THE APPLICATION OF SYSTEMS THINKING IN CATTLE PRODUCTION

by

DOUGLAS SHANE

B.S., Kansas State University, 2011
D.V.M., Kansas State University, 2015

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Diagnostic Medicine and Pathobiology
College of Veterinary Medicine

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Abstract

Applying systems methods to cattle production requires investigators to think about whole systems when addressing study objectives. The research conducted for this dissertation emphasized studying whole systems using different methods. We studied cattle production systems through mathematical simulation and new indirect monitoring technologies. While the methods used for the research in this dissertation may be very different, all utilized systems methods to address the study objectives.

Firstly, we applied systems thinking methods and developed a dynamic, deterministic systems simulation of cow-calf production over a 10-year horizon. This model was used to investigate the effects the duration of postpartum anestrus (dPPA) has on reproductive performance. A large range of dPPA have been reported, so various primiparous cow and multiparous cow dPPA were simulated. We found that increasing the dPPA for primiparous and multiparous cows had a negative impact on herd performance and that the dPPA is an important factor in determining cow-calf performance success. We then used the cow-calf simulation to explore the effects of breeding nulliparous cows prior to the rest of the herd, known as providing Heifer Lead Time (tHL). We found that increasing tHL improved herd performance, especially with longer dPPA for primiparous cows.

Secondly, real-time location systems (RTLS) were used to indirectly monitor cattle behavior. These systems have been used to determine the amount of time cattle spend at eating and drinking locations. We modeled the probability of cattle participating in eating and drinking behavior when determined to be at these locations by RTLS and found that significant differences exist between individual calves and period of the day.

Finally, we explored associations between bovine respiratory disease (BRD) and animal-to-animal contacts as determined by RTLS in beef cattle. We found that the probability of BRD

diagnosis was associated with the amount of time 4 days' ago that a calf was in calf-contact with calves assumed to be shedding BRD pathogens.

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Dedication

I would like to dedicate this dissertation to my wife, Katelin.

Chapter 1 - The application of the systems approach in food animal production and food animal veterinary medicine: a review

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Abstract

The systems approach uses methods and processes that are useful for studying complex systems of interest. Scientists using the systems approach conceptualize a mental model of a system of interest and then use mathematics to simulate the system. The systems approach allows investigators to explore and discover complexity that would not be possible with traditional methods. The objective of this review was to identify research investigating food animal production and health where investigators identified that systems approaches were used and to describe characteristics of the simulation models implemented to address the study objectives.

The review identified 30 studies that reported using the systems approach to investigate livestock systems. These papers simulated swine, small ruminant, dairy cattle, and beef cattle systems at the individual animal level and production enterprise level. This review identified ways in which the systems approach has been applied to food animal production and veterinary medicine. Current practice is to utilize systems dynamics to simulate systems over longer periods of time. More robust simulations of food animal systems will be developed as software and computational abilities improve. The systems approach will continue to be a useful means to study complex livestock systems.

Introduction

The systems approach has been described as a "philosophical basis for problem identification, analysis and decision making" (Fitzhugh and Byington, 1978). It has also been described as the process of applying systems thinking and systems dynamics methodology to answer questions about complex systems (Cavana and Maani, 2000). Systems dynamics has its roots in industrial engineering and was developed by Jay Forrester, a scientist at MIT. Users conceptualize a mental model of a system and implement equations to describe the relationships between parts of the system over time (Forrester, 1958). These methods have been increasingly applied to multiple disciplines including epidemiology, public health, medicine, engineering, chemistry, and ecology (Galea et al., 2010; Ouyang et al., 2010; Kappagoda, 2014; Carey et al., 2015; Azanu et al., 2016).

The application of the systems approach to veterinary science and animal agriculture was advocated by Scott Hurd in 2011 where he called for these methods to be utilized by veterinarians and scientists when studying food production systems (Hurd, 2011). There have been multiple reviews over the use of simulation models in veterinary science and calls have been made for broader application of the methods (Hirooka, 2010; Vetharaniam et al., 2010; Doeschl-Wilson, 2011; Hurd, 2011; Headon, 2013). Calls for the integration of various simulation models and experimental data into larger, more complex systems models have also been made (Levine and Hohenboken, 1982). These reviews offer excellent examples of mathematical simulation models, but do not reveal the current state of use of the systems approach in animal agriculture and veterinary science. The objective of this review was to identify research investigating food animal production and veterinary medicine where investigators identified that systems approaches were used and to describe characteristics of the simulation models implemented.

Materials and Methods

Criteria for inclusion

To be considered for inclusion in the review, authors of the manuscript needed to explicitly state that systems approaches were used and needed to simulate livestock production species or livestock enterprises with outcomes related to animal performance, animal health, or economics. Simulation models with an environmental or ecological outcome of interest were not eligible for selection. The full text needed to be available in English for inclusion.

Search strategy

Electronic databases used for the search included PubMed, CABI, and AGRICOLA. All searches were restricted to the years 1960 to 2016. The search terms used were ("systems analysis" OR "systems analyses" OR "systems oriented approach" OR "system dynamics" OR "systems dynamics" OR "systems approach" OR "systems thinking" OR "systems modeling" OR "system modeling") AND (livestock OR cattle OR calves OR cows OR dairy OR pig OR pigs OR chicken OR chickens OR poultry). The original search was conducted on June 16, 2016 and was updated on July 20, 2016.

Selection of manuscripts

The search and review of the literature was conducted by a single graduate student (D.D. Shane). Research manuscripts and dissertations identified as applying systems methods to food animal production or food animal veterinary science with outcomes related to animal performance, animal health, or operation finances were selected for inclusion.

Results

The initial search, including review of titles and abstracts, resulted in 69 studies being identified for further review. After reviewing the complete manuscripts, 39 were excluded for the following reasons: 16 were reviews over the use of simulation models, 9 did not have the full text article available in English, 6 did not use systems methods, and 6 did not have an outcome of interest to the review. A total of 30 articles were used in the review, all of which simulated livestock production using some variation of systems methods (Fig. 1.1).

Multiple livestock species were identified in the search of the literature and included swine, small ruminants, dairy cattle, and beef cattle. Articles were divided based on the specie of interest. The treatment of time (static vs dynamic) is described, as is the discrete time unit or time step of calculation for dynamic models. The treatment of variability (stochastic vs deterministic) is also described for each model. A summary of the manuscripts identified by this review and their characteristics is shown in Table 1.1.

Swine

Swine production systems are marked by movement of animals through the production system at regular time intervals and are defined by production constraints such as gestation length, time of weaning, growth rates, and finishing weights. Swine operations must also intensely manage the animal population to maximize the use of facilities. In traditional research, swine production systems may be more easily controlled when compared to other food animal systems, but researchers are limited to a small number of factors to investigate at a time due to constraints of live animal research. Furthermore, many swine systems are hierarchical and interdependent, with decisions made at one level of production potentially having impacts on other levels of the system. These facts make it difficult to understand how multiple system components interact to impact outcomes in the system. Commercial swine producers generally collect some form of animal data at regular intervals (day or week) which may be used to help develop systems models. Developing models of swine production may allow investigators to study the system over multiple turns of animals within a single level of the production system such as the nursery phase or over the entire production cycle.

Two papers were identified as applying systems methods to swine production. Investigators at North Carolina State University performed a systems analysis to study the impact that different sow replacement rates had on profitability over a 10-year period in a hierarchical breeding structure (Faust et al., 1993). The analysis used a stochastic bioeconomic simulation model of a market hog production system and accounted for stages of production including non-pregnant sows, gestating sows, lactating sows, service boars, replacement gilts, and growing stock (Faust et al., 1992). The time unit of calculation was set to one week. This analysis allowed for multiple breeding management practices to be compared without requiring live animal studies. From this analysis the authors learned how replacement rates affect swine performance over a 10-year horizon and what characteristics differed between the most profitable and least profitable herd scenarios.

In 2014, a deterministic, dynamic simulation model of a pig supply chain was developed to visualize the movement of pigs through the entire production chain of an integrated pig company and was used to identify important factors at each level of production that affect the number of pigs available for slaughter (Piewthongngam et al., 2014). The model was built to incorporate great grandparent, grandparent, and parental stocks, as well as fattening units. Complexity at several production stages such as breeding, gestation, farrowing, replacement, boar management, and piglet growth was incorporated. The time step for calculation was set to one week and simulations were set to occur over a three-year period. This model allowed for identification of factors important to determining the number of available pigs for harvest and likely enhanced long term strategizing efforts. This model could be applied to future investigations involving the simulated production system.

Small Ruminant

Small ruminant production systems do not collect individual animal data as frequently as swine production systems, which may limit the availability of data from commercial enterprises. Despite this, systems methods have utility because data may be incorporated from multiple sources and a model of the system may be used to investigate problems not amenable to investigation in traditional production or research settings. Small ruminant production systems are greatly defined by the species' seasonal breeding physiology and gestation length. Physiologic parameters such as these may be incorporated with the data or information collected from commercial enterprises such as weaning weights.

The physiologic constraint of seasonal breeding limits the times at which live animal studies may take place and may also limit the number of replicates available for live animal studies. Unlike swine production, where there are likely to be pigs in each stage of production at any given time, whole herds of sheep and goats will be simultaneously in each production stage as a group. Knowing the long term implications of a management strategy or studying many production factors across multiple production cycles is nearly impossible and will be met with significant error due to differences in weather, forage availability and quality, and animals between production cycles. Systems thinking methods allow small ruminant systems to be examined under numerous scenarios over longer periods of time than would be feasible with live animal studies, while holding factors constant that may vary significantly in the field situations.

Six systems methods papers involving small ruminant species were identified. Profitability and productivity of confinement sheep production systems have been studied using a sheep-forage-grain simulation model (Smith and Lee, 1980). Investigators were interested in the return on investment of various management practices and labor, and incorporated parameters for reproduction, growth, survival, and economics. The simulation was conducted using a deterministic mathematical model and had outcomes calculated for a single production year as a static model. This was an early mathematical model that described profitability under numerous scenarios and improved the understanding of confinement sheep operations without performing a multiple year, multiple site live animal study.

A simulation model of sheep production was developed to investigate the "*effects of varying genetic potentials, nutritional levels, and management alternatives on estrus, conception, birth, lactation, nutrient intake, growth, wool growth, and death"* (Blackburn and Cartwright, 1987a). The model was deterministic and was constructed around different biological states within a sheep production cycle. A 15-day time-step was used for the model and was based on sheep reproductive physiology. The model was designed to simulate 10 years of sheep production. This model was used to investigate the effects of shifting environmental conditions on production and efficiency, as well as effects of genotype and environment on production characteristics (Blackburn and Cartwright, 1987b, c). Inclusion of the dynamic relationships that exist between model parameters allowed for a broader understanding of the production system and highlighted important relationships that exist in small ruminant production such as the relationship that was found to exist between environment, body size, and ewe milk production.

In 2006, a deterministic production simulation was developed to study grass-based lamb production systems in Chile at the farm level (Aguilar et al., 2006). The model was built to represent various regional sheep production systems and incorporated sub-models for the animals, the pastures, management factors, climatic conditions, and market conditions. The model simulated production per day over a single production year. This model was utilized to identify systems and situations in which production costs were minimized and net returns were maximized. This study specifically examined various supplementation strategies and stocking rates in different environmental and pasture scenarios. It would be nearly impossible to explore differences in productivity of the "same herd" under so many varying parameters through live animal studies. The methods revealed that some new technologies of interest would not provide benefit for farms in the region of interest in Chile and did so without incurring the significant expense of implementing new methods on farms without prior testing.

Scientists in Brazil developed a simulation of dairy goat production that accounted for the dynamic flow of animals through the production cycle of a dairy farm (Guimarães et al., 2009). The simulation model was used to identify system components that may have an impact on herd dynamics and compared the economic differences between two management practices of interest. The authors report the model was mostly deterministic in nature, but variability was introduced to some model parameters. Components accounting for management practices, reproductive constraints, nutrient demands, season, and costs of operation were included in the model. The simulation modeled production over 10 years and had a simulation time step of 1 month. This model found that a two breeding season management strategy was superior to a one breeding season management strategy for commercial dairy goat herds. Studying these various breeding strategies in live animals would have required multiple herds and multiple years to adequately compare the strategies.

Dairy Cattle

Similar to swine production systems, dairy cattle production systems capture data at frequent, regular time intervals, especially for cows in lactation. Many types of data are collected daily such as health status, milk production, and feed delivery. Prior research has also contributed a large body of data related to cattle physiology and production. Unlike small ruminants, dairy cattle are not strictly seasonal breeders. In commercial dairy cattle systems cohorts within the herd will be in one of several production states at any given point in time in a production year, making them different from beef cattle production systems in which whole herds tend to be in a similar stage of production. For many livestock systems, important outcomes are related to a single, final harvesting weight of animals for meat production. In dairy systems, lactation and daily milk production are important outcomes in addition to harvest of the animals for meat. This results in dairy cows contributing to production outcomes over their productive life, as opposed to having a one-time sale or harvest value. The complex relationships between reproduction, lactation, nutrition, environment, and other factors can be challenging to understand and control, thus making systems methods an excellent tool to study dairy cattle systems.

Seven articles were identified which applied systems methods to dairy cattle. The economic impact of various estrus detection rates and insemination success rates were investigated utilizing a stochastic model simulating reproduction in dairy cattle at the herd level (Oltenacu et al., 1981). In this model, dairy cattle were modeled through a dynamic sequence of reproductive events that were modified by management, environmental, and biological factors. The analysis simulated a single production cycle and the time step used for calculation was 1 day. This model accounted for costs associated with additional labor expenses and sought to identify practices that resulted in the best reproductive performance and economic returns without needing to execute a live animal study.

A dairy cow production model was developed to perform an economic comparison of utilizing artificial insemination versus natural service breeding programs accounting for costs, expected reproductive performance, and genetic improvement potential (Hillers et al., 1982). The deterministic mathematical model was applied to a single production cycle and was static. The static nature of the model did not allow for description of the dynamic relationships that may exist in different production scenarios. The model found differences that would be expected to exist between dairy systems utilizing artificial insemination breeding management and dairy systems utilizing natural service breeding management but added additional value by incorporating the value of genetic improvement.

A deterministic systems analysis of buffalo production in India was conducted via a simulation model to identify system traits that optimize productivity on dairy farms (Sethi and Nagarcenkar, 1987). Dairy farm enterprises were simulated by the model, with day serving as the time-step of simulation. The authors reported simulating “multiple years” but did not indicate the amount of time simulated. The authors accounted for multiple cow production states and components of the dairy management system.

Australian scientists integrated previously developed simulation models to investigate a newly developed intensification system for dairy farms and compared the economic risks of the new system compared to conventional systems (Fariña et al., 2013). The study incorporated a dairy production simulation model, a pasture growth simulation model, a forage crops growth model, and a whole farm budget model to produce model outcomes that could be further analyzed using a stochastic budgeting technique to evaluate the business risk for the various production scenarios evaluated (Keating et al., 2003; Johnson et al., 2008; Bryant et al., 2010). Simulations were set to model two years of production at a 1-month time step. This analysis introduced a new approach by incorporating previously developed simulation models into a single integrated model to perform a broader systems analysis.

A dynamic model was developed to improve the understanding of feed intake patterns and fluxes in energy and protein reserves in dairy cattle as they exhibit various body condition scores in different phases of the reproductive cycle (Tedeschi et al., 2013). A commercial modeling program, Vensim Decision Support System version 5.9 (Ventana Systems Inc., Harvard, MA) was used for development of the model. The model was stochastic and simulated nutritional, metabolic, and reproductive dynamics of an individual cow over 5 lactations and 4 dry periods. A time unit of simulation of 0.0625 days (90 minutes) was used. Investigators then planned to incorporate the model into other nutritional models, creating a broader system simulation of dairy cow nutrition under various physiologic conditions.

In 2014, investigators developed a model of adipose tissue metabolism (Huber et al., 2014b). This model was integrated with pre-existing nutritional models for dairy cows and a model of reproductive processes (Baldwin and Donovan, 1998; Boer et al., 2011). The integrated model was then used to investigate the impact adipose tissue gene expression may have on dairy cow performance and reproduction in the face of normal variation of other system parameters. The prior integrated model was then incorporated with a model simulating estrous cyclicity in dairy cows to explore how dairy cow performance may change in response to variation in milk production and feed intake, and adipose and visceral tissue metabolism (Huber et al., 2014a). Both of these studies simulated complex systems within the dairy cow. The time step used for simulation was 0.1 days and the models were validated against 140 days of lactation data.

Beef

The beef industry is marked by a few distinct and different production stages including the cow-calf stage, the backgrounding or stocker stage, the feeding or finishing phase, and the harvesting stage. The cow-calf stage is dependent on reproduction and is the source of cattle to the other production stages, as well as serving as its own supply of replacement animals. Because a cow is capable of having one calf in a years' time, typically a herd will have one calf crop in a year with the possibility of a ranch having two separate herds, each calving at different times of the year and each producing their own calf crop. Studying changes in production or performance is challenging in cow-calf systems because treatments are commonly applied at the herd level, making replication in field studies difficult. Backgrounding and feedlot production systems are marked by cattle entering and leaving the production system at irregular intervals throughout a production year. These systems are largely defined by cattle growth and expectations for carcass size and or quality at the time of harvest. Daily data is commonly available on cohorts of animals, but individual animal data are not as commonly collected. While pens of cattle are easier to enroll in studies when compared to cow-calf herds, it may still be too expensive to attain enough pens of cattle to effectively perform a study involving complex interactions of interest over time. Studying the relationship between cow-calf systems and backgrounder or finishing systems is potentially more obscure than studying individual stages of production due to the stages often being at separate sites, not being owned by the same individuals, and cattle being commingled from multiple sources.

Fifteen articles were identified that applied systems methods to beef cow production. In the 1970's, Long et. al. developed a deterministic simulation model of beef production at the herd level to determine how changes in production efficiency related to different mature cow sizes and herd management practices (Long et al., 1975). The same model was used to simulate differences related to cross breeding programs, heterosis, and breed complementarity (Cartwright et al., 1975; Fitzhugh et al., 1975). A Texas A&M graduate student used an updated version of the model to simulate cow-calf production in the country of Venezuela to determine impacts different genotypes and management strategies have on production (Ordóñez-Vela, 1979). A single production cycle was simulated and the model was static. These analyses identified which production scenarios resulted in best outcomes and were early examples of the application of systems methods to beef production. The model used in these analyses was used to address multiple different objectives, highlighting how models may be used to efficiently address multiple questions.

Differences in the efficiency of the production of beef among various mature cow-sizes, feeding programs, and slaughter weights were examined using a deterministic mathematical model (Fox and Black, 1976). The modeled beef herds had components for energy requirements, feed consumption, feed nutritional content, reproduction, and calf growth. The model was static and performed calculations for one production cycle. Although this was an early model and was constrained by available computing capabilities, it incorporated a remarkable amount of complexity and was able to address an objective that would have been prohibitive to pursue with live animal studies.

Beef production scenarios were examined to determine what factors may be important in determining farm economic success for a specific region of South Africa using a deterministic simulation model. Various cattle marketing practices, climatic and environmental conditions, and management practices were incorporated in the analysis (Louw et al., 1978). The time unit of calculation was 1 year and a total of 53 years were included in the simulation. This was a very large time horizon and it is unclear whether forecasting 53 years of production was useful, but certainly understanding the factors that contribute to long term economic success in this region under all of the scenarios of interest would not have been possible without application of the methods.

Another deterministic model was developed to simulate plant growth, animal growth and reproduction and to determine energy use, cash flow, and net worth for simulated beef production enterprises (Loewer et al., 1980). The model was built to replicate the dynamic movement of cattle through production stages, and account for various cattle types, pasture types, and management scenarios. The model reports outcomes for a single production year and the time step of calculation was set to one day. While only a single production year was simulated, the model incorporated the dynamic relationships that exist between many different parts of the system.

A simulation model of cow-calf production systems in Montana range environments was developed to study herd performance under different production systems using deterministic and stochastic model components (Tess and Kolstad, 2000a). The authors built the model with the goal of examining changes in production outcomes related to “genotype, physiological state, gross forage quality, and management”. These authors then simulated various scenarios while varying the model parameters of interest, described their results, and analyzed the validity of the model (Tess and Kolstad, 2000b). The model used a 1-day time step and modeled a single group of replacement heifers for an expected longevity duration of 6 or 7 years of age, as opposed to modelling multiple age groups of animals within a single year. The model incorporated data and parameters from across disciplines and allowed for multiple questions to be addressed regarding cow-calf production systems.

A dynamic system model of a Nebraska beef production enterprise was developed to investigate the implications of various marketing scenarios for mature cows (Turner et al., 2013). The deterministic model accounted for cow population dynamics and financial dynamics. The main outcomes of interest were related to the net income of the operation. The model simulated 22 years, with the first 10 years serving as a stabilization period and the final 12 years being used for the analysis. The time unit of calculation was 1 week. This model was developed for a very specific production system but accounted for multiple age groups of cattle and multiple dynamic relationships that likely hold true in other production systems. Of interest was the use of a 10-year stabilization period, a method not clearly discussed in the other papers. The authors’ did this to allow for the model to stabilize and start replicating the behavior of the production system they were simulating.

Investigators developed the Northern Australia Beef Simulations Analyzer to model beef operations in northern Australia with the objective of studying the impact various interventions had on enterprise-level production and financial success (Ash et al., 2015). The deterministic simulation model had a 1-month time step and incorporated models for reproduction, growth, crop/forage growth, and pasture growth to be able to model the effects various interventions had on reproductive performance, calf growth, and mortality. The analyzer can be used to simulate multiple years of production. As with the previously discussed dairy system analysis that incorporated many simulation tools, this analysis also incorporated multiple previously developed tools and simulations.

Investigators have also designed simulation models for parasites of cattle including *Trypanosoma spp* and *Ostertagia ostertagi*. The deterministic model of trypanosomiasis was developed to improve the understanding of "infection characteristics in Ethiopian cattle" (Habtemariam et al., 1983b). The model simulated the spread of the disease among a population of cattle on a continuous basis over a 10-year period. This model was used in a broader systems analysis evaluating the effectiveness and cost-benefits of various control programs for the disease (Habtemariam et al., 1983a; Habtemariam et al., 1983c). The deterministic model of ostertagiasis described the parasite life-cycle, pasture conditions, and animal growth as applied to a population of cattle (Ward, 2006). The model was designed to investigate the effectiveness of various parasite control programs and accounts for the complex relationships that exist between parasite, host, and environment. The time step of simulation was 1 day and a total of 400 days were simulated.

Discussion

This review has identified that the systems approach has been applied to studying whole animal production systems and systems within individual animals including tissue and cellular systems. The purpose of this review was not to assess the quality of the models in the articles identified but to provide a brief overview of the types of systems models developed for livestock production.

One of the main objectives of systems analysis and the systems approach is “to integrate, interpret, and apply scientific information from several disciplines in a way that the information can be directly applied to decision making” (Cartwright, 1979; Tess and Kolstad, 2000a; Hirooka, 2010). Experts in systems methods recognize that the definition of systems thinking and the systems approach may differ depending on the individual and as this review identified, many variations of the systems approach have been used to address research objectives regarding livestock species (Lane, 2016). This review has revealed that the current state of the systems approach appears to be focused on applying Systems Dynamics methodology. Systems dynamics focus on studying system behavior over time as determined by the complex interconnected and interdependent relationships between components of the system (Lane, 2016; Walters et al., 2016).

As Walters et al. 2016 identified, dynamic systems models do not generally lend themselves to validation against real world data. Many times these models simulate scenarios, relationships, and outcomes that may not have associated real world data. This is not to say that systems models are exempt from standard model quality checking efforts. Verification that the underlying model assumptions are valid, the equations and computer programming are adequate, the model operates as intended, and that model outcomes are not overly sensitive to model parameters are well described practices used to ensure model quality (Sargent, 2005). We believe that these should be considered the minimum standards of practice conducted to ensure the quality of systems models. While data specific to the outcomes of interest for the entire system model may not be available, components within each model for which data are available for comparison likely exist. These components of models for which real world data exist should be identified and used for model validation, especially when real world data are not available for the main model outcomes. We believe attempts should be made a priori or early in development of the model to determine how verification and validity of the model will be tested.

Many of the simulation models identified by this review were deterministic. Deterministic models do not allow model parameters to take on a random value from an assumed underlying distribution of possible values (stochastic) and true variability in model outcome estimates is not obtained. Users of deterministic models should recognize this limitation. It should also be recognized that varying a few model components of interest does not make a model stochastic because these values were not chosen at random to simulate variability in the parameter. The value of stochastic model parameters and inclusion of variability in a simulation is that, in addition to giving a measure of central tendency, a range of possible values for the outcomes is provided as opposed to having a single measure for the outcome in a chosen scenario. Not having a range of possible values, as is the case with deterministic modeling, may be objectionable to some scientists, but well-constructed deterministic models are still informative. Stochastic models also allow multiple scenarios to be run through iteration to determine what parameters the model outcomes are most sensitive too. It can be challenging to perform sensitivity analysis in deterministic models because stochasticity in model parameters is not incorporated. However, sensitivity analysis of deterministic models should still be performed by incrementally changing model parameters to ensure the model is not overly sensitive to model parameters.

Walters et al. 2016 stated a belief that many traditional mechanistic and statistical models developed in livestock and agricultural research are limited due to the need for large amounts of input data, as well as extensive calibration and validation prior to use. We agree that access to large data sets and specialized training is needed to create usable models, but as more animal and veterinary scientists are trained in a broader offering of modeling modalities, a variety of research and production questions can be addressed efficiently. The advent of software programs such as Stella (isee systems, Lebanon, NH) and Vensim (Ventana Systems, Inc, Harvard, MA) that aid in visualization and development of dynamic simulation models has improved the ease with which dynamic systems models may be constructed. We believe that, ideally, user-friendly models should be developed and made accessible that require minimal training prior to use. The previously mentioned software programs aid in that goal. The ability for people to use and modify a model in the future may improve scientific discovery, hypothesis generation, and decision making processes. We believe that, in many cases, a deterministic model may be more user-friendly when compared to a stochastic model. However, as software capabilities and computational capacities improve we expect incorporation of stochasticity in most dynamic systems models in the future. Of course, it must also be recognized that a risk of accessible, user-friendly models is that the model may be misused or outcomes may be misinterpreted or over-interpreted.

One common characteristic of the more recent dynamic simulation models is that longer periods of time are simulated than would be reasonable with live animal studies (e.g. 10 years). Additionally, the discrete time-steps used are smaller when compared to older models. In the past, computational capacity may have limited dynamic time steps to larger units of time such as a month. The discrete times steps used most recently are commonly set to 1 day or to meaningful time-step such as 1 week to provide greater detail about the dynamic relationships that exist in the system. The use of systems models gives investigators the opportunity to simulate multiple production cycles (possibly years), a significant advantage of modeling over experimental studies. One may easily think of many situations in which modeling a system over many years would be useful. Suppose a dairy producer wished to understand the implications of various culling criteria for his dairy cow herd such as increasing the cull criteria for daily milk production so that cows needed to produce more milk to stay in the herd. How would this change the farms culling rate, replacement needs, productivity, and health outcomes? How long would it take to achieve a new equilibrium for the herd after implementation of the new culling program? How would this affect the operating expenses over the next 5 to 10 years? This example highlights how the ability to examine impacts over several years may have a significant impact on a decision made today and how systems methods are useful to help drive investigation and decision making.

Selection of the appropriate amount of time to simulate and the time-step of calculation is not trivial and must be selected based on the objective of the study, the constraints of the species or production system modeled, and the granularity or quality of the data used to develop the model. Some models utilize larger discrete time steps such as weeks or months because production events and outcomes may be summarized and described by these time units. For example, a small ruminant model identified by this review used a time step of 15-days which is equivalent to the length of the estrous cycle for sheep because the authors determined this time step was adequate to summarize and describe phenomena in the system (Blackburn and Cartwright, 1987a). For animal production systems, the dynamic movement of animals through the production system day to day has potential implications on production outcomes. The authors of this review believe that in the future, projects using the systems approach should have dynamic time steps as small as reasonable to maximally capture the impacts these dynamics have on outcomes.

Dynamic relationships in systems can be challenging to assess if a model is not accurately representing the system of interest. The loading of an initial population of units of interest can be challenging to do well and in a defensible manner. An approach taken by Turner et. al to help ensure the model was accurately simulating the system of interest was to provide a 10 year stabilization period for the model after initiation (Turner et al., 2013). This practice allowed the model to equilibrate and start replicating the behavior of the specific production system the model was simulating. This was a method not explicitly used in other simulations but it is an interesting method to consider adopting. To these authors, this may be a valuable practice especially when loading and initiation of the model is challenging. Providing a burn-in or stabilization period after initial loading of a model might allow for more defensible baselines to be established for complex simulation models.

Many of the articles identified in this review simulated specific geographic regions or specific production systems of interest. It is not clear how well these models could be applied to other regions or dis-similar production systems. This is not a criticism of these models, as it is important for model builders to define the confines of the system they are simulating. However, this does limit the usefulness of the model to the specific system for which they were constructed. This may be considered a benefit, in that these models were likely useful for the specific systems they were developed for and were internally valid. However, external applicability to other systems may be limited, which may also limit the value of the model to being used for a few number of studies. We believe that user-friendly models that can be parameterized to fit multiple regions and scenarios can be powerful tools to improve the efficiency of hypothesis generation and decision making. As indicated previously, we believe the ability to do this will continue to improve into the future due to technological advances.

