and one wean to finish site) and the “Maintenance” department was in all but two wean to finish sites out of the 10 total sites included in Table 4.3. This highlights their role in increasing the connectivity between sites within different phases of production.

Within the whole-system network, there was a total of 19 strongly connected components with the largest (equivalent to the giant strongly connected component) comprising of 484 sites (86%), which can be an estimation of the upper bound of outbreak potential at the end of the study duration (one month) (Table 4.4). The transitivity of the whole-system network was 0.106, which is the estimated probability that any two sites that share a connection with a single site are also connected to each other. This measure is also a measure of how clustered a network is, with higher values representing a more clustered network, and can be an indication of how easy or difficult it may be for a pathogen to spread throughout a network, as higher clustering means that pathogens could be trapped within an individual cluster. The transitivity estimate of the whole-system network in this study is higher than those reported by Passafaro et al. (2020), which reported an average of 0.017, and Makau et al. (2021) which reported similar transitivity estimates. However, this contrast is likely due to those studies evaluating networks established by swine movements, which follow a hierarchical flow through the system based on production phase, whereas the present study evaluated networks established through employee movements. The "Wean to Finish" department had the most strongly connected components out of any department category with 48; the largest strongly connected component containing 55 sites. However, the "Wean to Finish" department category also had the high transitivity of 0.137, indicating a higher level of clustering compared to the other departments. Transitivity was negligible for the "GDU", "Sow" and "Other" (encompassed Health Services, Nutrient Management, Production Well Being, and Ventilation and filtration), department categories. This is a reflection of their small network sizes (e.g. number of nodes, density, average path length, and network diameter) and their role in the formation of the whole-system network as it compares to the other departments. This could be a further indication that the employees within these department categories stay contained within their respective production areas. This makes sense intuitively from a biosecurity standpoint, as these site types are considered of higher importance on the health pyramid and thus would typically not want to be moving amongst sites lower on the health pyramid (e.g. wean to finish or finisher sites).

In contrast, the "Communications & Information Systems" department had the second highest size of the largest strongly connected component and the lowest transitivity value (Table 4.4). This, along with their average path length of 3.24 and network diameter of 11 (indicating a more "spread out" network), could further highlight this department's role in connecting sites of different types within the whole-system network.

There was a total of 12 nights down breaches identified during the study duration (Table 4.5). The department with the highest number of breaches was the "Communications & Information Systems" department, which accounted for 75% (9/12) of the breaches. These breaches predominately consisted of a movement from a finishing site to a sow farm, however movements from a GDU to a sow farm as well as from a finishing site to a GDU also occurred multiple times during the study period. Interestingly, the "Communications & Information Systems" department was the most represented across different movement types during the study. These findings, along with the aforementioned network properties, further supports the significance of these service provider and technical support roles with respect to potentiality of disease transmission between different sites.

There were limitations within the present study that may contribute to bias introduction into the results. The first would be the limited duration of the study interval, which only included one month of employee movements between sites. The temporally dynamic nature of swine production may limit the inference that can be made with such a limited interval of time and future studies evaluating site connectivity patterns from employee movements should include a longer duration to evaluate these changes over time (Makau et al., 2021). Additionally, the nights down biosecurity rules included in the dataset were established by the participating production company (System 2) and may have comprised of site entries that were acceptable by the company's standards but were unable to be verified here (e.g. employee staying on the outside of the premise and not entering the barn). This occurrence could result in misclassification bias with respect to the description of biosecurity breaches presented here. Furthermore, with only a few production systems included in the present study, generalizability of these findings to other production systems in different regions may be limited. However, both of these production systems did involve a large number of sites. This study demonstrated a proof-of-concept of the potential benefits in the information obtained through the use of geofencing technology and its application to vertically integrated production systems.

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Chapter 5: Conclusions

The work within this dissertation was driven with the goal of offering science-based insights pertaining to animal caretaker turnover on swine breeding farms and the potentiality of technological applications to swine production aimed at facilitating internal and external biosecurity monitoring. The specific objectives were to investigate the association between employee turnover and subsequent productivity, as well as to evaluate two technological applications aimed at facilitating internal and external biosecurity monitoring under field conditions.

In the first study (chapter 2), turnover of animal caretaking personnel in the participating farrow-to-wean farms was confirmed to be highly variable and considerably high in the majority of farms in this study. Additionally, animal caretaker turnover was associated with subsequent trends of production. The implications of the statistical analysis point towards improvements in both monthly productivity measures evaluated (number of pigs weaned per sow (PWS) and pre-weaning mortality (PWM) two months after an involuntary termination of an employee. However, only trends between the voluntary turnover (represented as linear spline segments) and subsequent productivity were observed. These findings warrant a deeper look at this relationship with a larger sample size and the inclusion of factors related to new hires and onboarding procedures. Nonetheless, frequent voluntary turnover was observed in many of the participating farms in this study. Frequent turnover coupled with the high importance of the animal caretaker role in maintaining high productivity and implementing internal and external biosecurity procedures consistently, monitoring the compliance of the biosecurity procedures among this dynamic workforce remains an important consideration for producers.

In the following study (chapter 3), an internal employee movement monitoring system was evaluated under field conditions within three farrow-to-wean farms. Increased movements between farrowing rooms over a two week duration were associated with decreases in subsequent productivity measured as PWS. This could be an indication of inadequacies in the effectiveness or implementation of biosecurity steps when moving between farrowing rooms, such as the proper maintenance of footbaths. While footbaths were used within two of the three participating farms, the maintenance of this procedure was not evaluated during the study. Validation of such internal biosecurity procedures under field conditions is needed. Howbeit, this proof-of-concept study showed that internal movement monitoring technologies can be successfully applied in the field, even in on-farm conditions within relatively remote rural areas in the U.S.

The final study (chapter 4), evaluated the application of geofencing technology within two vertically integrated multi-site swine production systems. The geofencing technology platform was assessed through estimating the proportion of site entries that were recorded manually by employees that were also digitally recorded by the mobile geofencing platform. This resulted in the geofencing platform accurately capturing employee site entries as compared to the written logs approximately 95% of the time. The geofencing platform was also used to capture employee movements between sites over the course of a month. This information was then used to create a social network of indirect site connections and to investigate the occurrence of potential breaches to the production system's standard operating nights down protocol. The results highlighted the importance of technical support and service provider roles within the company are with respect to increasing the number of indirect connections between sites that are within different phases of production. However, a more in-depth look at this relationship is warranted within a longer duration of time than what was captured in this study.

In conclusion, the application of technology to the production environment using beacon-sensing technology, or to the larger production system using geofencing technology, demonstrated how these can be implemented in the field to collect meaningful information. This information can be utilized to facilitate biosecurity compliance monitoring and direct disease mitigation strategies. These aspects become increasingly important among an evolving swine industry that experiences high employee turnover. Future steps for this research include evaluating the impact of animal caretaker turnover on productivity and the occurrence of disease challenges within farrow-to-wean farms with consideration of company onboarding, training, and incentive programs, as well as the capture of new hire information. Additionally, research into geofencing applications to swine production systems to evaluate social networks of indirect connection of swine facilities through employee movements should be further investigated with the inclusion of multiple production systems for a longer duration. Furthermore, the effect of biosecurity compliance technology on operational level biosecurity decision making of production workers should be assessed through prospective feedback and messaging techniques within swine production systems and include interdisciplinary collaboration with social sciences to better understand change in human behavior.

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