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Use of Software Modeling Tools to Understand Population Health Dynamics: Application to Bovine Respiratory Disease in US Beef Calves Prior to Weaning

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Use of software modeling tools to understand population health dynamics: application to bovine respiratory disease in US beef calves prior to weaning

By

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Use of software modeling tools to understand population health dynamics: application to bovine respiratory disease in US beef calves prior to weaning

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Bovine respiratory disease (BRD) is a significant health problem for cattle producers in terms of economic cost and animal welfare. In the United States (US), it is one of the leading causes of sickness and death in beef calves prior to weaning. Although much research has been conducted to develop vaccines for prevention and antibiotics for treatment, the morbidity and mortality of BRD in beef calves prior to weaning has not improved over the years.

The identification of risk factors associated with BRD is an area of focus which might ultimately allow producers to minimize morbidity and mortality from BRD. Little research has been performed to understand factors contributing to the risk of BRD in beef calves prior to weaning. BRD affects the beef cattle industry through losses due to mortality, prevention cost, treatment cost, or morbidity effect on productivity. Currently, the economic losses due to BRD for beef calves prior to weaning is not available. Price paid for feeder cattle is a major factor influencing the income of producers. The effect of BRD is a complicated problem since the parameters associated with the cost of BRD in beef cow-calf production are variable and interrelated. To better understand the economic

effect of BRD in beef calves prior to weaning, concepts of uncertainty, variability, stochasticity, nonlinearity, and feedback might be involved during the process of assessing risk.

The objectives of this dissertation are the following: 1) to test if calf sex, birth weight, and age of dam are associated with BRD of beef calves prior to weaning in different age periods; 2) to identify factors affecting the national market price of beef feeder cattle in the US and how the prices change over time; 3) to investigate the prevention and treatment cost of BRD in beef calves prior to weaning; 4) to estimate the economic cost of BRD in US beef calves prior to weaning; and 5) to understand the effect of BRD occurrence or absence on the national net income of the US beef cow-calf industry.

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LITERATURE REVIEW OF BOVINE RESPIRATORY DISEASE

The United States (US) is the third largest beef-producing country in the world after China and Brazil, which represents 11% of the global beef production in 2012 (FAO, 2012). Beef cattle sales reached $29.6 billion in 2012, accounting for 7% of total US agriculture sales (USDA, 2012). US beef cattle production can be roughly divided into two production sectors: cow-calf operations and cattle feeding (USDA, 2017b). Beef cow-calf production is the beginning stage of beef production, and it accounts for 33% (31.2 M/93.6 M) of total US cattle inventory (USDA, 2017a). As the foundation of beef production cycle, cow-calf management influences the entire beef production system.

Bovine respiratory disease (BRD), also called shipping fever, continues to be one of the leading causes of sickness and death in beef cattle and calves in the US. It has a negative impact on the beef cattle industry in terms of economics and animal welfare (USDA, 2010a, 2011). Much effort has been made to study BRD pathogens, vaccines, and treatment, mainly in feedlot cattle (R. W. Fulton, 2009; Griffin, 2010; Panciera & Confer, 2010; Taylor, Fulton, Lehenbauer, Step, & Confer, 2010b). Research of BRD in beef cow-calf sectors is limited (R. W. Fulton, 2009; Griffin, 2010; Stokka, 2010). Despite the industry efforts, there has been no reduction in the morbidity and mortality of BRD in beef calves prior to weaning over the years (USDA, 1997, 2010a).

This chapter provides a literature review of the pathogenesis, diagnosis, epidemiology, and economic impacts of BRD.

Introduction of BRD

Under normal conditions, the respiratory system relies on complex biochemical, physiological, and immunological mechanisms to protect itself (Griffin, Chengappa, Kuszak, & McVey, 2010). Factors such as adverse weather conditions (G. Snowder, 2009), viruses (J. A. Ellis, 2009), and stress (Aich, Potter, & Griebel, 2009) may compromise an animal's defense system and contribute to the development of BRD. Viral–bacterial synergy plays a significant role in the development of BRD, and several viruses and bacteria are summarized here (Babiuk, Morsy, Campos, & Harland, 1995; Callan & Garry, 2002).

Pathogenesis

The viruses most frequently involved in BRD include bovine herpesvirus-1 (BHV-1) or infectious bovine rhinotracheitis virus (IBRV), bovine viral diarrhea virus (BVDV), parainfluenza 3 virus (PI3V), and bovine respiratory syncytial virus (BRSV) (J. A. Ellis, 2009; Panciera & Confer, 2010; Srikumaran, Kelling, & Ambagala, 2007; Taylor, Fulton, Lehenbauer, Step, & Confer, 2010a; Woolums et al., 2014). Other virus including bovine adenovirus 3 (BAdV3), bovine adeno-associated virus (BAAV), bovine coronavirus (BoCV), bovine influenza D virus, bovine parvovirus 2 (PBV-2), bovine herpesvirus 6 (BoHV-6), bovine rhinitis A virus (BRAV), and multiple genotypes of bovine rhinitis B virus (BRBV) have also been detected in cattle with BRD clinical signs (Ng et al., 2015). Viruses may cause the death of infected cells, production of proinflammatory cytokines, enhancement of bacterial colonization, and suppression of immune response (J. A. Ellis, 2009). Therefore, while viruses generally may not directly cause pulmonary disease, they can predispose the lungs to bacterial infections (Callan & Garry, 2002).

The most common bacteria attributed to BRD are *Mannheimia haemolytica* (formerly *Pasteurella haemolytica*), *Pasteurella multocida*, *Histophilus somni*, and *Mycoplasma bovis.* With the exception of *Mycoplasma bovis,* these bacteria are commensal pathogens of the upper respiratory tract in healthy calves and calves from farms without BRD problems (Griffin, 2010; Taylor et al., 2010a; Welsh, Dye, Payton, & Confer, 2004). Normally they are present in small numbers due to the clearance of the mucociliary escalator of the trachea and large bronchi (Hodgins, Conlon, & Shewen, 2002). Some factors may impair bacterial clearance, which decreases the resistance and allows colonization of the lungs (Caswell, 2014). Each bacteria has virulence factors, including capsules, biofilm, endotoxins, exotoxins, adhesion proteins, and enzymes, which promote its ability to adhere to epithelial cells, colonize lower airway, evade the immune system, destroy tissue, and stimulate inflammatory response (Panciera & Confer, 2010). Consequently, bacterial pathogens may cause suppurative bronchopneumonia, fibrinous pneumonia, or caseonecrotic pneumonia (Panciera & Confer, 2010). *Mannheimia haemolytica* and *Pasteurella multocida* are the most widely recognized and frequently identified bacteria associated with BRD in young calves and weaning and feedlot cattle (Confer, 2009; Dabo, Taylor, & Confer, 2007; Griffin et al., 2010; Portis, Lindeman, Johansen, & Stoltman, 2012; Welsh et al., 2004).

Diagnosis of BRD

The clinical syndromes of BRD can range from hardly noticeable to sudden death. Commonly reported signs may include nasal or ocular discharge, increased respiratory rate, anorexia, depression, cough, dehydration, and fever (Apley, 2006; Griffin et al., 2010; Schneider, Tait, Ruble, Busby, & Reecy, 2010; G. D. Snowder, Van Vleck, Cundiff, & Bennett, 2006). Diagnosis plays a fundamental role in early treatment and reducing the death loss due to BRD (Wolfger, Timsit, White, & Orsel, 2015). Cases of BRD are commonly identified and treated based on the observations of clinical signs in the beef industry (Buczinski, Forte, Francoz, & Belanger, 2014; Griffin et al., 2010; Schneider et al., 2010; G. D. Snowder, Van Vleck, Cundiff, & Bennett, 2005; G. D. Snowder et al., 2006; B. J. White & Renter, 2009). However, not all calves with BRD have typical clinical signs (Wittum, Woollen, Perino, & Littledike, 1996), and a diagnosis of BRD based on clinical signs may not accurately distinguish a respiratory condition from other diseases (Schneider et al., 2010; G. D. Snowder et al., 2005), such as acidosis, pain, fever of any cause, left-sided heart failure, and emphysema (Montgomery, 2009). Researchers reported diagnosis according to visual observations alone has low sensitivity and specificity in post-weaned calves (61.8% and 62.8%, respectively) (B. J. White & Renter, 2009) and feedlot cattle (64.5% and 69.1%, respectively) (Brad J. White et al., 2016). Therefore, laboratory tests are sometimes used to improve the accuracy of diagnosing BRD and identify infectious agents.

Necropsy and laboratory testing for BRD pathogens are the gold standards to diagnose cases of BRD. Imaging methods, such as thoracic radiography and ultrasound, are also available to diagnose BRD while relying on relatively expensive equipment and specialized technicians (Buczinski et al., 2014; Love, Lehenbauer, Kass, Van Eenennaam, & Aly, 2014). Diagnostic tests for BRD involve culture, serology, immunohistochemistry (IHC), *in-situ* hybridization and PCR, which can be conducted for detecting pathogens, antibody, and antigens (Robert W. Fulton & Confer, 2012).

Nasal or nasopharyngeal swabs, tracheal wash, and bronchoalveolar lavage (BAL) are antemortem methods for BRD diagnosis. Nasal or nasopharyngeal swabs are noninvasive diagnostic methods, and they can be used for culture to detect viral and bacterial pathogens. Tracheal wash or BAL can provide samples for a broader diagnostic approach and can be used for culture, PCR, IHC (Cooper & Brodersen, 2010; Robert W. Fulton & Confer, 2012).

Once animals have died of BRD, lung lesion samples and other tissues at necropsy can be collected (Cooper & Brodersen, 2010). Postmortem examination shows the distribution and texture of lesions that indicate one or more morphologic patterns of lung disease and providing tissues for confirmatory testing (Caswell, Hewson, Slavic, DeLay, & Bateman, 2012). For example, fibrinous pneumonia, commonly caused by *Mannheimia haemolytica*, is characterized by a bilateral, cranioventral distributed, firm, compressible lung consolidation with fibrins on pleura (Panciera & Confer, 2010).

Serology tests involving ELISA, complement fixation tests, and agglutination tests are antibody assays and mainly provide detection of vaccine responses and past infections (Robert W. Fulton & Confer, 2012). Culture has been used to isolate viruses or bacteria. However, not all viruses show cytopathology, such as noncytopathic BVDV, and these have to be detected by serology tests (Robert W. Fulton & Confer, 2012). Immunohistochemistry utilizes samples from lung lesions or other tissues to detect antigen within the lesion. PCR can be conducted on samples from nasal, nasopharynx, and tracheal washes, BAL, and lung lesion or other tissues to detect organism DNA or RNA, which provides evidence of specific pathogens (Robert W. Fulton & Confer, 2012). *In-situ* hybridization, unlike PCR using molecular amplification methods, measures the spatial expression of a particular gene and identifies infectious agents in the lung lesion (Wunderlich, Bragdon, & DePace, 2014). Most of the laboratory tests are expensive and time-consuming, and they cannot provide timely results needed at the point of on-farm treatment. They are often times applied for the identification of pathogens due to antimicrobial resistance or investigation of an epidemic in herds after initial treatment for BRD (Klima et al., 2014; Love et al., 2014).

Epidemiology of BRD

BRD morbidity

The USDA National Animal Health Monitoring System (NAHMS) reported the estimated national morbidity of BRD in beef calves prior to weaning in the Beef 1997 and Beef 2007 - 08 surveys. In 1996, the morbidity (± SE) of BRD in calves <3 weeks of age and ≥ 3 weeks of age were 0.5 ± 0.1% and 0.8 ± 0.1% of calves born alive, respectively (USDA, 1997). According to the Beef 2007 - 08 survey, 3.8 ± 0.6% of pre-weaned calves were treated for BRD, which was the leading cause of sickness prior to weaning (USDA, 2010a). Of calves born alive, the mean percentage (± standard deviation) affected by BRD prior to weaning was 3.0 ± 7.1% (G. A. Hanzlicek et al., 2013). The higher standard deviation of the mean percentage indicated that morbidity in herds with BRD problems was highly variable and skewed (e.g., many herds with a low incidence of BRD, but some with high incidence). Some herds may have no BRD problem, but others may have more serious concerns requiring further study and risk analysis.

Several research papers reported the incidence of BRD in beef calves prior to weaning. Two large multiyear studies reported the cumulative incidence of BRD in beef calves within herds in US Meat Animal Research Center (MARC), and great differences between years and also between herds were observed. One paper reported that 1,396 out of 10,142 beef calves born from 1983 to 1988 had BRD prior to weaning with an average annual incidence of 13.8% which varied by year and ranged from 2.6% to 31.1% (Muggli-Cockett, Cundiff, & Gregory, 1992). Another research study evaluated the incidence of BRD in 41,986 beef calves prior to weaning born from 1983 to 2001, which ranged from 3.3% to 23.6% per year, with an average annual incidence of 10.5% (G. D. Snowder et al., 2005).

Two recent large surveys estimated the herd level prevalence of BRD in US cow calf operations. One survey conducted in 2,600 US cow-calf producers in 3 eastern and three plains states with 459 producers' response reported about one-fifth of herds had BRD problems in beef calves prior to weaning (Woolums et al., 2013). Another survey of 574 US veterinarians was carried out in 3 eastern and three plains states with 61 respondents. The results indicated 18% of their cow-calf clients had nursing calves with BRD, 14% of their clients had at least one calf died of BRD, and 5% of their clients had at least 5% calves infected by BRD (Woolums et al., 2014).

BRD mortality

BRD is a primary cause of loss in pre-weaned calves (USDA, 2010a). According to the USDA NAHMS Beef 1997 survey, of all beef calves born alive during 1996, 3.4 ±

0.1% (mean ± standard error) died or were lost from any cause prior to weaning. Of these calves, 16.3 ± 1.2% of the calves died due to BRD, which was the 3rd largest category of losses after weather causes (20.2 ± 1.4%) and unknown causes (17.5 ± 1.4%) (USDA, 1997). Of the beef calves born alive during 2007, 3.6 ± 0.2% (mean ± standard error) died or were lost from any cause prior to weaning. For beef calves < 3 weeks of age, 8.2 ± 1.4% of beef calves died (accounting for all causes) from BRD, which is the 5th largest category of death after calving related problems (25.7 ± 3.4%), weather-related causes (25.6 ± 3.6%), unknown causes (18.6 ± 3.9%), and digestive problems (14.0 ± 2.4%). For beef calves ≥ 3 weeks of age to weaning, 31.4 ± 3.9% of beef calves that died or were lost was due to BRD. BRD was the leading category of death in this age period (USDA, 2010a).

Factors associated with BRD

BRD is a complex infectious disease due to multifactorial interactions. Pathogen factors, host factors, and environmental factors interact to contribute to BRD development in cattle. Understanding these factors may help producers develop management practices to decrease the losses due to BRD. Compared to the feedlot cattle, the predisposing factors associated with BRD in beef calves prior to weaning has not been well documented. Due to the differences in management practices for pre-weaned calves and post-weaned calves, the extrapolation and mitigation of risk factors in feedlot cattle may not be applicable to calves prior to weaning. Therefore, the underlying factors associated with BRD in calves prior to weaning are summarized.

Host factors

Host-associated factors for BRD in calves include age, sex, genetics, and immunity, which can influence calves' exposure, susceptibility, or response to the causative agent.

Age

BRD can occur at any time in beef calves prior to weaning, but different ages may have various levels of susceptibility. Weaning typical occurs between 3 and 8 months of age (Filley, 2011), and the average weaning of calves in the US is 207 days of age (USDA, 2008). One study analyzed birth and health records (1983 - 2002) for calves in one farm over 20-year period, and the average age for calves to contract BRD was 101 days. The distribution of cases as seen by age showed that sporadic cases of BRD occurred when calves were < 75 days of age, followed by an increase of cases when calves were between the ages of 75 to 170 days, and finally a rapid decrease in cases until weaning (G. D. Snowder et al., 2005).

Sex

Human and animal studies suggested sex differences in respiratory physiology and the incidence, susceptibility, and severity of a variety of lung diseases (Carey et al., 2007). In humans, males are more likely get pneumonia and have more severe cases than females (Gutierrez et al., 2006; Z. Yang et al., 2014). There is limited information regarding sex differences for pre-weaning BRD in calves. One study of calves born in 1983-1988 indicated male calves (14.4 ± 1.18%) had greater incidence of BRD in beef calves prior to weaning than female calves (9.5 ± 1.18%). Furthermore, the incidence of

BRD was higher in males (17.2 ± 1.44%) than females (12.5 ± 1.44%) during the post-weaning period (Muggli-Cockett et al., 1992). However, distinction between bull or steers status compared to heifers was not included in that study.

Breeds/genetics

Several papers reported that heritable resistance to BRD in beef calves prior to weaning was low, ranging from 0 to 0.26 (Muggli-Cockett et al., 1992; Schneider et al., 2010; G. D. Snowder et al., 2005). There were significant differences in the incidence of BRD between purebred and composite breeds during the pre-weaning phase (Muggli-Cockett et al., 1992; G. D. Snowder et al., 2005). Muggli-Cockett, et al. (1992) reported that the pre-weaning BRD incidence ranged from 4.8 ± 1.21% to 20.1 ± 1.27% among breeds in different geographic locations. Snowder, et al. reported the incidence (ranging from 8.34 to 18.85%), mortality (ranging from 7.0 to 17.7%), and total death loss (ranging from 0.8 to 1.9%) varied among breeds, where crossbred cattle had a significantly lower incidence of BRD prior to weaning than purebred calves (G. D. Snowder et al., 2005). These studies suggest there might be different immune factors among breeds of cattle.

Prior disease

Diarrhea is an important disease for beef calves prior to weaning. According to the USDA NAHMS Beef 2007 - 08 survey, of all beef calves born during 2007, BRD and diarrhea were the primary diseases which resulted in the death of calves prior to weaning. There were 3.8 ± 0.6% and 3.5 ± 0.5% of the calves treated for BRD and diarrhea, respectively. For beef calves that died < 3 weeks of age, 8.2 ± 1.4% and 14.0 ± 2.4% of the deaths (accounting for all causes) were due to BRD and digestive problems, respectively. For beef calves that died ≥ 3 weeks of age to weaning, 31.4 ± 3.9% and 22.6 ± 4.8% of beef calves' deaths were due to BRD and digestive problems, respectively. These two diseases were responsible for more than one-half of all calf deaths (USDA, 2010b). Prior disease experience may increase the risk for subsequent BRD. According to the previously described survey conducted in 2,600 US cow-calf producers in 3 eastern and three plains states, the odds of experiencing BRD problems in herds having at least one calf with diarrhea was 8.4 (95% CI: 4.1–17) times compared to the herds without diarrhea problems (Woolums et al., 2013). Similar results were reported in dairy cattle (Gulliksen et al., 2009; Waltner-Toews, Martin, & Meek, 1986). One research study on 104 randomly selected dairy farms reported diarrhea and pneumonia were significantly associated with each other at both the farm and calf levels. The odds of farms which had above the median number of treatment days for diarrhea was two to three times greater of having above median treatment days per calf per pneumonia than farms with a lower number of treatment days; the odds of being treated for BRD in calves which had a history of diarrhea was three times greater than the odds in calves without diarrhea (Waltner-Toews et al., 1986). Another study performed on 135 randomly selected dairy herds reported calves with previous history of diarrhea during the first month of age had 3.9 (95% CI: 2.3–6.7) times the risk of infection with BRD compared to herds which had calves without diarrhea (Gulliksen et al., 2009). The association between diarrhea and pneumonia may be due to common predisposing factors, such as failure or partial failure of transfer of passive immunity through colostrum, stress, nutrition, etc., which can impact immunity. Also, immunity may be adversely influenced by the previous disease directly or indirectly through diseases resulting in malnutrition and electrolyte imbalances (Gulliksen et al., 2009; Gregg Alan Hanzlicek, 2010).

Birth weight

Birth weight has been associated with perinatal mortality in several studies (Johanson & Berger, 2003; Morris, Bennett, Baker, & Carter, 1986). Snowder, et al. (2005) reported birth weight did not affect ($P \geq 0.87$) the incidence of BRD in beef calves prior to weaning. However, other papers reported heavier newborn calves are more likely to cause dystocia which may increase the risk of BRD in beef calves prior to weaning. As reported, a 1 kg increase in birth weight corresponded to an increase of 13% odds of dystocia (Johanson & Berger, 2003), and calves born to dams having severe dystocia were 1.7 (95% CI: 1.6-1.9) times more likely treated for BRD than calves born to dams without dystocia (Lombard, Garry, Tomlinson, & Garber, 2007).

Environmental factors

Stress

Stress is known to impair immune system function and predispose humans and animals to certain infectious diseases (Marsland, Bachen, Cohen, Rabin, & Manuck, 2002; Peterson et al., 1991). This is done through complicated interactions among the central nervous system (CNS), the endocrine system, and the immune system (Freestone, Sandrini, Haigh, & Lyte, 2008; E. V. Yang & Glaser, 2000). One possible mechanism is the perception of stress by the CNS activated hypothalamic-pituitary-adrenal axis to release adrenocorticotropic hormone which mediate the production of glucocorticoids from the adrenal cortex and consequently result in the dysregulation of immune responses (S. M. Smith & Vale, 2006; E. V. Yang & Glaser, 2000).

Calves born to cows exposed to heat stress during late gestation have compromised passive immune transfer compared to those born to dams in a cooler environment (Monteiro, Tao, Thompson, & Dahl, 2016; Strong, Silva, Cheng, & Eicher, 2015). This may be due to lower colostrum IgG concentration (Tao, Monteiro, Thompson, Hayen, & Dahl, 2012), and/or lower IgG absorption in calves due to heat stress in utero (Monteiro, Tao, Thompson, & Dahl, 2014; Tao et al., 2012). Also, maternal heat stress during late gestation can alter calves' innate immunity function by changing cellular interactions (CD14 and CD18) with pathogens, acute phase cytokines, and pathogen recognition molecules (Strong et al., 2015).

Dehorning of cattle is a procedure performed on young calves when the horn is small or only horn buds are present (AVMA, 2014), which may cause pain if anesthetics are not used. Similarly, castration of male cattle is a stressor due to acute pain, and age at which these procedures are performed is directly correlated with stress (Robertson, Kent, & Molony, 1994). Calves castrated at ≤ 6 months of age had lower stress response than that of calves castrated at > 6 months of age (Bretschneider, 2005). Minimizing pain associated with dehorning and castration may decrease the modification of behavioral and physiologic states caused by the pain-stress distress cascade (AVMA, 2014; Hulbert & Moisa, 2016).

Weaning is one of the most stressful experiences in calves' life and happens when they are approximately 3-8 months of age (Filley, 2011). Some of the various stressors including dietary changes, weather changes, and social changes may occur simultaneously during weaning (Enriquez, Hotzel, & Ungerfeld, 2011). Factors that may influence age at weaning, such as body condition of dams or drought conditions, can also influence immunity. Calves weaned at a younger age may not have had time to develop proper immunity.