We identified that adding to or incorporating previously developed models into one larger scale simulation to create a broader system analysis seems to be a powerful recent advance in the application of the systems approach. Ash et. al 2015 and Fariña et. al 2013 showed examples of this practice and how it could be applied to different scenarios (Fariña et al., 2013; Ash et al., 2015). We believe that opportunities exist to use similar methods for North American livestock production systems. It should be recognized that for dynamic simulations, unless the incorporated models use the same discrete time step, the analysis will be limited by whichever model has the largest discrete time step. We recommend that using models with different discrete time steps be avoided when possible. It is also our opinion that the assumptions made by each model should be congruent even though the system in each incorporated model may be very different (e.g. pasture growth vs reproduction). Using previously developed models is an efficient use of resources and enhances the ability to perform broader systems analysis, so long as proper precautions are taken.

Of particular interest to the authors was how the systems approach has been applied to beef production systems in North America, specifically cow-calf production systems. This review identified that existing dynamic models are limited to specific production systems or geographic regions (Tess and Kolstad, 2000a; Turner et al., 2013). We believe that opportunities exist to create a systems simulation of North American beef production systems that can be used by investigators to address a diverse array of objectives under various production scenarios. Specifically, development of a cow-calf production model that accounts for the daily dynamics of animal movement through a production cycle would be of benefit due to the implications the distribution of animals may have on production outcomes. We have developed a dynamic simulation model of cow-calf operations with a daily discrete time-step with an emphasis on reproductive constraints to capture the dynamics of cattle flow through cow-calf enterprises (Shane et al., Submitted 2016). As with other studies, we intend to integrate parameters or sub-models for disease, forage quality, and economics to perform broad based systems analyses of cow-calf production enterprises.

A limitation of this review is that it does not incorporate all livestock models, but this does not take away from the fact that numerous models have been created of livestock production that share qualities with those stating they used a systems approach. This has been well addressed by some of the reviews that have addressed using systems methods and simulation to model livestock production, reproduction, nutrient metabolism, host-pathogen interactions, biological processes, and other systems of interest. It must be acknowledged that several scientists have worked diligently to create simulation models over the years that could likely be considered to use the systems approach.

Conclusions

Researchers should consider implementing the systems approach in their field of expertise to drive research decisions and to further investigate the implications of findings from other research studies. As this review has found, the systems approach has been used to learn more about complex systems, but there is opportunity for continued growth and improvement of these methods. Systems methods will continue to have a positive impact on knowledge of complex livestock systems.

Figure 1.1 PRISMA graphic of the selection process for articles included in a review of the systems approach in food animal production and food animal veterinary medicine (Moher et al., 2009).

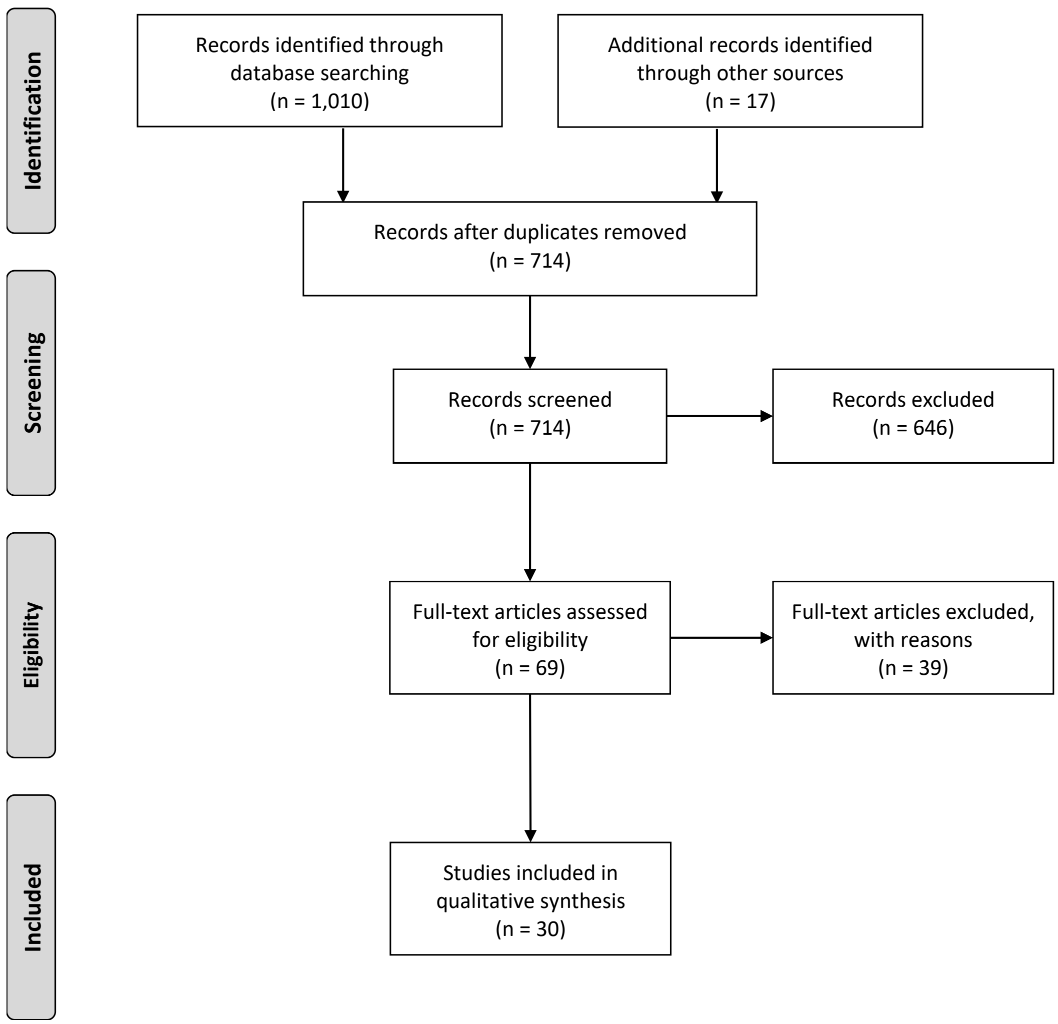

Table 1.1 Descriptive table of the manuscripts identified by the review to utilize the systems approach and characteristics of the systems simulations used.

Species and Manuscript	Treatment of Time	Time Step	Amount of Time Simulated	Treatment of Variability
Swine				
(Faust et al., 1993)	Dynamic	1 week	10 years	Deterministic
(Piewthongngam et al., 2014)	Dynamic	1 week	3 years	Deterministic
Small Ruminant				
(Smith and Lee, 1980)	Static	-	1 year	Deterministic
(Blackburn and Cartwright, 1987a, b, c)	Dynamic	15 days	10 years	Deterministic
(Aguilar et al., 2006)	Dynamic	1 day	1 year	Deterministic
(Guimarães et al., 2009)	Dynamic	1 month	10 years	Deterministic
Dairy Cattle – Herd Level Simulation				
(Oltenacu et al., 1981)	Dynamic	1 day	1 production cycle	Stochastic
(Hillers et al., 1982)	Static	-	1 production year	Deterministic
(Sethi and Nagarcenkar, 1987)	Dynamic	1 month	10 years	Deterministic
(Fariña et al., 2013)	Dynamic	1 month	2 years	Stochastic and Deterministic
Dairy Cattle – Intra-animal Simulation				
(Tedeschi et al., 2013)	Dynamic	0.0625 days	5 lactations	Stochastic
(Huber et al., 2014a, b)	Dynamic	0.1 days	140 days	Deterministic
Beef Cattle				
(Cartwright et al., 1975; Fitzhugh et al., 1975; Long et al., 1975; Ordóñez-Vela, 1979)	Static	-	1 year	Deterministic
(Fox and Black, 1976)	Static	-	1 production cycle	Deterministic
(Louw et al., 1978)	Dynamic	1 year	53 years	Deterministic
(Loewer et al., 1980)	Dynamic	1 day	1 year	Deterministic
(Tess and Kolstad, 2000a, b)	Dynamic	1 day	7 years	Deterministic and Stochastic
(Turner et al., 2013)	Dynamic	1 week	10 years	Deterministic
(Ash et al., 2015)	Dynamic	1 month	20 years	Deterministic
(Habtemariam et al., 1983a, b; Habtemariam et al., 1983c)	Dynamic	Continuous	10 years	Deterministic
(Ward, 2006)	Dynamic	1 day	400 days	Deterministic

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Chapter 2 - A deterministic, dynamic systems model of cow-calf production: The effects of the duration of postpartum anestrus on production parameters over a 10 year horizon

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Abstract

The duration of postpartum anestrus (**dPPA**) is important to consider for reproductive performance and efficiency in cow-calf operations. We developed a deterministic, dynamic systems model of cow-calf production over a 10-year horizon to model the effects that dPPA has on measures of herd productivity including the percent of cows cycling before the end of the first

21-days of the breeding season (**%C21**), the percent of cows pregnant at pregnancy diagnosis (**%PPD**), the distribution of pregnancy by 21-day breeding intervals, the kilograms of calf weaned (**KW**), the kilograms of calf weaned per cow exposed (**KPC**), and the replacement percentage (**%RH**). A 1,000 head herd was modeled, with the beginning and ending dates for a 63-day natural service breeding season being the same for eligible replacement heifers (nulliparous cows) and cows (primiparous and multiparous cows). Herds were simulated to have a multiparous cow dPPA of 50, 60, 70, or 80 days, with the dPPA for primiparous cows being set to 50, 60, 70, 80, 90, 100, or 110 days. Only combinations where the primiparous dPPA was greater than or equal to the multiparous dPPA were included, resulting in 22 model herds being simulated in the analysis. All other model parameters were held constant between simulations. In model season 10, the %C21 was 96.2% when the multiparous cow and primiparous cow dPPA was 50 days, and was 48.3% when the multiparous cow and primiparous cow dPPA was 80 days. The %PPD in model season 10 for these same herds was 95.1% and 86.0%, respectively. The percent of the herd becoming pregnant in the first 21-days of the breeding season also differed between these herds (61.8% and 31.3%, respectively). The 10 year total KW was over 275,000 kg greater for the herd with a 50-day multiparous cow and primiparous cow dPPA when compared to the herd with the 80-day multiparous and primiparous cow dPPA, and had a model season 10 KPC of 180.8 kg compared to 151.4 kg for the longer dPPA. The model results show that both the multiparous cow and primiparous cow dPPA affect herd productivity outcomes and that a dPPA less than 60-days results in improved production outcomes relative to longer dPPA. Veterinarians and producers should consider determining the dPPA to aid in making management decisions to improve reproductive performance of cow-calf herds.

Introduction

The cow-calf production phase of the cattle industry is comprised of diverse operations that have various cattle management practices (Feuz and Umberger, 2003). Understanding the long-term effects of production factors is challenging in cow-calf operations because of the one-year production cycle length between breeding seasons and the variability between production years. Furthermore, identifying where leverage points may exist in the production cycle is challenging because of the dynamic flow of cattle through the production cycle. Systems thinking and systems dynamic modeling are useful tools for improving the understanding of complex system of interest and have been applied to agricultural and biological systems (Forrester, 1993; Coyle, 1998; Rhoades et al., 2014; Walters et al., 2016). User-friendly software programs have been developed for building dynamic systems models (Stella Professionsal, isee systems, Lebanon, NH) and have been used for modelling various dynamic systems (Ouyang et al., 2010; Turner et al., 2013; Azanu et al., 2016; Marois and Mitsch, 2016; Møller et al., 2016; Walters et al., 2016). Research has indicated that the duration of postpartum anestrus (**dPPA)** impacts reproductive performance of cow-calf herds (Short et al., 1990; Cushman et al., 2007). Our objective was to develop a deterministic, dynamic systems model of cow-calf production over a 10 year horizon and to understand the impact dPPA has on the percent of cows having fertile estrous cycles prior to the 21st day of the breeding season, the percent of cows pregnant at pregnancy diagnosis, the distribution of pregnancies in 21-day breeding intervals, the kilograms of calf weaned, the kilograms of calf weaned per cow exposed, and the replacement percent.

Materials and Methods

Software overview

The software program used for developing the dynamic systems model allows users to develop conceptual models with visual building blocks and implement equations for the flow of units based on the conceptual model. The model building blocks used for the model in this analysis include stocks, conveyors, flows, converters, and connectors. Model units may be subcategorized through the use of arrays and different flow rates may be used for each level of the array.

Model overview

The systems model represents cow-calf production as commonly practiced in the Great Plains and Midwestern regions of the United States of America. The time unit of measure was set to 1 day, with a total of 11 breeding seasons being modelled to create a 10-year horizon ($j = 0 – 10$). Classes of animals include cows, heifer calves, and bull calves. Physiologic, reproductive, or management parameters are held constant except for parameters of interest. An initial integer number of animals are loaded into model breeding season 0, but movement of animals between states is determined by calculated rates resulting in real (non-integer) values of cattle movement between states in the model. Non-integer output values of animal units were resolved by truncating non-integer values of animals to integer values.

Description of model herds

For all herds, the breeding season was modeled to last for 63-days. The target herd size was set as 1,000 cows. The initial herd was set to have a pregnancy distribution with 65% of the herd being categorized as becoming pregnant in the first 21-day interval, 23% in the second 21-day interval, and 7% in the third 21-day interval, and was assumed to have 95% of the herd pregnant in the prior breeding season. This distribution has been described as an ideal distribution of pregnancy for cow-calf herds (Larson and White, 2016a).

The dPPA for multiparous cows was modeled to be 50, 60, 70, or 80 days in duration, with primiparous cows modeled to have a 50, 60, 70, 80, 90,100, or 110 day dPPA (Randel, 1981; Doornbos et al., 1984; Sharpe et al., 1986; Randel, 1990; Patterson et al., 1992; Fike et al., 1996; Ciccioli et al., 2003; Cushman et al., 2007; Mulliniks et al., 2013; Larson and White, 2016b). The range of estimates for primiparous dPPA reported in the literature is quite variable, which is the reason so many values were included in the analysis. Only combinations in which the primiparous dPPA was greater than or equal to the multiparous cow postpartum were included, resulting in a total of 22 model herds being included in the analysis.

Breeding

A simplified schematic of the breeding section of the model is illustrated in Fig. 2.1. Cows are subcategorized through the use of arrays by parity at the start of the breeding season ($i = 0 – 10$) and by model breeding season ($j = 0 – 10$). Parity was defined as the number of calves born to a cow, with replacement heifers (nulliparous cows) considered to be parity 0.

Cows enter a model breeding season as they complete their specified postpartum period, defining the time from calving to the time of fertile estrous cycle onset. Replacement heifers enter the breeding season after completing their pre-pubertal period. Puberty was defined as the time at which replacement heifers start fertile estrous cycles. Cows completing the postpartum period of the j-1 breeding season and replacement heifers born from the $j – 2$ breeding season completing the pre-pubertal period become cycling cows in the j^{th} breeding season. The total number of replacement heifers and cows that become cycling cows are counted and reported as the Total Breeding Herd (**TBH**), and includes animals that may start cycling after the breeding season has ended. The number of cows and replacement heifers that become cycling cows prior to the 21st day of the breeding season is reported as **C21**.

At the start of each 21-day period of the breeding season, cycling cows are classified as breeding cows in the k^{th} 21-day interval from the start of breeding in which they started fertile estrous cycles and may become pregnant if the model time is within the model breeding season for the herd. The time of the breeding season is set by the breeding season start and breeding season end. Cows becoming pregnant is determined by the pregnancy risk and the number of cycling cows in the breeding interval. The pregnancy risk was defined as the percentage of breeding cows having fertile estrous cycles exposed to a bull in a 21-day breeding interval that have a detectable pregnancy 60 days following exposure. The pregnancy risk was assumed to be the same for each breeding interval and was set to 65% (BonDurant, 2007). The rate of animals becoming pregnant is assumed to be representative of cycling cows being equally likely to become pregnant on any given day within a breeding season based on 21-day estrous cycles. Cows not becoming pregnant in the k^{th} breeding interval enter the k+1 breeding interval and may become pregnant if the model time is still within the model breeding season. As cows become pregnant they are subcategorized by the 21-day breeding interval from the start of breeding in which conception occurred ($k = 1 – 9$). Once the model time is greater than the end of the j^{th} breeding season all remaining animals are considered to not become pregnant, become classified as open cows, and are removed from the model.

Pregnancy and calving

A simplified schematic of the pregnancy section of the model is illustrated in Fig. 2.2. Heifers and cows becoming pregnant are classified as pregnant cows and have a transit time equivalent to the gestation length of 283 days. Pregnant animals are removed from pregnancy at the rate of cows aborting, as determined by the Abortion Risk. Abortion was modeled to start occurring after 60 days of gestation because the definition of pregnancy risk in the model accounts for early embryonic loss and abortion prior to 60-days gestation. The abortion risk was set to 1.5% of pregnant animals (Waldner, 2005, 2014). Pregnant animals that abort become open cows and are removed from the model.

Animals completing pregnancy through calving either give birth to a dead calf or give birth to a live calf, as determined by the probability of the i^{th} parity giving birth to a dead calf. All cows giving birth to a dead calf are classified as open cows and are removed from the model. The probability of giving birth to a dead calf was assumed to be 5.8% of replacement heifers calving (becoming primiparous cows) and 1.9% of calving from parity 1 to 10 cows at the start of the breeding season (NAHMS, 2008b). All animals giving birth to a live calf enter the postpartum period and end the postpartum period after completing a transit time equivalent to the **dPPA**.

The number of herd members pregnant at the pregnancy diagnosis day of the j^{th} breeding season was reported as Pregnant at Pregnancy Diagnosis (**PPD**). The pregnancy diagnosis day occurred 60 days following the end of the j^{th} breeding season.

Open Cows

Cows not becoming pregnant, aborting, and giving birth to a dead calf are classified as open cows and are removed from the model.

Postpartum cows

The postpartum period section of the model is illustrated in Fig. 2.2. Cows giving birth to a live calf will enter the postpartum period (**PP**). Cows may be removed from the model through dying or voluntary culling. Cows that are not removed enter the j+1 breeding season after a transit time equivalent to the **dPPA** and are classified as entering the i+1 parity. The dPPA was defined for each model run as the time from calving to resumption of fertile estrous cycles. The number of possible parities for cows is limited to 10, a supported expectation for cow longevity (Riley et al., 2001; Thrift and Thrift, 2003; Cushman et al., 2013). This results in all cows that have an 11^{th} calf being removed from the model, with these cows being approximately 12 years old at the start of their last breeding season. The calves born to these cows are retained and modeled with other calves.

Cow mortality occurs as a rate of cows in the postpartum period, as determined by the probability of death. Although cows die at other times in the production cycle in the biological world, cow mortality was modeled to only occur during the postpartum period for the purposes of this model. The probability of cow death was defined as the percentage of cows in the postpartum period that will die and was set to 1.5% (NAHMS, 2008b).

Voluntary culling of cows for reasons other than not becoming pregnant, aborting, or giving birth to a dead calf occurs out of postpartum period. While no specific reasons for voluntary culling are simulated, possible reasons include bad udders, musculoskeletal problems, selection decisions, and other reasons for cows to be voluntarily culled. The percent of cows in the postpartum period removed through voluntary culling is equal to the voluntary cull risk, which was defined as the percentage of cows in the postpartum period to be removed through voluntary culling. The voluntary cull risk is determined by the minimum culling percent, defining the minimum percent of the herd to be culled for any reason in a production cycle (model season). The minimum culling percent was determined by the probability of a heifer being retained in the herd until parity 10 and the number of the i^{th} parity, resulting in an increasing minimum culling percent as parity increases. The probability of a heifer being retained in the herd until parity 10 was set to 15% (Cushman et al., 2013). The probability of death was subtracted from minimum culling percent because the estimates for prRH account for loss of cattle to death.

If the percent of the herd removed for not becoming pregnant, aborting, or giving birth to a dead calf is less than the minimum culling percent, the voluntary cull risk is the difference between the minimum culling percent and the percent of the herd already removed from the model. If the percent of the herd already removed was greater than or equal to the minimum culling percent the voluntary cull risk was 0% because it was assumed cows would not be culled for other reasons if the percent of the herd culled for not becoming pregnant, aborting, and giving birth to a dead calf was greater than or equal to the minimum culling percent.

Calves

A simplified schematic of the calf section of the model is illustrated in Fig. 2.3. Heifer calves and bull calves are subcategorized by the parity of dam as classified at the beginning of the breeding season the calf was conceived (i= 0 – 10) and by the model breeding season in which they were conceived (j = 0 – 10).

Heifer calves are born at a rate of 50% of cows giving birth to a live calf. Pre-weaning heifer calves are retained until completing the time to weaning transit time, defining the number of days from the current model day to the day to wean. The day to wean was set to be 205 days following the start of calving (BIF, 2010). A percentage of pre-weaning heifer calves are removed through heifer calf mortality, as determined by the probability of calf mortality of 3.5% (NAHMS, 2008b). All heifer calves surviving to the day to wean become weaned heifer calves through weaning.

Bull calves are modeled in the same fashion as heifer calves with bull calves being born being classified as pre-weaning bull calves. Mortality occurs through bull calf mortality at the same rate as heifer calf mortality. Surviving pre-weaning bull calves become weaned bull calves after reaching the day to wean.

Kilograms of calf

A simplified schematic of the kilograms of calf section of the model is illustrated in Fig. 2.3. As heifer calves are born they are multiplied by the heifer calf birth weight of heifer calves from the i^{th} parity of dam and are classified as kilograms of pre-weaning heifer calf. Birth weights for each parity were determined using the 9^{th} Edition of the Beef Improvement Federation Guidelines adjustments for birth weight (BIF, 2010). Based on the guidelines, it was assumed that the standard birth weight for heifers was 31.8 kg.

Growth was modeled as the rate of daily gain of pre-weaning heifer calves, as determined by the heifer calf average daily gain. The model results in a one-unit increase in ADG per heifer calf-day. The pre-weaning heifer calf ADG was adjusted for parity of dam using the BIF Guidelines 205-day weaning weight adjustment for parity of dam. The 205-day weaning weight adjustment was divided by 205 and subtracted from the standard ADG for heifers, which was set to 0.91 kg per day (Bourdon and Brinks, 1982; Doornbos et al., 1984; NAHMS, 2008a; Cushman et al., 2013). After reaching the day to wean, kilograms of pre-weaning heifer calf are classified as kilograms of weaned heifer calf. Heifer calf mortality was accounted for and resulted in an appropriate number of kilograms being removed based on when calves were removed for dying.

Kilograms of pre-weaning bull calf are modeled in the same fashion as kilograms of pre-weaning heifer calf, with bull calves being born multiplied by the bull calf birth weight as they are born and adding the daily gain of pre-weaning bull calves. Surviving kilograms of pre-weaning bull calf are classified as kilograms of weaned bull calves after day to wean. The standard bull calf birth weight was assumed to be 34.1 kg and the standard pre-weaning bull calf ADG was assumed to be 1.0 kg per day.

Replacement heifers

A simplified schematic of the replacement heifer section of the model is illustrated in Fig. 2.4. Heifer calves are simultaneously modeled in a section of the model that is a parallel flow of the previously discussed heifer calf section. This section is used to track heifer calves for possible use as replacement heifers, and accounts for calf classification by parity of dam and calf mortality. All model component names in this section are followed by a TFR, which stands for Tracking for Replacement. Heifer calves are classified as pre-weaning heifer calves TFR and have a transit time equivalent to the time from the start of calving to the next pregnancy diagnosis. Pre-weaning heifer calves TFR are classified as weaned heifer calves at the time of weaning which coincides with the time of pregnancy diagnosis of the breeding season following their birth.

Weaned heifer calves TFR become heifers sold weaned or become replacement heifers. The rate of keeping heifers for replacement was determined by the number of replacements needed, the number of weaned heifer calves TFR, and the number of replacement heifers already kept. The number of replacements needed is an estimated number of replacement heifers needed to maintain a stable herd size. The oldest heifers are selected first and no outside replacements are modeled to be introduced to the herd. After the total in number of replacement heifers is equal to the number of replacements needed, all remaining weaned heifer calves are sold at weaning.

Replacement heifers enter the breeding season portion of the model after completing the time to puberty, defining the time from selection as a replacement to starting fertile estrous cycles. The time to puberty is the difference between the age of puberty and time from the start of calving to the next pregnancy diagnosis. The age of puberty was set to 365 days (Diskin and Kenny, 2014).

Model outcomes

Model outcomes include the percent of the herd having fertile estrous cycles prior to the 21st day of the breeding season (**%C21**), percent of cows pregnant at pregnancy diagnosis (**%PPD**), the %PPD in each 21-day interval of the breeding season, the total kilograms of calf weaned (**KW**), the kilograms of calf weaned per cow exposed (**KPC**), and the replacement percent (**%RH**).

The %C21 was calculated by dividing the number of cows cycling within the first 21-days of the breeding season (**C21**) by the Total Breeding Herd (**TBH**). The %PPD was determined by dividing the PPD by the TBH. The percentage of TBH pregnant within each 21-day breeding interval was also calculated. The KPC was determined by dividing the KW by the TBH. The %RH was determined by dividing the number of replacement heifers in a model year by the total number of cows entering the j^{th} breeding season. All reported results are descriptive in nature with no inference testing due to the deterministic nature of the model.

The conceptual model was not designed around a specific production system or set of data. In general, systems models such as this do not lend themselves to traditional validation procedures (Walters et al., 2016). Despite this, we wished to qualitatively assess the model for operational validity and compare the model results to data in published literature to support the validity of the model.

Results

Operational validation

The model was qualitatively tested to determine if it performed as expected based on the conceptual model and flow equations. We tested various levels of model parameters to determine if herd size remained stable and if the model responded as expected to changes in model parameters. Parameters that were varied included the pregnancy risk (0.5 – 0.8), length of the breeding season (45 – 169), probability of death (0.0 – 0.05), abortion risk (0.0 – 0.05), and probability of remaining in the herd until parity 10 (0.1 – 0.2).

The herd size for each model year was stable for each model test. The number of animals pregnant in each 21-day breeding interval was consistent with the set pregnancy risk, with a lower pregnancy risk resulting in fewer animals becoming pregnant in a 21-day breeding period. Increasing the breeding season length resulted in more possible 21-day breeding periods in which cattle became pregnant and also resulted in more cows becoming pregnant. Increasing the probability of death and abortion risk resulted in more animals being removed from the herd and an increased replacement percent. Increasing the probability of remaining in the herd until parity

10 resulted in a lower replacement percent. These findings show the model responds to changes in model parameters as expected and was operationally valid.

Comparison of model results to published literature

The model shows that an increasing average herd dPPA has a negative impact on herd performance and efficiency when using a fixed duration breeding season. Our results are aligned with a review of reproductive efficiency of primiparous cows reporting that a negative correlation exists between the dPPA and subsequent pregnancy risk (Morris, 1980). Research has also shown a lower percent of replacement heifers cycling prior to the breeding season negatively impacts the pregnancy percentage and the percent calving in the first 21-days of the calving season (Funston et al., 2012). Research has also indicated that ovulating prior to the breeding season increases the pregnancy percentage (McNaughton et al., 2007).

The weight of calves at weaning in the model was consistent with reported weaning weights from commercial cow-calf operations (NAHMS, 2008a). Herds with a longer dPPA did not have as many animals pregnant in the first 21-days of the breeding season and had fewer kilograms of calf weaned. Past research has found that herds with longer breeding seasons and fewer calves born in the first 21-days have fewer kilograms of calf weaned (Miller et al., 2001). Earlier born calves will be older at the time of weaning and will be heavier on average than their younger counterparts (Funston et al., 2012). The model herds with fewer animals pregnant in the first 21-days also had greater replacement percentages, consistent with research that found longevity is decreased for animals becoming pregnant later in the breeding season (Cushman et al., 2013).

Based on the agreement between the published literature and production data, we believe that the model is valid and accurately represents cow-calf production.

Percent of cows having fertile estrous cycles within the first 21-days of breeding (%C21)

The 10-year horizon %C21 decreased as both the multiparous cow dPPA and primiparous cow dPPA increased (Fig. 2.5). Each increase in the primiparous dPPA resulted in a decrease in %C21, but when the primiparous dPPA was less than 80-days there was minimal impact on the %C21 for a herd. A multiparous cow dPPA of 50 days and a primiparous cow dPPA less than or equal to 80 days resulted in at least 90% of the herds cycling in the first 21-days of breeding, as did a multiparous cow dPPA of 60 days and primiparous cow dPPA of 60 days.

Herds with a 50-day and 60-day multiparous cow dPPA had less variability in %C21 across all model breeding seasons (Table 2.1). When the multiparous cow dPPA was 70 days or 80 days, the %C21 decreased with each model breeding season. The %C21 was slightly higher for the herd with an 80-day multiparous cow dPPA and 110-day primiparous cow dPPA when compared to the herd with an 80-day multiparous cow dPPA and 100-day primiparous cow dPPA, due to a higher replacement percentage resulting in more cycling nulliparous cows and fewer non-cycling primiparous and multiparous cows.

Percent of cows pregnant at pregnancy diagnosis (%PPD) and distribution of pregnancy

The 10-year horizon %PPD decreased as the dPPA increased (Fig. 2.6). Herds with a multiparous cow dPPA of 50 days or 60 days had a stable %PPD across breeding years in the model, while herds that had a 70-day or 80-day multiparous cow dPPA had reductions in %PPD with each model breeding season (Table 2.2). Herds with shorter dPPA and greater %C21 had more pregnancies occurring in the first 21-day interval of breeding. The percent of pregnancies occurring in the first 21-days decreased each model year for herds that had a multiparous cow dPPA of 70 days and 80 days (Table 2.3). This pattern was not manifested the same way for pregnancies occurring in the second 21-day interval of breeding (Table 2.4), but decreases in the percent of the herd becoming pregnant in the second 21-days were seen for the herd with a multiparous cow dPPA of 80 days and a primiparous cow dPPA of 110 days. The percent of the herd becoming pregnant in the third 21-day interval of breeding increased with each model year when the multiparous cow dPPA was 70 days or 80 days (Table 2.5).

Kilograms of calf weaned (KW) and kilograms of calf weaned per cow exposed (KPC)

The 10-year horizon total KW decreased as the dPPA increased for both multiparous and primiparous cows (Fig. 2.7). Herds with a 50-day or 60-day multiparous dPPA had greater KW compared to herds with longer multiparous dPPA, with increasing primiparous dPPA not causing dramatic reductions in KW until the primiparous dPPA was 110 days. A 498,179 kg difference existed between the 10-year total KW of the herd with a 50-day multiparous cow dPPA and 50-day primiparous cow dPPA, and the herd with an 80-day multiparous cow dPPA and 110-day primiparous cow dPPA.

Herds with shorter dPPA had greater KPC in each model breeding season (Table 2.6). These herds also had a greater %PPD and more herd members becoming pregnant in the first 21-

day interval of breeding. The KPC decreased with each model breeding season for herds with an 80-day multiparous cow dPPA, while remaining stable for other herds.

Replacement percentage (%RH)

Consistent with lower %PPD, the 10-year horizon %RH increased as both multiparous and primiparous dPPA increased (Fig. 2.8). The relationship of the dPPA to %RH is similar to the relationship with %PPD, in that the %RH is fairly stable for herds with a 50-day or 60-day multiparous dPPA until the primiparous dPPA is greater than or equal to 80-days (Table 2.7). Herds with a multiparous cow dPPA of 70-days and 80-days had a greater %RH that was not as stable in each model breeding season.

Discussion

A deterministic, dynamic systems model of cow-calf production over a 10-year horizon was successfully developed using commercially available software. This model of cow-calf production simulates cow-calf production in a new way and accounts for the flow of animals through the production system on a daily basis while accounting for cattle age groups and other factors. This model was developed with particular interest in how the distribution of animals in the production cycle and reproductive constraints impact production. The model is not conceptualized around specific production systems or regions and is able to be parameterized to describe numerous cow-calf production scenarios. Additionally, this dynamic model allows beef cow reproduction to be modeled under various biologic and management constraints over long horizons and will serve as a foundation for improving the understanding of beef cow reproductive systems by quantifying important production outcomes.

Using this model, we have described the impacts the dPPA has on production over a 10-year horizon. Prior research has explored the impacts the dPPA may have on reproductive performance in the short term, but interpretation of these studies is challenging due to differences in management, cattle type, and treatments. In general, multiple year live animal studies are challenging to conduct and have many potential confounding factors between years and between herds. This model allowed us to examine a wider range of dPPA than may be reasonable to do in a live animal study and did not require attempts to modify multiple herds' average dPPA to make sure different dPPA were represented in a study. It also allowed us to explicitly determine the differences in production caused by the dPPA, while holding other factors constant.

A longer dPPA results in a decreased likelihood that a cow will resume fertile estrous cycles in time to achieve the 365-day calf-to-calf interval most producers desire and will decrease the number of opportunities to become pregnant during the breeding season. Our model shows that herds with a multiparous cow dPPA of 70 days or 80 days will have an increased number of herd members not cycling in the first 21 days of breeding, fewer animals becoming pregnant, and decreased kg weaned per cow exposed compared to herds with shorter dPPA. These results indicate that the dPPA could be a major contributing factor to herds with poor reproductive performance and low kg weaned per cow exposed over time. Our results show that a dPPA less than 60 days results in improved production outcomes when compared to a longer dPPA. We believe that herds with a shorter dPPA are more resilient to the negative effects of various unpredictable and sporadically occurring adverse production events.

Quantifying a herd's dPPA could be useful to veterinarians and producers seeking to improve reproductive management and performance. Producers and veterinarians may wish to intervene if a herd has a prolonged dPPA. An estimate of the dPPA could be determined by selecting a sample of cows in a herd that have calved at various time points in the calving season and monitoring them for signs of estrus behavior, indicating they have resumed estrous cycles. Several technological aids have been developed to assist with monitoring cattle for estrus behavior.

Based on our results, it may be inappropriate to recommend a shorter, restricted breeding season for herds with longer dPPA, a view espoused by past views on reproductive management (Larsen et al., 1994). While we did not model different breeding season lengths, a future analysis should be conducted to determine the length of breeding season that maximizes pregnancy percentages and kg weaned per cow exposed for herds with various dPPA.

The dPPA is largely dependent on appropriate pre- and postpartum nutrition but has also been shown to also be dependent on the maternal bond with a calf (Houghton et al., 1990; Randel, 1990; Crowe et al., 2014). Other factors such as season, parity, breed, dystocia at calving, and bull exposure have also been associated with dPPA (Short et al., 1990; Yavas and Walton, 2000; Cushman et al., 2007). All of these factors could be examined for opportunities for intervention to improve the dPPA of a herd and subsequently improve reproductive performance.

Cushman et al. 2007 reported that, for spring calving herds, the dPPA decreased with increasing Julian day, with similar findings being cited by Yavas et al (Yavas and Walton, 2000). It has been determined that season may truly have a role in modifying the dPPA through daylight stimulation of the pineal gland, however the relative importance is unclear (Sharpe et al., 1986). Presumably, the differences in dPPA associated with season or Julian day could also be related to quality and quantity of available forage. We desired that the model apply to multiple seasons of the year in diverse geographic regions. Thus, we modeled a single “average” dPPA for a herd, which captures the fact that some herds will have a shorter or longer dPPA on average, regardless of any changes in dPPA occurring as the breeding season progresses, and thus interpretation of the model should be done comparing those herds that generally have a shorter or longer dPPA.

A limitation of the model is that it is deterministic and does not allow for variability to exist within a model run for individual units. However, the model provides adequate estimates for what may be expected to occur on average. Another limitation of the deterministic nature of the model is that pregnancy is modeled to occur as a constant rate for all females with fertile estrous cycles, when a more biologically plausible assumption would be that pregnancy occurs as a probability based on breeding exposure for a single estrus event. Despite the limitations of a deterministic model, the authors believe the results are reflective of what may be expected to occur in biological systems.

Future analyses using this tool should be conducted to determine breeding season durations that may be the most appropriate based on an average herd dPPA, if replacement heifers should be bred prior to cows, and other cow-calf production system related questions.

Figure 2.1 Simplified schematic of the breeding section of a deterministic, dynamic systems model of cow-calf production over a 10 year horizon.

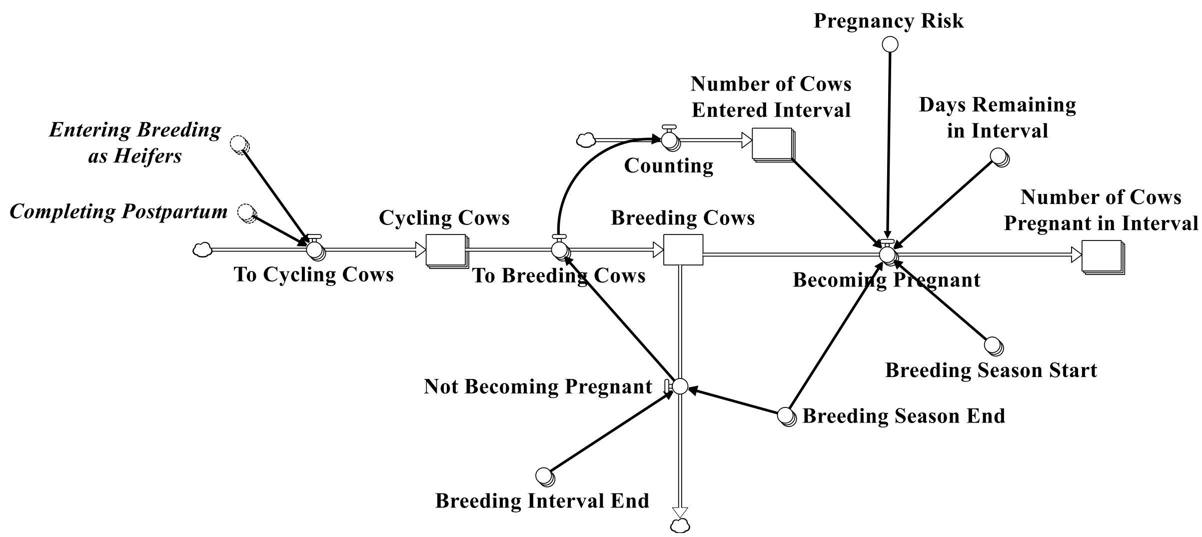


Figure 2.2 Simplified schematic of the pregnancy and postpartum period section of a deterministic, dynamic systems model of cow-calf production over a 10 year horizon.

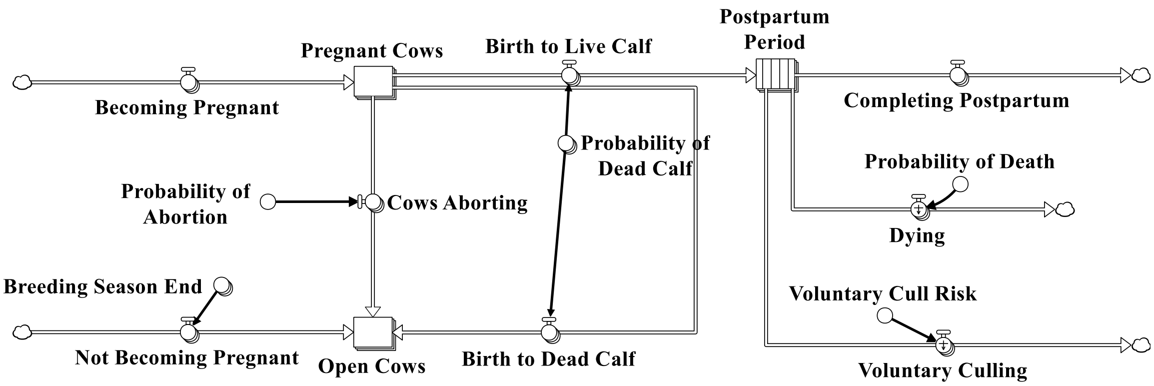


Figure 2.3 Simplified schematic of the calf section of a deterministic, dynamic systems model of cow-calf production over a 10 year horizon.

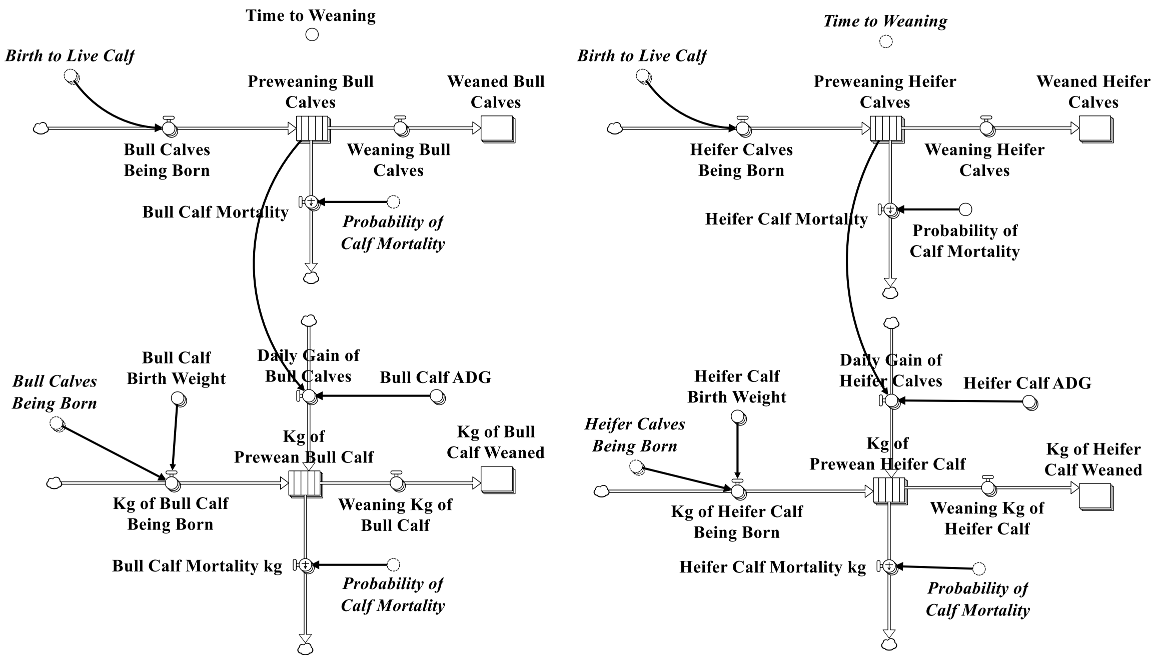


Figure 2.4 Simplified schematic of the tracking heifer calves for replacement section of a deterministic, dynamic systems model of cow-calf production over a 10 year horizon.

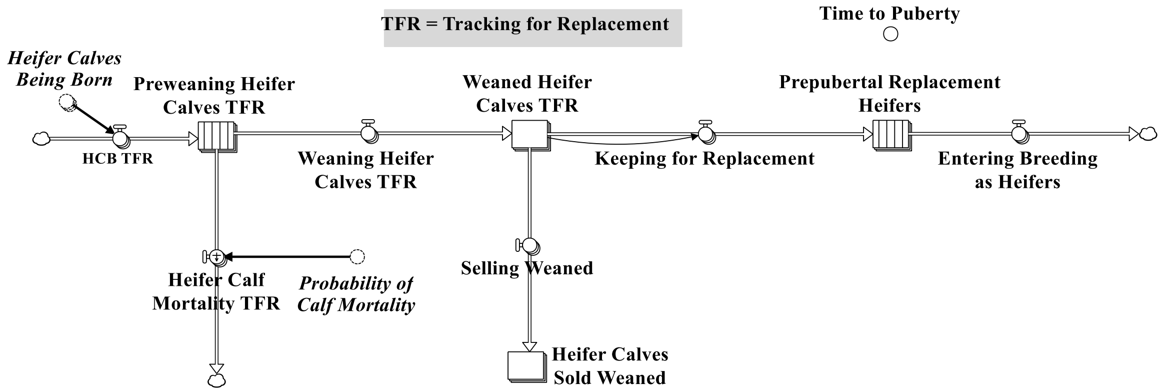


Figure 2.5 Percent of the herd resuming fertile estrous cycles by the 21st day of the breeding season in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 50-, 60-, 70-, or 80-days and a primiparous cow duration of postpartum anestrus of 50-, 60-, 70-, 80-, 90-, 100- or 110-days. Herds were modeled to have a 63-day natural service breeding season that started and ended on the same dates for cows and replacement heifers.

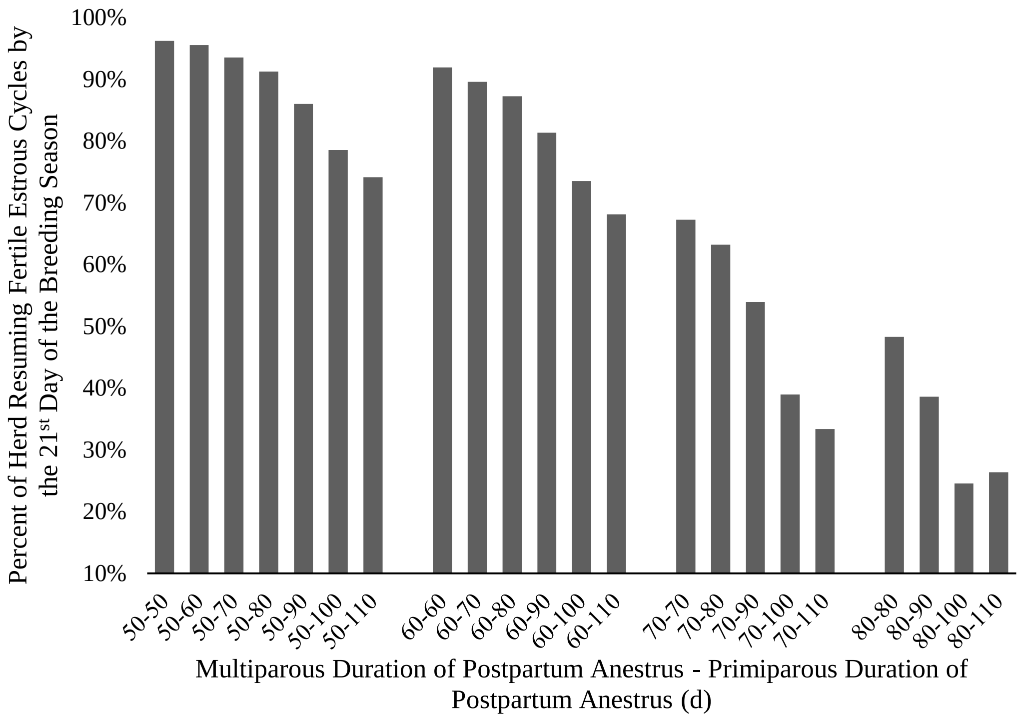


Table 2.1 Percent of the model herd resuming fertile estrous cycles prior to the 21st day of the breeding season by model breeding season and duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Percent of the Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	96.8%	96.2%	96.2%	96.2%	96.2%	96.2%	96.2%	96.2%	96.2%	96.2%	96.2%
	60	96.2%	95.6%	95.5%	95.5%	95.5%	95.5%	95.5%	95.5%	95.5%	95.5%	95.5%
	70	94.6%	93.6%	93.5%	93.5%	93.5%	93.5%	93.5%	93.5%	93.5%	93.5%	93.5%
	80	92.9%	91.5%	91.2%	91.3%	91.3%	91.3%	91.3%	91.2%	91.2%	91.2%	91.2%
	90	88.5%	86.9%	86.0%	86.1%	86.0%	86.0%	85.9%	86.0%	86.0%	86.0%	86.0%
	100	83.8%	81.2%	78.9%	78.7%	78.4%	78.3%	78.3%	78.3%	78.4%	78.5%	78.5%
	110	82.8%	79.6%	75.4%	74.9%	73.9%	73.8%	73.6%	73.7%	73.8%	74.0%	74.1%
60	60	93.8%	91.8%	91.8%	91.9%	91.9%	91.9%	91.9%	91.9%	91.9%	91.9%	91.9%
	70	92.1%	89.6%	89.5%	89.6%	89.6%	89.6%	89.6%	89.6%	89.6%	89.6%	89.6%
	80	90.5%	87.4%	87.2%	87.2%	87.3%	87.2%	87.2%	87.2%	87.2%	87.2%	87.2%
	90	86.1%	82.5%	81.5%	81.4%	81.3%	81.3%	81.3%	81.3%	81.3%	81.3%	81.4%
	100	81.3%	76.5%	74.2%	73.7%	73.4%	73.3%	73.3%	73.3%	73.4%	73.4%	73.5%
	110	80.4%	74.8%	70.4%	69.3%	68.2%	67.9%	67.7%	67.7%	67.8%	68.0%	68.1%
70	70	84.1%	74.7%	70.9%	69.0%	68.1%	67.6%	67.4%	67.3%	67.3%	67.3%	67.2%
	80	82.4%	71.9%	67.6%	65.5%	64.4%	63.8%	63.5%	63.4%	63.3%	63.3%	63.2%
	90	78.0%	66.2%	60.6%	57.8%	56.1%	55.2%	54.7%	54.4%	54.3%	54.1%	53.9%
	100	73.3%	58.9%	51.0%	46.6%	43.6%	41.8%	40.6%	39.9%	39.5%	39.3%	38.9%
	110	72.4%	58.9%	49.2%	44.3%	40.4%	38.0%	36.3%	35.2%	34.4%	34.0%	33.3%
80	80	74.4%	58.4%	52.7%	50.4%	49.6%	49.5%	49.4%	49.3%	49.0%	48.6%	48.3%
	90	70.0%	52.5%	45.6%	42.4%	41.0%	40.4%	40.1%	39.9%	39.5%	39.2%	38.6%
	100	65.3%	45.7%	36.8%	32.1%	29.5%	28.0%	27.0%	26.4%	25.8%	25.3%	24.5%
	110	64.3%	46.8%	37.5%	33.3%	30.8%	29.5%	28.7%	28.2%	27.7%	27.3%	26.4%

Figure 2.6 The percent of the herd pregnant within 21-day breeding intervals for model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 50-, 60-, 70-, or 80-days and a primiparous cow duration of postpartum anestrus of 50-, 60-, 70-, 80-, 90-, 100- or 110-days. Herds were modeled to have a 63-day natural service breeding season that started and ended on the same dates for cows and replacement heifers.

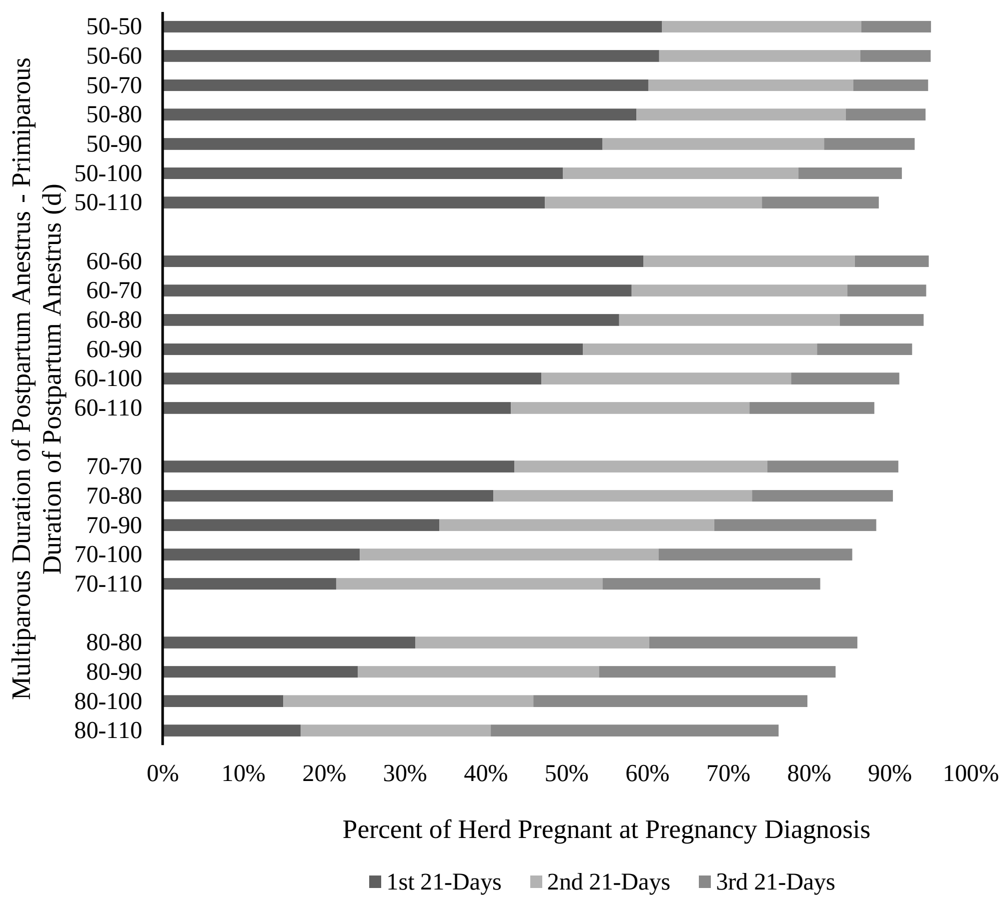


Table 2.2 Percent of the model herd diagnosed as pregnant by model breeding season and duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Percent of Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%	95.1%
	60	95.1%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%
	70	94.8%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%	94.7%
	80	94.5%	94.4%	94.4%	94.4%	94.4%	94.4%	94.4%	94.4%	94.4%	94.4%	94.4%
	90	93.4%	93.2%	93.0%	93.1%	93.0%	93.0%	93.0%	93.0%	93.0%	93.1%	93.1%
	100	92.4%	92.0%	91.5%	91.5%	91.4%	91.4%	91.4%	91.4%	91.5%	91.5%	91.5%
	110	90.3%	90.2%	88.8%	88.8%	88.5%	88.5%	88.5%	88.5%	88.5%	88.6%	88.6%
60	60	94.7%	94.8%	94.8%	94.8%	94.8%	94.8%	94.8%	94.8%	94.8%	94.8%	94.8%
	70	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%	94.5%
	80	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%	94.2%
	90	93.1%	92.9%	92.8%	92.8%	92.8%	92.8%	92.8%	92.8%	92.8%	92.8%	92.8%
	100	92.0%	91.7%	91.2%	91.2%	91.1%	91.1%	91.1%	91.1%	91.1%	91.2%	91.2%
	110	89.9%	89.8%	88.4%	88.3%	88.0%	88.0%	87.9%	87.9%	88.0%	88.0%	88.1%
70	70	93.3%	92.2%	91.6%	91.3%	91.2%	91.1%	91.1%	91.1%	91.1%	91.1%	91.1%
	80	93.0%	91.7%	91.1%	90.7%	90.6%	90.5%	90.4%	90.4%	90.4%	90.4%	90.4%
	90	91.9%	90.3%	89.4%	88.9%	88.6%	88.5%	88.4%	88.4%	88.4%	88.3%	88.3%
	100	90.9%	88.7%	87.4%	86.6%	86.1%	85.8%	85.6%	85.5%	85.4%	85.4%	85.3%
	110	88.8%	86.9%	84.6%	83.7%	82.8%	82.2%	81.8%	81.6%	81.5%	81.4%	81.4%
80	80	91.6%	89.2%	87.6%	86.8%	86.5%	86.3%	86.3%	86.2%	86.1%	86.1%	86.0%
	90	90.5%	87.6%	85.7%	84.7%	84.1%	83.8%	83.7%	83.6%	83.5%	83.4%	83.3%
	100	89.4%	86.1%	83.7%	82.3%	81.4%	80.8%	80.5%	80.3%	80.1%	80.0%	79.8%
	110	87.3%	84.3%	81.2%	79.5%	78.3%	77.6%	77.1%	76.8%	76.6%	76.5%	76.2%

Table 2.3 Percent of the model herd diagnosed as becoming pregnant in the first 21-day breeding interval by model breeding season and duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Percent of Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	62.3%	61.8%	61.8%	61.8%	61.8%	61.8%	61.8%	61.8%	61.8%	61.8%	61.8%
	60	61.8%	61.5%	61.5%	61.5%	61.5%	61.5%	61.5%	61.5%	61.5%	61.5%	61.5%
	70	60.7%	60.2%	60.1%	60.1%	60.1%	60.1%	60.1%	60.1%	60.1%	60.1%	60.1%
	80	59.5%	58.8%	58.6%	58.6%	58.6%	58.6%	58.6%	58.6%	58.6%	58.6%	58.6%
	90	56.4%	55.1%	54.5%	54.5%	54.4%	54.4%	54.4%	54.4%	54.4%	54.4%	54.5%
	100	53.3%	51.4%	49.8%	49.6%	49.4%	49.4%	49.4%	49.4%	49.4%	49.5%	49.5%
	110	53.3%	50.9%	48.2%	47.8%	47.2%	47.1%	47.0%	47.0%	47.1%	47.2%	47.3%
60	60	59.5%	59.4%	59.5%	59.5%	59.5%	59.5%	59.5%	59.5%	59.5%	59.5%	59.5%
	70	58.4%	58.0%	58.0%	58.0%	58.0%	58.0%	58.0%	58.0%	58.0%	58.0%	58.0%
	80	57.1%	56.6%	56.5%	56.5%	56.5%	56.5%	56.5%	56.5%	56.5%	56.5%	56.5%
	90	54.1%	52.8%	52.1%	52.1%	52.0%	52.0%	52.0%	52.0%	52.0%	52.0%	52.0%
	100	51.0%	49.0%	47.3%	47.0%	46.8%	46.7%	46.7%	46.7%	46.8%	46.8%	46.9%
	110	51.0%	47.7%	44.8%	43.9%	43.2%	43.0%	42.9%	42.9%	42.9%	43.0%	43.1%
70	70	53.2%	48.4%	45.9%	44.7%	44.1%	43.8%	43.7%	43.6%	43.6%	43.6%	43.5%
	80	51.9%	46.6%	43.8%	42.4%	41.7%	41.3%	41.2%	41.1%	41.0%	41.0%	40.9%
	90	48.9%	42.3%	38.6%	36.7%	35.6%	35.0%	34.7%	34.5%	34.4%	34.3%	34.2%
	100	45.8%	37.5%	32.3%	29.4%	27.5%	26.2%	25.5%	25.0%	24.8%	24.6%	24.4%
	110	45.8%	38.1%	31.8%	28.6%	26.1%	24.5%	23.4%	22.7%	22.2%	21.9%	21.5%
80	80	45.8%	37.8%	34.1%	32.7%	32.2%	32.1%	32.0%	32.0%	31.8%	31.5%	31.3%
	90	42.7%	33.4%	28.8%	26.7%	25.7%	25.3%	25.1%	25.0%	24.8%	24.5%	24.2%
	100	39.7%	29.0%	23.1%	20.0%	18.2%	17.2%	16.5%	16.1%	15.7%	15.4%	14.9%
	110	39.7%	30.3%	24.3%	21.6%	19.9%	19.1%	18.6%	18.3%	18.0%	17.7%	17.1%