Commingling cattle from multiple sources may increase exposure to pathogens and also lead to social stress (Callan & Garry, 2002; Taylor et al., 2010b). The cumulative incidence of treating pre-weaning BRD in herds with ≥ 1 calf from an outside source introduced to the operation was 2.6 (95% CI: 1.2–5.5) times as high as the herds without introducing calves from outside sources (Woolums et al., 2013). Decreasing the number of stressors during weaning by using good management practices may contribute to reducing overall stress that can negatively impact immunity.

Weather factors, including extreme cold or hot weather, may be associated with the BRD mortality in pre-weaned calves due to stress (Carstens, 1994; Lorenz, Earley, et al., 2011; Stokka, 2010; Taylor et al., 2010a). In the US, about 51% of beef calves were challenged by moderate to cold stress when born, and almost 77% of neonatal mortality was due to cold stress (Azzam et al., 1993). Of calves born alive, but died less than three weeks of age, 25.6 ± 3.6% of the deaths were due to weather (USDA, 2010a). Also, calves born in extremely cold or hot weather may experience reduced passive transfer due to the delayed time of nursing (Stokka, 2010). Eighty-five percent of veterinarian responders selected weather as one of the factors associated with BRD in beef calves prior to weaning (Woolums et al., 2014).

Colostrum management

Calves are born without protective immunoglobulins because cattle have synepitheliochorial placentas which prevent the transfer of serum proteins to the fetus in utero (Borghesi, Mario, Nogueira, Favaron, & Miglino, 2014; Weaver, Tyler, VanMetre, Hostetler, & Barrington, 2000). Therefore, passive transfer of colostral immunoglobulins from dams plays a significant role in protecting younger calves' health since calves are born with no immunity until they can develop their acquired immune system (McGuire, Pfeiffer, Weikel, & Bartsch, 1976; Niewiesk, 2014). Adequate passive transfer depends on the quality, quantity, and timing of colostrum, as well as calves' ability of sucking and absorption. The timing of colostrum is critical for passive immunity transfer because intestinal closure happens about 24 hours after birth, where large molecules are no longer able to be absorbed through the intestinal walls (Lorenz, Mee, Earley, & More, 2011; Weaver et al., 2000).

Failure of passive transfer (FPT) of colostral immunoglobulins is defined as a calf serum of IgG concentration of < 1,000 mg/dl about 24 hours of age (Perino, 1997; Tyler et al., 1996). Studies have shown FPT was associated with subsequent disease in beef calves prior to weaning (R. D. Dewell et al., 2006; Wittum & Perino, 1995). Calves with inadequate IgG concentration (< 800 mg/dl) at 24 - 72 hours of age are more likely to develop diseases and have less chance of survival than calves with adequate IgG concentration (> 1,600 mg/dl). One research study showed that compared to calves with adequate IgG concentration at 24 hours after birth, pre-weaning mortality (OR = 5.4, 95% CI: 1.3–23.5), neonatal morbidity (OR = 6.4, 95% CI: 2.6–15.7) and pre-weaning morbidity (OR = 3.2, 95% CI: 1.6–6.4) were higher in calves with inadequate IgG concentration (Wittum & Perino, 1995). Another recent research study showed similar results, where calves with inadequate IgG1 at 24 - 72 hours after birth were 2.2 (95% CI: 1.5–3.3) times more likely to become ill and 4.9 (95% CI: 2.5–9.5) times more likely to die than calves with adequate IgG1 concentrations prior to weaning (R. D. Dewell et al., 2006). Therefore, the ingestion of sufficient amounts of colostrum is essential for protection against and decreasing the severity of disease during the first 2 to 5 weeks of life in calves (Chase, Hurley, & Reber, 2008; Ridpath, Neill, Endsley, & Roth, 2003).

Although maternal antibodies are crucial for survival, they may suppress active immune responses to vaccination in calves prior to 2 or 3 months of age (Menanteau-Horta, Ames, Johnson, & Meiske, 1985; Waldner & Kennedy, 2008). Calves with high concentration of BVDV specific maternally derived antibodies blocked the immune response to modified live vaccine (MLV) for BVDV given at 10 - 14 days of age (J. Ellis, West, Cortese, Konoby, & Weigel, 2001). Others reported that maternal antibodies in calves at 84 days of age did not interfere with the immune response of MLV BVD vaccination but inhibited the response of MLV IBR vaccination. Maternal antibodies did not interfere with either vaccine in calves at 196 days of age (Menanteau-Horta et al., 1985). Another study reported the antibody titers to each of the viruses (BVDV 1a, BVDV 1b, BVDV2, BHV-1, PI3V, and BRSV) were not different among vaccinated and non-vaccinated calves at approximate 95 days of age since maternal immunity might inhibit serum antibody responses in calves (R. W. Fulton et al., 2004).

Age of dam

Age of dam was associated with BRD due to differences in the transfer of passive immunity (Weaver et al., 2000). Younger dams may transfer lower levels of passive immunity to their calves due to poor mothering skills, the smaller size of udders, and fewer antibodies in their colostrum compared to older dams (Frerking & Aeikens, 1978). Papers reported colostral immunoglobulin levels and calf serum immunoglobulin concentrations increased with the increase of age of dam (Frerking & Aeikens, 1978). Compared to beef calves born to cows three years of age or older, calves born to heifers had a lower ($P = 0.0001$) concentration of IgM and IgG1 at 24 h of age (Odde, 1988). Other research studies had similar results. The level of IgG1 at 24 to 48 h postpartum was significantly lower in calves born to heifers (20.3 mg/ml) than 3-year-old cows (26.6 mg/ml) or cows 4-year of age or older (31.0 mg/ml) (Muggli, 1986). Several studies reported the IgG concentration in calves, however limited research has been done about the effect of age of dam on pre-weaning BRD by field study. Only one research study reported calves born to 2-year old dams had increased risk for pre-weaning BRD compared to calves from older dams, and the risk for pre-weaning BRD had no significant difference in calves born to dams three years of age or older (Muggli-Cockett et al., 1992).

Economic impact of BRD

BRD has a significant economic impact on the beef cattle industry due to morbidity, mortality, prevention costs, treatment costs, production losses, and reduced carcass values (Engelken, 1997; R. W. Fulton, 2009; R. W. Fulton et al., 2002). BRD is the primary cause of death for feedlot cattle (Loneragan, Dargatz, Morley, & Smith, 2001), weaned dairy heifers (USDA, 2007), and beef calves ≥ 3 weeks of age prior to weaning (USDA, 2010a). Estimates have widely varied depending on beef cow inventory and economic factors evaluated, however, researchers agree that BRD causes a large economic loss of beef cow-calf industry. According to the USDA National Agricultural Statistics Service (NASS) Cattle death loss report, BRD accounted for 26.4% of all cattle and calf death losses in the US during 2010, which represents approximately $643 million in economic losses across all segments of the beef industry. In this report, death loss for cattle value per head is based on the average price reported in January 2010 and 2011, and calf value per head is based on the market year average calf price with 300 pounds of weight (USDA, 2011). As anecdotally reported, the death loss due to BRD was higher than any other cause of animal death, which was estimated approximately $1 billion annually, and the estimated expenditure for prevention and treatment was over $3 billion annually in the US (Griffin, 1997). The impact of BRD in feedlot cattle has been well studied, while limited information is available for beef calves prior to weaning.

Impact on feedlot cattle

BRD is the leading cause of morbidity and mortality in US feedlots (USDA, 2001). Several factors, including shipping, commingling, nutritional changes, etc., may increase the risk of BRD in feedlot cattle. One review based on 14 separate studies found the incidence of BRD morbidity in feedlots ranging from 0% to 69%, with most reports between 15% and 45%. The mortality in the same period ranged from 0% to 15% with most reports between 1% and 5% (Kelly & Janzen, 1986). One study on 59 feedlots with 28,108 head of cattle in the Great Plains reported 44.1% of all deaths were attributed to BRD (Vogel & Parrott, 1994). Additional research investigated BRD risk factors in 18,112 feedlot calves from 1987 to 2001. The incidence of BRD ranged from 3.3% to 23.6% per year with an average annual incidence of 17.0%. The average mortality of BRD was 3.9%, ranging from 0.1% to 8.9% (G. D. Snowder et al., 2006). According to feedlot surveys conducted by USDA within 12 states, the overall BRD incidence in 1999 and 2011 were 14.4% (USDA, 2000b) and 16.2% (USDA, 2013), respectively. The death losses due to BRD increased from 52.1% in 1994 to 61.5% of all deaths in 1999 (USDA, 2000a).

BRD is a costly disease in feedlot cattle in the US. Compared with healthy cattle, feedlot cattle affected with BRD bring an average of $23 to $151 less per head (R. A. Smith, 2009). The treatment costs associated with BRD is also substantial in feedlot cattle. The average cost for treating BRD was $23.60 (USDA, 2013) per sick animal in 2011, and the cost was nearly doubled compared to the cost of $12.59 per sick animal in Feedlot 1999 survey (USDA, 2000b). Compared to cattle never treated, the growth performance and carcass values decreased $23.23, $30.15, and $54.01 for cattle treated 1, 2, and 3 or more times, respectively (Schneider, Tait, Busby, & Reecy, 2009). The economic cost associated with death, reduced feed efficiency, and treatment costs due to BRD in US feedlot cattle was estimated at $800 million to $900 million annually (Chirase & Greene, 2001).

Impact on beef calves prior to weaning

BRD is an important health issue in beef cow-calf operation, and over 33% of US cow-calf operations strongly agreed or agreed that BRD has a significant economic impact on their operations (13.4% and 20.5% of operations, respectively) (USDA, 2010a). Those costs due to BRD included prevention costs, treatment costs, decreases in weaning weights due to BRD, as well death losses due to BRD. However, there has been limited research performed examining these costs in beef calves prior to weaning.

Prevention cost

Studies conducted almost 30 years ago estimated the annual costs in preventing respiratory disease in beef cow-calf operations, which included veterinary service, labor, and vaccine/drug costs in beef cow-calf operations, ranging from $1.01 to $1.28 per cow (Hird et al., 1991; New, 1991; Salman MD, 1991). These studies reported the costs due to all respiratory system diseases which included diphtheria, pneumonia, and nonspecific respiratory tract infections. Costs to prevent respiratory system disease were not categorized by cattle classification, and the reported treatment costs were not specific to respiratory system disease in pre-weaned calves. Furthermore, these costs are likely to have changed since the late 1980s due to increased costs of both vaccine products and labor.

Treatment cost and death loss

Current literature reporting the cost to treat BRD and cost of death losses due to BRD in pre-weaned calves is limited. One unpublished paper depicted the total economic cost (not including labor) of pre-weaning BRD from one large beef herd in the year 2000 was $50.46 per case, of which, the treatment cost, weaning weight loss, and the death loss were $6.02, $17.17, and $27.27, respectively. For all accounted calves, the cost due to pneumonia per calf was $2.83 not including labor cost (G. Dewell, Keen, Dewell, Laegreid, & Hungerford, 2002).

Weight loss

Weaning weight is an important indicator to measure the effect of BRD that occurred in calves pre-weaning (G. D. Snowder et al., 2005; Wittum et al., 1994). Some papers reported calves that experienced BRD prior to weaning have inferior growth rates compared to the healthy calves. One research study evaluated the incidence of BRD in 41,986 beef calves prior to weaning born from 1983 to 2001. Calves treated for BRD were 6.76 kg lighter than healthy calves (least squares means of 251.71 ± 0.51 kg and 258.47 ± 0.39 kg, respectively) (G. D. Snowder et al., 2005). Another research study in Colorado beef herds done with 2,609 calves during 1990 to 1991 showed BRD was the most influential disease on growth performance. Calves with BRD prior to weaning were 16.5 kg ($P < 0.01$) lighter than calves without BRD, which represented $33.33 loss per case due to weight loss in their herds (Wittum et al., 1994). Another research study conducted in 1,470 crossbred beef calves at US MARC found that the weaning weight of calves treated for BRD prior to weaning weighed 11 kg less than normal calves (G. Dewell et al., 2002). However, other papers showed that BRD had no significant effect on weaning weights. Schneider, et al. evaluated the effect of BRD in Iowa included 1,519 pre-weaned calves, with results showing neither incidence of BRD ($P = 0.35$) nor number of treatments ($P = 0.77$) had a significant effect on weaning weights (Schneider et al., 2010).

Conclusions

BRD is a multifactorial disease, and identifying risk factors associated with BRD is an area of focus which might ultimately allow producers to minimize morbidity and mortality from this costly disease. BRD can occur at any time in beef calves prior to or after weaning. The risk factors affiliated with BRD in beef calves prior to weaning may vary during different age periods. Currently, only one study has reported the effect of sex and age of dam associated with BRD in beef calves prior to weaning, but no studies have estimated the effects of these factors at different age periods in beef calves prior to weaning.

BRD is a costly disease due to morbidity, mortality, treatment, and prevention in beef calves prior to weaning. While studies were performed several years ago describing some of the herd-level economic losses of pre-weaning BRD, there is no current research estimating the total direct economic costs of BRD in US beef calves prior to weaning.

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CHAPTER II

LITERATURE REVIEW OF QUANTITATIVE ANALYSIS TO EVALUATE RISK

Several definitions of risk are available in the field of risk assessment and risk management (FAO & WHO, 2009; McNeil, Frey, & Embrechts, 2015).The Oxford English Dictionary defines risk as "exposure to the possibility of loss, injury, or other adverse or unwelcome circumstance; a change or situation involving such a possibility" ("Oxford English Dictionary. Risk.," n.d.). According to the US Presidential / Congressional Commission on Risk Assessment and Risk Management, “risk is the probability that a substance or situation will produce harm under specified conditions” (Omenn et al., 1997). From these two general definitions for risk, we can summarize that risk is the probability for an event to occur which may result in adverse effect on something under specific situations.

People can address simple analyses through their thought processes. However, as risk models are developed and the complexity of the analysis rises (i.e., the model contains many variables and interaction components; some parameters are random variables or reflect uncertainty; the relationship among variables are nonlinear with feedback, etc.), computer-based tools need to be involved (Kellner, Madachy, & Raffo, 1999). Modeling is the process of building a model that is a similar and simpler representation or abstraction of a real or conceptual complex system of under study (Kellner et al., 1999; Maria, 1997). A simulation model is a computerized model used to represent and simulate the system of interest, and it provides a less expensive and less time-consuming way to test and explore different "what if" scenarios to support decision-making (Kellner et al., 1999).

Bovine respiratory disease (BRD) is a costly disease in beef calves prior to weaning, and concepts of uncertainty, variability, stochasticity, non-linearity, and feedback might be contained during the process of assessing risk. This chapter reviews two methods, risk analysis and system dynamics, which can be utilized to quantitatively evaluate the risk of BRD in calves.

Risk analysis

Decisions are often made based on inadequate knowledge and with a high degree of uncertainty about a situation. Risk analysis provides a better way to address the uncertainties and variabilities in risk assessments (Aven, 2016). It has been used widely in many fields, such as environmental protection (Bogen & Spear, 1990; Refsgaard, van der Sluijs, Højberg, & Vanrolleghem, 2007), food safety (Jaykus, 1996; WHO & FAO, 2009) , and human and animal health (Knight-Jones, Njeumi, Elsawalhy, Wabacha, & Rushton, 2014; Ozawa et al., 2016; Smith et al., 2014).

Concept of risk analysis

The Food and Agriculture Organization (FAO) and World Organization for Animal Health (OIE) describe risk analysis as a process including hazard identification, risk assessment, risk management, and risk communication (Arthur et al., 2009; FAO, 2000; OIE, 2010) The Codex Alimentarius Commission (CAC) defines risk analysis as "a process consisting of three components: risk assessment, risk management, and risk communication" (CAC, 1999). The difference between the definitions is whether hazard identification is involved in the process of risk assessment. Here we use risk analysis with four components as defined:

Hazard identification – the process of identifying hazards that potentially have the probability to produce adverse consequences (Arthur et al., 2009).

Risk assessment – the process of evaluating the risks associated with a hazard (i.e., likelihood and consequences of the hazard by qualitative or quantitative method (Arthur et al., 2009; OIE, 2010).

Risk management – the process of evaluating alternative policies regarding the results of risk assessment and selecting appropriate actions to lessen the possible risk (CAC, 1999; FAO & WHO, 2009).

Risk communication – the process of communicating information and opinions on risk and risk management among risk assessors, risk managers, consumers and other interested parties (CAC, 1999; FAO & WHO, 2009).

Methodology of risk assessment

Risk assessment is the process of evaluating risks, and it can be conducted through either qualitative or quantitative methods.

Qualitative risk assessment is the process of compiling, combining, and presenting evidence to support decision making about the risk under study (Malik, Erginkaya, Ahmad, & Erten, 2014). It is mostly conducted when there is little or no historical data available on the risk or probability of an event occurring (Casebeer & Verhoef, 1997; Lurie, Goldberg, & Robinson, 1993). Although some inputs may consist of numerical data, the final risk estimate does not form a mathematical model (Malik et al., 2014). The probabilities of risk occurring, for example, is presented as high, medium or low (Arthur et al., 2009). Qualitative risk assessment is often applied at earlier stages of hazard identification and risk assessment to screen the more significant risks, which can be further selected for study by quantitative techniques (Abdelgawad, 2011).

Quantitative risk assessment, also called quantitative risk analysis (QRA), is intended to quantify data by using deterministic modeling or stochastic modeling. Deterministic models are mathematical models which produce single estimates of decision outcomes which are determined by the single value of each input variable, and the uncertainty or variation around the value is not considered (Fazil, 2005; Uusitalo, Lehikoinen, Helle, & Myrberg, 2015). Conversely, stochastic modeling possesses some random components. Input variables are described by probability distributions estimated from historical data or deduced from expert opinion to assess uncertainty and variation in factors limiting the outcome (Albright, Winston, & Zappe, 2011; Lurie et al., 1993). Each single simulation of stochastic modeling produces only one possible result while multiple runs provide an estimate of the output by a range or a statistical distribution. Therefore, stochastic modeling may provide decision-makers additional information to make informed decisions about risk under uncertain conditions (Fazil, 2005). In this dissertation, only stochastic modeling was considered in the evaluation of risk as related to BRD.

Uncertainty and variability

Creating polices or making decisions in areas such as health may be challenging due to two kinds of difficulties: inherent limitations on the power of the analysis, and practical restraints imposed by external pressures (NRC, 1983). External pressures may come from many factors, such as public concern and economic interests (NRC, 1983), which cannot be considered by analysis method. The power and reliability of the analysis depends on the uncertainty and variability of available data, which might be improved by QRA.

Uncertainty refers to the lack of knowledge regarding some risk-related characteristics (Bogen & Spear, 1990; Vose, 2008; WHO & FAO, 2009). Uncertainty can be derived from inaccurate or imprecise parameter estimates, or unavailable relevant data or information (Bogen & Spear, 1990). Therefore, uncertainty has been further described as epistemic uncertainty, subjective uncertainty, or lack-of-knowledge uncertainty (Filipsson, 2011; Vose, 2008; WHO & FAO, 2009). Uncertainty may be reduced by further study, more precise or targeted measurement, or by expert consultation (Bogen & Spear, 1990; Vose, 2008; Waters et al., 2015).

Variability refers to the inter-individual heterogeneity (i.e., variations among individuals over space or time) concerning certain risk-related characteristics (Bogen & Spear, 1990; Vose, 2008; WHO & FAO, 2009). Variability arises from stochasticity (Filipsson, 2011). Therefore, variability is also known as stochastic variability, or inter-individual variability (Vose, 2008). Variability can be better characterized, but cannot be decreased by further study or investigation, in contrast to uncertainty (Bogen & Spear, 1990; Filipsson, 2011; NRC, 2009).

The QRA process quantifies uncertainty and variability in conducting a risk assessment. Probability distributions can be used to describe the range of values for variable inputs or outputs, as well as the probability that these variables will take on specific values (Vose, 2008). When stochastic methods are used, the probabilities associated with each event are generated based on several iterations of repeated random sampling based on specified distributions of inputs (Vose, 2008). A detailed explanation of the stochastic simulation process will be summarized later.

Process of risk assessment

A risk assessment is used for evaluating the likelihood of occurrence and impacts of the risk factors under study. It is the most critical component in the process of conducting a risk analysis, which can be summarized into four steps: 1) identify the measurements for the outcome, 2) develop a deterministic model including the connection between inputs and outcomes, 3) collect information associated with inputs and define probability distributions based on historical data, scientific papers, expert opinions, surveys, etc., and 4) perform stochastic simulation and calculate the outcomes based on probability distributions of inputs (Aven, 2003). Step 2 may be unnecessary if uncertainty distributions of inputs are available.

Simulation

Monte Carlo simulation is a computer-based modeling method developed in the 1940s which uses stochastic sampling techniques in obtaining probabilistic distributions for the solution of mathematical problems (Firestone et al., 1997). Monte Carlo simulation runs repeatedly and randomly generates samples from distributions assigned to each input, and creates possible values of outcomes with their probability distributions. Each probability distribution, for either input or outcome variable, describes the range of the values that each variable may take and the responding probability for each specific value (Vose, 2008).

There are two commonly used sampling for stochastic simulation: Monte Carlo and Latin Hypercube sampling. Monte Carlo sampling is a pure and entirely random sampling method, and the random value produced by one iteration will have no effect on the next iteration (Vose, 2008). Latin Hypercube sampling is another widely used method in many risk analysis simulation software programs (e.g. @risk, Crystal Ball). Unlike Monte Carlo sampling, Latin Hypercube sampling works as stratified sampling (Firestone et al., 1997; Vose, 2008). Each input probability distribution is divided into several intervals (i.e., the number of iterations) with equal probability, and only one sample can be selected from each interval. Also, each interval can only be sampled once (Vose, 2008). That helps ensure that samples will be selected evenly from the entire range of distributions. Therefore, Latin Hypercube sampling more accurately reflects the inputs' probability distributions by performing fewer iterations compared to Monte Carlo sampling (Vose, 2008).

Sensitivity analysis

Several inputs are sampled based on their distributions by Monte Carlo simulation. For this process, it is important to thoroughly identify factors contributing to the outcomes, investigate the likelihood of adverse effects due to changes in input variables, and estimate actions that might mitigate possible adverse effects (Iloiu & Csiminga, 2009). Sensitivity analysis is a "what if "analysis used to evaluate the variation in the outputs of the model responding to the changes in the values of input parameters (Pianosi et al., 2016; Saltelli, Tarantola, & Campolongo, 2000).