Table 2.4 Percent of the model herd diagnosed as becoming pregnant in the second 21-day breeding interval by model breeding season and duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Percent of Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	24.3%	24.6%	24.6%	24.6%	24.6%	24.6%	24.6%	24.6%	24.6%	24.6%	24.6%
	60	24.6%	24.8%	24.9%	24.9%	24.9%	24.9%	24.9%	24.9%	24.9%	24.9%	24.9%
	70	25.0%	25.3%	25.4%	25.4%	25.4%	25.4%	25.4%	25.4%	25.4%	25.4%	25.4%
	80	25.5%	25.8%	25.9%	25.9%	25.9%	25.9%	25.9%	25.9%	25.9%	25.9%	25.9%
	90	26.4%	27.1%	27.3%	27.4%	27.4%	27.4%	27.4%	27.4%	27.4%	27.4%	27.4%
	100	27.3%	28.4%	29.0%	29.1%	29.2%	29.2%	29.2%	29.2%	29.2%	29.2%	29.2%
	110	24.4%	26.2%	26.4%	26.8%	26.8%	26.9%	26.9%	26.9%	26.9%	26.9%	26.9%
60	60	25.9%	26.2%	26.1%	26.1%	26.1%	26.1%	26.1%	26.1%	26.1%	26.1%	26.1%
	70	26.3%	26.7%	26.7%	26.7%	26.7%	26.7%	26.7%	26.7%	26.7%	26.7%	26.7%
	80	26.8%	27.2%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%	27.3%
	90	27.7%	28.6%	28.9%	29.0%	29.0%	29.0%	29.0%	29.0%	29.0%	29.0%	29.0%
	100	28.6%	30.0%	30.6%	30.8%	30.9%	30.9%	30.9%	30.9%	30.9%	30.9%	30.9%
	110	25.8%	28.3%	28.6%	29.2%	29.3%	29.5%	29.5%	29.5%	29.5%	29.5%	29.5%
70	70	28.1%	29.7%	30.5%	30.9%	31.1%	31.2%	31.3%	31.3%	31.3%	31.3%	31.3%
	80	28.6%	30.2%	31.1%	31.5%	31.8%	31.9%	31.9%	32.0%	32.0%	32.0%	32.0%
	90	29.5%	31.5%	32.7%	33.2%	33.6%	33.8%	33.9%	33.9%	34.0%	34.0%	34.1%
	100	30.4%	32.9%	34.5%	35.4%	36.0%	36.4%	36.6%	36.7%	36.8%	36.9%	37.0%
	110	27.6%	29.6%	30.8%	31.5%	31.9%	32.1%	32.3%	32.5%	32.6%	32.7%	32.9%
80	80	31.0%	31.6%	30.9%	30.1%	29.5%	29.2%	29.0%	29.0%	29.0%	29.0%	29.0%
	90	32.0%	32.7%	32.0%	31.2%	30.6%	30.2%	30.0%	29.9%	29.9%	29.9%	29.8%
	100	32.9%	33.8%	33.2%	32.5%	31.9%	31.5%	31.3%	31.2%	31.2%	31.1%	31.0%
	110	30.0%	29.9%	28.4%	26.9%	25.7%	24.8%	24.3%	24.0%	23.8%	23.6%	23.6%

Table 2.5 Percent of the model herd diagnosed as becoming pregnant in the third 21-day breeding interval by model breeding season and duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Percent of Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	8.5%	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%
	60	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%	8.7%
	70	9.1%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%	9.3%
	80	9.6%	9.8%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%	9.9%
	90	10.7%	11.0%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%	11.2%
	100	11.7%	12.2%	12.7%	12.8%	12.8%	12.8%	12.9%	12.8%	12.8%	12.8%	12.8%
	110	12.5%	13.1%	14.2%	14.3%	14.6%	14.6%	14.6%	14.6%	14.6%	14.5%	14.5%
60	60	9.3%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%
	70	9.7%	9.7%	9.8%	9.7%	9.7%	9.7%	9.7%	9.7%	9.7%	9.7%	9.7%
	80	10.2%	10.3%	10.4%	10.4%	10.3%	10.4%	10.4%	10.4%	10.4%	10.4%	10.4%
	90	11.3%	11.5%	11.8%	11.8%	11.8%	11.8%	11.8%	11.8%	11.8%	11.8%	11.8%
	100	12.4%	12.7%	13.3%	13.4%	13.4%	13.4%	13.5%	13.4%	13.4%	13.4%	13.4%
	110	13.1%	13.8%	15.0%	15.2%	15.5%	15.5%	15.6%	15.6%	15.5%	15.5%	15.4%
70	70	12.0%	14.1%	15.2%	15.7%	16.0%	16.1%	16.1%	16.2%	16.2%	16.2%	16.2%
	80	12.4%	14.9%	16.2%	16.8%	17.1%	17.3%	17.4%	17.4%	17.4%	17.4%	17.4%
	90	13.5%	16.5%	18.1%	19.0%	19.4%	19.7%	19.8%	19.9%	20.0%	20.0%	20.0%
	100	14.6%	18.3%	20.5%	21.8%	22.6%	23.2%	23.5%	23.7%	23.8%	23.9%	24.0%
	110	15.4%	19.2%	22.0%	23.6%	24.8%	25.6%	26.1%	26.4%	26.7%	26.8%	27.0%
80	80	14.7%	19.8%	22.6%	24.1%	24.8%	25.1%	25.2%	25.3%	25.4%	25.6%	25.7%
	90	15.8%	21.5%	24.9%	26.8%	27.8%	28.3%	28.5%	28.7%	28.8%	29.0%	29.3%
	100	16.9%	23.3%	27.4%	29.8%	31.2%	32.1%	32.6%	32.9%	33.2%	33.5%	33.9%
	110	17.6%	24.1%	28.5%	31.0%	32.7%	33.6%	34.2%	34.6%	34.9%	35.1%	35.6%

Figure 2.7 The total kilograms of calf weaned for all model breeding seasons (data labels indicate the percent difference from the average kilograms of weaned of herds in the analysis). Herds had a multiparous cow duration of postpartum anestrus of 50-, 60-, 70-, or 80-days and a primiparous cow duration of postpartum anestrus of 50-, 60-, 70-, 80-, 90-, 100- or 110-days. Herds were modeled to have a 63-day natural service breeding season that started and ended on the same dates for cows and replacement heifers.

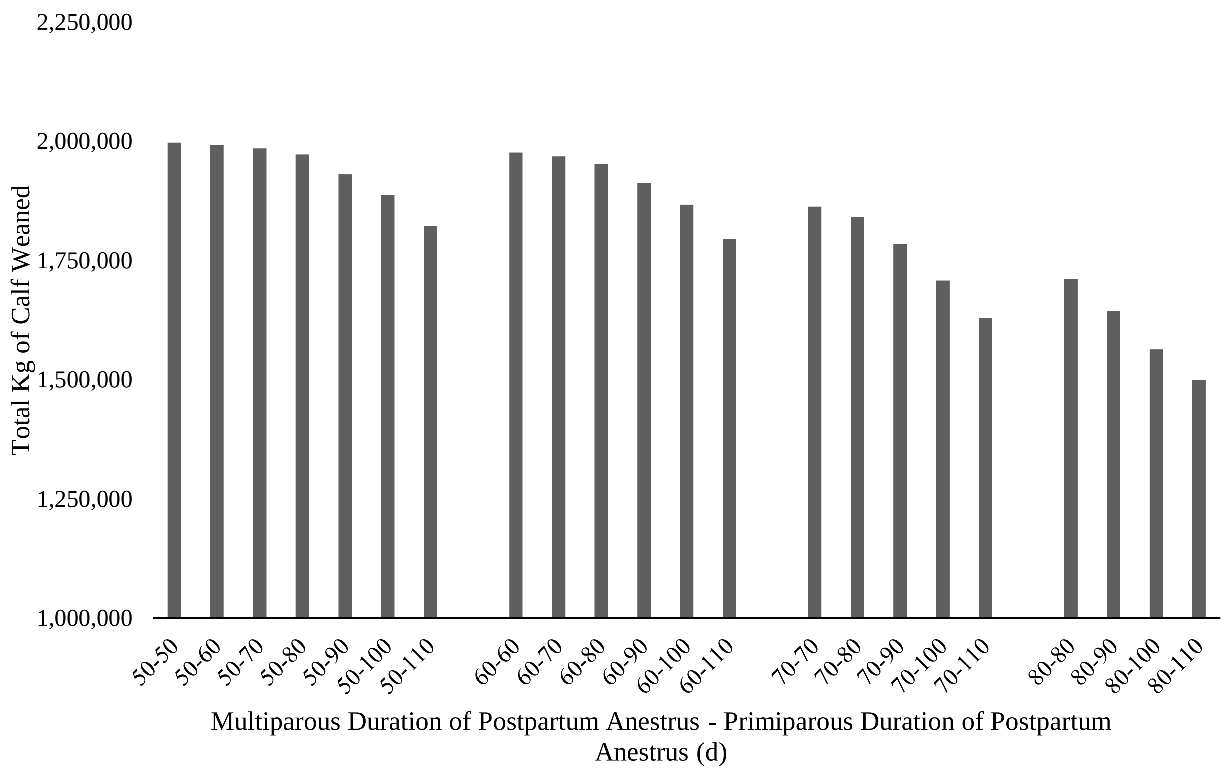


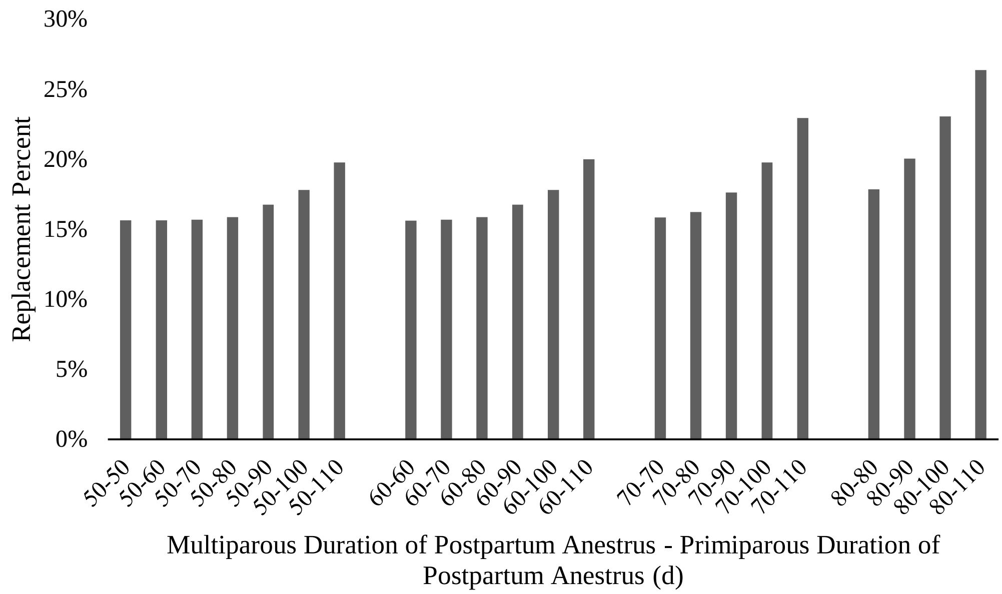
Table 2.6 Kilograms of calf weaned per cow exposed by model breeding season and the duration of postpartum anestrus.

Duration of Postpartum Anestrus (d)		Kilograms of Calf Weaned per Cow Exposed										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	181.0	180.8	180.8	180.8	180.8	180.8	180.8	180.8	180.8	180.8	180.8
	60	180.7	180.5	180.6	180.6	180.6	180.6	180.6	180.5	180.5	180.5	180.5
	70	179.9	179.6	179.6	179.7	179.7	179.6	179.6	179.6	179.6	179.6	179.6
	80	178.9	178.5	178.4	178.4	178.4	178.4	178.4	178.4	178.4	178.4	178.4
	90	176.4	175.4	174.7	174.7	174.6	174.6	174.6	174.6	174.6	174.7	174.7
	100	173.8	172.2	170.6	170.3	170.1	170.1	170.1	170.1	170.2	170.3	170.5
	110	170.1	168.4	164.7	164.2	163.3	163.3	163.1	163.2	163.5	163.7	164.0
60	60	179.2	179.1	179.2	179.2	179.2	179.1	179.1	179.1	179.1	179.1	179.1
	70	178.5	178.1	178.1	178.1	178.1	178.1	178.1	178.1	178.1	178.1	178.1
	80	177.5	176.9	176.8	176.9	176.9	176.9	176.8	176.8	176.8	176.8	176.8
	90	174.9	173.7	173.0	172.9	172.8	172.8	172.8	172.8	172.9	172.9	173.0
	100	172.3	170.4	168.7	168.4	168.1	168.1	168.1	168.1	168.2	168.4	168.5
	110	168.6	166.4	162.5	161.7	160.7	160.5	160.3	160.4	160.6	160.9	161.2
70	70	174.5	170.8	169.0	168.1	167.6	167.4	167.3	167.3	167.3	167.3	167.3
	80	173.5	169.4	167.2	166.0	165.4	165.1	165.0	165.0	165.0	165.0	165.0
	90	171.0	165.6	162.5	160.9	159.9	159.3	159.1	159.0	159.0	159.0	159.0
	100	168.4	161.7	157.0	154.4	152.5	151.4	150.8	150.4	150.4	150.4	150.5
	110	164.7	158.1	151.4	148.0	145.2	143.4	142.2	141.5	141.3	141.3	141.4
80	80	168.3	160.7	156.0	153.6	152.4	151.9	151.8	151.7	151.7	151.5	151.4
	90	165.8	156.7	151.0	147.7	145.9	145.0	144.6	144.4	144.3	144.2	143.9
	100	163.2	152.9	145.6	141.2	138.4	136.7	135.8	135.2	134.9	134.7	134.3
	110	159.5	149.6	140.8	135.8	132.3	130.3	129.0	128.2	127.9	127.6	127.2

Table 2.7 Replacement percent of model herds by model breeding season and duration of postpartum anestrus

Duration of Postpartum Anestrus (d)		Percent of the Herd										
		Model Breeding Season										
Multiparous	Primiparous	0	1	2	3	4	5	6	7	8	9	10
50	50	15.8%	15.8%	15.4%	15.5%	15.5%	15.6%	15.6%	15.6%	15.6%	15.6%	15.6%
	60	15.8%	15.6%	15.4%	15.5%	15.6%	15.6%	15.6%	15.6%	15.6%	15.6%	15.6%
	70	15.8%	15.9%	15.5%	15.6%	15.6%	15.6%	15.7%	15.7%	15.7%	15.7%	15.7%
	80	15.8%	16.1%	15.8%	15.8%	15.9%	15.9%	15.9%	15.9%	15.9%	15.9%	15.9%
	90	15.8%	17.2%	16.8%	17.1%	17.0%	17.1%	17.1%	17.0%	17.0%	16.9%	16.7%
	100	15.8%	18.2%	18.0%	18.4%	18.4%	18.4%	18.4%	18.3%	18.2%	18.1%	17.8%
	110	15.8%	20.2%	19.9%	20.9%	20.8%	21.0%	20.9%	20.8%	20.6%	20.4%	19.8%
60	60	15.8%	15.6%	15.4%	15.5%	15.6%	15.6%	15.6%	15.6%	15.6%	15.6%	15.6%
	70	15.8%	15.9%	15.5%	15.6%	15.6%	15.6%	15.7%	15.7%	15.7%	15.7%	15.7%
	80	15.8%	16.1%	15.8%	15.7%	15.9%	15.9%	15.9%	15.9%	15.9%	15.9%	15.9%
	90	15.8%	17.2%	16.9%	17.1%	17.1%	17.1%	17.1%	17.0%	17.0%	16.9%	16.7%
	100	15.8%	18.2%	18.1%	18.5%	18.4%	18.5%	18.4%	18.3%	18.3%	18.2%	17.8%
	110	15.8%	20.2%	20.0%	21.1%	21.1%	21.3%	21.2%	21.1%	20.9%	20.7%	20.0%
70	70	15.8%	15.8%	15.6%	15.9%	16.0%	15.8%	15.9%	15.9%	15.9%	15.9%	15.8%
	80	15.8%	16.1%	16.1%	16.5%	16.5%	16.5%	16.5%	16.5%	16.4%	16.4%	16.2%
	90	15.8%	17.2%	17.5%	18.1%	18.3%	18.3%	18.3%	18.3%	18.2%	18.0%	17.6%
	100	15.8%	18.2%	19.1%	20.1%	20.6%	20.9%	20.9%	20.9%	20.8%	20.5%	19.8%
	110	15.8%	20.2%	20.9%	22.8%	23.5%	24.2%	24.4%	24.5%	24.3%	24.1%	22.9%
80	80	15.8%	16.4%	17.3%	18.2%	18.6%	18.8%	18.7%	18.6%	18.2%	18.0%	17.8%
	90	15.8%	17.4%	18.9%	20.0%	20.7%	21.1%	21.2%	21.1%	20.8%	20.5%	20.0%
	100	15.8%	18.5%	20.4%	22.1%	23.1%	23.8%	24.2%	24.3%	24.1%	23.8%	23.0%
	110	15.8%	20.5%	22.2%	24.5%	25.8%	26.9%	27.4%	27.6%	27.6%	27.3%	26.4%

Figure 2.8 The replacement percent for herds in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 50-, 60-, 70-, or 80-days and a primiparous cow duration of postpartum anestrus of 50-, 60-, 70-, 80-, 90-, 100- or 110-days. Herds were modeled to have a 63-day natural service breeding season that started and ended on the same dates for cows and replacement heifers.



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Appendix A - **Model entry of an initial population**

With the exception of replacement heifers, an initial population of cows were loaded into the model as the Initial Population of Cows (**IC**) categorized by parity and breeding interval. IC enter the model through Entering the Model (**EM**) into model breeding season 0.

$$EM_{ik} = \frac{INIT(IC_{ik})}{21} \text{ if } t \geq DSC_{ik}$$

The term $INIT(IC_{ik})$ is the initial count of IC of the i^{th} parity and the k^{th} breeding interval, with the **DSC** being the Day to Start Cycling of the i^{th} parity and k^{th} breeding interval. The DSC was defined as the day the first cow within i^{th} parity and the k^{th} breeding interval would start normal estrous cycles and is calculated by adding the First Day to Start Cycling (FDC) of the i^{th} parity and k^{th} breeding interval to the product of 21 and the breeding interval number (**K**). The FDC was defined as the day the first cow of the i^{th} parity starts normal estrous cycles.

$$DSC_{ik} = FDC_i + (21 \text{ x } K)$$

For parities 1-10 the FDC was determined by adjusting the Start of the Breeding Season (**tBS**) of i^{th} parity by 365 to account for the time at which the prior breeding season would have occurred and adding the tGL and Postpartum Length (dPPA) of the i^{th} parity.

$$tC = (tFB + tGL) - 365$$

Replacement heifers were loaded into the model through the Initial Population of Replacement Heifers (**IH**), which categorized replacement heifers by the i^{th} parity of dam and the k^{th} breeding interval. The population in IH enters the model through Initial Population of Heifers

Starting Puberty (**iHSP**) after reaching the Initial Day of Puberty (**idP**) for replacement heifers from the i^{th} parity of dam and the k^{th} calving interval.

$$iHSP_{ik}=\frac{INIT(IH_{ik})}{21} \text{ if } t \geq idP_{ik}$$

The idP is calculated from the Start of Calving (**tSC**) of breeding season 0 and the Age of Puberty (**aPu**). The tSC was adjusted by 365 to account for the replacement heifers being born from two breeding seasons prior. The tSC was determined by adding the tGL to the tBS (or tAI for replacement heifers with an AI exposure).

$$idP_{ik}=(tSC_{ik}-365) + aPu + (21 \times K)$$

Heifers then get selected to be retained in the model based the number of replacement heifers intended to be kept for the model (**nOH**). The actual number of replacement heifers to be loaded into the model was based on the THS and Probability of a Heifer Being Retained in the Herd Until Parity 10 (**prRH**) and will not include the entire initial population IH. The selected animals flow through Replacement Heifers Entering the Model with the rate calculated in the same fashion as Kept for Replacement (kR) flow. This flow is then added to the Entering the Model (EM) flow.

To provide a source population of replacement heifers for breeding season 1 it was necessary to include an initial population of heifer calves in the model which are born in the season prior to breeding season 0. This Initial Population of Heifer Calves (**IHC**) were subcategorized by breeding interval and parity of dam. The IHC enter the model through the Initial Population Heifer Calves Being Born (ibHC) after the model time is greater or equal to the Start of Calving (tSC) of the i^{th} parity of dam and k^{th} calving interval.

$$\mathrm{ibHC}_{ik} = \frac{\mathrm{INIT}(\mathrm{IHC}_{ik})}{21} \text{ if time} \geq \mathrm{tSC}_{ik}$$

Appendix B - **Loading herd**

A loading herd with a total of 1,000 cows and replacement heifers was used for all models in the analysis. The Target Herd Size (**THS**) was set to 1,000 breeding animals. The distribution of the initial population by first calculating the Percent of an Original Number of Replacement heifers remaining per parity increase (**pOR**) based on the Annual Percentage Loss per Parity (**pAL**) and Parity Number (**P**) of the ith parity.

$$pOR_i = PERCENT(100)-(pAL \text{ x } PN_i)$$

An initial number of replacement heifers intended to be kept for the model (**nOH**) was then determined. The nOH is then used to determine a total population of initial cows (TIC) for parities 1 to 10.

$$nOH = \frac{THS}{\sum pOR_i}$$

$$TIC_i = pOR_i \text{ x } nOH$$

The nOH was then multiplied by the presumed percentage of animals in each 21-day breeding interval. For cows, the initial population was assumed to be distributed as 68.4% in the first 21-day interval, 23.2% in the second 21-day interval, and 8.4% in the third 21-day interval. These percentages correlate to these animals coming from a herd with a 95% pregnancy risk with a pregnancy distribution of 65% pregnant in the first 21-day interval, 22% pregnant in the second 21-day interval, and 8% pregnant in the third 21-day interval. The IH and IHC were then determined by dividing the number of cows of the ith parity and kth calving interval by 2 to account for an expected 1:1 ratio of heifer and bull calves.

Chapter 3 - A deterministic, dynamic systems model of cow-calf production: The effects of breeding replacement heifers before mature cows over a 10 year horizon

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Abstract

Some cattle production experts believe that cow-calf producers should breed replacement heifers (nulliparous cows) before cows (primiparous and multiparous cows), sometimes referred to as providing a Heifer Lead Time (**tHL**). Our objective was to model the effects different durations of tHL may have on measures of herd productivity including the percent of the herd cycling before the end of the first 21 days of the breeding season (**%C21**), the percent of the herd pregnant at pregnancy diagnosis (**%PPD**), the distribution of pregnancy by 21-day breeding intervals, the kilograms of calf weaned per cow exposed (**KPC**), and the replacement percentage

(**%RH**) using a deterministic, dynamic systems model of cow-calf production over a 10-year horizon. We also wished to examine differences in the effect of tHL that may be related to the primiparous duration of postpartum anestrus (**$dPPA_p$**). The study model examined six different $dPPA_p$ for primiparous cows (60, 70, 80, 90, 100, or 110 days). The multiparous cow duration of postpartum anestrus was set to 60 days. The breeding season length for nulliparous cows was 63-days, as was the breeding season length for primiparous and multiparous cows. Nulliparous cows were modeled with a tHL of 0, 7, 14, 21, 28, 35, or 42 days. The herd size was set to 1,000 head. All combinations of $dPPA_p$ and tHL were simulated, resulting in 42 model herds in the analysis. Results are reported for the final breeding season of the 10-year horizon. Increasing tHL resulted in a greater %C21 for the herd and for primiparous cows. For herds with a $dPPA_p$ of 80 days, the %C21 for the herd was 87.4% when tHL was 0 days, but increased to 90.7% when tHL was 14 days. Length of tHL had minimal impact on the %PPD unless the $dPPA_p$ was 80 days or greater, but resulted in fewer pregnancies occurring in the first 21 day breeding interval. For a $dPPA_p$ of 110 days, a 0 day tHL resulted in the herd having 88.1% PPD. When tHL was 21 days the %PPD increased to 93.0%. The KPC was 161.2 kg when the dPPA was 110 days and tHL was 0 days, and improved to 183.2 kg when tHL was increased to 42 days. The %RH did not vary much unless the $dPPA_p$ was 90 days or greater, but increasing tHL resulted in decreased %RH. Based on the model results, increasing tHL improves the production outcomes included in the analysis, but herds with $dPPA_p$ of 90 days or greater had the greatest degree of improvement in outcomes. For these herds, approximately two-thirds of the improvement in outcomes by increasing tHL from 0 days to 42 days was realized when tHL was 21 days. Costs are likely incurred when implementing tHL in a breeding management program and an ideal tHL likely depends on the $dPPA_p$ of the herd, the expected improvement in productivity, and the costs associated with increasing tHL. Many herds likely have a $dPPA_p$ between 80 and 90 days, but there are numerous herds that have shorter or longer $dPPA_p$. Determining the $dPPA_p$ of a herd could assist veterinarians and producers develop optimal herd management strategies.

Introduction

Veterinarians and cattle production experts frequently recommend that cow-calf operators breed replacement heifers (nulliparous cows) before the remainder of the herd in an effort to improve reproductive efficiency. This is sometimes referred to as providing a Heifer Lead Time (**tHL**) and has the intention of providing more post-calving recovery time for primiparous cows prior to the next breeding season. In the 1970's, researchers sought to develop cow-calf production systems to improve reproductive efficiency by shortening the breeding season to 45 days and by breeding nulliparous cows 20 days before primiparous and multiparous cows (Wiltbank, 1974). Other researchers have recommended that producers breed nulliparous cows 21 to 42 days prior to the remainder of the herd (Mossman and Hanly, 1977). However, disagreement exists in the veterinary and scientific community regarding the value and necessity of these recommendations. It has been shown the primiparous cow duration of postpartum anestrus (**$dPPA_p$**) impacts the distribution of pregnancies in a breeding season and that increasing $dPPA_p$ negatively impacts herd productivity (Shane et al., Submitted 2016). The objective of this analysis was to determine differences that exist between herds with various tHL using a deterministic, dynamic systems model of cow-calf production over a 10-year horizon and to determine if the effects were different between herds with various durations of $dPPA_p$. Outcomes of interest included the percent of the herd cycling before the 21st day of the cow breeding season (**%C21**), percent of cows pregnant at pregnancy diagnosis (**%PPD**), the distribution of pregnancies by 21-day breeding intervals, the kilograms of calf weaned per cow exposed (**KPC**), and the replacement percentage (**%RH**).

Materials and Methods

Cow-Calf production model

The analysis was performed using a deterministic, dynamic systems model of cow-calf production over a 10-year horizon developed with a commercially available software program (Stella Professional, isee systems, Lebanon, NH) (Shane et al., Submitted 2016). Shane et al. provides a thorough description of the model structure. In the model, pregnancies are classified into 21-day breeding intervals from the start of breeding primiparous and multiparous cows, meaning that herds with a tHL may have nulliparous cows becoming pregnant in "negative" 21-day breeding intervals. Values for model parameters are listed in Table 3.1. Parameters were held constant between model herds.

Model herds

Herds were modeled to have a $dPPA_p$ of 60, 70, 80, 90, 100, or 110 days, with the multiparous cow duration of postpartum anestrus being fixed at 60 days (Azzam et al., 1991; Patterson et al., 1992; Ciccioli et al., 2003; Cushman et al., 2007; Hickson et al., 2012; Mulliniks et al., 2013; Larson and White, 2016). We assumed that many U.S. commercial cow-calf herds have an average $dPPA_p$ of 80 or 90 days. We wanted to examine $dPPA_p$ at these lengths as well as herds with a $dPPA_p$ that may be 10 and 20 days shorter or longer than our assumed common $dPPA_p$. Herds were modeled to have a tHL for the nulliparous cow breeding season of 0, 7, 14, 21, 28, 35, or 42 days (Wiltbank, 1974; Mossman and Hanly, 1977).

All model herds had a 63-day natural service breeding season for nulliparous cows and a 63-day natural service breeding season for primiparous and multiparous cows. The nulliparous cow breeding season ended prior the multiparous cow breeding season in herds with a tHL greater than 0, despite having the same length of breeding season. An initial herd of 1,000 nulliparous, primiparous, and multiparous cows was loaded into the model. It was assumed that there was a prior pregnancy percentage of 95% and a distribution of 65% of the herd becoming pregnant during the first 21-day breeding interval, 23% becoming pregnant in the second 21-day interval, and 7% becoming pregnant in the third 21-day breeding interval. This resulted in 68.4% of the loading population being classified into the first 21-dy breeding interval, 24.2% being classified into the second 21-day interval, and 7.4% being classified into the third 21-day interval.

Model outcomes

Model outcomes included the percent of the herd cycling prior to the 21st day of the primiparous and multiparous cow breeding season (%**C21**), percent of the herd pregnant at pregnancy diagnosis (**%PPD**), the distribution of pregnancies by 21-day breeding intervals, the kilograms of calf weaned per cow exposed (**KPC**), and the replacement percentage (**%RH**). The %RH was determined by dividing the number of nulliparous cows that were selected for replacement to maintain a stable herd size by the total breeding herd. Results are reported for the final breeding season of the 10-year horizon (season 10). For outcomes that classify cows into time periods such as %C21 and interval classification of %PPD, nulliparous cows are included and contribute to the final outcome. Nulliparous cow pregnancies occurring prior to the first 21-day breeding interval of the primiparous and multiparous cow breeding season were classified into 21-day intervals occurring before the start of cow breeding (negative intervals). No inference testing was conducted due to the deterministic nature of the model.

Results

Percent of cows cycling prior to the 21st day of the breeding season (%C21)

As the tHL increased the %C21 increased, with relatively larger increases occurring for herds with longer $dPPA_p$ (Fig. 3.1). The %C21 plateaued with shorter $dPPA_p$ ($\leq$ 80 days) as tHL increased. The %C21 for primiparous cows exhibited similar relationships with $dPPA_p$ and tHL, but, as a subset of cows in the herd, were effected more than the overall herd (Fig. 3.2).

Percent of the herd pregnant at pregnancy diagnosis (%PPD) and distribution of pregnancy

The %PPD did not dramatically vary between model herds until the $dPPA_p$ was greater than or equal to 90 days (Fig. 3.3). No level of tHL resulted in a meaningful impact on the %PPD if the $dPPA_p$ was less than or equal to 80 days. The relative increase in %PPD for herds with a $dPPA_p$ of 90 days or greater decreased as the tHL increased. A similar pattern was also seen for primiparous cows in the herd, but the %PPD for primiparous cows was more negatively affected by $dPPA_p$ than the overall herd %PPD (Fig. 3.4).

The percent of the herd pregnant in the first 21 days of the breeding season or earlier was greater for herds with a shorter $dPPA_p$ and for herds with a longer tHL (Table 3.2). Increasing tHL also resulted in fewer pregnancies occurring in the second and third 21 days of the breeding season. When tHL was greater than 0 for herds with $dPPA_p$ of 100 and 110 days, the percent of the herd pregnant in each of the negative 21-day intervals were increased compared to the negative 21-day intervals of herds with shorter dPPAp. The distribution of pregnancy for primiparous cows exhibited a similar relationship, but, similar to %PPD, the percent of pregnancies occurring in each 21-day breeding interval for primiparous cows were affected to a greater degree by $dPPA_p$ than were the pregnancies in each 21-day breeding interval for the whole herd (Fig. 3.4). No primiparous cows became pregnant in the first 21-day breeding interval when $dPPA_p$ was 100 days and 110 days when tHL was 0 days, but increasing tHL had meaningful impacts on the percent of cows becoming pregnant earlier in the breeding season.

Kilograms of calf weaned per cow exposed (KPC)

The KPC for all model years increased for all levels of $dPPA_p$ as the tHL increased (Fig. 3.5). Herds with a shorter $dPPA_p$ tended to have more KPC, but the relative improvement for each 7-day increase in tHL was greater for herds with a longer $dPPA_p$, though the relative improvement decreased as tHL increased.

Replacement percentage (%RH)

The %RH was reflective of the %PPD, with tHL having minimal impact on the %RH when the $dPPA_p$ was 80 days or less (Fig. 3.6). Herds with a $dPPA_p$ of 90 days or longer had a greater %RH when compared to herds with shorter $dPPA_p$. A tHL of 21-days resulted in the %RH being decreased to less than 16% for herds with a 90 day $dPPA_p$.

Discussion

The objective of this analysis was to determine differences in cow-calf herds that began the nulliparous cow breeding season at different time points prior to the rest of the cows in the herd. The model used for this analysis has been previously utilized to determine differences related to the herd dPPA (Shane et al., Submitted 2016). The tHL has been proposed to be an important management strategy to maximize reproductive efficiency and reduce the risk of primiparous animals not becoming pregnant in the breeding season following the birth of their first calf, although some believe that the value of implementing tHL is not conclusive (Funston and Deutscher, 2004). It has been shown that cows that calve later in the calving season are less likely to have a calf and remain in the herd the next year and that earlier born calves will be heavier at weaning due to being older (Lesmeister et al., 1973; Cushman et al., 2013). Examining these potential effects over a 10-year horizon has not been explored, nor have the implications on herd dynamics. Furthermore, the dynamic relationships which exist in the movement of animals through a production cycle have not been incorporated or accounted for in traditional analyses. This model is a novel approach to explore different breeding management practices over multiple years and enhances the understanding of tHL.

Cows and heifers that calve later in the calving season are less likely to resume fertile estrous cycles prior to or early in the next breeding season, subsequently leading to fewer opportunities to become pregnant in a fixed-time breeding season. The utilization of tHL is thought to ensure that primiparous cows be more likely to start cycling early in the next breeding season, increasing the probability of becoming pregnant following their first calving (Larson and White, 2016). Our model shows this assumption is likely true if the $dPPA_p$ is greater than or equal to 90 days. We believe that the literature supports an assumption that many cow-calf operations have $dPPA_p$ of 80 or 90 days(Larson and White, 2016).

The model revealed that providing a tHL increases the %C21, but has minimal impact on the %PPD if the $dPPA_p$ is 80 days or less. The minimal impact on the %PPD is likely related to the age of puberty assumed for nulliparous cows, which was 365 days. Under the scenarios modeled, the youngest age of nulliparous cows at the start of the breeding season in which they would be eligible would be 384 days if tHL was 0 and 342 days if tHL was 42 days. The model selects the oldest heifer calves for use as replacement first so it is likely that all nulliparous cows selected for replacement were pubertal by the start of the breeding season, although this was not specifically examined. This fact would result in nulliparous cows having three opportunities to become pregnant in a 63-day breeding season, regardless of tHL. Once $dPPA_p$ extended beyond 80 days, primiparous cows started to cycle later in the breeding season, providing fewer opportunities to become pregnant, and subsequently reducing the pregnancy percentage.

The model showed increases in KPC as tHL increased, regardless of dPPA. Increases in KPC when there were minimal or no changes in %PPD are related to the increasing age of calves from nulliparous cows at the time of weaning as tHL increased. Of course, when tHL resulted in an increased %PPD the increased number of calves weaned also contributed to increases in KPC.

This analysis shows that increasing tHL results in improvement of the outcomes measured, however additional labor and input costs may be incurred by providing tHL to nulliparous cows. Determining if tHL would be beneficial to a herd would be largely dependent on the balance between the expected magnitude of improvement in herd performance and the costs associated with the management practices implemented. As long as any costs associated with implementation of tHL do not exceed the improvement achieved by implementing tHL, then using tHL would be beneficial. An economic analysis should be performed to determine where an economic advantage may exist for a tHL in various production scenarios.

Our analysis indicates that use of tHL may provide minimal benefit if $dPPA_p$ is less than 80 days, therefore providing justification to collect herd data that would allow an accurate estimate of dPPAp. Our analysis shows about two-thirds of the improvement in productivity related to increasing tHL from 0 days to 42 days for herds with $dPPA_p$ of 90 days or greater is realized with a 21-day tHL, and that about half of the improvement is realized with a 14 day tHL. This means that meaningful improvements in productivity are realized with shorter tHL and that there are diminishing improvements in outcomes as tHL increases. The “ideal” tHL that maximizes efficiency and net returns of the cow-calf herd is likely largely dependent on the $dPPA_p$ for each herd. The range of estimates of primiparous cow $dPPA_p$ is large, so it may be of value for veterinarians and producers to determine each herd’s expected range of $dPPA_p$ to improve management strategies. A prior analysis using this model concluded that it is also important to determine the duration of postpartum anestrus for multiparous cows in order to improve management decisions (Shane et al., Submitted 2016).

A limitation of this model is that it is deterministic and does not account for variability in model parameters. Interpretation of the model is based on knowing this limitation and recognizing that the model is an imperfect representation of the biological world. However, our analysis indicates that the use of a tHL may not be beneficial under all circumstances and the benefit is likely dependent on the average $dPPA_p$ of the herd.

Table 3.1 Model parameters and associated values for model herds.

Description	Value/Equation	Units	Ref
Start of the first model breeding season	1	d	-
End of the first model breeding season	63	d	-
Probability of pregnancy in a 21-day breeding period	0.65	-	(BonDurant, 2007)
Days to pregnancy diagnosis from end of breeding	60	d	-
Gestation length	283	d	-
Probability of abortion after 60-days gestation	0.015	-	(Waldner, 2005, 2014)
Probability of giving birth to a dead calf (primiparous cows)	0.058	-	(NAHMS, 2010)
Probability of giving birth to a dead calf (multiparous cows)	0.019	-	(NAHMS, 2010)
Duration of postpartum anestrus (primiparous cows)	50, 60, 70, 80, 90, 100, 110	d	(Larson and White, 2016)
Duration of postpartum anestrus (multiparous cows)	60	d	(Larson and White, 2016)
Probability of death	0.015	-	(NAHMS, 2010)
Probability of heifer remaining in the herd to parity 10	0.15	-	(Cushman et al., 2013)
Time to wean from the end of calving	205	d	-
Probability of calf mortality	0.035	-	(NAHMS, 2010)
Heifer calf birth weight – adjusted for parity of dam (0 to 10)	28.2, 29.5, 30.9, 31.8, 31.8, 31.8, 31.8, 31.8, 31.8, 30.4, 30.4	kg	(Beef Improvement, 2010)
Bull calf birth weight - adjusted for parity of dam (0 to 10)	30.5, 31.8, 33.2, 34.1, 34.1, 34.1, 34.1, 34.1, 34.1, 32.7, 32.7	kg	(Beef Improvement, 2010)
Heifer calf average daily gain - adjusted for parity of dam (0 to 10)	0.79, 0.83, 0.87, 0.91, 0.91, 0.91, 0.91, 0.91, 0.91, 0.87, 0.87	kg	(Doornbos et al., 1984; Beef Improvement, 2010)
Bull calf average daily gain – adjusted for parity of dam (0 to 10)	0.87, 0.91, 0.96, 1.00, 1.00, 1.00, 1.00, 1.00, 1,00, 0.96, 0.96	kg	(Doornbos et al., 1984; Beef Improvement, 2010)
Age of Puberty	365	d	(Diskin and Kenny, 2014)
Target Herd Size	1000	Cows	-

Figure 3.1 Percent of the herd resuming fertile estrous cycles by the 21st day of the breeding season in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 60 days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.

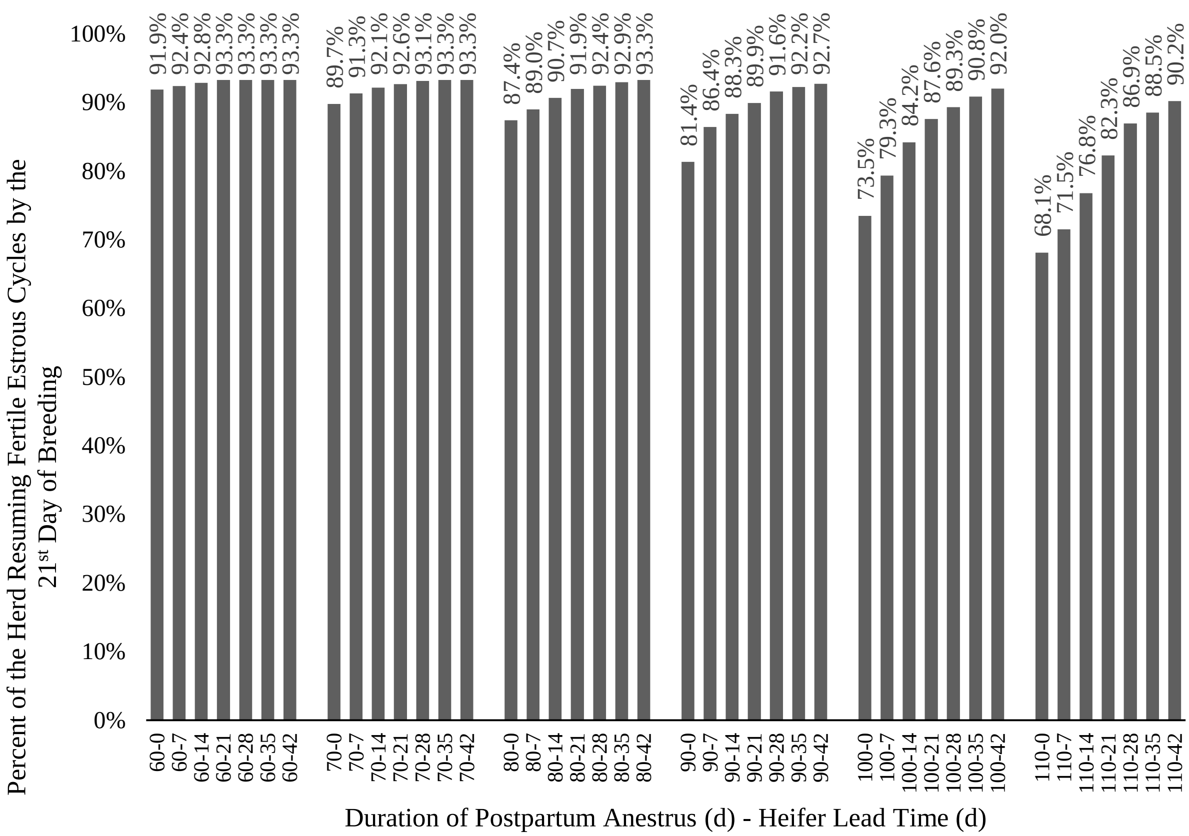


Figure 3.2 Percent of primiparous cows resuming fertile estrous cycles by the 21st day of the breeding season in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 60 days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.

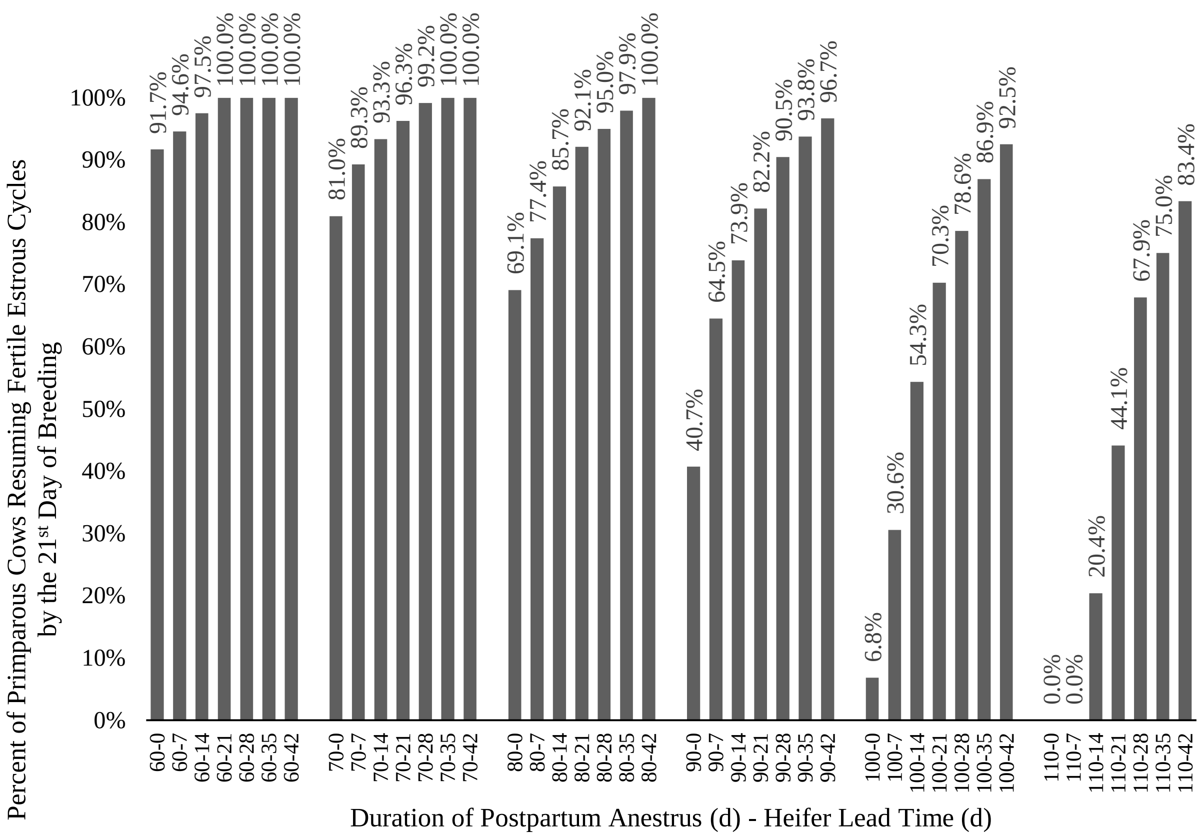


Figure 3.3 Percent of the herd pregnant at pregnancy diagnosis in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 60 days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.

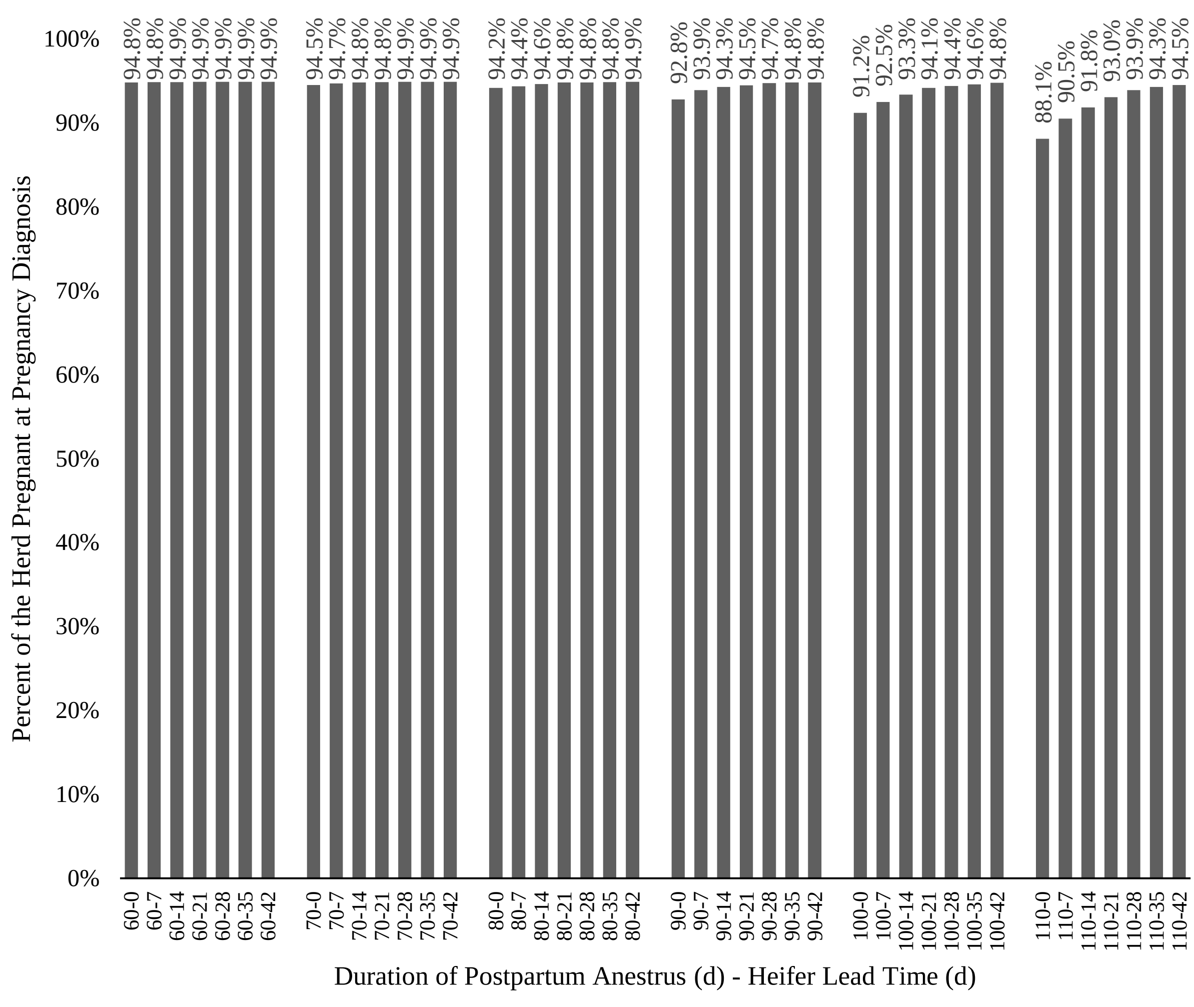


Figure 3.4 Percent of primiparous cows pregnant at pregnancy diagnosis by 21-day breeding interval in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 60 days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.

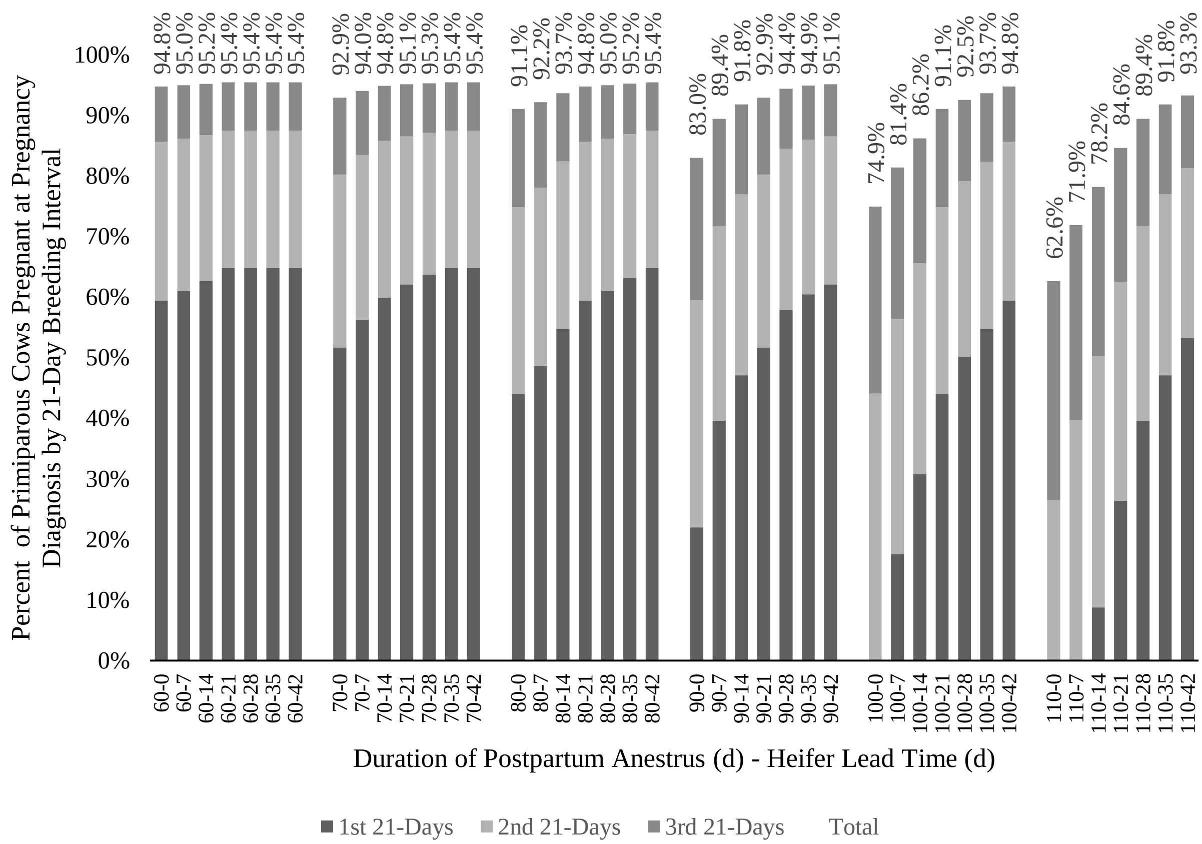


Table 3.2 Percent of the model herd diagnosed as pregnant in each 21-day interval of model season 10 by primiparous cow duration of postpartum anestrus and heifer lead time.

Duration of Postpartum Anestrus (d)	Heifer Lead Time (d)	Percent Pregnant by 21-Day Breeding Interval				
		2nd Negative 21-Days	1st Negative 21-Days	1st 21-Days	2nd 21-Days	3rd 21-Days
60	0	-	-	59.5%	26.1%	9.2%
	7	-	3.0%	57.8%	25.3%	8.7%
	14	-	6.6%	55.8%	24.3%	8.2%
	21	-	10.1%	53.9%	23.2%	7.7%
	28	3.0%	8.1%	53.2%	22.9%	7.7%
	35	6.6%	5.8%	52.4%	22.4%	7.7%
	42	10.1%	3.5%	51.5%	22.0%	7.7%
70	0	-	-	58.0%	26.7%	9.7%
	7	-	3.0%	57.0%	25.7%	9.0%
	14	-	6.6%	55.3%	24.6%	8.3%
	21	-	10.1%	53.4%	23.5%	7.8%
	28	3.0%	8.1%	53.0%	23.0%	7.7%
	35	6.6%	5.8%	52.4%	22.4%	7.7%
	42	10.1%	3.5%	51.5%	22.0%	7.7%
80	0	-	-	56.5%	27.3%	10.4%
	7	-	3.1%	55.4%	26.2%	9.6%
	14	-	6.6%	54.4%	25.0%	8.7%
	21	-	10.1%	52.9%	23.8%	7.9%
	28	3.0%	8.1%	52.5%	23.3%	7.9%
	35	6.6%	5.8%	52.1%	22.6%	7.8%
	42	10.1%	3.5%	51.6%	22.0%	7.7%
90	0	-	-	52.0%	29.0%	11.8%
	7	-	3.1%	53.6%	26.9%	10.2%
	14	-	6.6%	52.8%	25.6%	9.3%
	21	-	10.1%	51.4%	24.4%	8.5%
	28	3.0%	8.1%	52.0%	23.6%	8.0%
	35	6.6%	5.8%	51.6%	22.9%	7.9%
	42	10.1%	3.5%	51.1%	22.3%	7.8%
100	0	-	-	46.9%	30.9%	13.4%
	7	-	3.3%	48.9%	28.6%	11.7%
	14	-	6.9%	49.4%	26.7%	10.3%
	21	-	10.3%	49.8%	25.0%	9.1%
	28	3.0%	8.2%	50.4%	24.1%	8.6%
	35	6.6%	5.8%	50.6%	23.4%	8.3%
	42	10.1%	3.5%	50.6%	22.6%	7.9%
110	0	-	-	43.1%	29.5%	15.4%
	7	-	3.5%	44.0%	29.6%	13.4%
	14	-	7.3%	44.3%	28.4%	11.8%
	21	-	10.7%	46.0%	26.2%	10.2%
	28	3.1%	8.3%	48.2%	24.9%	9.4%
	35	6.6%	5.9%	49.0%	23.9%	8.9%
	42	10.1%	3.5%	49.4%	23.0%	8.4%

Figure 3.5 Kilograms of calf weaned per cow exposed in model season 10. Herds had a multiparous cow duration of postpartum anestrus of 60 days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.