Approaches to sensitivity analysis include global sensitivity analysis (GSA) and local sensitivity analysis (LSA) (Campolongo, Saltelli, & Cariboni, 2011; Pianosi et al., 2016). GSA considers variations within the entire range of variability of the input factors (Pianosi et al., 2016; Sarrazin, Pianosi, & Wagener, 2016; van Griensven et al., 2006). The association between output and input variables can be assessed based on the regression analysis or correlation analysis (Hamby, 1995; Iooss & Lemaître, 2015). Compared to GSA, which allows exploring the sensitivity of model outputs to multiple input parameters simultaneously (Lebedeva et al., 2012), LSA is an estimation of partial derivatives which acts as a one-at-a-time measure (Campolongo et al., 2011; Pianosi et al., 2016). It can be calculated based on the switching value of input variables, which usually is defined as changes (e.g. ± 10%, ± one standard deviation) from the base case of input. The percent change in the output resulting from a given change of one factor was assessed when the other factors remain at their expected values (Brigham & Houston, 2008; Campolongo et al., 2011). Although LSA cannot detect the interactions among factors which work together to influence the outputs, it is the easiest way to understand which input variables have greater impact on the outputs (Campolongo et al., 2011).

Strengths and limits

The strength of a QRA is determined by the involvement of uncertainty and variability identified during the assessment. QRA does not give rise to a fixed or single answer, rather it provides a range or statistical distribution of values which may provide decision-makers additional information under uncertain situations (Fazil, 2005; Uusitalo et al., 2015). It is well understood that QRA is a data-driven approach which provides risk evaluations dependent upon sufficient quantities of available data (Gamado, Marion, & Porphyre, 2017).

Risk analysis is a methodical approach to making decisions, and it cannot be used as a replacement for personal judgment or expertise (Palisade-Corporation, 2016). Risk analysis is simple in context, but it cannot represent the changes of effects over time due to each output having one aggregated estimate based on several simulations (Soliman, Mourits, Oude Lansink, & van der Werf, 2010). In addition, any changes of the outputs may also impact on other input variables, although such changes are not considered in the risk analysis modeling. Therefore, risk analysis may not be suitable to estimate long-term risk effects which change over time.

System dynamics modeling

Risk analysis provides an insight to the quantification of possible risks and their probabilistic effects while considering uncertainty and variability in the process of decision-making. However, it does not address feedback loops or temporal changes during the modelling process. System dynamics is a modeling approach utilizing systems thinking, which is a problem-solving approach that addresses problems as components of an overall system rather than "isolated islands" (Bala, Arshad, & Noh, 2016). It was developed during the 1950s by Forrester at Massachusetts Institute of Technology (Forrester, 1985). System dynamics focuses on closed loops in thinking by using interconnected feedback loops which drives behavior over time (Sterman, 2000, pp.12-14). System dynamics have been applied widely in many fields, such as business (Lyneis, 1999; Sterman, 2000), social-ecological systems (Enfors, 2013; Stave, Goshu, & Aynalem, 2017), economics (Cannella, Ashayeri, Miranda, & Bruccoleri, 2014; Forrester, Mass, & Ryan, 1976), health care (Homer & Hirsch, 2006), agriculture (Li, Dong, & Li, 2012; Walters et al., 2016) , and animal science (Tedeschi, Nicholson, & Rich, 2011).

Concept of system dynamics

According to the Merriam-Webster dictionary, a system is defined as “a regularly interacting or interdependent group of items forming a unified whole” ("Merriam-Webster online dictionary. System," n.d.). In 1971, Ackoff proposed a system as “a set of interrelated elements,” in which at least two elements and a relationship between each element and at least one other element in the set were involved (Ackoff, 1971). Later, Meadow stated that systems consist of three components: a function or purpose, elements (characteristics of systems thinking), and interconnections (ways that elements can take effect and are related to each other). The function or purpose mostly determines the system's behavior (Meadows, 2009).

Systems thinking is the foundation of the field of system dynamics and has been applied in addressing complex system issues. However, Forrester stated there is no clear definition of the term systems thinking, and systems thinking was often utilized as the same as system dynamics (Forrester, 1994). Some researchers described systems thinking literally as “a system of thinking about systems” (Arnold & Wade, 2015).

There are several definitions describing system dynamics, and the most accepted definitions were stated by Richardson and Sterman. Richardson described system dynamics as “a computer-aided approach to policy analysis and design.” (Richardson, 1991). Sterman defined system dynamics as “a method to enhance learning in complex systems ... a method for developing … computer simulation models, to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies." (Sterman, 2000, p. 4).

System structure and patterns of behavior

System dynamics modeling investigates the feedback processes which accompany stock and flow structures, time delays, and nonlinearities to determine the dynamic behavior of a system (Sterman, 2000, p. 12). Causal loops and stocks and flows structures are the two central concepts of system dynamics modeling (Sterman, 2000, p. 191). Time is an important variable in the system since stocks or other variables may change over time, and delays are a critical source of dynamics that are used to reflect processes in the system (Hirsch, Levine, & Miller, 2007). Causal loops, stocks (accumulations), flows (rates), and time delays are the core elements of system dynamics (Marshall et al., 2015).

Causal loop and feedback

The building of a system dynamics model begins with the development of a causal loop diagram, which seeks to capture the causal relationships among key variables in the system (Neal, 2017). A causal loop diagram contains variables connected by arrows representing the causal influences among them. Each arrow is denoted with either positive (+) or negative (–) sign. Positive (+) represents an increase or decrease of one factor causes an increase or decrease in the other, while negative (-) depicts an increase or decrease in one factor causes a decrease or increase in the other (Sterman, 2000, pp. 138-139).

Feedback loops act as consequences of the closed causal boundary. There are two types of feedback loops: positive (or self-reinforcing) feedback loops and negative (or self-correcting) feedback loops. Positive feedback loops work to drive the behavior of system growth or decline, while negative feedback loops intend to balance and equilibrate. The interaction of different loops are used to build various systems (Sterman, 2000, p. 12).

Stocks and flows

A causal loop diagram presents a conceptual model of the system, however, it cannot distinguish between stocks and flows and sometimes more detailed information need to be specified (Sterman, 2000, pp. 167, 191). Therefore, causal loop diagrams need to be converted into stocks and flows in the formal analysis of system dynamics modeling (Neal, 2017). Stocks and flows look similar in causal loop diagrams, however function differently in stocks and flows structure. A stock is an accumulation of some resource, while a flow is a process through which levels of a stock rise or fall over time. Flows work as actions or activities, and flows into and out of the stocks directly affect the inventory of stocks (Sterman, 2000, p. 192).

Time delay

Time is an important variable since model behavior may demonstrate temporal changes. Time delay is a key feature of system dynamics modeling, which means there is a lag period which occurs between actions and their effects on the state of the system (Barlas, 2009). It is critical to investigate time delay in the system for situations in which there are obvious discrepancies between the desired and actual state of the system (Sterman, 2006). Oscillation is one of the common modes of behavior in dynamic systems. It is a type of periodic motion, in which the state of the system constantly closes and keeps away from its equilibrium state (Sterman, 2000, p. 114).Time delays with negative feedback in the structure may lead to oscillation since changes of variables cannot be detected immediately and results in a delay occurring in decision making (Sándor, 2004; Sterman, 2000, pp. 23, 114).

Process of system dynamics modeling

There are several courses, published papers, and books describing the steps of performing system dynamics (Albin, 1997; Forrester, 1994; Richardson, 1991; Sterman, 2000). Several sources summarized the approach of system dynamics modeling into four steps: 1) defining the purpose of the model (i.e., focusing on a problem) and the model boundary (including necessary components or key variables), and diagramming the basic model using causal-loop diagrams or feedback loops to explain the problem, 2) turning causal loop diagrams into stock and flow equations, 3) testing the model including model simulation, assumption testing, and sensitivity analysis, and 4) evaluating the model's response regarding various "what if" policies and implementation of possible policies (Albin, 1997; Forrester, 1994).

Strengths and limitations

System dynamics has some advantages regarding the management of complexity. First, system dynamics is a combined approach of qualitative and quantitative methods. It uses a qualitative method to describe the system, and then converts the diagram into stock and flow equations for quantitative simulation (Coyle, 1996). Second, system dynamics is characterized as a top-down approach and starts with a conceptual model of a system in which several elements are involved and related. System dynamics attempts to understand system-level relationships with the changes of elements at the bottom of the system (Neal, 2017). Third, the system dynamics model structure incorporates dynamics (i.e., variables change over time), feedback (i.e., interactions of variables), non-linearity (i.e., non-proportional cause-effect relations) in the process of decision making (Grösser, 2017; Marshall et al., 2015). Fourth, system dynamics can be used to explore the expected outcomes of various “what if” scenarios, which is helpful for evaluating the effects of different policies (Neal, 2017; Sterman, 2000, p. 86). And finally, system dynamics emphasizes continuous temporal changes and the feedback influences among variables, which can be used to better understand short-term and long-term dynamics of a system (Grösser, 2017).

System dynamics has limitations despite the above strengths. System dynamics models derived from our mental models or thought processes, are often oversimplified as compared to the complexity of the systems themselves (Featherston & Doolan, 2012). Therefore, we are unable to imitate the real world by system dynamics models (Featherston & Doolan, 2012; Lane, 2000). The objective of system dynamics is to use simulation to assist people to understand complex mental models whose inferences are beyond our capability of understanding (Featherston & Doolan, 2012). Risk analysis is a stochastic approach in which inputs and outputs contain probability distributions and estimates possible values, and the results are the aggregation of multiple iterations. System dynamics models may have random functions to create values regarding their distributions. Each variable can have various values at a given time in each iteration, while system dynamics models cannot provide the aggregation results for all the iterations.

Conclusions

QRA is a method to evaluate risks which accounts for uncertainty and variability. BRD has a significant economic impact on the beef cattle industry. Many variables, such as BRD mortality, BRD morbidity, treatment cost, loss of weaning weight due to BRD, market price, calving percentage, etc. are involved in the cattle production system, and variability and uncertainty of these variables need to be considered to get a better estimate of economic cost due to BRD. Several stochastic models have been developed to study the cost of BRD in dairy cattle (Mohd Nor, Steeneveld, Mourits, & Hogeveen, 2012; van der Fels-Klerx, Sorensen, Jalvingh, & Huirne, 2001) and feedlot cattle on a specific farm or in another country (Buhman, Hungerford, & Smith, 2003; Theurer, White, Larson, & Schroeder, 2015). However, there are no reports which estimate the economic cost of BRD in US beef calves prior to weaning.

A partial budgeting of economic costs due to BRD can be estimated by QRA where feedback is not involved. However, system dynamics is an approach used to simulate the sequence of risk and its effect considering feedback and possible changes over time. For example, in the beef cattle industry, a change of supply in the market may affect the market price and net profit, and net profit will have an impact on the cow inventory which affects the supply in the market, and so on. Therefore, system dynamics modeling might be useful to better understand the effect of BRD in US beef calves prior to weaning on profitability in the cow-calf sector. Currently, there is no information available to understand the risk of BRD by system dynamics modeling.

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CHAPTER III

THE EFFECT OF SEX, BIRTH WEIGHT, AND AGE OF DAM ON THE RISK FOR CALVES TO DEVELOP BOVINE RESPIRATORY DISEASE PRIOR TO WEANING

Introduction

Bovine respiratory disease (BRD), sometimes called shipping fever or pneumonia, is a leading cause of sickness and death in beef cattle and calves in the US. BRD accounts for 26.4% of all cattle and calf death losses in the US, and results in approximately $643 million in economic losses over the entire industry (USDA, 2011b). Although great strides have been made in research of pathogens (Griffin, Chengappa, Kuszak, & McVey, 2010), development of vaccines (Fulton, 2009), and antibiotics, BRD continues to be one of the leading health issues in the cattle industry (USDA, 2011a, 2013).

BRD is a multifactorial disease, resulting from the interactions of agent (Panciera & Confer, 2010; Welsh, Dye, Payton, & Confer, 2004), host (Snowder, Van Vleck, Cundiff, & Bennett, 2005), and environmental factors (Aich, Potter, & Griebel, 2009; Taylor, Fulton, Lehenbauer, Step, & Confer, 2010). The identification of factors that contribute to the risk for BRD is important to understand management practices which may help decrease the risk of BRD. Little research has been performed to understand factors associated with BRD in beef calves prior to weaning (Muggli-Cockett, Cundiff, &

Gregory, 1992; Schneider, Tait, Ruble, Busby, & Reecy, 2010; Snowder et al., 2005; Woolums et al., 2013). BRD can occur at any time in beef calves prior to weaning, but different ages may have different susceptibility and risk factors. Weaning typical occurs between 3 and 8 months of age (Filley, 2011), and the average weaning of calves in the US is 207 d of age (USDA, 2008).

In one study that analyzed health records of 31,243 calves from a single herd over a 20-year period, the average age for calves to contract BRD was 101 d. The distribution of cases as seen by age showed that sporadic cases of BRD occurred when calves were < 75 d of age, followed by an increase of cases when calves were between the ages of 75 to 170 d, and finally a rapid decrease in cases until weaning (Snowder et al., 2005). In our previous research, we found a similar epidemic pattern (Smith, 2014). We hypothesized that risk factors associated with BRD may be different based on the age of the calf. Currently, only one study has reported the effect of sex and age of dam on BRD risk in beef calves prior to weaning (Muggli-Cockett et al., 1992), and no studies have estimated the effects of these factors at different age periods.

Therefore, the objective of this study was to test the effect of sex, birth weight, and age of dam on the risk for beef calves to develop BRD in different age periods (< 75 d, 75 d to 149 d, and ≥ 150 d to weaning) prior to weaning.

Materials and methods

Data

Health records of 9,921 calves from 28 cattle management groups within 7 Nebraska, US beef cattle ranches with a history of BRD were collected from 2005 to 2014. There were 9,140 calves born from January to June and 781 calves born from July to November. Information recorded for the calves included ranch, management group, day of birth, weight at birth, age of dam, age at weaning, age at first BRD treatment, and sex (bull, steer, heifer). Management groups were herds of cattle managed separately, even though they may have been under the same ownership. Health records indicated if a calf was pulled and treated for BRD. Treatment was determined by individual producers based on observation of BRD clinical signs. Occurrence of BRD was binary, and the first treatment date was considered the incident event.

Statistical analysis

A commercial statistical analysis software program (SAS, version 9.4, SAS Institute Inc, Cary, NC) was used to analyze the data. Calves that died at birth or immediately after, and calves without information for sex or date at birth were excluded from all statistical analyses. Calves at risk for each age period were those calves present that had not had BRD previously. Descriptive statistics were performed on continuous variables by PROC MEANS and PROC UNIVARIATE. Results were presented as means (± standard deviation) or medians (± semi-interquartile range). Frequency analyses were conducted on categorical variables by PROC FREQ. Separate multilevel, multivariable log-binomial models by PROC GLIMMIX with a log link and a binomial distribution were used to test which factors were associated with the incidence of BRD among calves prior to weaning in different age periods (< 75 d, 75 d to 149 d, and ≥ 150 d). The response variable was whether calves were treated for BRD or not in each age periods (1 = treated, 0 = not treated). Fixed effects included sex (bull, steer, heifer), birth weight, and age of dam (2 years old, ≥ 3 years old). Management group was included as a random effect. Manual forward selection was utilized to determine the final models.

Relative risk (RR) and 95% CI were calculated for significant variables in each age period. The ratio of the generalized chi-square statistic and its degrees of freedom was used to assess model fit. An alpha level of 0.05 was used to determine statistical significance for all methods.

Results

Descriptive results

Among health data from a total of 9,921 calves, there were 96 calves that died at birth or immediately after and 243 calves had incomplete records. Therefore, data was limited to 9,582 calves with recorded sex or age of dam information that were born alive and lived more than 24 hours. The number of calves included from each ranch varied from 179 to 3,364 and ranged from 26 to 906 calves within each management group (Table 3.1). For the calves included for the analysis, from birth to the age at risk the mean interval was 156 d (± 59) and median was 154 d (± 35) ranging from 1 to 314 days of age.

Birth weight was recorded for 4,017 calves from 10 cattle management groups within 3 ranches. Calf birth weight ranged from 15.9 kg to 68.0 kg, with an average weight of 38.0 kg (± 5.9) and median of 37.6 kg (± 3.4). The distribution of birth weight was approximately normal, with 80.8% of the calves weighing between 30 kg to 45 kg. Age of dam was recorded for 8,869 of 9,952 calves. The mean age of the dam was 4.4 years (± 2.3), and the median was 4 years ranging from 2 to 16 years.

There were 877 calves treated at least once prior to weaning for BRD. The cumulative incidence was 9.2% and ranged from 4.7% to 45.3 % within the 7 ranches and 0 to 73.9% within the 28 management groups (Table 3.1). The annual incidence within ranches was from 1.6 % to 45.3%. The crude cumulative incidence of BRD in bulls, steers, and heifers were 12.9% (151/1023), 8.8% (331/3450), and 8.5% (395/4232), respectively.

Of all calves treated for BRD, the age first treated ranged from 3 d to 232 d, with an average of 101 d (± 43) and median of 103 d (± 27). The overall epidemiological patterns indicated sporadic cases in young calves (< 75 d), then sudden outbreaks in older calves (75 d to 149 d), and finally a rapid decrease to weaning (Figure 3.1). The epidemiological pattern in each ranch or group may be different from the overall pattern based on the mean, median, minimum, and maximum age of treated for BRD. Some herds had BRD with an extended period from an early age to more than 150 d of age, while some herds had BRD in short periods (i.e., either at a younger age or at an older age) (Table 3.1).

The number of calves treated for BRD over the number at risk at the beginning of each age period < 75 d, 75 d to 149 d, and ≥ 150 d were 183/9,582, 593/9,061, and 101/5,221, respectively (Table 3.2). Factors associated with BRD in different age periods in beef calves prior to weaning were summarized (Table 3.3).

Table 3.1 Number of calves treated for BRD, cumulative incidence, and age treated for BRD by ranch and management group

Ranch	**Management Group**	**Year**	**Calves (head)**		**Crude cumulative incidence (%)**	**Age treated for BRD (d)**		
			n	**No. treated for BRD**		**Mean (SD)**	**Median (SIR)**	**Min-Max**
A			2,058	96	4.7	81 (63)	49 (59)	5-232
	A1	2005	569	9	1.6	88 (72)	99 (69)	6-166
	A2	2006	494	37	7.5	45 (46)	29 (11)	5-232
	A3	2007	487	36	7.4	108 (62)	132 (61)	7-224
	A4	2008	508	14	2.8	107 (52)	105 (48)	28-179
B			2,275	93	4.1	120 (28)	117 (15)	12-182
	B1	2012	256	0	0	—	—	—
	B2	2012	906	57	6.3	124 (29)	118 (10)	12-182
	B3	2013	256	0	0	—	—	—
	B4	2013	857	36	4.2	114 (26)	107 (22)	60-161
C	C1	2011	179	81	45.3	34 (19)	33 (15)	6-90
D			3,364	235	7.0	89 (23)	87 (7)	7-159
	D1	2013	487	17	3.5	92 (21)	99 (6)	36-114
	D2	2013	717	127	17.7	86 (9)	87 (5)	55-109
	D3	2014	482	27	5.6	72 (22)	78 (8)	9-97
	D4	2013	500	36	7.2	89 (9)	89 (4)	67-117
	D5	2014	437	6	1.4	47 (56)	33 (17)	7-157
	D6	2014	282	0	0	—	—	—
	D7	2014	459	22	4.8	138 (11)	138 (9)	120-159
E	E1	2012	579	135	23.3	105 (21)	106 (10)	3-156
F	F1	2008	295	87	29.5	133 (11)	134 (8)	110-167
G			832	150	18.0	134 (40)	145 (13)	7-199
	G1	2008	255	45	17.7	142 (48)	155 (20)	7-199
	G2	2011	33	5	15.2	117 (21)	124 (19)	92-135
	G3	2012	26	0	0	—	—	—
	G4	2012	94	3	3.2	45 (24)	33 (22)	30-73
	G5	2011	79	26	32.9	137 (33)	150 (21)	35-167
	G6	2012	109	5	4.6	37 (30)	24 (3)	22-90
	G7	2012	27	0	0	—	—	—
	G8	2011	69	51	73.9	141 (10)	143 (5)	86-150
	G9	2012	75	2	2.7	50 (42)	50 (30)	20-79
	G10	2011	65	13	20.0	152 (23)	158 (21)	121-186
Total			9,582	877	9.2	101 (43)	103 (27)	3-232

n = Number of calves. No. treated for BRD = Number of calves treated for BRD; SD = standard deviation. SIR= semi-interquartile range

Table 3.2 Number of calves and number of treated for BRD in different age periods by sex and age of dam

Age Period	**Category**	**Calves (head)**	
		n	**No. treated for BRD**
<75 d		**9582**	**183**
	Sex	9582	183
	Bull	1174	47
	Steer	3782	52
	Heifer	4627	84
	Age of dam	8869	104
	2 years old	2066	42
	≥ 3 years old	6803	62
75 d to 149 d		**9061**	**593**
	Sex	9061	593
	Bull	1098	102
	Steer	3577	215
	Heifer	4386	276
	Age of dam	8475	591
	2 years old	1955	81
	≥ 3 years old	6520	510
≥ 150 d to weaning		**5221**	**101**
	Sex	5221	101
	Bull	628	2
	Steer	2036	64
	Heifer	2557	35
	Age of dam	4746	101
	2 years old	1404	15
	≥ 3 years old	3342	86

n = Number of calves at risk at the beginning of each age period.
No. treated for BRD = Number of calves treated for BRD during each age period.

Table 3.3 Separate log-binomial models for factors associated with BRD in beef calves prior to weaning at different age periods

Age Period	Variable	Comparison	RR (95% CI)	*P*-value*
< 75 d	Age of dam	2 years old vs. ≥ 3 years old	4.9 (3.1 – 7.8)	<.0001
75 d to 149 d	Age of dam	2 years old vs. ≥ 3 years old	0.6 (0.4 - 0.7)	<.0001
≥ 150 d to weaning	Sex			0.021
		Steer vs. Bull	2.3 (0.5 – 11.1)	0.311
		Steer vs. Heifer	1.7 (1.2 – 2.6)	0.007
		Bull vs. Heifer	0.8 (0.2 – 3.7)	0.737

* Management group was included as a random effect to account for clustering by herd level factors.

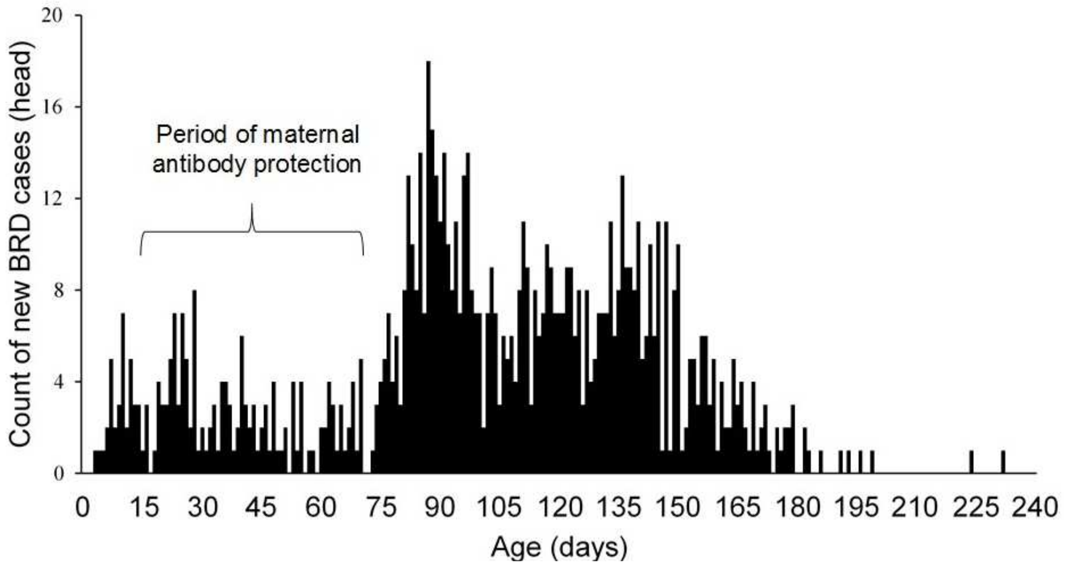

Figure 3.1 Frequency distribution of age of first BRD treatment for 877 calves from 7 beef cow-calf ranches

Factors associated with pre-weaning BRD in different age periods

Factors associated with BRD prior to 75 d of age—Age of dam was associated with BRD in calves prior to 75 d of age ($P < 0.0001$). Calves born to two-year-old dams were 4.9 times more likely treated for BRD than calves born to cows 3 years or older (Figure 3.2). Neither sex ($P = 0.78$) nor birth weight ($P = 0.83$) was associated with BRD in calves prior to 75 d of age.

Factors associated with BRD between the age of 75 d and 149 d—Age of dam was associated with BRD in calves between the age of 75 d and 149 d ($P < 0.0001$). Calves born to two-year-old dams were 0.6 times as likely treated for BRD than calves born to cows 3 years or older (Figure 3.2). Sex ($P = 0.34$) and birth weight ($P = 0.96$) were not associated with BRD for calves during this age period.

Factors associated with BRD from 150 d to weaning—Sex was associated with BRD in calves from 150 d of age to weaning ($P = 0.02$) (Figure 3.3). Steers were 1.7 times more likely treated for BRD than heifers between 150 d of age and weaning, and there was no difference ($P \geq 0.31$) between bulls and heifers or between bulls and steers (Table 3.3). Age of dam ($P = 0.06$) and birth weight ($P = 0.28$) were not associated with BRD for calves during this age period.

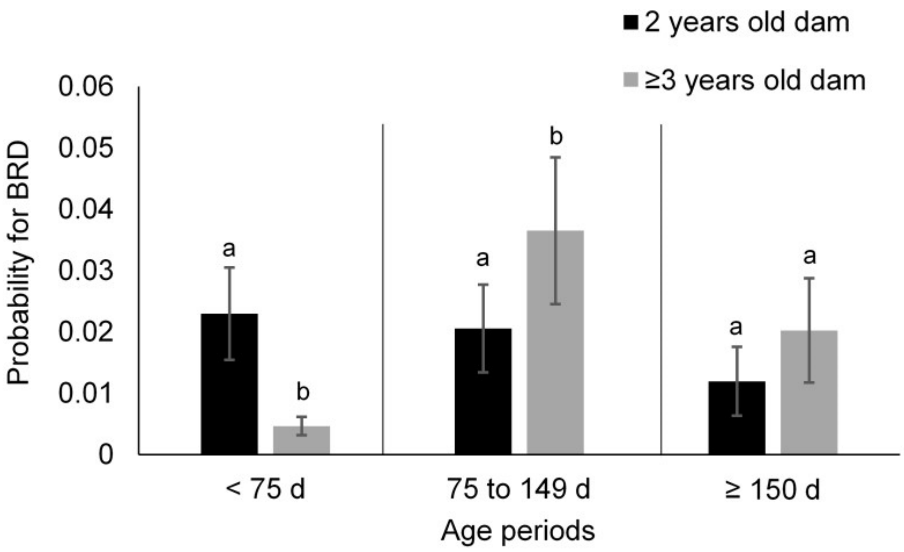

Figure 3.2 Separate models adjusted probability for BRD by age of dam from 8,844 calves in different age periods

Differing superscripts within age periods are significantly different at an α level of 0.05.

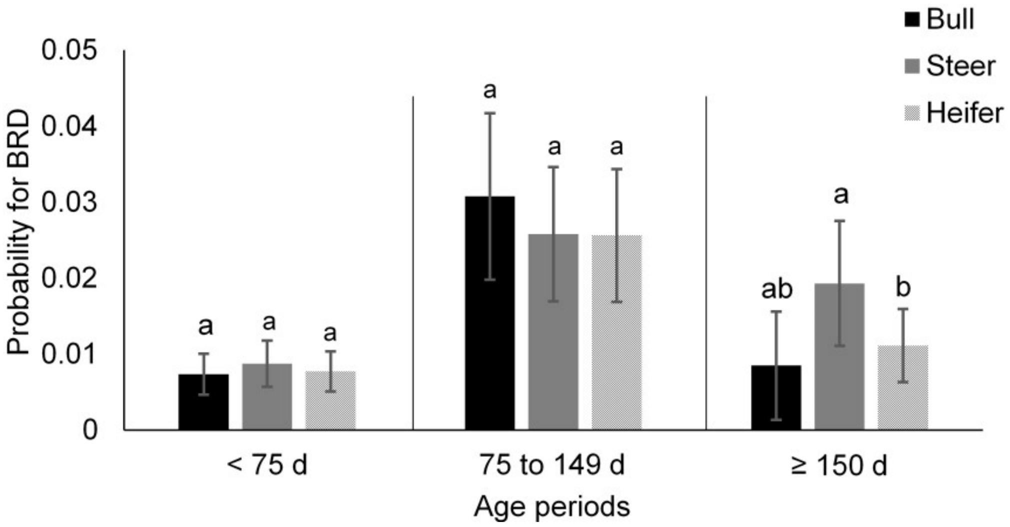

Figure 3.3 Separate models adjusted probability for BRD by sex from 9,553 calves in different age periods

Differing superscripts within age periods are significantly different at an α level of 0.05.

Discussion

This study utilized field health data to assess factors associated with BRD in different age periods for beef calves prior to weaning. We reported the cumulative incidence of BRD over several years within multiple ranches, and we found that age of dam and sex were significantly associated with pre-weaning BRD in different age periods.

The cumulative BRD incidence of this study was slightly lower than a previous multiyear study (Snowder et al., 2005). High variability in BRD incidence among ranches and management groups of cattle was observed in our study, as other researchers and the national survey have reported (Hanzlicek et al., 2013; Snowder et al., 2005). Our analysis estimated cumulative incidence to be 9.2%. The annual incidence in ranches ranged from 1.6 % to 45.3%, and ranged from 0 to 73.9% within management groups. Snowder et al. (2005) analyzed birth and health records (1983 - 2002) from the USDA Meat Animal Research Center for calves. The average incidence over a 20-year period was 10.5% ranging from 3.3% to 23.6% yearly and from 8.3% to 18.9% yearly among breeds. The national survey of beef producers in 2007-2008 conducted by the USDA reported the mean percentage (± SD) of calves born alive affected by BRD prior to weaning as 3.0 ± 7.1% (Hanzlicek et al., 2013). The relatively large SD of the mean percentage indicated that the incidence of BRD within herds was highly variable and skewed (e.g., many herds had low incidence of BRD, but some had high incidence).

The overall distribution of the number of calves first treated for BRD by age in our study was very similar to the previous report (Snowder et al., 2005). Of calves treated, a large proportion got BRD between 75 d to 149 d, and a smaller fraction were infected at a younger age (< 75 d) or at an older age (≥ 150 d). The pattern of the epidemic curve in one herd might be different from other herds and from the population pattern. This observation may be due to differences among herd immunity (Smith, 2014).

Passively acquired maternal immunity plays an important role in protecting the health of younger calves until they can develop their own acquired immune system (Besser & Gay, 1994). Maternal IgG in calves peaks at 24 hours after birth with a half-life ranging from 16 d to 32 d (Bush, Aguilera, Adans, & Jones, 1971; Suh et al., 2003). The occurrence of BRD at a very early age may be due to failure of passive transfer of maternal immunity through colostrum. Calves at 75 d to 149 d of age were at increased risk for BRD, which may be associated with the loss of passive immunity and the delayed acquired immune response in young calves. Chase et al. reported this "window of susceptibility" as the period in which animals are no longer protected by passive immunity and active immunity has not been stimulated (Chase, Hurley, & Reber, 2008).

Our results showed age of dam was associated with BRD in calves prior to 75 d of age and from 75 d to 149 d of age period, but the effects were different. Age of dam might affect BRD risk due to differences in transfer of passive immunity. Younger dams may transfer lower levels of passive immunity to their calves due to fewer antibodies in their colostrum compared to older dams or poor mothering skills. Calves with younger dams had decreased immunoglobulin levels compared to calves of older dams (Bradley, Niilo, & Dorward, 1979; Frerking & Aeikens, 1978; Noelle Elizabeth Muggli, 1986). Muggli et al. (1987) reported that IgG1 level at 24 to 48 h was lower ($P < 0.01$) in calves of 2-year-old (20.3 mg/ml) dams than 3-year-old (26.6 mg/ml) or 4-year or older (31.0 mg/ml) dams. Research studies have shown failure of passive transfer may increase morbidity and mortality in beef calves (Dewell et al., 2006; N. E. Muggli, Hohenboken, Cundiff, & Mattson, 1987; Wittum & Perino, 1995). Wittum and Perino (1995) reported that compared to calves with adequate IgG concentration (> 1,600 mg/dl), pre-weaning mortality (OR = 5.4), neonatal morbidity (OR = 6.4) and pre-weaning morbidity (OR = 3.2) were more likely in calves with inadequate IgG concentration (< 800 mg/dl). Dewell et al. (2006) reported calves with serum IgG1 concentration < 2,400 mg/dl were 1.6 times as likely to become ill before weaning and 2.7 times as likely to die before weaning, compared to calves with higher serum IgG1 concentrations. Therefore, it may explain the increased susceptibility to BRD prior to 75 d of age in calves born to two-year-old dams compared to calves born to older dams reported in our study. Passive immunity provides protection against disease for neonatal and young calves during the first 2 to 4 weeks of life (Chase et al., 2008). However, it can have negative effects on the development of active immune response, especially the development of antigen-specific immune response (Chase et al., 2008; Ellis, Gow, Bolton, Burdett, & Nordstrom, 2014; Nonnecke, Waters, Goff, & Foote, 2012). Calves born to two-year-old dams may be more susceptible to BRD at an earlier age, but lack of maternal antibody may stimulate them to develop their own active immune system and have increased immune response once older. This may help to explain why calves born to two-year-old dams were less likely to get BRD between 75 d to 149 d.

Human and animal studies suggest sex differences in respiratory physiology and in the incidence, susceptibility, and severity of a variety of lung diseases (Carey et al., 2007). One paper reported the effect of sex in pre-weaning BRD. Male calves (14.4 ± 1.18%) had greater incidence of BRD in beef calves prior to weaning than female calves

(9.5 ± 1.18%) (Muggli-Cockett et al., 1992). Details of bull or steer status compared to heifers were not included in that study. In our study, the incidence in bulls was not different from heifers or steers at any age prior to weaning. Steers were more likely than heifers to develop BRD during the age period of 150 d to weaning, with no significant difference in calves less than 150 d. A similar finding was reported in a study of BRD in feedlot cattle. The incidence of BRD in steers (20%) was significantly higher than heifers (14%) in the feedlot (Snowder, Van Vleck, Cundiff, & Bennett, 2006). One prior paper reported that IgG1 levels were not different in male and female calves during the perinatal period, but female calves had higher serum concentrations of complement C3 than male calves at the average age of 164 d (N. E. Muggli et al., 1987). Complement C3 plays an important role in innate and adaptive immune response to defend against infectious diseases (Dunkelberger & Song, 2010; Janssen et al., 2005), which may explain why males were more likely to get BRD than females in older age. Additionally, infection or stress due to castration may increase the risk of BRD in steers (Snowder et al., 2006).

Birth weight has been associated with perinatal mortality in several studies (Johanson & Berger, 2003; Morris, Bennett, Baker, & Carter, 1986). Our results showed birth weight was not associated with BRD as another paper has reported (Snowder et al., 2005). Additional papers reported heavier newborn calves are more likely to cause dystocia which may increase the risk of BRD in beef calves prior to weaning. As reported, a 1 kg increase in birth weight corresponded to an increase of 13% odds of dystocia (Johanson & Berger, 2003), and calves born to dams having severe dystocia were 1.7 times more likely treated for BRD than those born to dams without dystocia (Lombard, Garry, Tomlinson, & Garber, 2007).

A limitation of this study is the potential for under-reporting of disease, due to differences in disease detection and treatment policy. As other researchers have mentioned, animals infected with the same disease may have different clinical signs and exhibit varying degrees of illness (Snowder et al., 2005, 2006). It may be difficult to distinguish diseased calves from disease-free calves. Therefore, some calves may have been affected with BRD, but, lacking typical clinical signs, were not diagnosed or treated for the disease. Therefore, a bias toward the null hypothesis (no difference) may be present in this study.

Sex and age of dam affect immunity against BRD in beef calves prior to weaning, but risk factors are dependent on calf age period. In younger calves, earlier occurrence of BRD among calves born to heifers probably reflects greater risk for failure/partial failure of passive antibody transfer. In older calves, sex may affect immunity against pre-weaning BRD, specifically greater risk in steer calves. The results from this study may be helpful to better understand the factors affecting the risk of BRD in beef calves prior to weaning.

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CHAPTER IV

BEEF PRODUCER SURVEY OF THE COST TO PREVENT AND TREAT BOVINE RESPIRATORY DISEASE IN CALVES PRIOR TO WEANING

Introduction

Bovine respiratory disease (BRD) is a costly disease of beef cattle and calves in the US. In 2010, BRD accounted for 26.4% of all cattle and calf death losses in the US, which represented approximately $643 million in economic losses over all segments of the industry (USDA, 2011). The annual economic cost due to BRD for the entire beef cattle industry has been empirically estimated to approach $1 billon, and the annual prevention and treatment costs are estimated to exceed $3 billon (Griffin, 1997). Compared to cattle without BRD, feedlot cattle suffering from BRD are valued $23 to $151 less per head (Smith, 2009). The average treatment cost of BRD was $12.59/case from USDA feedlot 1999 survey (USDA, 2000), and nearly doubled over the following decade to $23.60/case in the USDA feedlot 2011 survey (USDA, 2013). However, there is limited research on the costs associated with preventing and treating BRD in beef calves prior to weaning.

The strategy of vaccination has been used for more than two centuries to prevent and control the spread of infectious disease in populations (Stern & Markel, 2005). Many commercial vaccines are currently available against the most common BRD pathogens, including bovine herpesvirus 1 virus; bovine viral diarrhea virus; parainfluenza 3 virus; bovine respiratory syncytial virus; *Pasteurella multocida*; *Mannheimia haemolytica*; and *Histophilus somnus* (Makoschey et al., 2008; Panciera & Confer, 2010; Perino & Hunsaker, 1997; Salt, Thevasagayam, Wiseman, & Peters, 2007; Tripp, Step, Krehbiel, Moberly, & Malayer, 2013; Vangeel, Ioannou, Riegler, Salt, & Harmeyer, 2009). Immunization of beef calves against BRD pathogens involves either: 1) administering vaccines to dams to stimulate maternal antibody production which can then be passively transferred to calves through colostrum; or 2) direct vaccination of calves to stimulate an acquired immune response (Chase, Hurley, & Reber, 2008; Cortese, 2009; Perino & Rupp, 1994).

In a national survey of US beef cow-calf producers, 39.4% of operations vaccinate calves against BRD in the period from birth to sale, representing 69.1% of all calves (USDA, 2010). However, the only published estimates of the annual costs of veterinary services and vaccines or drugs to prevent and treat respiratory system diseases in beef cow-calf operations are from almost 30 years ago (Hird et al., 1991; New, 1991; Salman MD, 1991). Therefore, the objective of this study was to estimate current costs incurred by beef cow-calf ranchers to prevent and treat BRD in beef calves prior to weaning.

Materials and methods

Sample

In June and July of 2016, a mail survey and an audience response system (electronic) survey of the costs to prevent and treat BRD in beef calves prior to weaning were conducted. Forty mail surveys were sent to beef cow-calf ranchers in Nebraska (n =

19), South Dakota (n = 11), and North Dakota (n = 10) with a known history of BRD, as identified by extension veterinarians. The electronic survey was administered to beef cow-calf producers at educational forums on nursing calf respiratory disease held in Nebraska (July 13rd), South Dakota (July 14th) and North Dakota (July 15th). Producers, researchers, and veterinarians attended these forums; however, responses were only collected from ranchers, and all attending ranchers were invited to voluntarily participate, even if not on the original invitation list.

A common recipient list was used for the mail survey and the invitation list for the educational forum. Both survey methods were used to get a higher response rate. Ranchers who completed the mail survey may also have attended the forum. To evaluate if there were duplicate entries, comparisons of the electronic survey and mail survey were manually performed based on responses to 12 questions regarding costs and time spent on preventing and treating BRD within the same herd size. If fewer than 60% of the responses were identical, the information was assumed to have been from different ranchers.

Questionnaire development

The mail survey was developed into a 3 page document. The electronic survey was developed based on CPS PowerPoint (version 6.75, eInstruction, Youngstown, OH, US). Both surveys included single choice and open-ended questions, but the electronic survey also included multiple choice questions. The mail survey was drafted by two authors and reviewed by seven veterinarians, then pretested by three beef cow-calf producers. The final version of the mail survey was developed based on responses and suggestions from the pretest. The electronic survey was developed based on the final version of the mail survey. Additional questions were added to the electronic survey because investigators would have more time to communicate with the producers during the survey. The electronic survey was similarly reviewed, and a pretest was administered to determine if 30 to 40 minutes was sufficient time to allow for completion of the survey and to address any problems with content. The final version of the electronic survey was developed based on suggestions from reviewers and responses on the pretest. The final mail survey consisted of 17 questions and took approximately 15 - 20 minutes to complete, and the final electronic survey consisted of 26 questions and required approximately 30 - 40 minutes to complete.

The final version of the mail and electronic surveys are summarized (Table 4.1). The mail survey included three parts: general information, cost of BRD prevention, and cost of treatment for pre-weaning BRD. The electronic survey had four parts, the three parts of mail survey and the cost of veterinary services related to BRD. It included most of the mail survey questions as well as additional questions, including the percentage of time spent on vaccination and treatment for gathering, sorting, preparing, and administering; percent of treatment cost due to antibiotic cost; and the cost of veterinary services related to BRD.

Table 4.1 Main content in mail and electronic surveys

Main Part	**Contents**
Part I	Beef cow-calf producer (Y/N)
General Information	State of residence
	Number of beef cows and replacement heifers* in January, 2016
Part II	**Section 2.1 Prevention of BRD in beef cows and heifers**
Cost of BRD prevention	Cost for vaccine per head per year
	Time spent to vaccinate per head per year
	Percent of time spent on gathering, sorting, preparing and administering†
	Cost for labor to vaccinate per head per year
	Personnel performing vaccination†
	Section 2.2 Prevention of BRD in beef calves prior to weaning
	Cost for vaccine per calf per year
	Time spent to vaccinate per calf per year
	Percent of time spent on gathering, sorting, preparing and administering†
	Cost for labor to vaccinate per calf per year
	Personnel performing vaccination†
Part III	Medicine cost to treat BRD per sick calf per year
Cost of treatment for pre-weaning BRD	Percent of treatment cost due to antibiotic cost†
	Time spent on treating per sick calf per year
	Percent of time spent on gathering, sorting, preparing and administering†
	Cost for labor to treat per sick calf per year
	People who performed the treatment†
Part IV Veterinary cost for BRD†	The cost of veterinary services (not including vaccines and drugs) related to BRD diagnosis, prevention, and treatment to beef calves per year†

*Only included in the mail survey.
†Questions only included in the electronic survey.
Others were included both mail survey and electronic survey.

Survey administration

The mail survey was sent to ranchers in June 2016 with a cover letter describing the study and a pre-addressed, postage-paid return envelope. If the survey was not returned within 60 days, we assumed no response. The electronic survey was administered to ranchers attending the forums who volunteered to participate in the study. Each rancher was supplied a CPS clicker (model KGEN2EI, eInstruction, Youngstown, OH) which was used to respond to the survey questions. Before the survey began, the goal of the survey was described and clicker use was demonstrated. During the electronic survey, ranchers could ask for technical help or clarification of any of the questions. Participants were asked to complete the surveys (mail and electronic) on their own, and all the responses were anonymous.

Statistical analysis

Data were evaluated to detect any errors due to incorrect input of numbers with the clickers. For example, in some cases decimal points may not have been entered correctly. An outlier value was defined as any observation more extreme than 1.5 times the IQR from the closer quartile (Q1 or Q3) (Morre, McCabe, & Craig, 2009). Outliers were not included in the analysis of preventive costs for BRD. For questions regarding percentage of time spent gathering cattle, sorting cattle, preparing, and administering the vaccine or treatment, we assumed that these activities accounted for most, if not all, of the total time spent. Therefore, we assumed the sum of the percentages for these activities by a single rancher should be between 80% and 100%. Those values from a rancher were deleted if their sum fell outside of the assumed range. Missing survey data was ignored. A commercial statistical analysis software (SAS, version 9.4, SAS Institute Inc, Cary, NC, US) was used to analyze the data. The Wilcoxon rank-sum test by PROC NPAR1WAY was used to determine whether costs or time spent on preventing and treating BRD were significantly different between electronic surveys and mail surveys due to low response rate in the mail survey.

Continuous data were analyzed by descriptive and inferential statistics. Mean, standard deviation, median, IQR, and range were reported. Separate linear mixed models were fit for those costs and time spent on preventing or treating BRD, and the cost of veterinary services cost in beef calves prior to weaning. For the cost of vaccine against BRD pathogens, cattle classification (cow, replacement heifer, and calf), herd size (≤ 199 head, 200-499 head, and ≥ 500 head), and whether a veterinarian was involved (yes/no) in the process of vaccination were included as fixed effects. State and rancher were included as random effects. A similar model was fit for the outcome of labor cost for vaccination with the additional fixed effect of time spent on vaccination. For the outcome of time spent on vaccination, cattle classification and herd size were included as fixed variables with rancher and state as random effects. For the outcome of medicine cost to treat BRD in beef calves prior to weaning, herd size and whether a veterinarian was involved in the process of treatment were fixed effects and state was a random effect. A similar model was fit for the outcome of labor cost for treatment with the additional fixed effect of time spent on it. For the outcome time spent on treatment, herd size was included as a fixed variable with state included as a random effect. For the cost of veterinary services, herd size and whether a veterinarian was involved in the process of preventing or treating BRD were fixed effects. State was included as a random effect. To test whether there was a significant difference between the cost of labor for vaccination or treatment and the cost of vaccines or drugs used, linear mixed models were fit for prevention costs for cows, prevention costs for replacement heifers, prevention costs for calves prior to weaning, and treatment costs in beef calves prior to weaning. State and rancher were included as random effects. For all linear mixed models, manual forward selection was used to obtain final models. Differences in LS means were determined for outcomes with significant effects. The simulate adjustment option was used to adjust for the effect of multiple comparisons. An alpha level of 0.05 was used to determine statistical significance for all methods and fit statistics were assessed to ensure appropriate model selection.