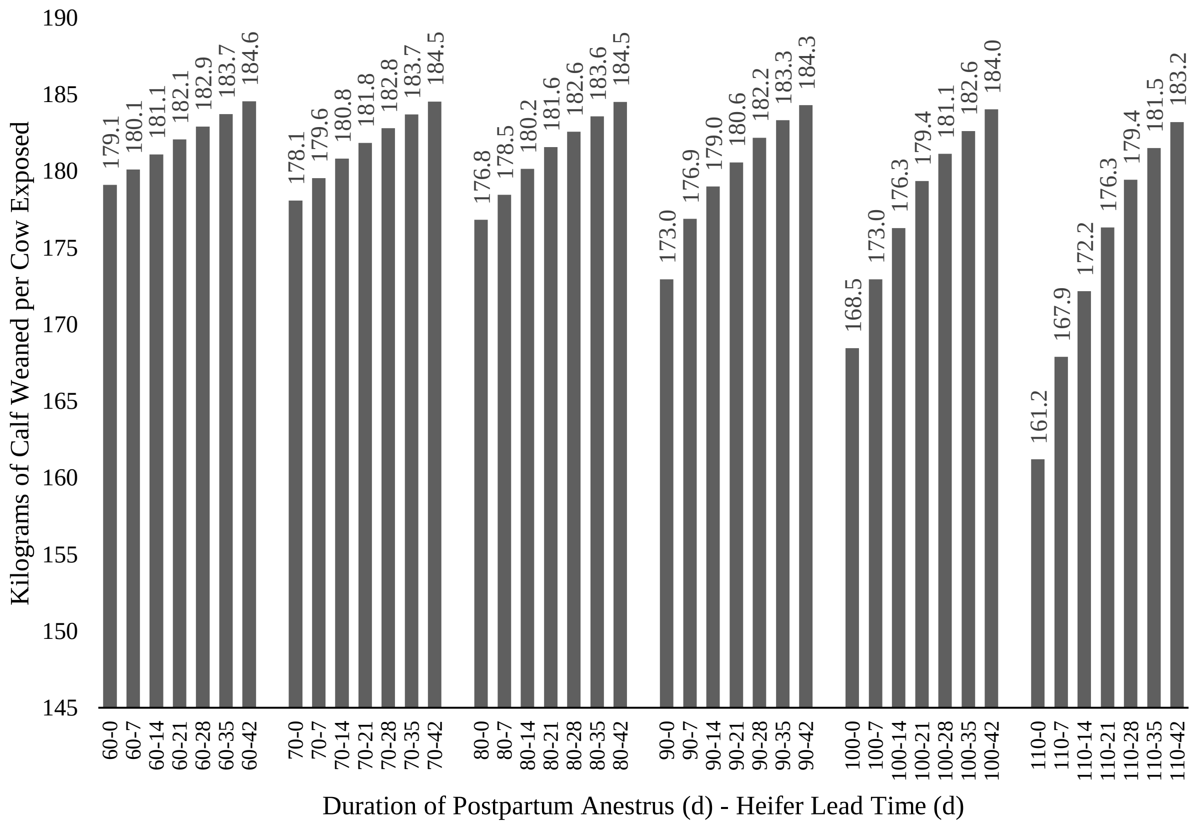
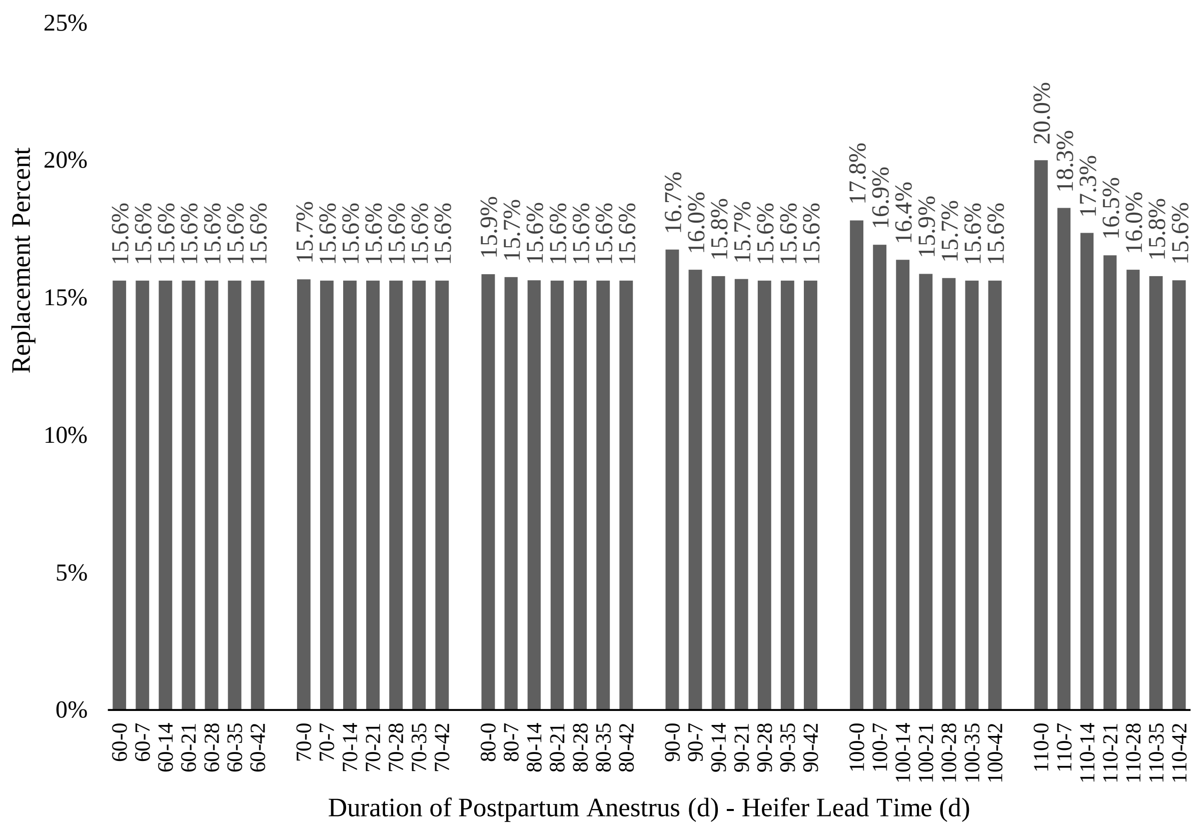


Figure 3.6 The replacement percent of model herds in model breeding season 10. Herds had a multiparous cow duration of postpartum anestrus of 60-days and a primiparous cow duration of postpartum anestrus of 50, 60, 70, 80, 90, 100 or 110 days. Herds were modeled to have a 63-day natural service breeding season for primiparous and multiparous cows that started at various time points following the start of breeding nulliparous cows (heifer lead time). Heifer lead times simulated were 0, 7, 14, 21, 28, 35, or 42 days.



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Chapter 4 - Probabilities of cattle participating in eating and drinking behavior when located at feeding and watering locations by a real time location system

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Abstract

Introduction: Animal location can be monitored and described through remote, real-time location system (RTLS) that locate animals within a defined housing area on a continuous basis using an X, Y coordinate system. These systems only collect locational data and do not measure participation in behaviors of interest. Video recording is a method for documenting animal behavior but analysis of the data is time consuming and prone to error. The objective of this research was to determine the probability of calves participating in eating or drinking behavior as classified by video when located by RTLS within 0.3 m of the hay, grain, or water.

Results: Two, separate 24 h trials monitored two independent groups of cattle in a dry lot pen. Trial 1 monitored 2- to 3-month old Holstein steer calves (n = 16) and Trial 2 monitored 4- to 5-month old beef heifer calves (n = 9). Video observers categorized each calf according to target behaviors as 0 (no behavior) or 1 (behavior observed) and video data was compared to RTLS data classifying calves as in-the-zone of interest. Analysis accounted for lack of independence of samples due to observer, repeated measures of calves, and period of the day (6 h block). Significant differences in the probability of engaging in a behavior of interest were observed between calves and periods of the day. When located in the zone of interest categorized as ‘‘in-the-water” by RTLS, individual calves displayed a model-estimated median (min, max) probability of drinking as categorized by video observation of 42.09% (26.58, 60.05) in Trial 1 and 54.49% (40.15, 75.01) in Trial 2. The model-estimated median probability of eating while located in the zone categorized as ‘‘in-the-hay” was 88.27% (65.10, 99.26) and 67.87% (22.63, 84.13) in Trials 1 and 2, respectively. The model-estimated median probability of eating when in-the-grain in Trial 1 was 59.59% (9.87, 88.07) and was 51.97% (36.86, 77.51) in Trial 2. *Conclusions:* The data from this trial provide an estimate of the median probability of participating in eating and drinking behavior when located at feeding and watering locations as categorized by RTLS. The observed data also highlights the significant variability in the probability of participating in a behavior of interest when at a location of interest between calves. This trial provides an improved understanding of the association between RTLS data and some of the behaviors of interest to researchers.

Introduction

Researchers use various direct and indirect methods of observation to assess health status (Theurer et al., 2013a). These methods are also used to monitor and quantify behaviors of interest, such as eating and drinking, when investigating the effects of a variable of interest. Direct observation methods such as assigning subjective clinical illness scores by trained observers have been used as a method to assess and describe health and wellness in cattle (Hanzlicek et al., 2010). Radio frequency transmitters have been used to determine presence and duration at feeding and watering locations, with this data being correlated to health status (Sowell et al., 1998; Quimby et al., 2001). Accelerometer technology and data logger technology utilizing electrical circuits have been validated and used to analyze postural behavior patterns of cattle (O'Driscoll et al., 2008; White et al., 2008; Robért et al., 2011). Walking activity and grazing bite activity have been successfully monitored through the use of pedometers (Devant et al., 2012; Umemura, 2013).

Technologies that integrate data from multiple measuring devices into one system may provide a benefit for investigating cattle behavior. Remote, real time locating system (RTLS) have been used to analyze the amount of time cattle spend at locations of interest, as well as distance traveled (White et al., 2012; Theurer et al., 2013b). These systems have been shown to have high precision regarding locational data of cattle in confined areas (Porto et al., 2014). RTLS can be used to detect differences or changes in cattle behavior associated with animal health and wellness and have many benefits over other systems for assessing behavioral differences (White et al., 2012; Theurer et al., 2013a; Theurer et al., 2013b; White et al., 2015). Unfortunately, the technology does not indicate the amount of time participating in various behaviors of interest, only whether or not cattle are located where they could participate in the activity. Thus, RTLS data must be interpreted knowing this limitation (Theurer et al., 2013a). Since feeding and watering behavior are associated with health status it would be beneficial to provide estimates for these behaviors of interest when using a RTLS system.

Direct observation of video recordings is a method that is frequently used to monitor and analyze cattle behaviors. Various behaviors such as eating, drinking, and lying down have been successfully monitored and assessed through the use of video recording (Szyszka et al., 2012; Huzzey et al., 2013; Uzal Seyfi, 2013). Though analysis of video data is difficult, time consuming, and often accompanied with error (Mitlöhner et al., 2001), it is frequently the most accurate method to assess cattle behavior. To address limitations of RTLS behavioral monitoring, the objective of this trial is to determine the probability of calves participating in eating or drinking behavior as classified by video when located within 0.3 meters of the hay, grain, or water as indicated by RTLS. Comparison of video data to the RTLS data will provide a better understanding of the data gathered from RTLS technology.

Methods

Cattle and husbandry

The research was conducted at the Large Animal Research Center at Kansas State University in Manhattan, Kansas. There were two individual trials conducted on separate groups of cattle. Animals used in Trial 1 were Holstein steer calves (n = 16) with an estimated age of 2- to 3-months. Trial 2 was conducted on beef heifers (n = 9) with an estimated age of 4- to 5-months. Observation periods were 24 h in duration with records being taken each second. Trial 1 was conducted from 12:00:00 PM on June 6, 2012 until 11:59:59 AM on June 7, 2012. Trial 2 took place from 12:00:00 PM on August 13, 2012 until 11:59:59 on August 14, 2012. The

Animal Care and Use Committee at Kansas State University approved the study under protocol number 3178.

Housing and weather conditions

Calves were housed in a standard livestock dry lot pen that was 12.2 m wide and 24.4 m long. Hay was fed ad libitum in a double sided 3.7 m bunk. A wood barrier was placed at the end of the hay bunk to ensure that feeding could not occur at the end of the bunk where video identification would be difficult. The water tank was a standard automatic ball fill tank with adequate space for a single calf to consume water at a time. Three feed bunks totaling 8.5 m in length place along one side of the pen were used to feed grain. Calves were fed grain daily at 08:30:00 AM and 04:00:00 PM. The layout of the pen is represented in Fig. 4.1.

Weather data were collected using the National Climatic Data Centre. The high and low temperatures recorded during Trial 1 were 31°C and 16°C, respectively. The maximum temperature during Trial 2 was 27°C and the minimum temperature was 16°C. Precipitation occurred during Trial 2 from 06:30:00 to 09:30:00 with a total 7.62 mm of measurable precipitation (Center, 2012).

Cattle identification

Calves in both trials were identified with a numbered ear tag and Ubisense Series 7000 compact tag RTLS tracking device (Ubisense, Denver, CO, USA). Numbered ear tags in Trial 1 were on the right ear, with the RTLS transmitters on the left ear. Calves in Trial 1 were identified in video using natural color pattern and by unique markings made with spray paint over the dorsal portion of the animal.

In Trial 2, beef heifers were given a numbered tag on their left ear, with the RTLS transmitter on the right ear. These calves were all black and were given unique markings with white spray paint in order to make identification on video possible. In both trials the Ubisense tag serial number was matched to the identification number on the ear tag.

Animal health monitoring

Cattle were observed twice daily for evidence of disease. Subjective clinical illness scores were assigned by a trained observer and the scores were utilized to evaluate wellness status (1 = clinically normal, 2 = slight illness, 3 = moderate illness, 4 = severely ill). Clinical indicators of health status included respiratory rate, visualization of cud chewing, tightness of the flank, willingness to move, coat condition, and others. Disease events were not expected in either trial. Clinical illness scores were used as part of standard animal husbandry procedures and were not used as data for this trial.

Remote, real-time location system

Real-time location system (RTLS) technology utilizes sensors and radio signals from transmitters to triangulate a location within a coordinate system designed for an area of interest. Ubisense Series 7000 compact tags (Ubisense, Denver, CO, USA) served as the transmitter and were attached to the ear of each calf using a modified ear tag and plastic cable zip tie.

The system interprets two pieces of information from the transmitter: The angle-of-arrival and the time-difference-of-arrival. The angle of arrival is the angle of the transmitter relative to the sensors. The time-difference-of-arrival is the difference in the amount of time it takes a signal from a transmitter to reach the different sensors. These measures are used to position the transmitter within the coordinate system. The system can then calculate the difference between time of arrival at one set of coordinates and the previous triangulation time point and calculate the amount of time spent at a respective coordinate. These coordinated data are then used to match and classify animals as present or absent in locations of interest using data mining software (MySQL, Oracle Corporation Redwood City, CA). The system included four RTLS sensors in close proximity to the pen of interest (Fig. 4.1). The coordinate system was programmed and validated for the pen used in the trial. Validation was completed by investigators placing tags at various locations in the pen and examining the locational data for agreement. Locational data were collected every second for each calf. The data matched by the mining software binomially classified the cattle as “in-the-zone” (1) or “not-in-the-zone” (0) for each location. “In-the-zone” refers to the RTLS transmitter tag being within 0.3 m of the water, hay, or grain. Each respective “in-the-zone” location may then be referred to as “in-the-water”, “in-the-hay”, or “in-the-grain”. Each location was assigned a mutually exclusive binomial response to each calf and the time each calf spent in the respective locations was aggregated. Time was matched to one of four 6 h periods of the day (Period 1 = 00:00:00 – 05:59:59, Period 2 = 06:00:00 – 11:59:59, Period 3 = 12:00:00 – 17:59:59, Period 4 = 18:00:00 – 23:59:59).

Video recording equipment

General Electric TruVision Cam Infrared Bullet Mid-Resolution Cameras (GE TVC-BIR-MR) (General Electric, Fairfield, CT) (n = 5) were strategically placed over feeding and watering locations to maximize behavior viewing (Fig. 1). Cameras recorded color video during the day and infrared video at night. The field of view for each camera was sufficient to capture the entirety of the location being filmed. Video recordings were stored on a Tyco TVR Digital Recorder Version 1 (Tyco, Princeton, NJ).

Observer training and validation

Observers were trained using behavior definitions as established by the investigators (Table 4.1) and video clips not included in the trial data. After training, all four observers were assigned a set of identical video clips from each location of interest (some were filmed during daylight and some during nighttime hours) for validation purposes. Observer data was then compared using a Kappa agreement test. The agreement across observers was 88.77% for the hay, 87.97% at the water, and 87.09% at the grain. After validation, results were discussed and any misunderstandings about definitions were clarified.

Data inclusion criteria

Only RTLS data collected during Period 2 and Period 3 were included for analysis of the grain location. Due to the feeding schedule of grain, it was known that grain eating behavior could only occur during these time periods and thus it was known that results from Periods 1 and 4 would have a 0% probability of participating in eating behavior. All other RTLS data was included in the analysis.

Video analysis

Prior to recording of video, the time stamp on the video recording device was confirmed by visual appraisal to be the same as the time on the computer-recorded RTLS data and time synchronization between video and RTLS data was confirmed within a 1 s interval. Video from

Trial 1 locations of hay and water were analysed by four observers. Video observations were divided into approximately 30-min time segments and randomized using an Excel random number generator. Clips were then systematically assigned to observers 1 through 4. The grain location was analysed by one observer and Trial 2 was analysed by one observer. Observers classified the behavior of each individual calf one at a time within a video clip so that observers were not attempting to classify behavior on more than one calf per viewing. Observers classified behavior for each second of the trial period for each individual calf.

The occurrence of the behavior related to that zone was indicated by observers as 1 for every second from the onset of behavior continuing until the behavior was completed. Times in which the behaviors of interest were not occurring were indicated by a 0. The hay and grain locations had two cameras and had their respective camera data merged together in order to provide a single indicator of behavior for each location.

Data Analysis

The video data and locational data were merged into a single dataset using commercial statistical software by matching the calf, date, and time (JMP 10, SAS Institute Cary, NC). Each calf had locational data and video data for each second within the respective trial periods. Only times in which calves were located in-the-zone by RTLS were used for analysis to address the objective of determining the probability of participating in eating or drinking behavior when located in-the-zone by RTLS. This data was then converted to a format that could be used for further analysis by SAS (SAS 9.2, SAS Institute Cary, NC). Trial 1 and Trial 2 were analysed separately to avoid confounding results because of differences in breed and age of the cattle, as well as the time of year.

Water and hay data from Trial 1 were analysed with a generalized linear mixed model using PROC GLIMMIX in SAS with model effects of repeated measures on calves, period of the day, and observer in order to evaluate the association of these effects with the probability of drinking occurring when in-the-water and the probability of eating when in-the-hay zone for each second located in-the-zone. Water and hay data from Trial 2 were analysed in a similar fashion, but did not include a model effect for observer. Grain data from Trial 1and Trial 2 were analysed with model effects of repeated measures on calves and period of the day in order to evaluate the association of these effects with the probability of eating when in-the-grain zone for each second in-the-grain.

Results

Trial 1

Trial 1 had a total of 7,927 individual seconds when individual calves were identified as being in-the-water by RTLS. The model adjusted probability of drinking as classified by video observations when calves were in-the-water was associated with individual calves ($P < 0.01$) and period of the day ($P < 0.01$), but not video observer ($P > 0.05$). For individual calves, the median probability of drinking when in-the-water-zone was 42.09% (minimum = 26.58%, maximum = 60.05%) (Fig. 4.2A). The highest probability of drinking when calves were located in-the-water occurred during Period 4 (Fig. 4.3A).

Calves were classified in-the-hay by RTLS a total of 94,451 s during Trial 1. The model adjusted probability of eating when calves were in-the-hay was associated with individual calves ($P < 0.01$), period of the day ($P < 0.01$) and video observer ($P < 0.01$). Individual calves had a median probability of participating in eating behavior when in the hay-zone of 88.27%

(minimum = 65.10%, maximum = 96.26%) (Fig. 4.2B). The probability of eating when at the hay was highest during Period 2 (Fig. 4.3B).

There were a total of 30,833 individual seconds when individual calves were identified by RTLS as in-the-grain. The model adjusted probability of eating when calves were in-the-grain was associated with individual calf ($P < 0.01$) and period of the day ($P < 0.01$). The individual median probability of eating when in the grain-zone was 59.59% (minimum = 9.87%, maximum = 88.07%) (Fig. 4.2C). The highest probability of eating was seen in Period 3 (Fig. 4.3C).

Trial 2

Drinking behavior in Trial 2 included 3,554 s when individual calves were located by RTLS as in-the-water. The model adjusted probability of drinking when calves were in-the-water was associated with individual calves ($P < 0.01$). The median probability of drinking when in the zone for individual calves was 54.49% (minimum = 40.15%, maximum = 75.01%) (Fig. 4.4A).

There were a total of 32,797 s when individual calves were classified in-the-hay by RTLS. The model adjusted probability of eating when calves were in-the-hay was associated with individual calves ($P < 0.01$) and period of the day ($P < 0.01$). When in-the-hay, the median probability of eating for individual calves was 67.87% (minimum = 22.63%, maximum = 84.13%) (Fig. 4.4B). The period with the highest probability of eating when in-the-hay was Period 2 (Fig. 4.5A).

RTLS located individual calves as in-the-grain a total of 20,334 s in Trial 2. The model adjusted probability of eating when calves were in the grain-zone was associated with individual calves ($P < 0.01$) and period of the day ($P < 0.01$). The median probability of eating for individual calves when in-the-grain was 51.97% (minimum = 36.86%, maximum = 77.51%)

(Fig. 4.4C). The highest probability of eating when in-the-grain occurred during Period 3 (Fig. 4.5B).

Discussion

Monitoring cattle eating and drinking behaviors can be a valuable research tool (Sowell et al. 1999). RTLS can provide a methodology to remotely and objectively measure the time spent at locations within a housing area with high precision (White et al., 2012; Theurer et al., 2013a; Theurer et al., 2013b; Porto et al., 2014). This study provides an improved understanding of the relationship between the probability of calves participating in eating when located by RTLS at an ad libitum hay feeding location and a limit-fed grain feeding location, as well as drinking when located by RTLS at an ad libitum watering location. We found obvious variability in the percent of time spent drinking when in-the-water, eating when in-the-hay, and eating when in-the-grain between individual calves, which is consistent with other reports (Schwartzkopf-Genswein et al., 2003).While the current project did not collect the data necessary to determine specific causes of variability between calves it is known that variability in feed intake and time spent eating has been attributed to differences caused by breed, temperament, and social interactions (Bennett and Holmes, 1987; Voisinet et al., 1997; Epps, 2002; Val-Laillet et al., 2008).

Some of the differences in the probability of participating in behaviors between calves when in-the-hay may be explained by the fact that some calves had their heads positioned under the bunk when in-the-hay and while in this position, these calves were not classified as eating even though they may have been eating off the ground. Video observation identified some calves lying and resting in or near zones of interest. These calves may have had a reduced probability of participating in behavior while in-the-zone. The probability of participating in a behavior of interest was modified by period of the day. It is well documented that cattle have behavioral patterns through different times of the day and the amount of time spent participating in different behaviors will vary throughout the day (Ray and Roubicek, 1971; Robért et al., 2011).

The results indicate that cattle may be more likely to participate in eating behavior when at an eating location when compared to drinking behavior at a watering location. However, differences in the probability of participating in drinking behavior may have been reduced because the water tank only allowed for one animal to drink at a time. The frequency of animals attempting to drink at the same time as another calf may have an impact the probability of drinking when located within 0.3 m of the water tank for this study. This finding may not be the same when watering locations allow for more than one animal to drink at a time. Alternatively, it is also possible that drinking is a more social behavior than eating behavior, resulting in clusters or groups of animal being at the water at the same time, although this study did not examine the possibility of this effect.

Conclusions

Prior research has shown RTLS technology is an effective tool for collecting locational data on cattle. The data from this trial provides estimated probabilities of cattle participating in eating and drinking when located at eating and drinking locations by RTLS. There is significant variability among calves in these probabilities. While this research did not examine differences due to health status, past research has shown changes in the amount of time spent at watering and feeding locations are reflective of health status changes in an animal. Locational data provided by RTLS are of great value as an indirect behavioral monitoring tool to determine when individual animals have changes in the amount of time spent at watering and feeding locations but may not be a good predictor of the amount of time actually spent participating in eating and drinking behavior. This trial provides an improved understanding of the association between RTLS data and the behaviors of interest investigated.

Authors' Contributions

DDS designed and set up the video recording system for the pen and was in charge of the observation of video. DDS was also responsible for data analysis and drafting of the manuscript. DEA was responsible for the set up and acquisition of RTLS data. BJW and RLL were responsible for trial design, assisted with the data analytical plan, and helped draft the manuscript. JLK assisted with trial planning, animal monitoring, set up, and data analysis.

Acknowledgments

We would like to thank Elizabeth Covington and Kayla Conroy for contributing to this trial through observing video and assisting with set up. There was no external funding provided for this research.

Figure 4.1 Schematic of real time location system and video recording system in dry lot pen. Radio signal transmission from locator tags send information to peripheral sensors. An angle of arrival and time difference of arrival are used to plot the animal at an X, Y coordinate. Cameras were placed over locations to capture the entire zone of interest.

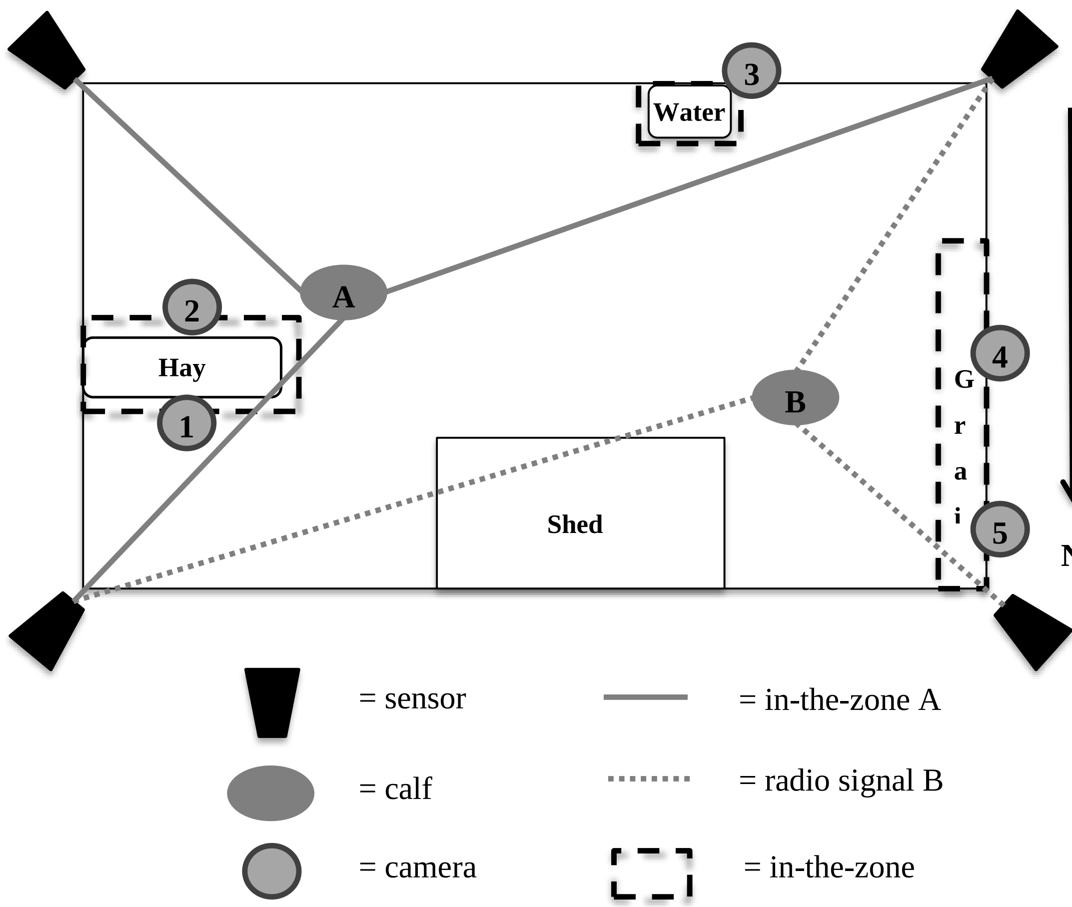


Table 4.1 Definitions of behavior as recorded by video recording device.

Behavior	Initiation of Behavior	End of Behavior
Hay eating	The calf is standing and The calf's muzzle is in the hay bunk and Vertical up and down movement of the head is observed AND/OR hay can clearly be seen entering or being held in the mouth of the calf	No signs of eating have occurred for 10 continuous seconds (>9)
Feed bunk eating	Feed is present in the feed bunk and The calf is standing and The calf's muzzle is in the feed bunk and The calf's head is lowered and the muzzle is in the feed bunk	The calf's head is out of the feed bunk for 10 continuous seconds (>9)
Drinking	The calf is standing and The calf's muzzle is located inside the opening of the water source	The calf's head is out of the water source for 5 continuous seconds (>4)

Figure 4.2 Distribution of probabilities of Holstein steer calves (n = 16) engaging in specific behaviors of interest (drinking (A); eating hay (B); eating grain (C)) per second when observed to be within 0.3 m of the location of interest over a 24 h period by a real time location system.