Results

Survey response

Mail surveys were returned by 9 of 40 (22.5%) beef cow-calf producers. One mail survey from North Dakota was disregarded because the producer also completed the electronic survey, and one survey from Nebraska that was incomplete was disregarded. Of the seven which were completed fully, five were from Nebraska, one from South Dakota, and one from North Dakota. Thirty-seven producers voluntarily responded to the electronic survey. There was one electronic survey from South Dakota which was incomplete. Of the 36 completed surveys, 22 were from Nebraska producers, 10 from South Dakota, and 4 from North Dakota. Although survey results were anonymous, comparison of data entries indicated that no producer completed both surveys. There was no significant difference ($P \geq 0.17$) in responses between survey types (Table 4.2). Therefore, a total of 43 completed surveys (mail n = 7, electronic survey n = 36) were merged and analyzed as one dataset with 27 surveys from Nebraska, 11 from South

Dakota and five from North Dakota. The distribution of herd sizes among the 43 ranches in January 2016 were the following: 10 with ≤ 99 head, 2 with 100-199 head, 17 with 200 - 499 head, and 14 with 500 or more head. Most ranchers vaccinated cows (35/43, 81%), heifers (40/42, 95%), and calves (43/43, 100%) prior to weaning. Forty of 43 (93%) respondents reported treating at least one beef calf prior to weaning for BRD in the last 3 years.

Prevention and treatment costs for BRD

Prevention costs for BRD—The annual costs to vaccinate a beef cow, a replacement heifer, and a beef calf prior to weaning against BRD are reported (Table 4.3). Cattle classification (cows, heifers, calves) was associated with vaccination cost ($P < 0.0001$). The unadjusted labor cost of vaccination by cattle classification are summarized (Table 4.4). Labor costs for vaccination were associated with time spent ($P < 0.0001$). Each additional minute spent on vaccination increased labor cost \$0.31. Labor cost for vaccination was greater than the cost of vaccines for cows ($P = 0.01$). There were no differences detected between labor costs and vaccine costs for replacement heifers or calves ($P \geq 0.18$).

Treatment costs for pre-weaning BRD—The reported costs of medicine and labor for treating BRD in a pre-weaned beef calf per year are summarized (Table 4.5). Herd size ($P \geq 0.29$) or whether a veterinarian was involved ($P \geq 0.64$) had no detectable association with medicine cost or labor cost for treatment. Time spent on treatment was associated with labor cost ($P < 0.0001$). For each additional minute spent on treatment, labor cost increased \$0.28. The cost of labor for treating BRD in a pre-weaned beef calf was greater than the cost of medicine ($P = 0.046$).

Time spent on vaccination and treatment

Time spent on vaccination—The adjusted annual median time required to vaccinate was 5 (IQR = 2.5–10) minutes per head. The proportion of the time spent on various activities related to vaccination are summarized (Table 4.6). The total time spent on vaccination was not different among cattle classification ($P = 0.40$). Herd size was associated with the time spent on vaccination ($P = 0.04$), with less time spent per head in herds with ≥ 500 head (4.12 ± 1.38 minutes/head) compared to medium size herds of 200 - 499 head (8.21 ± 1.17 minutes/head). Smaller herds of < 199 head (7.85 ± 1.33 minutes/head) were not different from medium or larger herds ($P \geq 0.11$). Sixty percent of the time it took to vaccinate dams or calves was spent gathering (40%) and sorting (20%).

Time spent on treatment—The unadjusted annual median time required for treatment prior to weaning due to BRD was 30 (IQR = 15–40) minutes per sick calf, ranging from 5 minutes to 4 hours (Table 4.7). Herd size was not associated with the time spent treating sick calves ($P = 0.77$). Gathering (60%) and sorting (20%) accounted for the majority of the total treatment time.

Personnel involved and veterinary services

Personnel involved in vaccination and treatment—More than 88% of producers reported being involved in the activities of vaccination and treatment. Forty-six percent and 41% of the ranchers reported that veterinarians participated in vaccinating cows or heifers, or pre-weaned calves, respectively. Forty-nine percent of ranchers reported that a veterinarian was involved in the process of treating BRD in beef calves prior to weaning. The involvement of a veterinarian in the process of vaccination was not associated with the cost of vaccine ($P = 0.76$) or associated labor cost ($P = 0.20$) to prevent BRD. Veterinary involvement was not associated with medicine cost ($P = 0.97$) or labor ($P = 0.64$) to treat BRD.

Veterinary services—The unadjusted annual median cost of veterinary services (not including vaccine or drug costs) related to diagnosis, prevention, and treatment of BRD in beef calves prior to weaning was $1.25 (IQR = 0.33–2.50) per calf, ranging from $0 to $10 per calf. Herd size ($P = 0.69$) and whether a veterinarian was involved in the process of prevention or treatment ($P \geq 0.86$) were not associated with the cost of veterinary services.

Table 4.2 Comparison between two survey types based on 12 questions

Questions	***P*-value***
What is your average cost for the vaccine you used per beef cow per year	0.171
How much time does it take to vaccinate a beef cow per year?	0.557
What is your cost for labor to vaccinate a beef cow per year?	0.635
What is your average cost for the vaccine you used per beef replacement heifers per year?	0.820
How much time does it take to vaccinate a beef replacement heifer per year?	1.000
What is your cost for labor to vaccinate a beef replacement heifer per year?	0.394
What is your cost for the vaccine you used for a beef calf per year?	0.276
How much time does it take to vaccinate a beef calf per year?	0.860
What is your cost for labor to vaccinate a beef calf per year?	0.345
What is your average cost for all medicine to treat a beef calf prior to weaning for pneumonia per year?	0.864
What is the time do you spend to treat a beef calf prior to weaning for pneumonia per year?	0.984
What is your cost for labor to treat a beef calf prior to weaning for pneumonia per year?	0.952

*Each question was compared by Wilcoxon rank-sum test.

Table 4.3 Annual cost for vaccine ($/head) to prevent BRD

Variable	***n***	**Mean (SD)**	**Median (IQR)**	**Range (Min, Max)**	**LS means***
Beef cow	25	2.99 (1.62)	2.25 (2.00–4.00)	1.25–8.00	3.18^a
Replacement heifer	37	4.22 (2.41)	4.00 (2.50–5.50)	1.50–12.00	4.48^a
Beef calf prior to weaning	40	7.44 (4.12)	6.25 (4.75–10.00)	1.45–18.04	7.67^b

n = Number of respondents.
*Model adjusted for state and rancher as random effects; differing superscripts are significantly different at an α level of 0.05.

Table 4.4 Annual labor cost for vaccination ($/head) to prevent BRD

Variable	***n***	**Mean (SD)**	**Median (IQR)**	**Range (Min, Max)**
Beef cow	30	5.39 (4.57)	4.58 (1.50–10.00)	0.40-15.00
Replacement heifer	36	3.62 (2.89)	3.00 (1.21–5.00)	0.50-10.00
Beef calf prior to weaning	38	6.30 (4.97)	5.00 (2.00–8.00)	0.50-20.00

n = Number of respondents.

Table 4.5 Annual treatment cost ($/sick calf) for pre-weaning BRD

Variable	***n***	**Mean (SD)**	**Median (IQR)**	**Range (Min, Max)**	**LS means***
Medicine cost	36	13.00 (7.41)	11.00 (6.00–16.50)	3.00–30.00	12.95^a
Labor cost	38	19.45 (18.12)	15.00 (8.00–20.00)	1.00–100.00	19.43^b

n = Number of respondents.
*Model adjusted for state and rancher as random effects; differing superscripts are significantly different at an α level of 0.05.

Table 4.6 Descriptive analysis of time spent on vaccination against BRD

Variable	***n***	**Mean (SD)**	**Median (IQR)**	**Range (Min, Max)**
Time spent on vaccination of dams				
Beef cow (minutes/head)	28	7 (6)	5 (3–10)	1–20
Beef replacement heifer (minutes/head)	39	6 (5)	5 (2.5–10)	0.5–20
Time spent on vaccination of dams, by activity				
Gathering (%)	26	38 (18)	40 (20–50)	10–75
Sorting (%)	25	20 (10)	20 (15–25)	2–40
Preparing (%)	26	12 (8)	10 (5–20)	0.75–30
Administering (%)	26	30 (18)	27.5 (18–40)	0.25–70
Time spent on vaccination of calves				
Beef calf prior to weaning (minutes/calf)	39	7 (6)	5 (2–10)	1–20
Time spent on vaccination of calves, by activity				
Gathering (%)	30	35 (18)	40 (20–50)	5–80
Sorting (%)	31	21 (9)	20 (15–30)	5–40
Preparing (%)	31	13 (7)	10 (10–20)	0.5–30
Administering (%)	30	32 (19)	30 (20–45)	0.5–70

n = Number of respondents.

Table 4.7 Descriptive analysis of time spent on treating pre-weaning BRD

Variable	***n***	**Mean (SD)**	**Median (IQR)**	**Range (Min, Max)**
Time for treatment pre-weaning BRD				
Beef calf prior to weaning (minutes/sick calf)	38	40 (45)	30 (15–40)	5–240
Time spent treating sick calves, by activity				
Gathering (%)	29	49 (27)	60 (25–70)	5–90
Sorting (%)	25	18 (11)	20 (10–25)	2–40
Preparing (%)	25	15 (15)	10 (7.5–15)	3–70
Administering (%)	26	18 (15)	10 (5–-30)	1–50

n = Number of respondents.

Discussion

To our knowledge, there are no estimates of current costs to prevent and treat BRD in beef calves prior to weaning in the US. This survey describes the costs incurred by beef cow-calf producers to prevent and treat BRD in pre-weaned calves in Nebraska, South Dakota, and North Dakota. The results we reported include: 1) prevention costs categorized by cows, replacement heifers, and calves prior to weaning; 2) costs to treat BRD in beef calves prior to weaning; 3) veterinary service costs; and 4) time spent on vaccination and treatment.

The annual per head cost to vaccinate calves against BRD was more than the cost per cow and per replacement heifer. One possible reason producers spent more money to vaccinate calves prior to weaning may be due to administration of booster doses of vaccines in calves compared to single annual vaccination of dams. More than 2/3 of the calves vaccinated against BRD are vaccinated two or more times from birth until the calves are sold from the cow-calf operation (USDA, 2010).

In the period of 1986-1989, the annual prevention costs of all respiratory system diseases which included diphtheria, pneumonia, and nonspecific respiratory tract infection were reported. In those studies, annual mean cost for vaccines or drugs to prevent respiratory system diseases ranged from \$0.81 to \$0.98 per cow in Colorado (Salman MD, 1991), Tennessee (New, 1991), and California (Hird et al., 1991); and the associated annual mean labor cost ranged from \$0.33 to \$0.46 per cow. These were average annual costs per cow based on the number of cows on each farm during the year. The costs in those studies were not categorized by cattle classification; therefore, some money may have been spent on other classes of cattle within the herd (i.e., calves or heifers). Accounting for Consumer Price Index rates of inflation (USDL-BLS, n.d.), these costs for vaccines or drugs to prevent respiratory disease were equal to $1.90 to $2.15 in 2016, and the associated labor costs were equivalent to $1.57 to $1.77. The estimates from our survey are greater for both annual cost for vaccines and labor cost for vaccination against BRD. The annual mean costs for vaccine for cows, replacement heifers, and pre-weaned calves were $2.99, $4.22, and $7.44 per head, respectively, and the associated annual mean labor cost were $5.39, $3.62, and $6.30 per head, respectively. Based on the comparison, prevention costs for BRD have increased during the past 30 years due to the increased costs of both vaccine products and labor.

Current literature reporting the cost to treat BRD in pre-weaned calves is limited. However, it may be that the treatment cost for BRD has increased, potentially driven by increased use of more expensive pharmaceuticals. One unpublished paper reported the treatment cost (not including labor) in beef calves prior to weaning from one large herd in 2000 to be $6.08 per sick calf (Dewell, Keen, Dewell, Laegreid, & Hungerford, 2002), equivalent to $8.47 in 2016 (USDL-BLS, n.d.). We estimated an annual median medicine cost of $11.00 per sick calf, with an additional $15.00 per sick calf spent on labor. In our survey, ranchers reported that labor, approximately $18/hour, was a large portion of the cost to prevent and treat BRD. Gathering and sorting cattle consumed the majority of the time spent on vaccination (60%) and treatment (80%).

The beef cow-calf producers we surveyed were from three states in a region of the US where income from calf sales are often the primary source of income for the ranch. These ranchers were selected for the survey because they had a history of pre-weaning BRD in their calves and were invited to participate in the survey by university extension veterinarians that were aware of the ranch health history. Therefore, there may be selection bias in our survey. For example, the prevention costs of BRD in beef calves and dams in the surveyed herds may be overestimated compared to herds without BRD problems because these producers may spend more money on preventive measures due to existing or previous problems. The ranchers surveyed may characterize a subset of cattle producers who more readily identify disease concerns and instigate prevention and treatment through more aggressive management. However, the results should represent the costs within herds with BRD problems from this region in the US. It is interesting to note that the ranchers in this survey reported widely varying costs of prevention and treatment. This variability may represent the diversity of the management systems represented in the survey. Because of the large variability in responses and the relatively small sample size, this survey may lack sufficient power to detect some important relationships.

We estimated the prevention and treatment costs of BRD in beef calves prior to weaning from ranchers who have experienced BRD problems in the past. The annual vaccination cost per pre-weaned calf was greater than the costs to vaccinate cows or replacement heifers. Labor cost for vaccination or treatment accounted for at least half of the total prevention or treatment costs. Most of the labor costs were due to time spent gathering and sorting cattle. It is important to realize the costs associated with labor as well as medication when designing BRD prevention and treatment plans because, in some circumstances, the plan may not be achievable because of the high cost or limited availability of labor or time.

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CHAPTER V

FACTORS AFFECTING THE NATIONAL MARKET PRICE OF BEEF FEEDER CATTLE IN THE UNITED STATES FROM 2006 TO 2015

Introduction

Beef cow-calf producers and cattle feeders know the importance of profiting from the cattle they purchase and sell. Many uncontrollable factors have been reported to affect the price of feeder cattle including drought (Burdine, 2011), grain and corn prices (Marsh, 1985), consumer demand due to the economy, or import/export rates (Lambert, McNulty, Grunewald, & Corah, 1989). But some factors, including muscle thickness, frame size, age, body weight, castration status, etc., are more manageable for producers. Understanding how these factors affect feeder prices may help them make management decisions and improve profitability. There have been reports of factors that affect calf selling price at markets within some states or regions of the US in various years (Barham & Troxel, 2007; Burdine, 2011; Lambert et al., 1989; Troxel & Barham, 2007). However, there is limited research reporting the factors affecting the national calf selling price over multiple years. Two studies reported the market price from multiple areas and years (King et al., 2006; Seeger, King, Grotelueschen, Rogers, & Stokka, 2011). Data used in those studies were collected from a livestock video auction service which may not represent the true national feeder cattle price. Additionally, no interactions between factors were considered in the analysis. Therefore, the objective of this study was to identify factors affecting the US national market price of beef feeder cattle.

Materials and methods

Data

Two datasets were collected and analyzed. The first was the weekly weighted average market price reports for feeder bulls, steers, and heifers weighing 90.7 kg or more from January 2006 to December 2015, collected from the USDA Agricultural Marketing Service website (USDA, 2006-2015). The second dataset was the annual US beef cow inventory from 2007 to 2016 obtained from USDA Economics, Statistics, and Market Information System National Agricultural Statistics Service website (USDA, 2008-2017).

Information collected for each auction market price report included the auction market location, date the price was reported, number of cattle within a weight category sold at that market on that day, sex (bulls, steers, or heifers), frame size (1 = small, 1 2 = small and medium, 2 = medium, 2 3 = medium and large, 3 = large), muscle score (1 = heavily muscled, 1 2 = heavily and medium, 2 = medium muscled, 2 3 = medium and lightly, 3 = lightly muscled), the range of each weight category, weighted average body weight, and the weekly weighted average price per 45.4 kg within a weight category sold at that market. Frame and muscle scores were based on the US standards for grades of feeder cattle (USDA, 2000). The week reported was categorized into seasons, spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, February). There were 28 states included in the original dataset and were categorized into 4 geographic regions according to USDA survey regions (USDA, 2008, 2011). These regions were Central (Iowa, Illinois, Kansas, Minnesota, Missouri, North Dakota, Nebraska, South Dakota, Wisconsin), East (Alabama, Arkansas, Florida, Georgia, Kentucky, North Carolina, South Carolina, Tennessee, Virginia), South Central (Oklahoma, Texas), and West (Arizona, California, Colorado, Montana, New Mexico, Oregon, Washington, Wyoming). Data were removed if the lowest value of the weight category was > 317.5 kg, the comments included "price per head", "replacement", or "yearling", location information was missing, states with less than 5 years of data, or if the average price per 45.4 kg was < $50 or > $500.

Methods

Statistical procedures

A commercial statistical software, SAS for Windows 9.4 (SAS Institute, Inc., Cary, NC, USA), was used for all statistical analyses. Descriptive statistics of continuous data were analyzed by PROC UNIVARIATE. The descriptive summary of average price by sex, weight category, frame size, muscle score, year, and location of auction market were determined by PROC MEANS. The proportions for categorical variables and their paired interactions were described using PROC FREQ. Three regression analysis models were developed:

Model 1: To test the effect of the beef cow inventory on the average national feeder cattle price, a quadratic regression model was fit for the annual average prices during 2006 to 2015 using PROC REG. Because the USDA January inventory each year was the number of cows and heifers that have calved in the previous year, the beef cow inventory one year after the feeder cattle price and its quadratic variable were included as fixed effects.

Model 2: To test factors associated with the market price of beef feeder cattle, a linear mixed regression model was developed by PROC MIXED. The fixed variables included in the model were: the number of cattle within a weight category sold at that market that day, weight, sex, frame size, muscle score, region, season, the beef cow inventory one year after the feeder cattle price and its quadratic, and the interactions of sex and weight, and frame size and muscle score. Market location and year were included as random effects.

Model 3: To determine the average price for each market at each year and the ten-year average price for each market for a hotspot analysis, separate linear models were fit using PROC MIXED. The fixed variables included in the model were the number of cattle within a weight category sold at that market that day, weight, sex, frame size, muscle score, and season.

For all models, a manual backward elimination process was used to obtain final models. Differences in least squares (LS) means were determined for outcomes with significant effects, and LS means ± standard error were reported. To account for the effect of multiple comparisons, the simulate adjustment was used to test for differences in LS means. An alpha level of 0.05 was used to determine statistical significance for all methods and model fit was assessed using AIC and BIC statistics or R-squared (R^2) (Xu, 2003) to ensure appropriate model selection.

Hotspot analysis

A hotspot analysis is a spatial clustering method which was used to identify statistically significant hot spots and cold spots using the Getis-Ord G_i^* statistic (McEntee & Ogneva-Himmelberger, 2008; Verter & Kara, 2001). The hotspot analysis tool in

ArcGIS Desktop 10.4.1 (ESRI, Inc., Redlands, CA, USA) was used to calculated Z-score and *P*-value of G_i^* to show the market clusters with significant high or low market prices. Separate hotspot analyses were performed at the county level for the adjusted average prices in 2006, 2009, 2012 and 2015 and the overall ten-year (2006 to 2015) adjusted average beef feeder cattle prices. A fixed distance band was used for the spatial conceptualization and Euclidean distance was used for the distance method option. Values above or below the 95% confidence interval (z-scores ≥ 1.96 or ≤ -1.96) were used to determine significantly hot (high price) and cold (low price) spots, respectively (Bhunia, Kesari, Chatterjee, Kumar, & Das, 2013; McEntee & Ogneva-Himmelberger, 2008).

Results

The final dataset used for analyzing the factors associated with market price of beef feeder cattle included 3,047,750 price reports representing 56,397,589 head of feeder cattle from 313 auction markets in 24 states. The data filter process is shown in Figure 5.1. The number of reports and number of cattle sold in the final dataset, as well as the average feeder cattle price during 2006 to 2015 are summarized in Table 5.1.

Results of model 1

The annual average market price paid for beef feeder calves from 2006 to 2015 was associated with the previous year's beef cow inventory (Figure 5.2). The R^2 of the final model equaled 0.83; therefore, approximately 83% of the variability of the average market price can be explained by the beef cow inventory one year after the feeder price and its quadratic.

Results of model 2

In the final model to test the effects of variables on the price of feeder cattle, the number of cattle within a weight category sold at that market that day, weight, sex, frame size, muscle score, region, season, beef cow inventory one year prior to the feeder price and its quadratic, and the interactions of sex and weight, and frame and muscle were included (Table 5.3).

The number of cattle sold within a weight category at that market that day was associated ($P < 0.0001$) with price. The average price increased by \$0.05/45.4 kg ($P < 0.0001$) for every 10 head increase in the number of cattle sold at a given sale.

The interaction of sex and weight was associated with the beef feeder cattle price ($P < 0.0001$). For each 22.7 kg increase in live weight, the sale price per 45.4 kg decreased for bulls, steers, and heifers by \$7.93, \$6.22, and \$4.72, respectively. When body weight was less than 136 kg, bulls were higher priced than steers ($P \leq 0.0002$), and heifers yielded higher prices than bulls when body weight exceeded 295 kg ($P < 0.0001$) (Figure 5.3).

There was a significant interaction between frame and muscle scores on price ($P < 0.0001$). For all frame categories except small and medium, heavier muscled (1, and 1 2) cattle had a significantly higher average price than lighter muscled (2 3, and 3) cattle. For cattle with the same muscle score, medium and large framed cattle had a higher average price than small, small and medium, and medium framed cattle (Figure 5.4) ($P < 0.0001$).

Season was associated with feeder cattle price ($P < 0.0001$). Prices per 45.4 kg were significantly higher ($P < 0.0001$) in spring ($133.24) and summer ($132.79) compared to fall ($126.46) and winter ($126.34).

Region was also associated with feeder cattle price ($P < 0.0001$). The price per 45.4 kg in the West ($133.64) was not different ($P = 0.99$) from the price in the Central region ($133.27), but was significantly higher ($P \leq 0.05$) than the price in the South Central ($129.51) and the East ($122.41). There were significant differences in prices among the Central, the South Central, and the Eastern regions ($P \leq 0.012$).