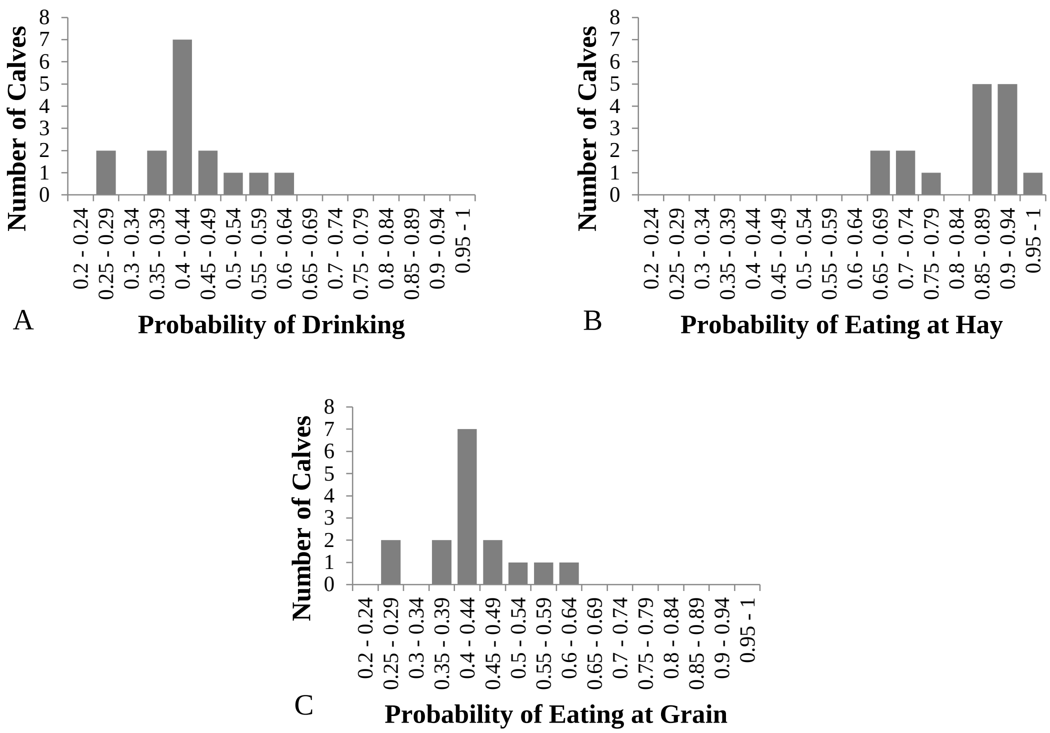
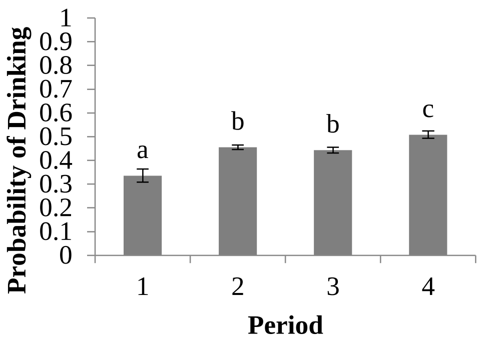
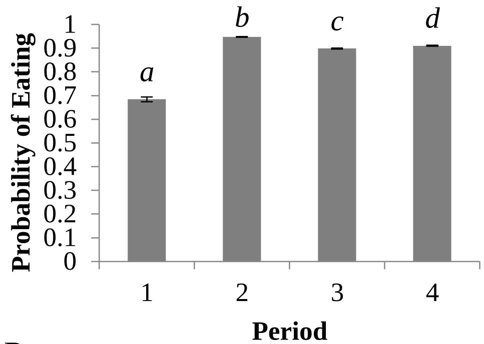


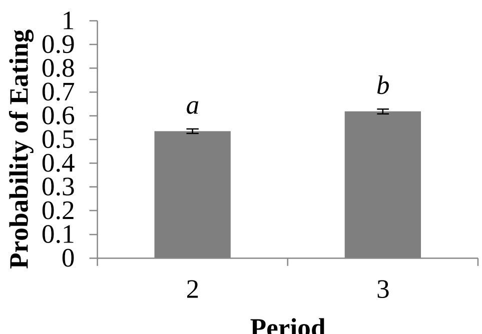
Figure 4.3 Probability of calves participating in behaviors of interest (drinking (A); eating hay (B); eating grain (C)) per second when observed to be within 0.3 m of the location of interest by real time location system by period of the day.



A



B



C

Figure 4.4 Distribution of probabilities of black heifer calves (n = 9) engaging in specific behaviors of interest (drinking (A); eating hay (B); eating grain (C)) per second when observed to be within 0.3 m of the location of interest over a 24 h period by a real time location system.

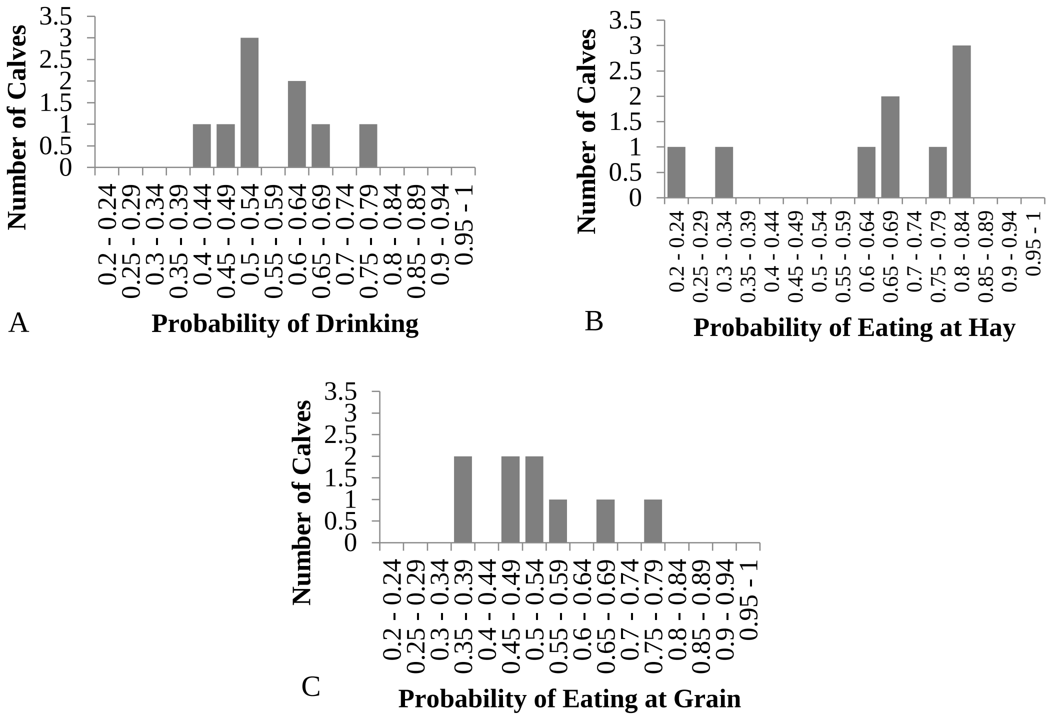
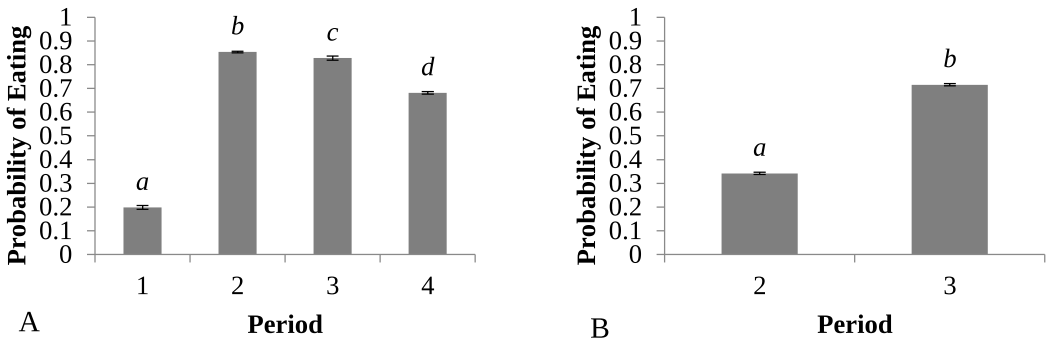


Figure 4.5 Probability of black heifer calves (n = 9) participating in behaviors of interest (drinking (A); eating hay (B); eating grain (C)) per second when located to be within 0.3 m of the location of interest by real time location system by period of the day.



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Chapter 5 - Associations between animal-to-animal contact as determined by a real time location system and the probability of bovine respiratory in beef cattle housed in a dry-lot pen

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Abstract

Bovine Respiratory Disease (BRD) is a multifactorial disease process with several associated risk factors. It has not been clear if BRD is a transmissible disease process. Real-time location systems (RTLS) collect high resolution locational data that may be used to determine when cattle were near each other and presumably in contact. The objective of this research was to determine if the probability of an initial BRD diagnosis on a given day for beef cattle during the first 28 days on feed (**pBRD)** was associated with greater calf-contact time on previous days

(3 days, 4 days, 5 days, 6 days, and 7 days ago), as determined by RTLS. Measures of calf contact included an individual calf's total time in calf-contact in a study day, the time in calf-contact with calves assumed to be shedding BRD pathogens in a study day, and the time in calf-contact with calves persistently infected with *Bovine Viral Diarrhea Virus* in a study day.

Commercial beef cattle (n = 70) from the southeastern United States were transported to a commercial feeding facility in Manhattan, KS. Cattle were processed and given an RTLS transmitter tag. Cattle were assigned daily clinical illness scores by a trained veterinarian. Cattle with abnormal clinical illness scores and a rectal temperature greater than 40°C were diagnosed with BRD and treated according to protocol. Locational data were used to determine when calves were within 0.5 m of one another, defining cattle contact. Locational data were used to determine an individual calf's total time in calf-contact on the day occurring 3 days ago (ALL3), 4 days ago (ALL4), 5 days ago (ALL5), 6 days ago (ALL6), and 7 days ago (ALL7). The amount of time in calf-contact on the day occurring 3 days ago, 4 days ago, 5 days, 6 days ago, and 7 days ago with calves assumed to be shedding BRD pathogens was determined (SHED3, SHED4, SHED5, SHED6, and SHED7, respectively), as was an individual calf's time in a day spent in contact with calves persistently infected with *Bovine Viral Diarrhea Virus* on the day occurring 3 days ago (PI3), 4 days ago (PI4), 5 days ago (PI5), 6 days ago (PI6), and 7 days ago (PI7). Contact variables were screened and a multivariable logistic regression model was constructed to model the individual log odds of BRD diagnosis on the day of interest. Log odds estimates were used to calculate predicted probabilities of BRD (pBRD) for statistically significant contact measures.

Contact variables significantly associated ($P \leq 0.05$) with the log odds of BRD included SHED4 and cALL7. Increasing the amount of time SHED4 increased the probability of BRD diagnosis. Very low time ALL7 was associated with increased pBRD. However, it was determined that a biological rational did not exist to support the finding of ALL7 being associated with pBRD.

The results indicate contacts between cattle affect BRD risk in feedlots and that direct transmission of BRD pathogens likely occurs. Future studies should be conducted to improve our understanding of the role contact structures and transmission plays in BRD outcomes. Cattle contact information may potentially be used in BRD intervention strategies in the future.

Introduction

Bovine Respiratory Disease (BRD) is a significant source of financial and animal health challenges for cattle producers (Griffin, 1997). It is a multifactorial disease process that has been associated with multiple viral and bacterial pathogens, as well as risk factors such as stress due to commingling and transport (Snowder et al., 2006; Taylor et al., 2010; Cernicchiaro et al., 2012a; Cernicchiaro et al., 2012b; Babcock et al., 2013; Hay et al., 2014). The role that cattle social behavior may have in BRD outcomes has not been explored. Social behavior of cattle could potentially be important in BRD outcomes if BRD is a transmissible disease. Past research has shown that direct transmission of pathogens may occur at feedlots and that seronegative animals at arrival are more likely to develop BRD during the feeding phase (Martin et al., 1990; Hay et al., 2016a). However, prior research has also indicated the BRD may not be a communicable disease process (Martin et al., 1988).

Real-time location systems have been used to study cattle contact structure in small groups of calves (Chen et al., 2013; Chen et al., 2014). These systems have been used to indirectly monitor cattle behavior with adequate accuracy and precision (Porto et al., 2014). They have been used to determine time spent at locations of interest, describe behavioral patterns, and detect changes in behavior to predict BRD (White et al., 2012; Theurer et al., 2013; White et al., 2015; Shane et al., 2016). Chen et al. (2014) showed cattle have heterogeneous contact structures that play an important role in transmission of enteric food borne pathogens under conventional commercial feeding practices. However, using RTLS to study cattle contact behavior and its potential relationship to BRD risk has not been done.

The objective of this research was to determine if the probability of an initial BRD diagnosis on a given day for beef cattle during the first 28 days on feed (**pBRD)** was associated with greater calf-contact time on previous days (3 days, 4 days, 5 days, 6 days, and 7 days ago), as determined by RTLS. Measures of calf contact included an individual calf's time in calf-contact in a study day, the time in calf-contact with calves assumed to be shedding BRD pathogens in a study day, and the time in calf-contact with calves persistently infected with *Bovine Viral Diarrhea Virus* in a study day.

Materials and Methods

The use of cattle for this study was approved by the Kansas State University Institutional Animal Care and Use Committee, protocol number 3732.

Cattle and husbandry

The research was conducted at a private feeding facility managed by the Veterinary and Biomedical Research Center in Manhattan, KS. A total of 70 castrated male commercial beef cattle weighing an average of 248.9 kg (range 202.7 kg to 306.4 kg) were procured from the southeastern region of the United States and were processed approximately 12 hours after arrival at the feeding facility. The study was conducted from 5/1/16 at 11:00:00 to 5/29/16 at 07:00:00.

Housing

Cattle were housed in a standard dry-lot pen with approximately 28 m^2 of pen space per calf. A complete mixed ration consisting of prairie hay, dry distillers grain and commercial blended grower ration were fed for the first 14 days of the study. Cracked corn was added to the complete mixed ration for the last 14 days of the study. Feed was delivered once daily to calves in a standard linear feed bunk with approximately 0.6 m of bunk space per calf. Ad libitum water was available via a standard float valve ball tank with enough room for one calf to drink at a time. A second oval shaped plastic water tank with a float valve was added to the pen on 5/9/16 at approximately 3:12:00 pm and remained in the pen for the remainder of the study.

Animal processing

Cattle were processed at day 0 approximately 12 hours after arrival at the facility. At the time of processing, calves were given double identification ear tags in sequential order and a RTLS tag placed in the left ear. Calves were weighed and were administered a 5-way modified live viral respiratory disease vaccine[a], a clostridial bacterin[b], and a pour-on ivermectin anthelmintic[d]. An ear notch biopsy was collected from each calf to screen for persistent *Bovine Viral Diarrhea virus* infections (**BVD-PI**) via RT-PCR. Calves with a ct value less than 30 were determined to be positive for BVD-PI.

Clinical Observations

Cattle were observed once daily by a veterinarian for clinical symptoms consistent with BRD. The veterinarian assigned a clinical illness score (CIS) for each calf according to predetermined CIS definitions (Table 5.1). Animals with a CIS of 2 or 3 were removed from the pen for examination. In the event a calf had a CIS of 4, the calf was to be humanely euthanized in the pen to prevent suffering. No animals were assigned a CIS 4 in the study.

Bovine respiratory disease case definition and treatment protocol

Animals that were assigned an abnormal CIS (2 or 3) were removed from the pen for examination following assignment of the CIS of all calves. Rectal temperatures were obtained and calves with a rectal temperature greater than 40°C were considered to have BRD and were treated according to the treatment protocol for BRD cases (Table 5.2). Each treatment for BRD had a 72-hour post-treatment interval from the time of treatment before being eligible for additional treatment. Had an animal been assigned a CIS of 4, a rectal temperature would have been obtained in the pen and the animal would have been humanely euthanized.

Real-time location system

Cattle location in the pen was monitored using a commercial RTLS system[c]. The system was installed, setup, and managed by a private third party company[e]. The real-time location system utilizes ultra-wide band tag signal transmitters placed on one ear of each animal and signal sensors placed around the perimeter of the pen to triangulate signals within the system area to determine calf location. The data were relayed to a central server and stored. The XY coordinate locations for each calf were logged for each second of the study period.

Data handling and management

The raw data were handled and processed by the RTLS data management company in a commercial database. In the event retention failure occurred for an RTLS tag, the data were examined backwards from the time the new RTLS tag was placed for the last point in time movement greater than 2 meters occurred as determined by the previous tag. This was considered the last valid locational data point and all data between this time point and placement of the new tag were missing data. The XY coordinates for each calf at each second of the study period were compared to the XY coordinates of all other calves at the same time point. Any second in which pairs of calf coordinates were within a Euclidean distance of 0.5 meters was considered to be contact occurring between calves. The distance of 0.5 meters was selected and agreed upon by the authors of this research. The total number of seconds of contact between individual pairs of calves were aggregated by the day, with day considered to occur from 12:00:00 am to 12:59:59 pm. These data were transferred from the data management company and then manipulated using an open source data analytics program[f]. Duplicated calf contact pair comparisons and invalid pairs of calf contact comparisons were removed from the dataset. Invalid pairs occurred when one of the calves in the pair was a null value and a comparison was not actually made.

Cattle were considered to be possible shedders of BRD pathogens for the 2 days prior to a BRD diagnosis and the 5 days following diagnosis (Fig 5.1). The shedding window was chosen based on a review of BRD pathogens which describes the onset of viral shedding and clinical symptoms for *Bovine Viral Diarrhea Virus* **(BVD)** and other pathogens implicated in BRD (Grissett et al., 2015). The review highlights that the peak onset of clinical symptoms and peak rectal temperature after challenge with BVD typically occurs about 7 days' post-challenge. We assumed that cattle were likely diagnosed around the time of peak symptoms and rectal temperature. According to the literature review, peak viral shedding of BVD post-challenge occurs about 2 days prior to peak clinical symptoms and typically resolves about 6 days following peak symptoms. These assumed shedding periods for calves diagnosed with BRD were added to the data set.

The objective of the study was to examine if the amount of calf-contact time in a day for various contact measures in previous days was associated with pBRD. We hypothesized that exposure to pathogens resulting in BRD morbidity would likely occur between 3 and 7 days prior to a diagnosis and that greater time spent in contact may be associated with BRD risk

(Grissett et al., 2015). The contact data reporting the number of seconds of contact between calf pairs for each day were then aggregated by individual calf to report an individual calf's total time spent in calf-contact on the day occurring 3 days ago (**ALL3**), 4 days ago (**ALL4**), 5 days ago (**ALL5**), 6 days ago (**ALL6**), and 7 days ago **(ALL7)**. Data were also aggregated to report an individual calf's total calf-contact time on the day that was 3 days ago, 4 days ago, 5 days ago, 6 days ago, and 7 days ago with calves considered to be shedding respiratory pathogens (**SHED3**, **SHED4**, **SHED5**, **SHED6**, and **SHED7**, respectively**)**. Finally, data were aggregated to report an individual calf's total calf-contact time with BVD-PI calves on the day occurring 3 days ago (**PI3**), 4 days ago (**PI4**), 5 days ago (**PI5**), 6 days ago (**PI6**), and 7 days ago (**PI7**). It should be clarified that if a calf was in contact with more than one calf at the same time the seconds of contact for each pair are added together. For instance, if a calf was in contact with two calves at the same time then 2-seconds of calf-contact would be counted. Any study day with 0 seconds in calf-contact for an individual calf were considered non-biologic values and were treated as missing independent variables in the data.

Study days at the beginning of the study period for which lag contact measures were not available were handled as missing values. The daily BRD diagnosis outcome for each individual calf was then added to the final dataset as a binary outcome variable.

Statistical analysis

Associations between cattle contact and the log odds of BRD diagnosis were analyzed with the PROC GLIMMIX procedure using a multivariable logistic regression model with a Quasi-Newton optimization technique[g]. To account for repeated measures on individual calves, a random residual term for individual calf was included. All lag contact measures were screened in individual models with day, the respective lag contact measure, and the day by lag contact measure interaction as the model effects. When interaction terms were not significant ($P > 0.1$) the interaction term was removed and a model with day and the lag contact measure as the model effects were screened. When interaction terms were significant ($P \leq 0.10$), the interaction term and associated main effects were selected for inclusion in a manual backwards selection procedure. Significant lag contact measure main effects ($P \leq 0.10$) identified after removal of the interaction term were also selected for inclusion in the manual backwards selection procedure.

Contact measures selected from the screening process were assessed for collinearity using a Pearson's and Spearman's correlation analysis with the PROC CORR procedure. For lag contact measures with a statistically significant ($P \leq 0.05$) correlation statistic of $|0.80|$ or greater, only one was selected for inclusion in the multivariate backward selection process. In the manual backwards selection process of the multivariate model, non-significant lag contact measures and interaction terms were removed from the model ($P > 0.05$) until only statistically significant lag contact measures ($P \leq 0.05$) remained. Study day was determined a priori to be a potentially confounding variable and was retained in the model. To determine if the linearity could be assumed, significant lag contact measures were categorized into quintiles and estimated odds ratios were obtained. The estimated odds ratios were plotted for visual evaluation of linearity in the odds of BRD. The log odds regression estimates from the model were used to calculate predicted probabilities for BRD associated with statistically significant lag contact measures. Calculated predicted probabilities were made for significant contact measures on a continuous basis and graphed for interpretation. Calculated predicted probabilities were also made for non-significant contact measures to qualitatively assess if a biological gradient existed to support the findings from the statistical model.

Results

The cumulative incidence of BRD during the study period was 40% with the peak daily incidence count occurring at study day 8 (Fig. 5.2). The treatment success rate for first BRD diagnoses was 100% and no calves were diagnosed a second time for BRD. A single calf was diagnosed as being a BVD-PI (Calf ID = 108). One calf (Calf ID = 154) was discovered to have dies at approximately 07:00:00 am on study day 12 and gross necropsy revealed a mild amount of lung consolidation and atelectasis in the cranial lung lobes. No other gross abnormalities were observed. Two calves (Calf ID = 103, 127) were diagnosed for infectious bovine keratoconjunctivitis on study day 17 and study day 9, respectively, and were treated with Tulathromycin at the label dose. Bovine respiratory disease diagnosis outcomes after the time of pinkeye treatment were removed from the analysis because it was believed that treatment for pinkeye could have an impact on the pBRD based on the characteristics of Tulathromycin (Evans, 2005). At various time points in the study calves had RTLS tags come out of the ear (n = 23). Calves missing RTLS tags at morning observations were removed from the pen and had new tags placed. The time and date of new tag placement was documented and was used as a starting point to examine locational data for an estimated time at which the prior tag had fallen from the ear, as discussed in the material and methods.

Significant variability was observed in contact measures, as determined by RTLS and aggregated by individual calf for each study day (Fig. 5.3a – 5.3c). Study day 0 and study day 27 were not included in the descriptive graphs because these days did not have a full 24 hours of locational data collected. Variability may be observed between calves within a study day but also between study days. Despite variability day to day for the total amount of time spent in calf contact (Fig. 5.3a) and the amount of time spent in contact with the BVD-PI (Fig. 5.3c), subjectively, the median amount of time in calf-contact did not vary in a meaningful way or display any obvious pattern. The median amount of time spent in calf-contact with animals assumed to be shedding BRD pathogens increased and decreased corresponding to the number of calves assumed to be shedding BRD pathogens (Fig. 5.3d).

The data file aggregating seconds of contact between individual pairs of calves by study day had 139,947 rows of calf contact data. After removing invalid calf pair comparisons, duplicated calf pairs, and study days occurring after pinkeye treatment a total of 136,490 rows of data remained in the data file. After aggregating the daily time in contact between pairs of calves by individual calf to report an individual calf's time spent in calf-contact a total of 1,904 rows of data existed in the final data set.

Study day was not found to be a statistically significant predictor in the model but was retained because it was decided a priori to be an important potential confounding variable. Contact variables found to be significantly associated ($P \leq 0.05$) with the log odds of BRD in the final multivariable model included SHED4 and ALL7 (Table 5.3). The model estimated intercept pBRD, as calculated from the log odds estimate, was 5.99%.

The estimated pBRD, as calculated from the log odds estimates, increased in a non-linear manner as SHED4 increased (Fig. 5.4). The estimated pBRD was 11.34%, 13.73%, 23.46%, 47.75%, and 89.04%, when the amount of time SHED4 was 500 seconds, 1,000 seconds, 2,500 seconds, 5,000 seconds, and 10,000 seconds, respectively. After plotting the predicted probabilities of SHED4 with the predicted probabilities of SHED3, SHED5, SHED6, and SHED7 it was determined that SHED3, SHED6, and SHED7 provided indistinguishable results and did not appear to have any kind of predictive association with pBRD (Fig. 5.5). However, SHED4 and SHED5 appeared to be predictive of pBRD, with SHED4 being the most predictive.

These findings suggest that a hypothesis that contact with calves predicted to be shedding BRD pathogens is an important contributor to BRD risk 4 to 5 days later should be evaluated further.

Very low time ALL7 was associated with increased pBRD (Fig 5.6). The estimated pBRD was 5.09%, 2.73%, 0.40%, and 0.02% when the amount of time ALL7 was 5,000 seconds, 10,000 seconds, 25,000 seconds, and 50,000 seconds, respectively. The plot of the predicted probabilities of ALL3, ALL4, ALL5, and ALL6 with ALL7 revealed an indistinguishable pattern of the contact measures with pBRD and do not show a discernable biological explanation (Fig. 5.7).

Discussion

Some BRD risk factors have been well established, but the role of cattle contact structure has not been determined (Cernicchiaro et al., 2012a; Cernicchiaro et al., 2012b; Babcock et al., 2013; Hay et al., 2014; Theurer et al., 2014; Hay et al., 2016b). Real time location systems have afforded the opportunity to collect high resolution locational data on a continuous basis and use the locational data to determine when direct contact between cattle may have occurred. These technologies have been used to quantify contacts between cattle and found that significant heterogeneity exists in cattle contact structures between individual cattle and between days (Chen et al., 2013). Our finding of significant variability in cattle contact measures aligns with this prior research and highlights the critical role individual animals may have in a disease epidemic.

Our research indicates that increased calf-contact with calves assumed to be shedding BRD pathogens increases the risk of BRD diagnosis 4 days later in a non-linear manner. This finding supports the hypothesis that direct transmission of BRD pathogens occurs and that increased contact with cattle shedding these pathogens increases the risk of disease. While not statistically significant, SHED5 displayed a similar pattern to SHED4; and both SHED4 and SHED5 were qualitatively different from SHED3, SHED6, and SHED7 patterns that showed very weak relationship between contact with calving predicted to be shedding BRD pathogens and risk of being diagnosed with BRD. Our interpretation of the results from associations between all the evaluated lag times between presumed exposure and BRD diagnosis indicate the possibility that contact with calves predicted to be shedding BRD pathogens results in increased risk of being diagnosed with BRD during a relatively narrow of time which we estimate to be 4 to 5 days later. While it is possible that contact 4 days ago is the important day on which contact occurs, we believe that contact with shedding calves 4 days prior may not the only important day on which meaningful contact with shedding animals occurs. This phenomenon detected in this data set may have been related to case definitions used in the study and related to how we defined the pathogen shedding period. While the shedding definition used in this study is supported, changing the shedding window could potentially alter the day found to be associated with BRD risk because the definition has possible implications on the number of cattle assumed to be shedding BRD pathogens on any given day. Regardless, the finding that higher degrees of contact with calves diagnosed with BRD that are shedding pathogens increases BRD risk likely still holds true. This potentially has implications on the future management of BRD in commercial feedlots. While some commercial feedlots send cattle treated for BRD to hospital pens, a majority of feedlots treat cattle diagnosed with BRD and return them to their home pen within 24 hours (NAHMS, 2011). Based on our results, we hypothesize this practice may increase the risk of disease for pen mates, especially those with higher degrees of contact with the calves shedding BRD pathogens, and that isolating calves until resolution of shedding may help reduce BRD incidence by mitigating cattle contact.

Identification of probable future pathogen shedders based on contacts with animals diagnosed with BRD may also help reduce disease incidence if these calves are removed from the pen prior to pathogen shedding. This would of course require real time monitoring of calf contacts. Early detection and diagnosis of BRD has been investigated through various indirect behavioral monitoring technologies (Jackson et al., 2016; Pillen et al., 2016). A system utilizing RTLS technology was found to detect cattle suspected of having BRD 0.75 days prior to trained observers (White et al., 2015). According to the definitions of shedding used for this study, we would assume that these calves would have started peak pathogen shedding just 1.25 days prior to detection by the remote monitoring system. Potentially in the future, RTLS may be used to quantify contact and determine which calves had the most contact in the preceding few days with calves newly diagnosed with BRD. This information could then be used in predictive algorithms to help determine BRD risk for individual calves which could then be removed from the pen even earlier in the disease process or monitored more intensely for early treatment decisions. This will require further research exploring the role of contact structures in naturally occurring BRD.

Past research has shown that seroconversion to respiratory pathogens from the time of study enrollment increases the odds of BRD in Australian feedlot cattle, indicating that possible direct transmission of and exposure to respiratory pathogens occurs at the feedlot (Hay et al., 2016a). Serum antibody titers indicate the ability of the animal to mount a humoral immune response to a disease challenge, which clearly played an important role in BRD outcomes in Hay et al. (2016a). This study did not collect serum antibody titers at enrollment, but doing so may have indicated calves at higher risk of BRD. The interaction between serostatus and contacts on BRD outcomes may be important and this information could be used to improve the ability to estimate probabilities of disease in individual calves. A future study examining the relationship between cattle contact and BRD should be conducted that collects serum antibody titers at the time of enrollment in the study to determine how serum antibody titers may impact associations between cattle contact and pBRD.

We assumed that calves would be shedding BRD pathogens around the time of a BRD diagnosis and found that increased degrees of contact with assumed shedding calves increased the pBRD. A weakness of this study is that pathogen shedding was not confirmed with virus isolation or other diagnostics, but we believe that the time window of assumed shedding is well supported (Grissett et al., 2015). Collecting daily samples in an attempt to track viral or bacterial shedding would not have been an externally valid practice related to commercial feedlots and the extra daily handling would have likely had an impact on cattle behavior and performance (Grandin, 1997; Francisco et al., 2012). We believe this would alter cattle social behavior and pathogen transmission. However, if pathogen shedding data could be collected in a way that did not alter cattle behavior it would have potentially been beneficial.

Our study indicates that low time cALL7 was associated increased pBRD. It is unclear why low total calf-contact time would increase BRD risk, but it is possible that normal, healthy social interactions are indicative of general wellness for individual calves and that cattle with less time spent in calf-contact should be suspected for current or future BRD diagnosis. However, the literature does not provide any evidence to support this claim. In addition, other lag times between total calf-contact time and pBRD did not show the same relationship. It seems unlikely to the authors that low total calf-contact time 7 days prior to BRD diagnosis is truly a risk factor but not 6 or 5 days prior to BRD diagnosis. Based on this we believe this finding is likely statistical type I error and low cALL7 does not actually serve as a risk factor in pBRD. Despite this, we believe future investigations should be conducted to determine if variations from normal amounts of contact for individual calves are indicative of alterations in physiologic wellness and pBRD.