Results of model 3 and spatial analysis

The adjusted beef feeder cattle market prices in each year from 2006 to 2015 and the ten-year average prices were used in a spatial analysis. Because 5 markets from 5 states did not represent a single, identifiable location, a total of 308 markets within 24 states were included in the spatial analysis. Figure 5.5 displays clustering of higher and lower prices of the adjusted beef feeder cattle in 2006, 2009, 2012, and 2015. In 2006 and 2009, the spatial analyses indicated very similar clustering patterns in market prices. During 2006 and 2009, the cold spots were located mainly within the Eastern region in States such as Kentucky, Virginia, Tennessee, North Carolina, South Carolina, and Georgia. The hot spots were located mainly in Texas and Oklahoma. However, in 2012 and 2015, many counties in Texas, which were hot spots in previous years, became cold spots.

Figure 5.6 shows the overall hotspot analysis of the average price over the 10-year period. The results indicate that overall, Texas markets had lower prices whereas, the markets in North Dakota, South Dakota, and Nebraska had clusters of higher prices.

Table 5.1 Weekly weighted average market price report and feeder cattle sold in final dataset during 2006 - 2015

Year	No. of market reports*	No. of cattle sold involved, head*	Average market price, $/45.4 kg
2006	327,944	5,194,053	116.27
2007	332,050	4,993,712	107.99
2008	324,172	4,852,356	97.77
2009	339,513	6,627,523	93.29
2010	348,595	6,869,622	107.56
2011	306,313	6,158,618	129.83
2012	259,938	5,755,996	151.72
2013	241,468	5,195,210	149.40
2014	283,027	5,467,368	222.90
2015	284,730	5,283,131	228.21

*Total of 3,047,750 price reports representing 56,397,589 head of feeder cattle were included for the analysis.

Table 5.2 Final model of market price associated with beef cow inventory

Effect	Estimate	SE	*P*-value
Intercept	12770	4665.454	0.029
One year earlier beef cow inventory of market price	-0.0008	0.0003	0.035
Square of the one year earlier beef cow inventory	1.230E-11	4.859E-12	0.039

The unit of market price was $/45.4 kg and the unit of beef cow inventory was head.

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Table 5.3 Final model to test factors associated with the feeder cattle price

Effect	**Estimate**	**SE**	**df**	***P*-value**
Intercept	177.95	1466.64	8	<.0001***
Number of cattle within a weight category, head	0.005	0.0002	3.00E+06	<.0001***
Weight, 0.454kg	-0.12	0.0002	3.00E+06	<.0001***
Sex			3.00E+06	<.0001***
Bulls	10.57	0.154	3.00E+06	<.0001***
Heifers	-30.14	0.102	3.00E+06	<.0001***
Steers	0	–	–	–
Region			3.00E+06	<.0001***
Central	-0.37	1.437	3.00E+06	0.797
Eastern	-11.22	1.359	3.00E+06	<.0001***
South Central	-4.12	1.627	3.00E+06	0.011*
West	0	–	–	–
Frame			3.00E+06	<.0007***
Large	-1.69	0.500	3.00E+06	<.0001***
Medium and large	-1.99	0.396	3.00E+06	<.0001***
Medium	23.23	0.267	3.00E+06	0.001***
Small and medium	17.42	0.397	3.00E+06	<.0001***
Small	0	–	–	–
Muscle			3.00E+06	<.0001***
Heavily	22.15	0.325	3.00E+06	<.0001***
Heavily and medium	20.33	0.276	3.00E+06	<.0001***
Medium	9.00	0.474	3.00E+06	<.0001***
Medium and lightly	3.05	2.297	3.00E+06	0.184
Lightly	0	–	–	–
Season			3.00E+06	<.0001***
Spring	6.90	0.032	3.00E+06	<.0001***
Summer	6.45	0.034	3.00E+06	<.0001***
Fall	0.12	0.032	3.00E+06	<.0001***
Winter	0	–	–	–
Frame × Muscle			3.00E+06	<.0001***
Large × Heavily	13.07	0.546	3.00E+06	<.0001***
Large × Heavily and medium	11.21	0.537	3.00E+06	<.0001***

Table 5.3 (continued)

Effect	**Estimate**	**SE**	**df**	***P*-value**
large × Medium	17.98	0.659	3.00E+06	<.0001***
large × Medium and lightly	2.82	2.506	3.00E+06	0.260
large × Lightly	0	–	–	–
Medium and large × Heavily	-1.49	0.327	3.00E+06	<.0001***
Medium and large × Heavily and medium	-4.97	0.280	3.00E+06	<.0001***
Medium and large × Medium	0.99	0.476	3.00E+06	0.038*
Medium and large × Medium and lightly	-4.16	2.298	3.00E+06	0.070
Medium and large × Lightly	0	–	–	–
Medium × Heavily	12.48	0.478	3.00E+06	<.0001***
Medium × Heavily and medium	9.88	0.434	3.00E+06	<.0001***
Medium × Medium	14.29	0.568	3.00E+06	<.0001***
Medium × Medium and lightly	16.89	2.376	3.00E+06	<.0001***
Medium × Lightly	0	–	–	–
Small and medium × Heavily	-14.98	0.469	3.00E+06	<.0001***
Small and medium × Heavily and medium	-16.57	0.461	3.00E+06	<.0001***
Small and medium × Medium	-1.80	0.570	3.00E+06	0.0016***
Small and medium × Medium and lightly	-8.72	2.422	3.00E+06	0.0003***
Small and medium × Lightly	0	–	–	–
Small × Heavily	0	–	–	–
Small × Heavily and medium	0	–	–	–
Small × Medium	0	–	–	–
Small × Medium and lightly	0	–	–	–
Small × Lightly	0	–	–	–
Sex × Weight			3.00E+06	<.0001***
Bulls	-0.03	0.0003	3.00E+06	<.0001***
Heifers	0.03	0.0002	3.00E+06	<.0001***
Steers	0	–	–	–

Market and year were included as random effects.
*$P < 0.05$; **$P < 0.01$; ***$P < 0.005$.

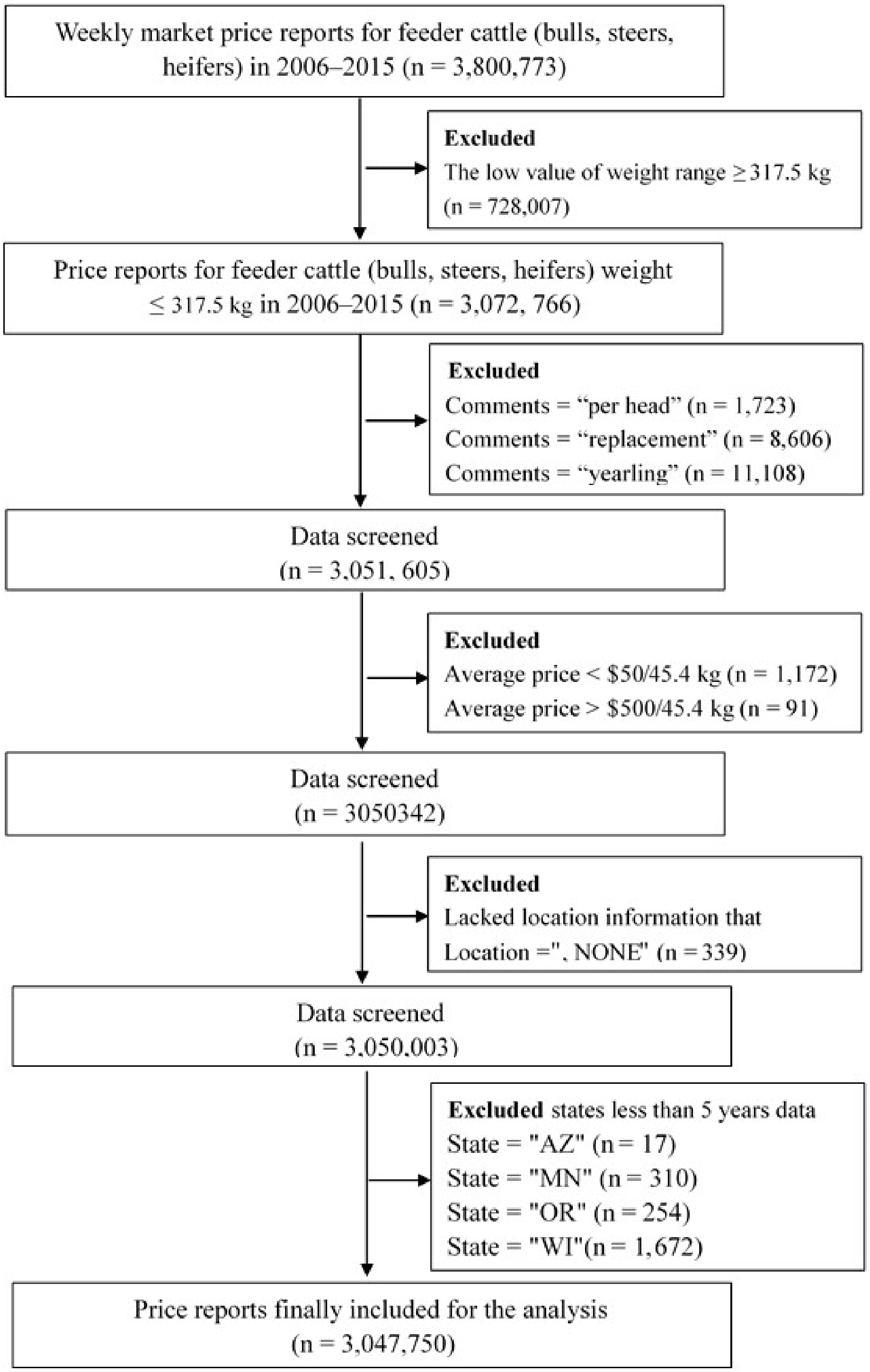

Figure 5.1 Flow chart for the market price data filter process

Data were collected from USDA Agricultural Marketing Service website.

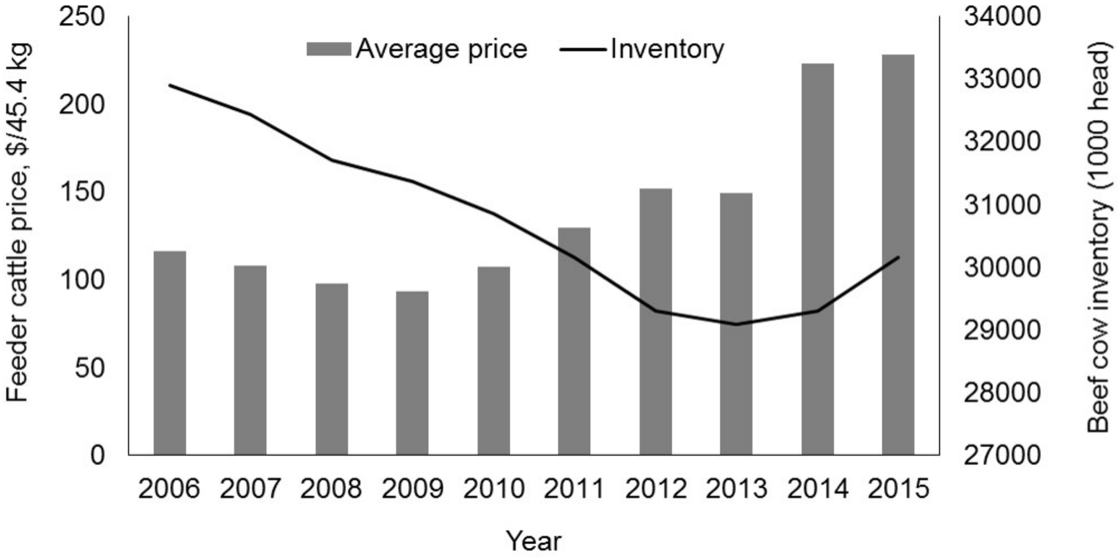

Figure 5.2 Average beef feeder cattle price and US beef cow inventory

Updated beef cow inventory in January 2007 - 2016 released in January 2018 - 2017 by USDA was adjusted to correspond to feeder cattle market price year during 2006 - 2015 when calves were born (e.g. Year = 2006 corresponds to the beef cow inventory in January 2007 released in January 2008 by USDA).

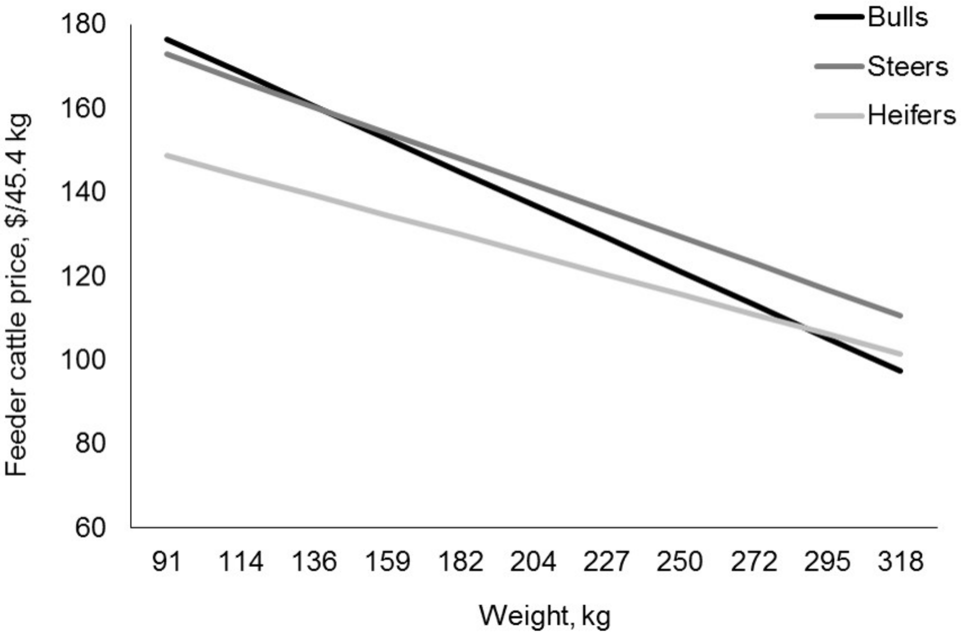

Figure 5.3 Effect of sex and weight on beef feeder cattle price

Effect of sex ($P < 0.0001$), weight ($P < 0.0001$), sex × weight ($P < 0.0001$).

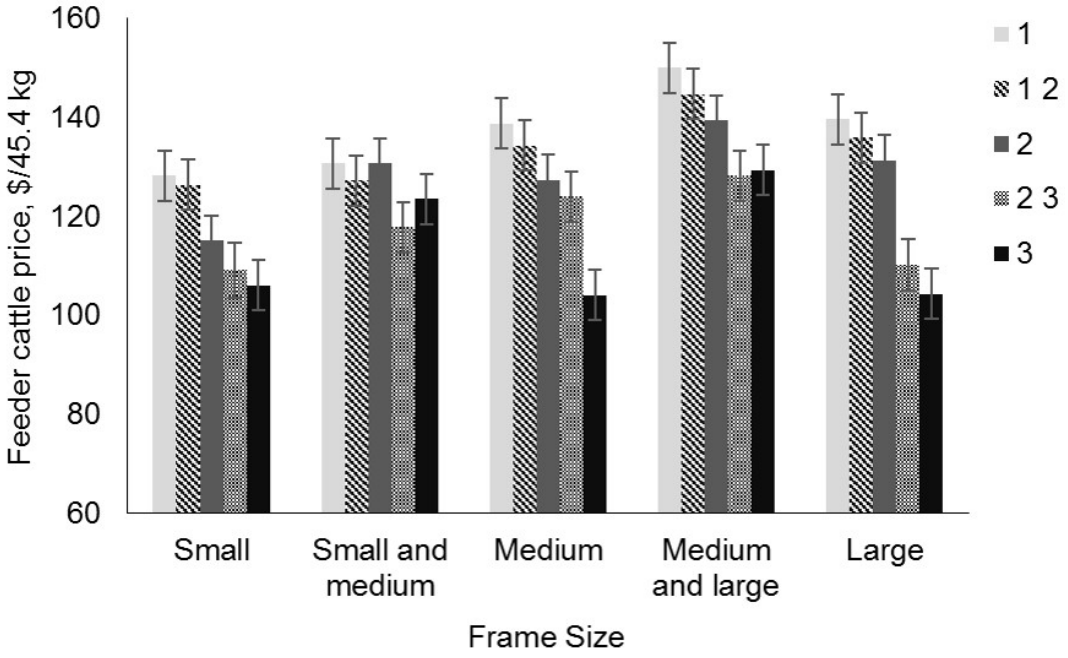

Figure 5.4 Effect of frame size and muscle score on beef feeder cattle price

Effect of frame size ($P < 0.0001$), muscle score ($P < 0.0001$), frame size × muscle score ($P < 0.0001$). 1 =heavily muscled, 1 2 = heavily and medium, 2 = medium muscled, 2 3 = medium and lightly, 3 = lightly muscled.

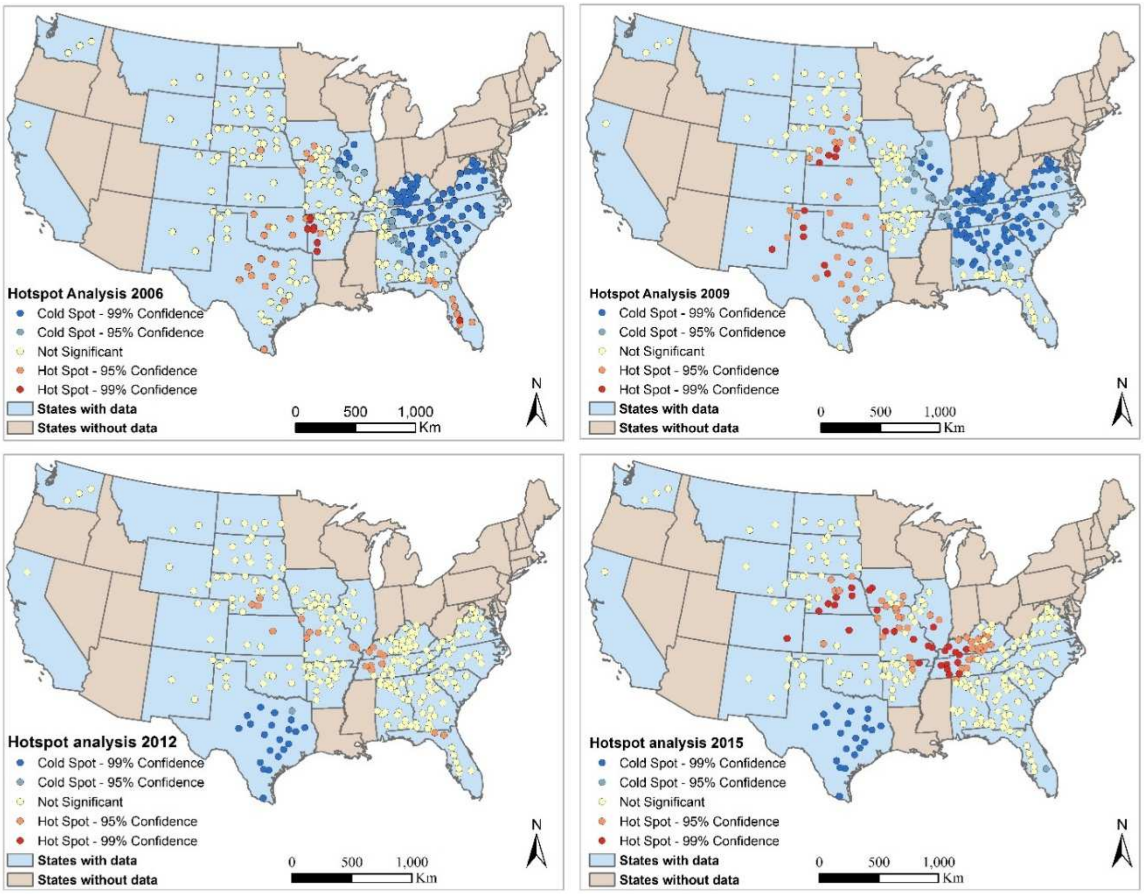

Figure 5.5 Hotspot analyses of US average annual feeder cattle price in 2006, 2009, 2012, and 2015

Clusters of cold spots and hot spots were used to determine significantly low price and high price markets, respectively.

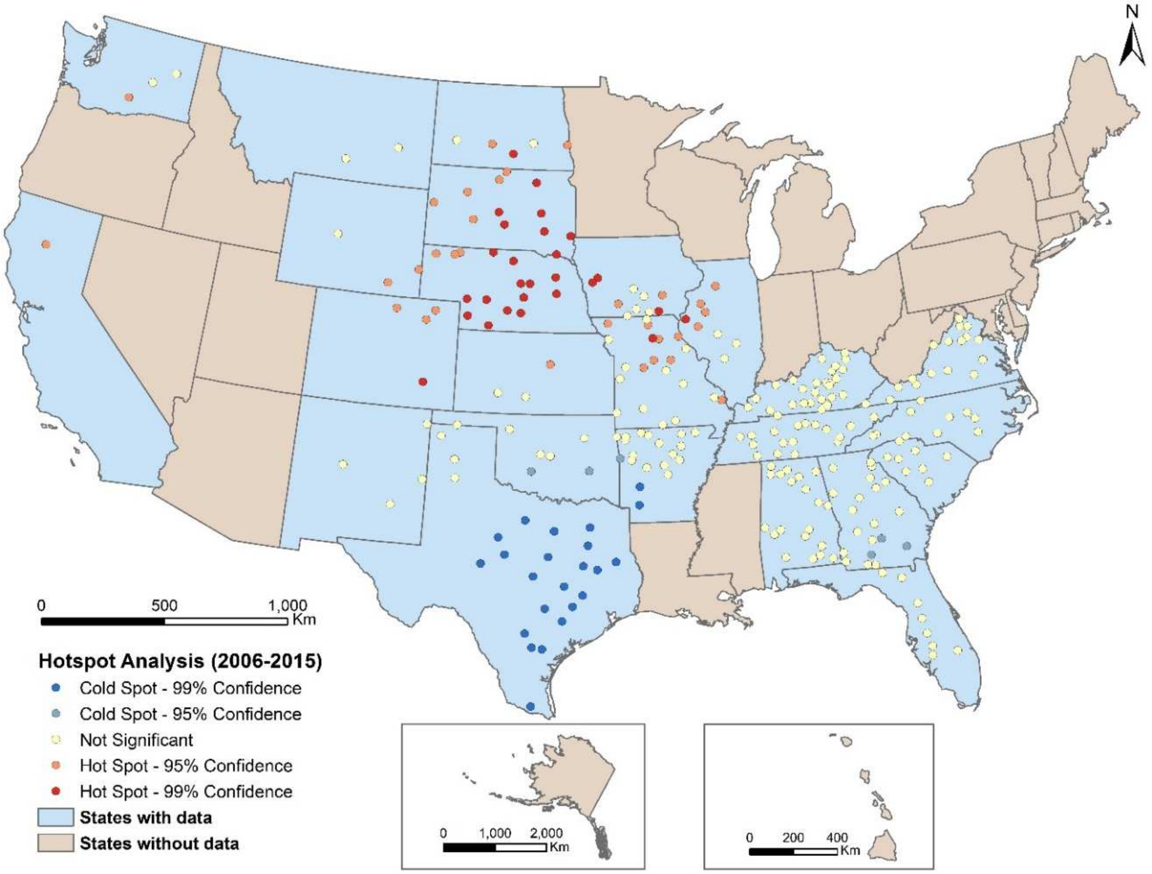

Figure 5.6 Hotspot analysis of US average feeder cattle price from 2006 to 2015

Clusters of cold spots and hot spots were used to determine significantly low price and high price markets, respectively.

Discussion

This study reported the factors affecting the market price of feeder cattle from 2006 to 2015. Factors that were significantly associated with the price were one year earlier beef cow inventory, number of cattle sold within a weight category sold at that market that day, the interaction of sex and weight, the interaction of frame and muscle, season, and region.

The US is the third largest beef-producing country in the world, following China and Brazil, and it represented 11% of the global beef production in 2012 (FAO, 2012). The beef cow inventory is the foundation of beef cattle production. The previous year's beef cow inventory was strongly associated with the current year's average feeder cattle price, which is likely reflecting a one-year marketing delay.

Some feeder cattle may weigh more than 317.5 kg at the time of marketing. However, we excluded market reports for cattle weighing 317.5 kg or more from model 2 and model 3 because those cattle are most likely yearling or replacement cattle. Papers have reported that beef feeder cattle prices decrease with increasing body weight, as well as the interaction of sex and weight (Barham & Troxel, 2007; Lambert et al., 1989). The inverse relationship between weight and price may be due to younger or lighter cattle's ability to grow faster than cattle that are approaching slaughter weight (King et al., 2006). The sex by weight interaction in our study indicated that the feeder price for bulls decreases more rapidly with increasing weight than steers and heifers. Steers usually yielded higher prices than bulls, and bulls more than heifers. At lower body weights, bulls were higher priced than steers; however, heifers and steers yielded higher prices than bulls when body weight exceeded 295 kg. This result was similar with a prior report

(Barham & Troxel, 2007), but cattle < 136 kg were not included in that study. The rate of decreasing bull prices may be due to the increased risk of weight loss associated with castration of heavier bull calves. Our results indicated that producers may get higher prices from bull calves if they are either marketed early as bulls at light weights or are castrated early and marketed as steers at heavier weights.

The muscle by frame interaction indicated that heavier muscled and medium and large framed cattle can yield the highest prices compared to all others. Other papers also reported that larger frame cattle were not preferred by feedlot operators and packers, which may be due to decreased uniformity compared to the average carcass size preferred in traditional meat packing (Lambert et al., 1989). The small and medium frame and light muscled cattle had higher prices. We speculate that this category of cattle has a higher value because it includes roping steers and calves with potential for compensatory gains. Large frame and light muscled cattle were associated with lower prices compared to others, which could represent Holstein breed-influenced cattle.

Seasonal variation is important to consider when marketing cattle, and several papers have reported seasonal effects on price (Barham & Troxel, 2007; Burdine, 2011; Schroeder, Mintert, Brazle, & Grunewald, 1988; Turner, McKissick, McCann, & Dykes, 1992). Our results showed spring and summer had higher prices than fall and winter in the US, and similar results were also observed in previous studies of prices in specific locations (Barham & Troxel, 2007; Burdine, 2011). This may be due to the supply and demand in the market, weather, and feed prices (Burdine, 2011; Coatney, Menkhaus, & Schmitz, 1996).

Traditional statistical analyses can indicate which regions in the US have significantly higher or lower prices than others. However, the spatial statistical analysis can show spatial patterns in high and low market prices. The patterns of cattle prices may not be the same within a region, or the adjacent locations in different regions may have similar price patterns. Our results showed that spatial patterns for average prices were different depending on the year. Clusters of higher or lower prices varied over time. We know that feeder cattle prices are also dependent upon many other factors, such as precipitation, grain and corn prices (Anderson & Trapp, 2000; Marsh, 1985), which also cluster in time and place. This may explain these changing patterns depending on the year.

This study identified the factors associated with the market price of beef feeder calves in the US and showed the spatial clustering patterns over several years. Understanding how these factors affect market prices may provide cattle producers with insight to work toward obtaining the best prices for their cattle.

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CHAPTER VI

THE COST OF BOVINE RESPIRATORY DISEASE IN US BEEF CALVES PRIOR TO WEANING, 2011 TO 2015

Introduction

Bovine respiratory disease (BRD) continues to be one of the leading causes of sickness and death in beef cattle and calves in the US (USDA, 2010a, 2011). The mean percentage (± standard deviation) of calves affected by BRD between birth to weaning was 3.0 ± 7.1% (Hanzlicek et al., 2013).The higher standard deviation of the mean percentage indicates that risk for BRD is highly variable and that some herds might not experience BRD, although others herds may experience high rates of BRD morbidity. In herds experiencing BRD problems, the average annual incidence of BRD in beef calves prior to weaning is more than 10% (Muggli-Cockett, Cundiff, & Gregory, 1992; Snowder, Van Vleck, Cundiff, & Bennett, 2005). BRD was responsible for 31 ± 4% of deaths among beef calves that died or were lost between 3 weeks of age to weaning, the leading category of death in this age group (USDA, 2010a).

The direct costs of BRD to the beef cow-calf industry include cattle deaths, expense of medicine and labor to treat affected calves, and decreased growth performance following recovery (Engelken, 1997). Over 33% of US cow-calf operations strongly agreed (13.4%) or agreed (20.5%) that BRD has a significant economic impact on their operations (USDA, 2010a). However, there have been few reports of the costs associated with the disease in the cow-calf segment of the beef industry (Dewell, Keen, Dewell, Laegreid, & Hungerford, 2002; Hird et al., 1991; New, 1991; Salman MD, 1991). Thirty years ago the annual costs to prevent and treat respiratory disease in beef cow-calf operations were estimated in three states (Hird et al., 1991; New, 1991; Salman MD, 1991). The treatment cost, weaning weight loss, and death loss due to BRD in beef calves prior to weaning from one large beef herd in 2000 was estimated to be $50.46 per case, although labor associated with BRD was not included (Dewell et al., 2002).

Risk analysis is a method for evaluating the probability and consequences (i.e., biological, social and/or economic) of events or actions, and it can be conducted through either qualitative or quantitative methods (Arthur et al., 2009; Vose, 2008). Quantitative risk analysis is conducted using deterministic or stochastic modeling. Deterministic risk analysis models produce single estimates which are determined by the single value of each input variable, and the amount of uncertainty or variation around the value is not considered (Fazil, 2005; Uusitalo, Lehikoinen, Helle, & Myrberg, 2015). Alternately, stochastic risk analysis models use probability distributions estimated from historical data or deduced from expert opinion to indicate uncertainty and variation in factors limiting the outcome (Albright, Winston, & Zappe, 2011; Lurie, Goldberg, & Robinson, 1993). Each estimated output is a range or statistical distribution which may provide decision-makers more information under uncertain situations (Fazil, 2005). Several stochastic models have been developed to study the cost of BRD in dairy cattle (Mohd Nor, Steeneveld, Mourits, & Hogeveen, 2012; van der Fels-Klerx, Sorensen, Jalvingh, & Huirne, 2001) and feedlot cattle on a specific farm or in another country (Buhman, Hungerford, & Smith, 2003; Theurer, White, Larson, & Schroeder, 2015). However, there are no similar models of the economic cost of BRD in US beef calves prior to weaning on a national basis.

Therefore, the objectives of this study were to stochastically model a partial budget analysis of the direct costs to the US beef cattle industry from BRD in beef calves prior to weaning, and to identify the factors that most strongly influence this cost.

Materials and methods

Model description

A stochastic partial budget analysis model was developed using Microsoft Excel (version 2013, Microsoft Corporation, Redmond, WA, US) and @risk (version 7.5, Palisade Corporation, Ithaca, NY, US) to estimate the costs of BRD in US beef calves prior to weaning. The model consisted of three parts: 1) the cost of BRD mortality; 2) the cost to treat BRD; and 3) the losses associated with decreased weaning weight due to BRD. Figure 6.1 shows a graphical representation of the model, with detailed information about model inputs, outputs, and notations described in Tables 6.1 and 6.2. The settings of the model were chosen to represent the entire US beef cow-calf system. The number of beef calves born in 2011 - 2015 was simulated according to the USDA beef cow inventory January 2012 - 2016 since the January inventory each year was the number of cows and heifers that have calved in the previous year (USDA, 2013, 2014, 2015, 2016, 2017a). The percent of cows that calved (USDA, 2009a) and percent of calves born alive (USDA, 2010b) were used to estimate the number of calves born alive each year. Although disease incidence is not static from year to year, particularly within a production unit, we assumed that BRD morbidity and mortality for the national herd remained constant within a defined level of uncertainty from 2011 to 2015, and that responses in the USDA Beef 2007 - 08 survey remained relevant.

Death losses due to BRD were estimated for: 1) deaths due to BRD in calves less than 3 weeks of age; and 2) deaths due to BRD in calves 3 weeks of age to weaning because the probability for calves to die from BRD were classified by those age groups in the USDA Beef 2007 - 08 survey. Of calves born alive but that died prior to weaning, 31.3%, 35.0%, and 33.7% died less than 24 hours, 1 day-3 weeks, and 3 weeks of age to weaning, respectively. For beef calves that died < 3 weeks of age and ≥ 3 weeks of age to weaning, 8.2 ± 1.4% and 31.4 ± 3.9% of deaths were due to BRD, respectively (USDA, 2010a). Regardless of the age at death, we assumed the economic value of calves was equal to the value the calf would have had at weaning as a 227-250 kg calf. Therefore, the cost of deaths due to BRD was estimated by multiplying the total number of calves that died due to BRD by the value of a weaned calf. This value was calculated by multiplying the average weaning weight of calves by the average annual price of 227-250 kg weaned calves in each of the years 2011-2015 (USDA, 2009b). We used this approach to approximate forgone revenue because cow-calf producers expect to market a weaned calf large enough to more than recover the fixed and variable costs associated with the raising the cow-calf pair. Most of these costs are incurred before the calf is born.

The estimated cost to treat BRD included the cost of labor and medicine to treat sick calves. We assumed all sick calves were treated. Therefore, the costs to treat BRD were calculated by multiplying the number of calves with BRD prior to weaning with the medicine cost per sick calf and labor cost spent on treatment per sick calf due to BRD including a factor of uncertainty.

The decrease in weaning weight from BRD morbidity was calculated by multiplying the number of calves that survived BRD to weaning by the average weight loss of 6.76 kg per calf attributed to BRD including a factor of uncertainty (Snowder et al., 2005). The number of calves that survived BRD prior to weaning was the number of calves that contracted pre-weaning BRD minus the number of calves that died due to BRD or died of some other cause prior to weaning.

Data sources

Information on model inputs, commands, distributions, and sources are summarized in Table 6.1. Inputs were obtained from USDA surveys (USDA, 2009a, 2009b, 2010a, 2010b) or reports (USDA, 2011-2015, 2013, 2014, 2015, 2016, 2017a), peer reviewed papers (Hanzlicek et al., 2013; Snowder et al., 2005), and a beef cow-calf producer survey (Wang et al., in Press). Morbidity and mortality data were from the USDA Beef 2007 - 08 survey (Hanzlicek et al., 2013; USDA, 2010a). Auction market data consisting of 189,747 weekly weighted market prices by weight range of 226.8–249.5 kg in feeder bulls, steers, and heifers from 2011 to 2015 were collected from USDA market news reports (USDA, 2011-2015). Because some market reports included per head sales or sales of post-weaned calves, data were removed if: the lowest value of the weight category was greater than 317.5 kg; the comments included “price per head”, “replacement”, or “yearling”; or if the average price per 45.4 kg was < $50 or > $500. The mean and standard error of the price were calculated from a total of 188,652 auction reports representing 4,805,690 head of feeder cattle using SAS (version 9.4, SAS Institute Inc., Cary, NC, US).

Most of the inputs in the model were obtained on the national level, but the treatment costs and decreased weight gain were not. The medicine cost and labor cost to treat BRD were estimated based on a survey of 43 beef cow-calf ranchers with a history of pre-weaning BRD in their calves (Wang et al., in Press). These estimates may be susceptible to selection bias because they came from a non-random subset of producers from a region of the US, however, these values represent the most recent estimate of these costs. Decreased weight gain due to BRD in pre-weaned calves has been reported previously, but with different values (Schneider, Tait, Ruble, Busby, & Reecy, 2010; Snowder et al., 2005; Wittum et al., 1994). We estimated the loss in weaning weight due to BRD using data from a study of 31,243 calves over a 20-year period (Snowder et al., 2005).

Table 6.1 Model inputs, commands, distributions, and sources

Input (unit)	**Notation**	**Command and distribution**	**Source**
Year	Year	RiskDiscrete ((2011,2012,2013,2014,2015), (0.2,0.2,0.2,0.2,0.2)*	–
US beef cow inventory in January 2012-2016 (head)	$N_{CowInventory}$	IF(Year=2011, 30157900, IF(Year=2012, 29297300, IF(Year=2013, 29085400, IF(Year=2014, 29302100, IF(Year=2015, 30165800)))))†	(USDA, 2013, 2014, 2015, 2016, 2017a)
Calving percentage	$P_{Calving}$	1-RiskLognorm (0.085,0.006)	(USDA, 2009a)
Percentage of calves born alive	$P_{CalfAlive}$	1-RiskLognorm (0.029,0.007)‡	(USDA, 2010b)
Percentage of calves born alive but died/lost before weaning	$P_{DeathPrewean}$	RiskLognorm (0.036,0.002)	(USDA, 2010a)
Random number	R_{Num}	RiskDiscrete ((1,2,3), (0.333,0.333,0.333))§	–
Of calves born alive but died prior to weaning, percentage of death in 24 hours	$P_{Death<24h}$	IF (RandNum=or (1,2), RiskLognorm (0.313,0.026),1-$P_{Death24h\text{-}3w}$ - $P_{Death\geq3w}$)§	(USDA, 2010a)
Of calves born alive but died prior to weaning, percentage of death 1day – 3 weeks	$P_{Death24h\text{-}3w}$	IF (RandNum =or (2,3), RiskLognorm (0.35,0.028),1-$P_{Death<24h}$ - $P_{Death\geq3w}$)§	(USDA, 2010a)
Of calves born alive but died prior to weaning, percentage of death $\geq$3 weeks of age to weaning	$P_{Death\geq3w}$	IF (RandNum =or (1,3), RiskLognorm (0.337,0.026),1-$P_{Death<24h}$ - $P_{Death24h\text{-}3w}$)§	(USDA, 2010a)
Of calves died/lost (from all causes), percentage of deaths due to BRD < 3 weeks	$P_{DeathBRD<3w}$	RiskLognorm (0.082,0.014)	(USDA, 2010a)
Of calves died/lost (from all causes), percentage of death due to BRD $\geq$3 weeks of age to weaning	$P_{DeathBRD\geq3w}$	RiskLognorm (0.314,0.039)	(USDA, 2010a)
Weaning weight of calves (kg/calf)	$W_{Weaning}$	RiskNormal (240.404,0.907)	(USDA, 2009b)

Table 6.1 (continued)

Input (unit)	**Notation**	**Command and distribution**	**Source**
Average price of 227-250 kg weaned calves in 2011-2015 ($/kg)	$C_{Calf/kg}$	IF(Year=2011, RiskNormal (2.79,0.0018), IF(Year=2012, RiskNormal (3.24,0.0024), IF(Year=2013, RiskNormal (3.21,0.0024), IF(Year=2014, RiskNormal (4.73,0.0040), IF(Year=2015, RiskNormal (4.81,0.0044))))))||	(USDA, 2011-2015)
BRD morbidity in beef calves prior to weaning (%)	$P_{MorbidityBRD}$	RiskLognorm (0.03,0.003373)	(Hanzlicek et al., 2013)
Medicine cost to treat BRD ($/sick calf)	$C_{Medine/sick}$	RiskNormal (13.00,1.24)¶	(Wang et al., in Press)
Labor cost to treat BRD ($/sick calf)	$C_{Labor/sick}$	RiskNormal (19.45,2.94)¶	(Wang et al., in Press)
Decreased weaning weight due to BRD (kg/sick calf)	$W_{LossBRD}$	RiskNormal (6.76,1.02)#	(Snowder et al., 2005)

*Random generation of year triggers specific simulations in $N_{CowInventor}$ and $C_{Calf/kg}$.

†Updated beef cow inventory in January 2012 - 2016 released in January 2013 - 2017 by USDA was adjusted to correspond to model year during 2011 - 2015 when calves were born (e.g. Year = 2011 corresponds to the beef cow inventory in January 2012 released in January 2013 by USDA).

‡The mean value used in the distribution was from the USDA report, while the standard error was calculated by the author from available data.

§The sum of $P_{Death<24h}$, $P_{Death24h\text{-}3w}$, and $P_{Death\geq 3w}$ should be 100%. A random number was generated to control which two variables would be simulated in each iteration, with the remaining variable calculated.

||The randomly generated year determined simulated price of weaning calves calculated using a statistical software[d] based on the auction market reports from the USDA.

¶The mean and standard error were used to estimate the national costs.

#The mean value was obtained from Snowder et al., 2005, while the standard error was from the simulated data based on the paper.

Table 6.2 Model calculations of intermediate and main outputs

Output (unit)	**Notation**	**Calculation**
Intermediate outputs		
Number of calves born (head)	$N_{CalfBorn}$	$N_{CowInventory} \times P_{Calving}$
Number of calves born alive (head)	$N_{CalfAlive}$	$N_{CalfBorn} \times P_{CalfAlive}$
Number of calves born alive but died/lost before weaning (head)	$N_{DeathPrewean}$	$N_{CalfAlive} \times P_{DeathPrewean}$
Number of calves born alive but died < 24 hours (head)	$N_{Death<24h}$	$N_{DeathPrewean} \times P_{Death<24h}$
Number of calves born alive but died in 1 day and less than 3 weeks (head)	$N_{Death24h\text{-}3w}$	$N_{DeathPrewean} \times P_{Death24h\text{-}3w}$
Number of calves born alive but died ≥ 3 weeks of age to weaning (head)	$N_{Death\geq 3w}$	$N_{DeathPreweaning} \times P_{Death\geq 3w}$
Number of calves that died due to BRD less than 3 weeks (head)	$N_{DeathBRD<3w}$	$(N_{Death<24h} + N_{Death24h\text{-}3w}) \times P_{DeathBRD<3w}$
Number of calves that died due to BRD ≥ 3 weeks of age to weaning (head)	$N_{DeathBRD\geq 3w}$	$N_{Death\geq 3w} \times P_{DeathBRD\geq 3w}$
Of calved died/lost (from all causes), percentage of deaths not due to BRD	$P_{DeathOther}$	$1- (P_{Death<24h} + P_{Death24h\text{-}3w}) \times P_{DeathBRD<3w} - P_{Death\geq 3w} \times P_{DeathBRD\geq 3w}$
Value of per weaning calf ($)	V_{Calf}	$W_{Weaning} \times C_{Calf/kg}$
Number of calves that got BRD prior to weaning (head)	N_{BRD}	$N_{CalfAlive} \times P_{MorbidityBRD}$
Number of calves that got BRD and recovered (head)	$N_{BRDRecover}$	$N_{BRD} - N_{DeathBRD<3w} - N_{DeathBRD\geq 3w}$
Number of calves that got BRD and survived to weaning (head)	$N_{BRDSurvWean}$	$N_{BRDRecover} \times (1- P_{DeathPrewean} \times P_{DeathOther})$
Main Outputs		
Death loss due to BRD less than 3 weeks (head)	$C_{DeathBRD<3w}$	$N_{DeathBRD<3w} \times V_{calf}$
Death loss due to BRD ≥ 3 weeks of age to weaning (head)	$C_{DeathBRD\geq 3w}$	$N_{DeathBRD\geq 3w} \times V_{calf}$
Cost of BRD mortality ($)	$C_{MortalityBRD}$	$C_{DeathBRD<3w} + C_{DeathBRD\geq 3w}$

Table 6.2 (continued)

Output (unit)	**Notation**	**Calculation**
Cost for medicine to treat pre-weaning BRD ($)	$C_{MedineBRD}$	$N_{BRD} \times C_{Medicine/sick}$
Cost for labor to treat pre-weaning BRD ($)	$C_{LaborBRD}$	$N_{BRD} \times C_{Labor/sick}$
Cost to treat pre-weaning BRD ($)	$C_{TreatBRD}$	$C_{MedineBRD} + C_{LaborBRD}$
Cost of lost weaning weight from BRD ($)	$C_{LossWtBRD}$	$N_{BRDSurvWean} \times W_{LossBRD} \times C_{Calf/kg}$
Total cost of BRD in beef calves prior to weaning ($)	$C_{TotalCostBRD}$	$C_{MortalityBRD} + C_{TreatBRD} + C_{LossWtBRD}$

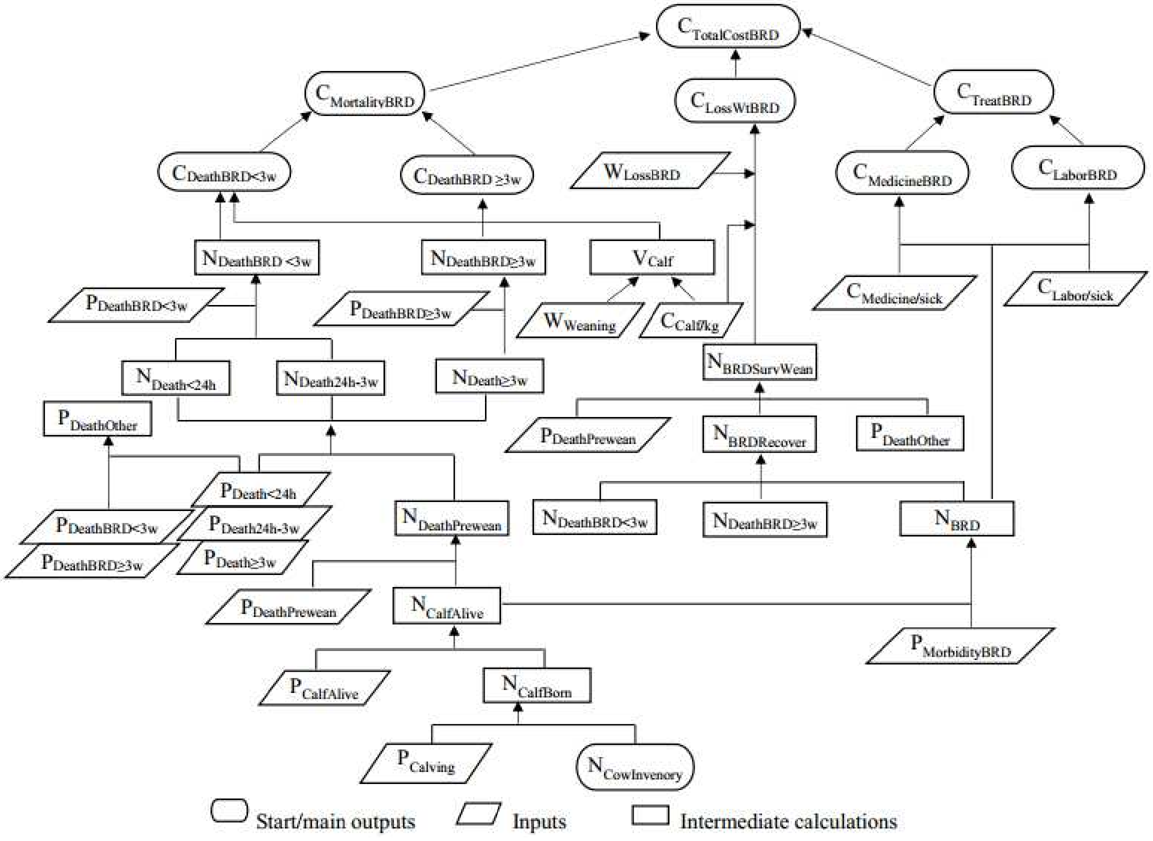

Figure 6.1 Framework of the model to estimate the cost of BRD in US beef calves prior to weaning

C = Cost, N=Number, P = Probability, V=Value, W=Weight

Model simulation

Simulations accounted for either uncertainty or variability in model inputs. The parametric distributions used for input variables included normal, lognormal, and discrete. The normal distribution was used when variables were normally distributed and included two parameters: mean and standard error. For distributions that could not have negative values, lognormal distributions were used, described by two parameters: mean and the standard error of log. Discrete distributions were described by two parameters: possible values and their corresponding probabilities (Palisade-Corporation, 2016).