It was interesting that study day was not found to be significantly associated with pBRD. We believed study day would significantly impact pBRD because it serves as a surrogate measure for disease incidence and other measures that could be important in determining pBRD. Also of interest was that contact with the BVD-PI was not found to be significantly associated with pBRD. Presence of a BVD-PI calf in a cohort of cattle has been associated with increased BRD risk (Loneragan et al., 2005). Other studies have found that the presence of a BVD-PI in the pen actually reduced BRD morbidity and mortality risk (O'Connor et. al 2000). In this study it is possible that contact with the BVD-PI that may have resulted in increased BRD risk occurred prior to the study period. It is also possible that many of the calves in this study came from the same source farm as the BVD-PI and had exposure to the strain of BVD shed by the PI at the source farm. These calves could potentially have immune memory to the BVD strain and be less susceptible. Another possible reason contact with the BVD-PI was not associated with pBRD was that there was not enough contact occurring with the PI to increase disease risk. There is no way to confirm these alternative hypotheses, but future studies should examine the role a BVD-PI animal has in a BRD epidemic through animal contact.

Transmitter tag retention failure for the RTLS system was a minor problem for this study, but tag loss occurred randomly throughout the study period. Retention failure resulted in data missing at random in the original raw dataset due to the missing values being associated with the specific calves who lost the tags (Dohoo et al., 2009). However, when examining the data, there did not appear to be any kind of association between tag retention failure and BRD diagnosis status or the amount of time in calf-contact. Reasons for retention failure included adverse calf interactions with facilities and poor tag placement.

This study was not able to determine contact that occurred prior to arrival at the feeding facility. Having some measure of cattle contact such as the degree of commingling and the number of morbid animals the cohort was exposed to may enhance our knowledge of risk related to contact prior to arrival. In the future, studies examining cattle contact and disease risk should be conducted using cattle that fall under several BRD risk factor conditions (e.g. different cattle types, weather conditions, and serostatuses). The associations between cattle contact and pBRD may be different for different cattle types and cattle with different predisposing risk factors. By further examining the associations of cattle contact and pBRD, we may be able to enhance our understanding of BRD risk and management.

Conclusions

Our study indicates the direct transmission of BRD pathogens likely occurs in cattle housed in commercial feeding pens and that cattle in greater contact with animals diagnosed with BRD have an increased probability of a future BRD diagnosis. Being able to quantify cattle contact structures will enhance our ability to study transmissible diseases and develop more effective disease mitigation strategies. In the future, contact data collected via RTLS may be used to monitor and determine intervention strategies for BRD and other disease processes.

Acknowledgements

We would like to express our gratitude to Dr. Sarah Capik who assigned clinical illness scores every morning for this study and took fantastic photos of contact occurring between cattle. We would also like to thank Hannah Seger, Alison Hoehn, and Tara Fountain for helping pull and treat cattle. The hard work of these individuals made this study possible.

Table 5.1. Clinical illness score system used for field health evaluations of cattle housed in a dry-lot pen

Clinical Illness Score	Definition
1	normal (no abnormalities noted)
2	slight illness, mild depression, +/- cough, +/- nasal/ocular discharge
3	moderate illness (severe depression, +/- labored breathing, +/- cough, +/- nasal/ocular discharge)
4	Moribund, little response to stimulus

Table 5.2 Treatment protocol for bovine respiratory disease cases

Bovine Respiratory Disease Diagnosis Number	Treatment
1	2.5 mg/kg Tulathromycin (100mg/ml) given subcutaneously
2	40 mg/kg Florfenicol (300 mg/ml) given subcutaneously
3	4 mg/kg Oxytetracycline (200 mg/ml) given subcutaneously
>3	Clinical observation

Figure 5.1 Illustration of the assumed window shedding of bovine respiratory disease pathogens occurs relative to the time of bovine respiratory disease diagnosis.

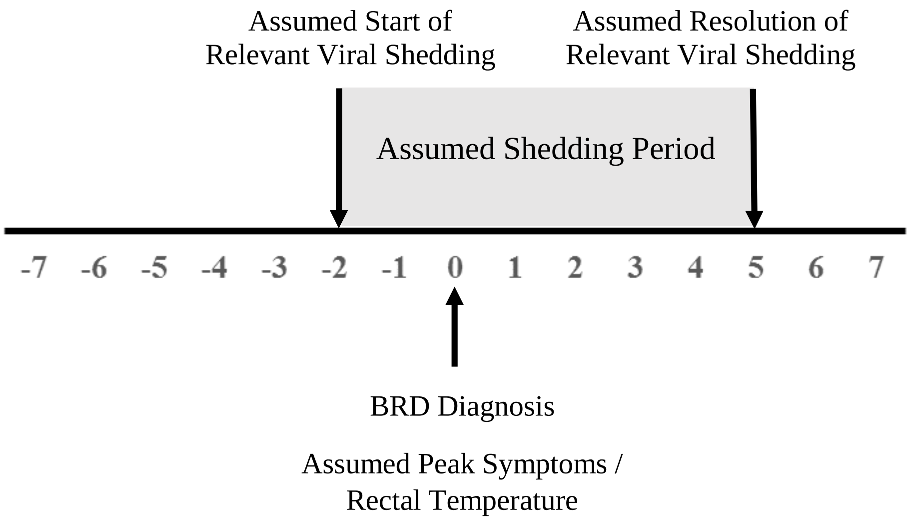


Figure 5.2 Daily incidence count and cumulative incidence of bovine respiratory disease in 70 castrated male beef calves housed in commercial dry-lot pen during the first 28 days on feed.

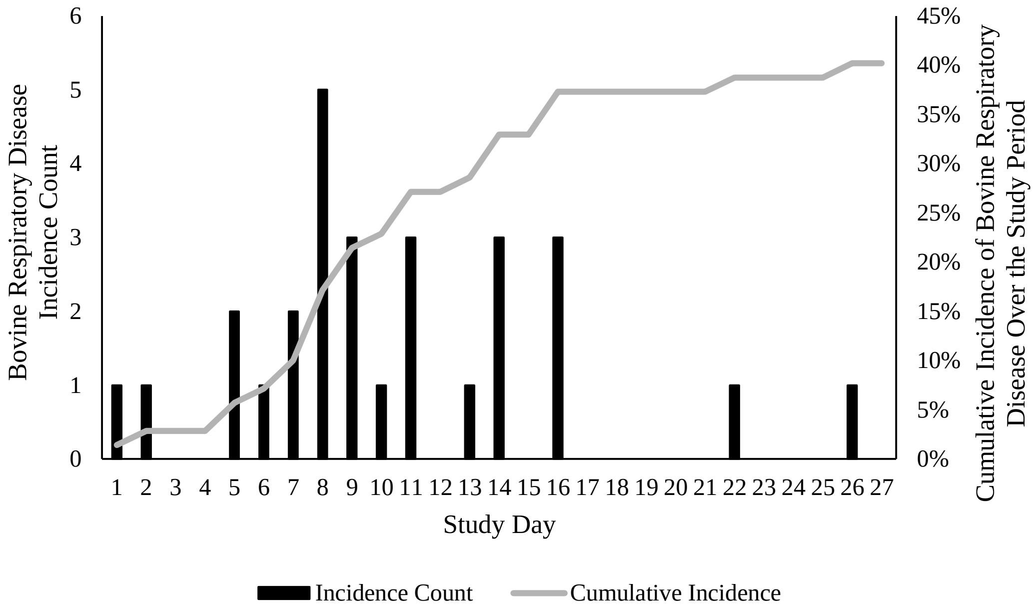


Figure 5.3 Box-plots for calf-contact measures as determined by RTLS aggregated by individual calf for each study day. Contact measures described include an individual calf's total time in calf-contact (3a), total time in calf-contact time with calves assumed to be shedding bovine respiratory disease pathogens (3b), and total time in calf-contact with the calf diagnosed as persistently infected with *Bovine Viral Diarrhea virus* (3c). The total number of calves assumed to shedding bovine respiratory disease pathogens each study day is also reported (3d).

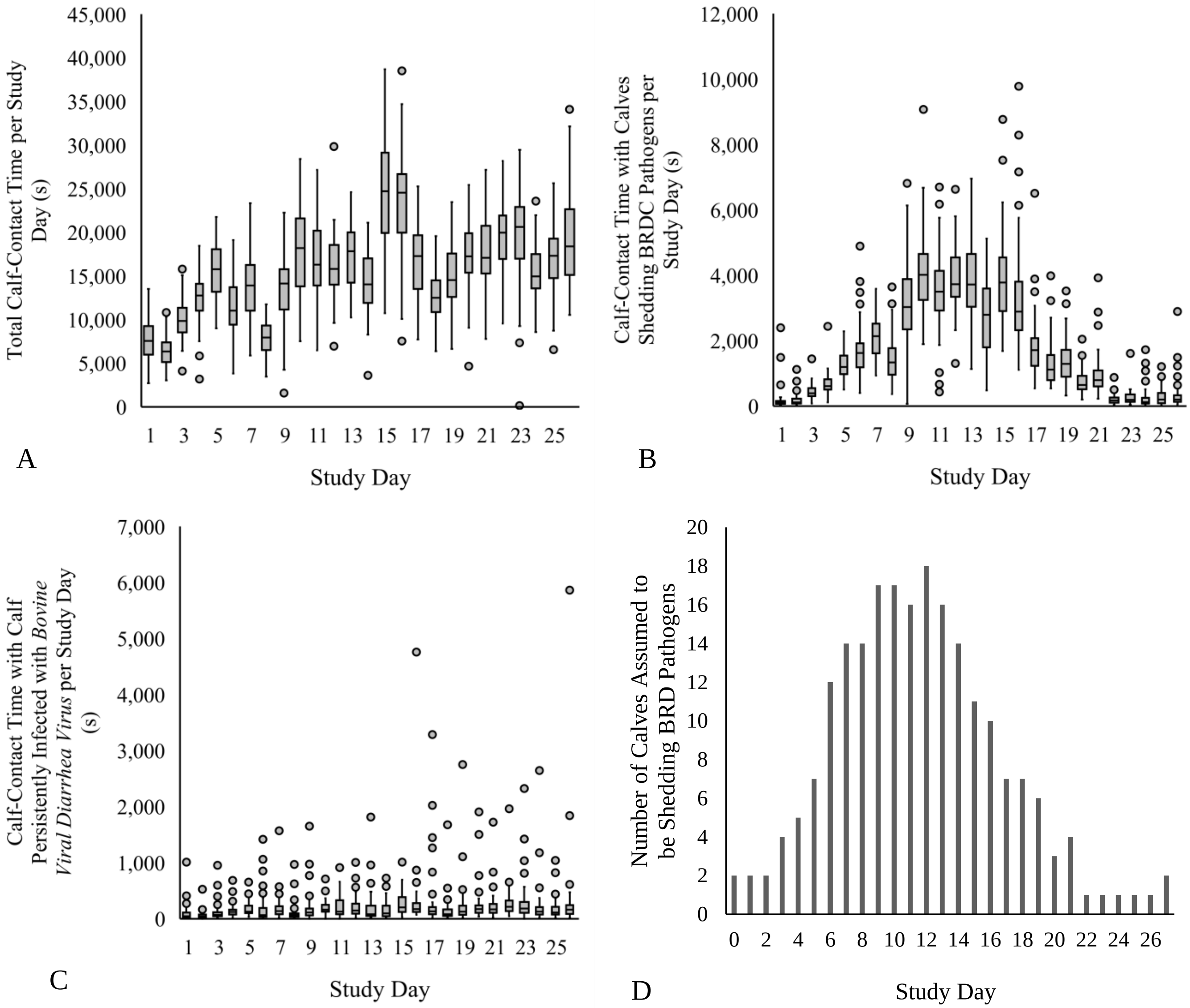


Table 5.3 Estimates for model effects on the log odds of bovine respiratory diagnosis.

Effect	Estimate (Log Odds)	Standard Error	*P – value*
Intercept	-2.7523	0.5853	<0.0001
Contact Measure			
SHED4	0.000437	0.000161	0.0066
ALL7	-0.00013	0.000046	0.0042
Study Day			
7	-	-	-
8	0.9614	0.5962	0.1409
9	0.4358	0.6485	0.9339
10	-0.6740	0.8619	0.2823
11	0.4531	0.6483	0.6554
12	-10.8462	111.89	0.9989
13	-0.6756	0.8624	0.1333
14	0.4522	0.6485	0.6659
15	-10.5541	96.6876	0.9988
16	0.4522	0.6485	0.6465
17	-10.9445	117.53	0.9989
18	-10.9445	117.53	0.9989
19	-10.9445	117.53	0.9989
20	-10.9445	117.53	0.9988
21	-10.9445	117.53	0.9989
22	-10.9445	117.53	0.999
23	-0.6574	0.8615	0.4706
24	-9.8056	67.0049	0.9989
25	-9.8056	67.0049	0.9989
26	-10.9445	117.53	0.999
27	-0.6574	0.8615	0.495
Random Residual (Calf)	0.4696	0.01776	-

Figure 5.4 Calculated predicted probabilities of bovine respiratory disease diagnosis on a given day for an individual calf by total calf-contact time occurring 4 days prior with calves assumed to be shedding bovine respiratory disease pathogens. Shaded areas indicate +/- 1 standard error. Predicted probabilities were calculated using the log odds regression estimates from a multivariate logistic regression model.

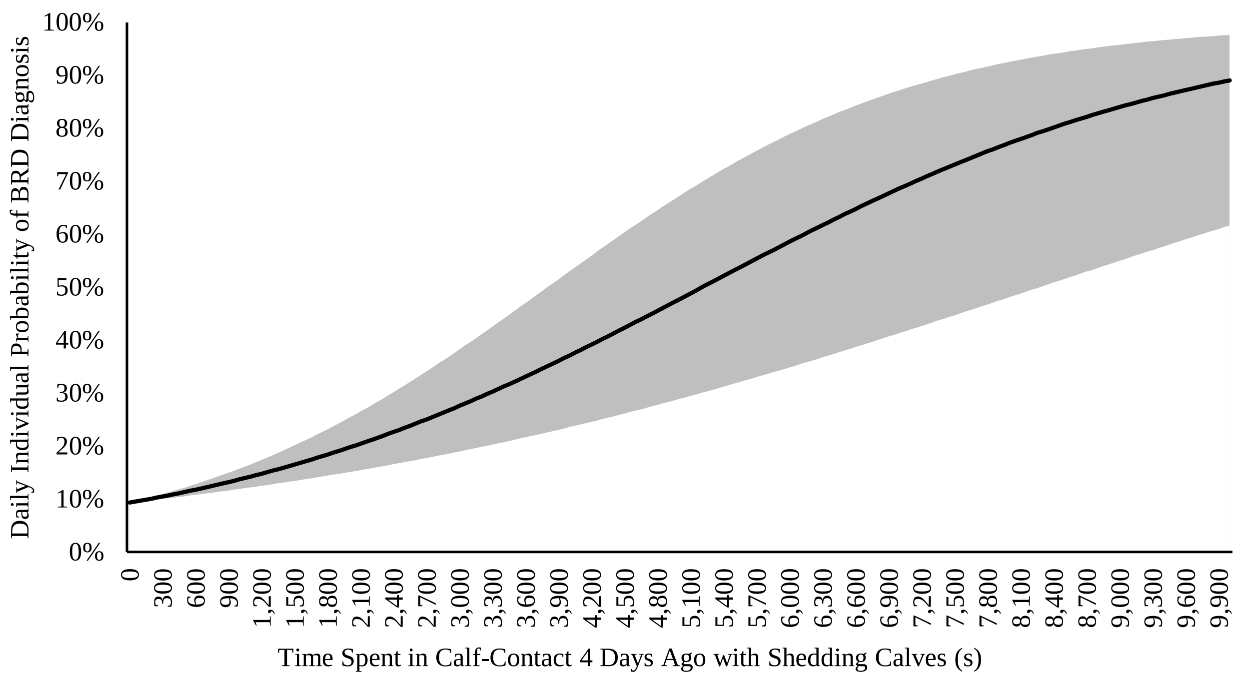


Figure 5.5 Calculated predicted probabilities of bovine respiratory disease diagnosis on a given day for an individual calf by total calf-contact time occurring 3 days ago, 4 days ago, 5 days ago, 6 days ago, and 7 days ago with calves assumed to be shedding bovine respiratory disease pathogens. Predicted probabilities were calculated using the log odds regression estimates from a logistic regression model.

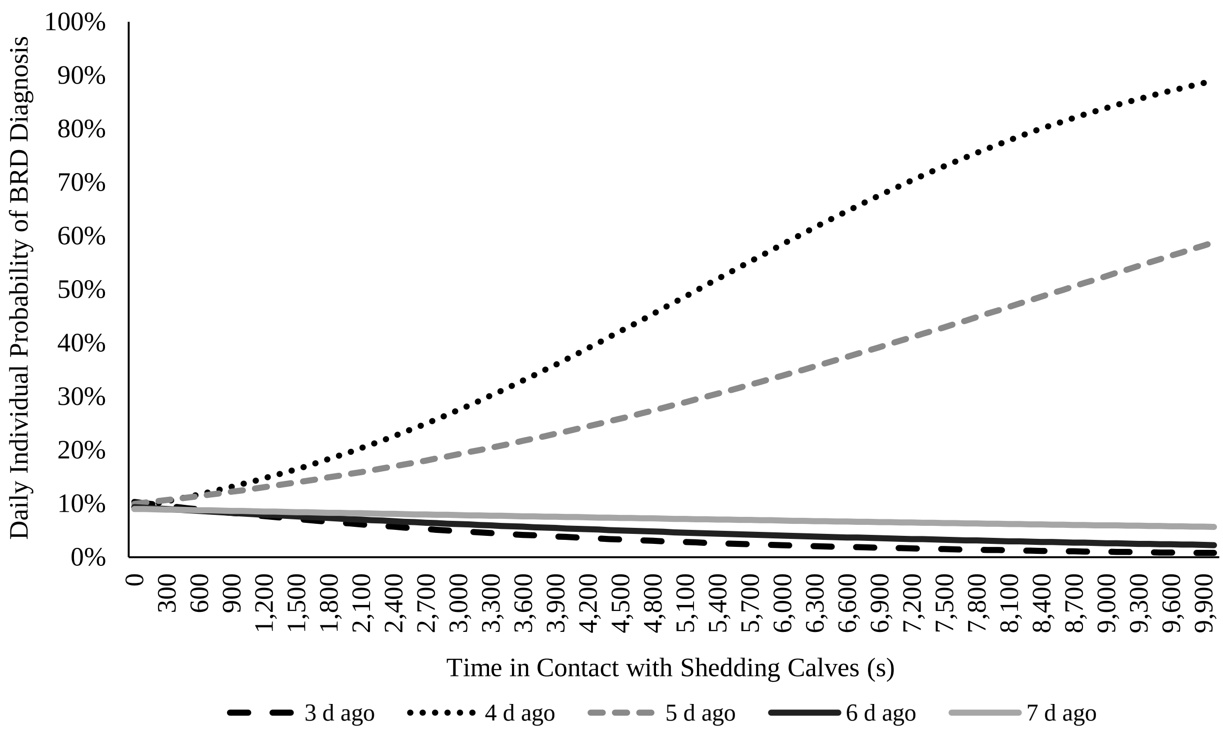


Figure 5.6 Calculated predicted probabilities of bovine respiratory disease diagnosis on a given day for an individual calf by total calf-contact time occurring 7 days prior. Shaded areas indicate +/- 1 standard error. Predicted probabilities were calculated using the log odds regression estimates from a multivariate logistic regression model.

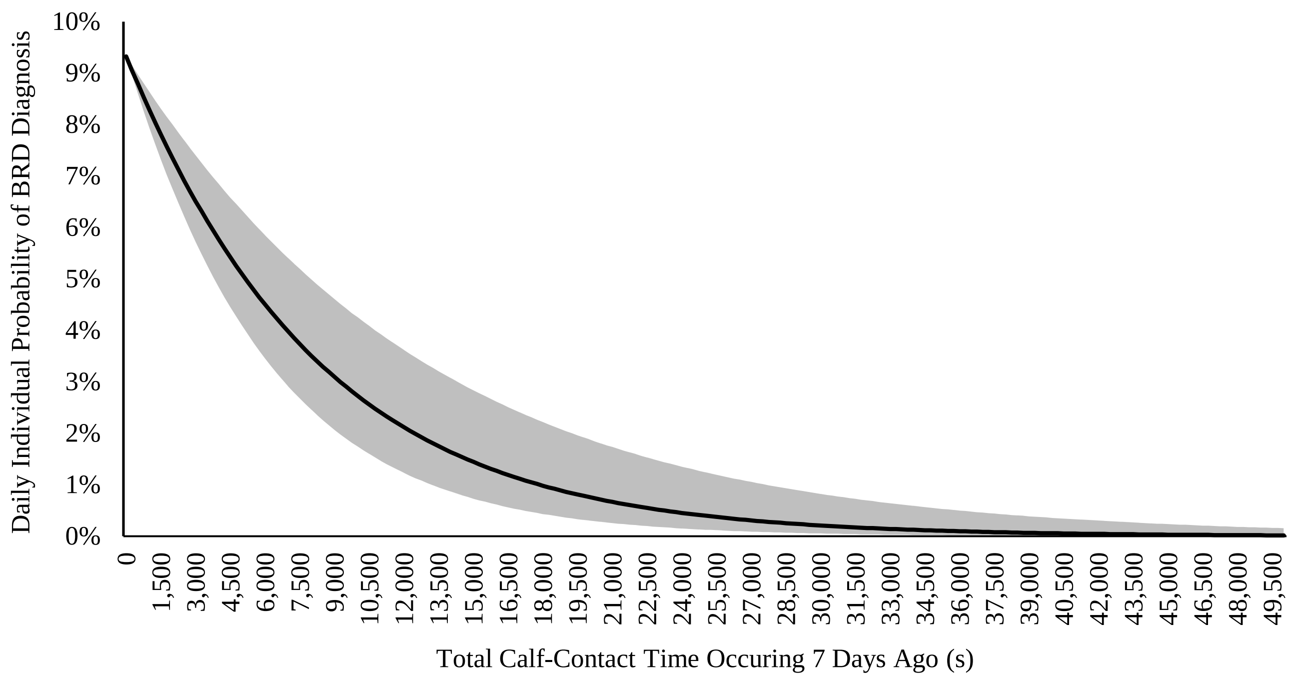
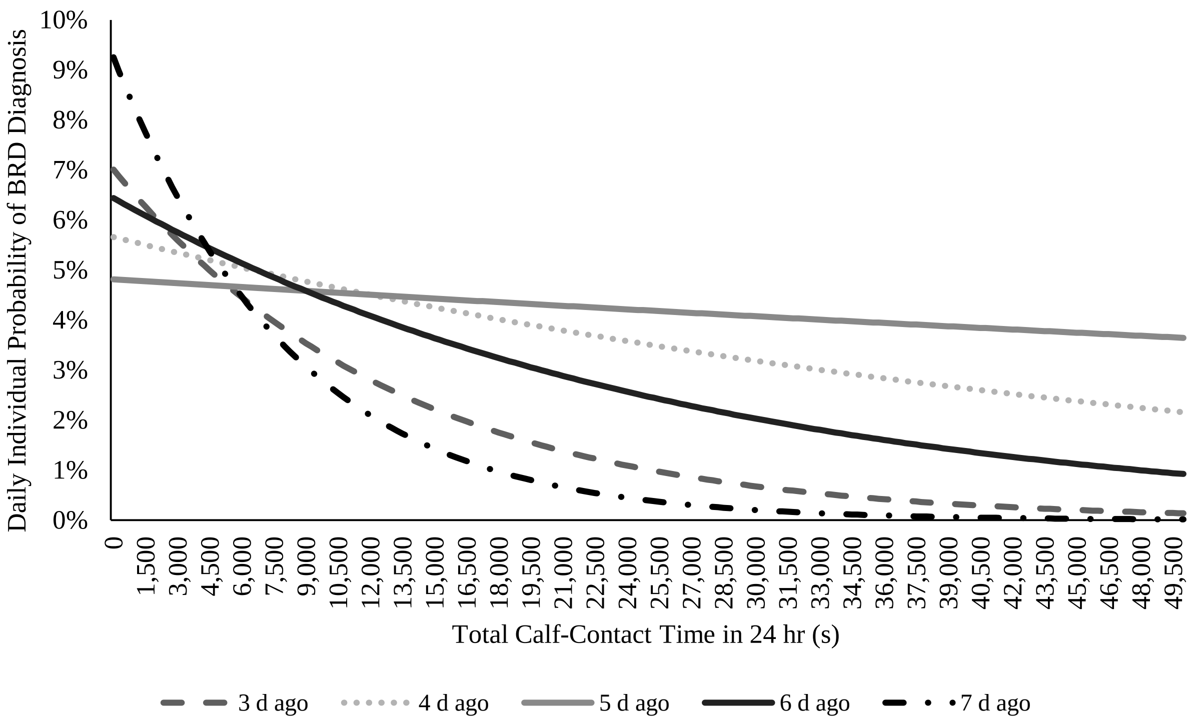


Figure 5.7 Calculated predicted probabilities of bovine respiratory disease diagnosis on a given day for an individual calf by total calf-contact time occurring 3 days ago, 4 days ago, 5 days ago, 6 days ago, and 7 days ago. Predicted probabilities were calculated using the log odds regression estimates from a logistic regression model.



Footnotes

[a] Bovi-Shield Gold 5, Zoetis, Florham Park, NJ

[b] Ultrabac 7, Zoetis, Florham Park, NJ

[c] Agrimectin, AgriLabs, St. Joseph, MO

[d] Smartbow, Jutogasse, Austria

[e] Precision Animal Solutions, Manhattan, KS

[f] KNIME Analytics Platform, Zurich, Switzerland

[g] SAS 9.4, SAS Institute, Cary, North Carolina

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Chapter 6 - Dissertation conclusions

Cattle production systems in North America are diverse and represent countless geographies. These systems exhibit dynamic relationships that exist between many working parts that define the production system. In many instances it is challenging to test hypotheses over the long term and compare production scenarios. Improved software and computational capacities have improved our ability to simulate cattle production systems to drive decision making, hypothesis generation, and problem solving. Technologies such as real-time location systems (RTLS) have also enhanced our ability to collect various types of data on cattle on a continuous basis. These systems have already changed cattle management systems in research and commercial production. The purpose of this research was to evaluate how systems methods have been applied to livestock science and animal health, develop a simulation model of cow-calf production to improve our knowledge of cow-calf production systems, improve our understanding of cattle behavior collected by RTLS, and use RTLS to determine how the social behavior of cattle may be associated with bovine respiratory disease risk.

We found that systems methods have been applied to livestock production systems in various ways over the last several decades and were able to identify that systems dynamics is among the most current methods applied to the field. These methods have allowed scientists to model complex relationships within systems over long periods of time. We adopted Systems Thinking principles and developed a deterministic, dynamic systems model of cow-calf production. We determined that the duration of postpartum anestrus (dPPA) plays an important role in herd reproductive performance and efficiency. We concluded that veterinarians and producers may consider determining a herd's dPPA, especially for herds with a history of reproductive woes. The dPPA could be a valuable piece of information for producers when making breeding management decisions.

We then wished to examine the impact that breeding replacement heifers before the rest of the herd might have on herd performance, known as providing a heifer lead time (tHL). We found that increasing tHL resulted in increases in reproductive performance for primiparous cows and the whole herd. The degree of improvement increased as the average dPPA for primiparous cows in herd increased. We concluded that any decisions regarding the use of a tHL should be made based on the expected improvement in production and the costs associated with implementing a tHL.

Real-time location systems have been used for monitoring cattle behavior and have been used to describe the amount of time cattle spend at various locations of interest. We were interested in the probability of cattle participating in eating and drinking behavior when cattle were located at watering and feeding locations by RTLS. We determined that there is significant variability in the probability of participating in behaviors of interest between cattle and between times of the day. It was concluded that RTLS technologies are not good predictors of the amount of time actually spent participating in eating and drinking behaviors.

Finally, we wished to use RTLS technologies to determine when cattle were in contact with each other and to determine if the amount of time spent in calf-contact at various lag periods was associated with bovine respiratory disease (BRD) risk. We found that increased amount of time in calf-contact with calves diagnosed for BRD is associated with increased BRD risk. We concluded that our findings provide evidence that BRD pathogens are likely directly transmitted in dry-lot pens and that, in general, increasing the amount of time in contact with calves diagnosed for BRD increases BRD risk. We believe future studies should be conducted to learn more about the relationship between cattle contact and BRD, and determine how contact data can be integrated into disease management strategies in commercial feedlots to reduce BRD morbidity.

While the methods used in these studies were very different, all were vested in improving our knowledge of cattle production systems. By simulating cow-calf production, we conceptualized the whole working system and improved our understanding of how physiologic and management constraints impact performance. Utilizing novel technologies such as RTLS has opened the doors to studying and managing cattle production systems in new ways. By taking a systems approach, we successfully improved our knowledge of how RTLS technologies may be used to study cattle production and were able to learn about important aspects of cattle behavior and disease dynamics. The research of this dissertation highlights the importance of understanding whole systems and the methods that may be used in pursuit of that endeavor.