Each iteration of the simulation began by randomly generating the year to trigger the simulation of beef cow inventory and market price. The values for each input variable were randomly generated simultaneously according to their respective probability distribution. The outcomes of each iteration were varied, and the overall results were updated based on each iteration. Using 10,000 iterations, the probability distributions of outputs were calculated and medians with upper and lower 90% confidence interval (CI) were reported.

Calves born alive but which died prior to weaning were grouped by the percent of death within 24 hours of birth, between 1 day to 3 weeks of birth, and 3 weeks of age to weaning, with components totaling 100% (USDA, 2010a). A discrete distribution was used to generate a random number to trigger the simulation of these three inputs at equal probability. In each iteration, only two of three were simulated based on their distribution, with the remaining value determined according to the two simulated inputs subtracted from 100%.

Convergence tolerance was set at 1% (with 95% CI) and tests were performed to estimate the median values of costs associated with BRD. Latin hypercube sampling with 10,000 iterations was conducted to meet the convergence criteria (i.e., the change in the median of main outputs will converge at 1.0% or less). These outputs included mortality costs (death < 3 weeks and death ≥ 3 weeks of age to weaning), treatment costs (medicine cost and associated labor cost), and the weaning weight loss due to BRD.

Sensitivity analysis

To identify the most influential factors and quantitatively evaluate the effects of inputs on the economic cost of BRD in beef calves prior to weaning, global and local sensitivity analysis methods were performed. Global sensitivity analysis was conducted to investigate the effect of changes to all input variables simultaneously by calculating Spearman rank correlation coefficients. Local sensitivity analysis was used to assess how uncertainty in one factor influenced the model output when the other factors kept their expected values (Campolongo, Saltelli, & Cariboni, 2011). Six variables associated with BRD mortality, morbidity, treatment, and loss of weaning weight were included. A tornado graph was created to show the percent change in the median of total cost of pre-weaning BRD as each input varied from -1 SD to + 1 SD of the median of its distribution.

Results

Economic costs

We estimated the total direct economic cost of BRD in beef calves prior to weaning between 2011 and 2015 to be $165 million with a 90% CI of $129–246 million (Figure 6.2).

The distribution of the 10,000-trial simulation was bimodal with one peak around $140 to 170 million and another around $210 to $230 million. Feeder cattle prices also followed a bimodal distribution between 2011 and 2015. The bimodal distribution of the value of calves explains the bimodal distribution in the sum direct costs of BRD (Figure 6.3). The average price for 227–250 kg feeder calves per kg varied from $2.79 to $3.24 between 2011 and 2013 and then averaged $4.73 in 2014 and $4.81 in 2015.

A summary of the costs of BRD are provided in Table 6.3, including mortality cost, treatment cost, and losses from lost weaning weight, as well as costs per cow due to BRD.

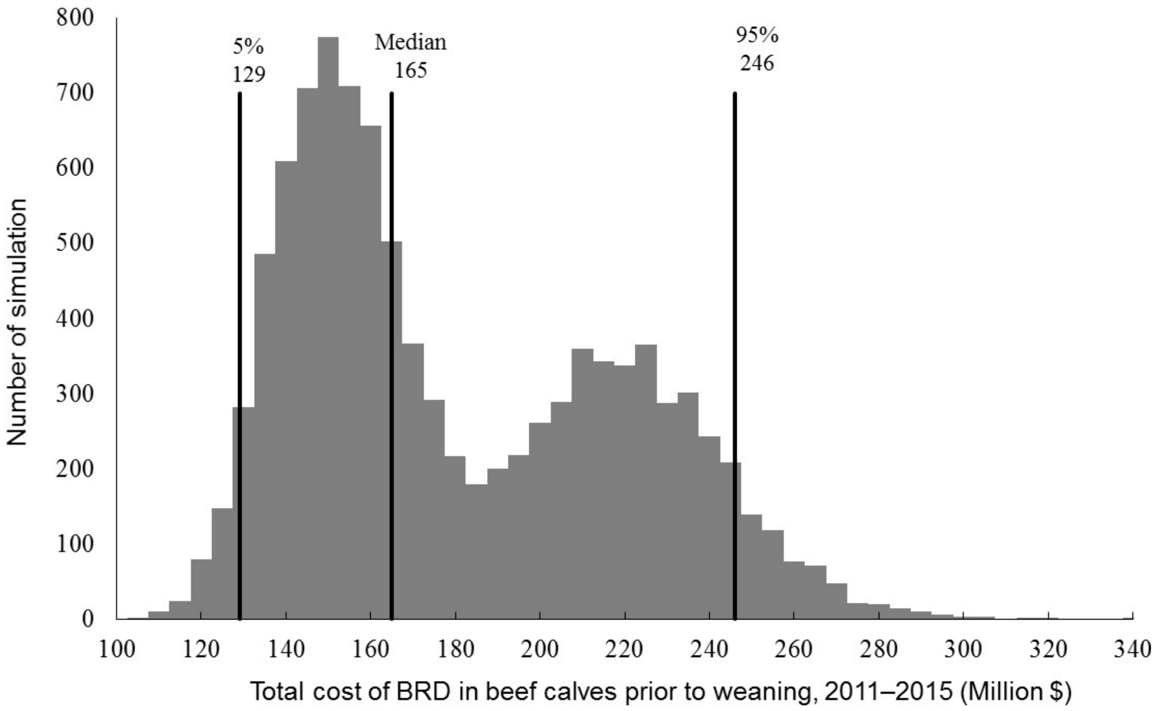

Figure 6.2 Distribution of the total cost of BRD in beef calves prior to weaning by 10,000-trial Monte Carlo simulation

The median of the total cost of pre-weaning BRD in the US was $165 million, and there is 90% probability that the interval of $129–246 million contains the true value.

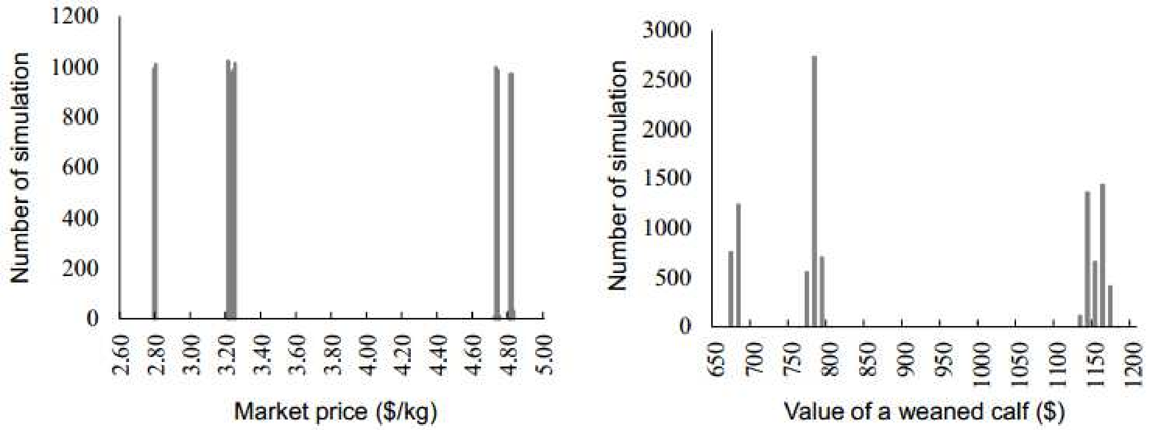

Figure 6.3 Distribution of market price and value of a weaned calf

Table 6.3 Model outputs: costs of calves prior to weaning due to BRD in the US, 2011-2015

Outputs	**Median (5%–95% CI)**	
	National cost (Million $)*	**Cost/cow ($)†**
Cost of BRD mortality ($C_{MortalityBRD}$)	126 (92–200)	4.30 (3.08–6.70)
Death loss due to BRD less than 3 weeks ($C_{DeathBRD<3w}$)	44 (29–72)	1.48 (0.96–2.42)
Death loss due to BRD ≥3 weeks of age to weaning ($C_{DeathBRD\geq3w}$)	84 (57–138)	2.87 (1.93–4.65)
Cost to treat pre-weaning BRD ($C_{TreatBRD}$)	25 (20–32)	0.86 (0.67–1.09)
Cost for medicine to treat pre-weaning BRD ($C_{MedineBRD}$)	10 (8–13)	0.34 (0.27–0.43)
Cost for labor to treat pre-weaning BRD ($C_{LaborBRD}$)	15 (11–20)	0.51 (0.37–0.69)
Losses from lost weaning weight from BRD ($C_{LossWtBRD}$)	15 (9–25)	0.50 (0.31–0.83)
Sum cost of BRD in beef calves prior to weaning ($C_{TotalCostBRD}$)	165 (129–246)	5.63 (4.33–8.26)

* National cost is each type of cost due to BRD per year.

† Cost/cow is the cost per cow due to BRD per year and is calculated by each type of cost divided by US beef cow inventory per year.

Sensitivity analysis

Year was the factor that had the greatest impact on the costs of BRD (Spearman rank order correlation coefficient = 0.80). Of the six variables directly associated with BRD, calves that died due to BRD 3 weeks of age to weaning was the most influential factor. A 10% increase in deaths due to BRD in calves 3 weeks of age to weaning, (e.g. from 31.4% to 34.5%), resulted in a 4.9% increase in the median of cost of BRD (Figure 6.4).

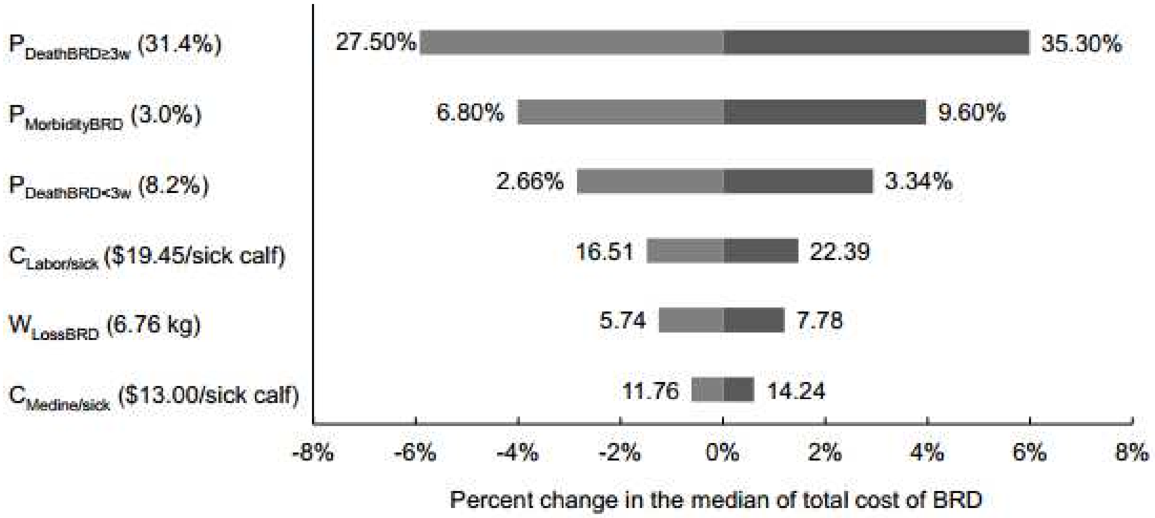

Figure 6.4 Tornado graph showing the one-way sensitivity analysis of six variables associated with the cost of BRD

Each bar represents the effect on the median of total cost of BRD as each input ± 1 SD of the median of its distribution, while other input variables kept their expected distributions. The percent change in the median total cost of BRD for each variable is the change corresponding to its variation compared to its base case result divided by the base result. $P_{DeathBRD<3w}$ and $P_{DeathBRD\geq3w}$ are the percentages of deaths due to BRD < 3 weeks and death due to BRD ≥ 3 weeks of age to weaning, respectively, of all calves died/lost (from all causes). $P_{MorbidityBRD}$ is BRD morbidity in beef calves prior to weaning. $C_{Medine/sick}$ and $C_{Labor/sick}$ are medicine cost and associated labor cost to treat BRD per sick calf, respectively. $W_{LossBRD}$ is decreased weaning weight due to BRD per sick calf.

Discussion

The primary objective of this study was to estimate the cost of BRD in beef calves prior to weaning to the US beef cattle industry. A simulation of a partial budget was used to estimate the cost of BRD due to treatment, production losses, and death. Vaccination costs were not included in the model because these are considered investments in BRD prevention rather than a direct cost of the disease.

Based on our results, the cost of BRD was $5.63 for every cow in the US each year during 2011 - 2015. Because these costs are borne by the approximately 20% of producers that experience BRD in their cow-calf herd annually (Woolums et al., 2013), this approximates a cost of $28 per cow in affected herds. The median total gross and net profit for the beef cow-calf industry in the US per cow per year during 2011 - 2015 was about $729 and $108, respectively (USDA, 2017b). Although the cost of BRD is a small part of the industry total gross per cow, BRD in calves prior to weaning might have a meaningful effect on the profitability within affected herds.

Based on the global sensitivity analysis, year was the most important input. It principally influences the direct costs of BRD because both cow-calf inventory and market price were determined by year. After considering the effect of year, BRD mortality and morbidity were the factors most influencing the costs of BRD. These highly influential inputs on the total cost were obtained from reliable national estimates (Hanzlicek et al., 2013; USDA, 2010a, 2011-2015, 2013, 2014, 2015, 2016, 2017a). Therefore, we believe the input data and probability distributions were well estimated and representative of the system modeled.

We conducted a partial budget analysis to evaluate the costs to the US cattle industry from BRD in beef calves prior to weaning. Our analysis did not consider drought, grain and corn prices, consumer demand, or factors occurring in the other livestock industries that may also affect demand or feeder cattle value. This partial budget model does not reflect the costs due to BRD that would be recouped by the industry if BRD in pre-weaned calves was eliminated. It is not appropriate to assume that feeder cattle market prices would remain that same if BRD were eliminated. The US cattle inventory and feeder cattle price typically move in opposite directions reflecting responses to supply and demand (Prevatt, 2015). Assuming no change in demand, if calves did not die or have reduced growth performance due to BRD, then the feeder cattle market price would be expected to decrease in response to the additional supply of calves reaching the market.

Currently, producers of herds not affected with BRD benefit from marketing more calves at a price determined by relatively less weight of calves in the market, whereas producers of affected herds market relatively less weight of calves, as well as bearing the cost of medicine and labor to treat sick calves. The direct costs we have estimated reflect this differential.

BRD is a substantial problem in beef calves prior to weaning, costing the industry about $165 million each year in the years 2011 to 2015. Death loss was the largest cost component representing more than three-quarters of the total cost. BRD cost in beef calves prior to weaning is a small part of the cow-calf industry total gross income, but it might adversely influence the net profit of infected herds. The present study provides important new information about the costs of BRD in US beef calves prior to weaning and identifies important factors influencing these costs.

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CHAPTER VII

EFFECT OF ELIMINATING BOVINE RESPIRATORY DISEASE IN CALVES PRIOR TO WEANING ON NET INCOME OF THE US COW-CALF INDUSTRY

Introduction

Bovine respiratory disease (BRD) is a major health problem in US beef calves prior to weaning. In a survey conducted by the USDA, more than 33% of US cow-calf operations strongly agreed or agreed that BRD has a significant economic impact on their operations (USDA, 2010a). Losses may occur due to death loss, medication costs, labor costs, and decreases in weaning weights due to BRD (Engelken, 1997). There has been limited research examining the costs of BRD in beef calves prior to weaning, and these research studies are limited to the costs in beef cow-calf producers with BRD problems in their calves in a large farm (Dewell, Keen, Dewell, Laegreid, & Hungerford, 2002) or in specific states (Hird et al., 1991; New, 1991; Salman MD, 1991; Wittum et al., 1994). There is no previous literature to estimate the cost of BRD in US beef calves prior to weaning. We used partial budget analysis to estimate that the cost of BRD is about $165 million per year in the US beef cow-calf industry (Chapter VI). However, this model did not consider the effect of feedback on market forces.

System dynamics is a modeling method focusing on closed loops and interconnected feedback loops which drive behavior over time (Vriens, 2004). The effect of BRD on the US beef cow-calf industry is a complex, dynamic problem since many factors in the system are interrelated and likely to change over time. The change in one parameter may affect one or more others, which means the association among parameters works through feedback (positive or negative) and is nonlinear. Therefore, a system dynamics approach might better help us understand the effect of pre-weaning BRD on the profitability in US beef cow-calf industry. However, no system dynamics model has been developed.

This paper describes the development of a system dynamics model to understand the effect of BRD on the net income of US cow-calf industry. More specifically, the objective of this study was to: 1) understand the effect of BRD occurrence or absence on the national net income of beef cow-calf industry; and 2) assess how the annual national net income is sensitive to changes in the value of several parameters associated with BRD.

Materials and methods

Model description

A system dynamics approach was used to develop dynamic models in Vensim Professional (version 7.0, Ventana Systems, Inc. MA, US). Several scenarios were designed: 1) the current situation with BRD in beef calves prior to weaning; 2) elimination of BRD without any cost; and 3) elimination of BRD with a cost of $10, $20, $30, $40, and $50 per cow, respectively. The sensitivity analysis was conducted using Vensim Professional and SAS (version 9.4, SAS Institute Inc, Cary, NC, US) to help understand the variation in the annual national net income of the model responding to the changes in several parameters. Validation was conducted to check whether or not the dynamic behavior may represent reality.

Hypotheses and boundary of the model

Our model assumed: 1) a one year calving cycle; 2) all calves are born in spring and enter the market in fall of the same year; 3) feeder cattle value is associated with feeder cattle supply in the market; 4) feeder cattle value impacts the net income for the producer; 5) net income influences the changes in the beef cow inventory; and 6) market demand does not change over time. The model did not consider the effect of the consumption of alternative protein sources or the effect of prices of grain and forages on the feeder cattle price.

Modeling process

The two-part modeling process included the development of a causal loop diagram (CLD) and a stock-flow model.

(1) Causal loop diagram—A CLD serves as a conceptual framework which represents the causal links among variables (Sterman, 2000, p. 102). A CLD is composed of arrows between factors and positive (+) and negative (-) pairwise factor polarities which show the causal influences from causes to effects (Sterman, 2000, p. 138). The CLD describing the BRD system is shown in Figure 7.1. An increase in beef cow inventory increases the feeder cattle supply in the market, and feeder cattle price decreases in response to increased supply and fixed demand in the market. Feeder cattle price increases the net profit per cow, which, in turn, stimulates producers to increase the

beef cow inventory. An increase in BRD morbidity and mortality decreases both the supply of feeder cattle and the net profit per cow.

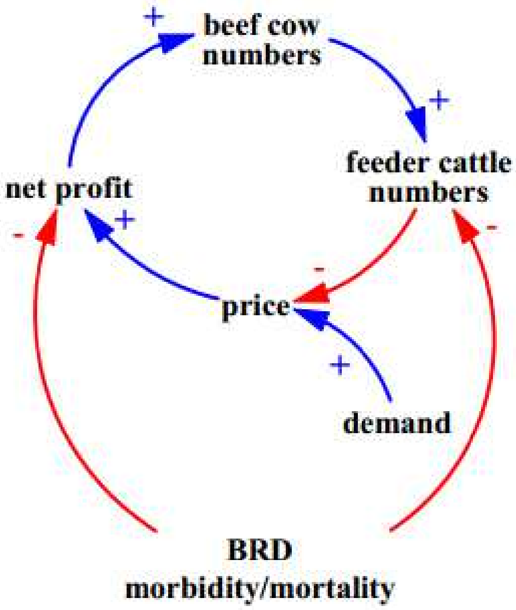

Figure 7.1 The CLD representing the influences of BRD on the national beef cow-calf industry

(2) Stock-flow model— A stock-flow model is used to simulate the dynamic effects of factors and their interactions developed from a CLD (Sterman, 2000, pp. 191-192). Figure 7.2 depicts a stock-flow model which represents movement of subjects from cow inventory to death or market; stocks, flows, auxiliary variables and information flows are essential structures in the model. Stocks, represented by boxes, show accumulation of units (e.g. beef cow inventory, cumulative total industry net income) at given moments. Flows, represented by double-line arrows with valve symbols, temporally affect stocks by inflows or outflows. Variables without shapes are auxiliary variables. Information flows, represented by single-lined arrows, indicate the

relationships between structures (Palma, Lounsbury, Schlecht, & Agalliu, 2016). A flow structure that begins or ends with a cloud icon represents an infinite source or sink, where units exist outside the scope of the model (Hovmand, 2013).

The model displays the movement from the beef cow inventory to the feeder cattle market with the number of feeder cattle marketed and weaning weight influencing the total feeder cattle weight supply in the market. The total feeder cattle supply changes feeder cattle value, affecting the net income per cow. Net income influences beef cow inventory two years later due to producers' delayed response to the market to retain heifer calves, and calves maturing to adulthood. The number of feeder cattle marketed is determined by calf crop percentage which is affected by BRD mortality. The average weight at weaning is affected by BRD morbidity and weaning weight loss due to BRD.

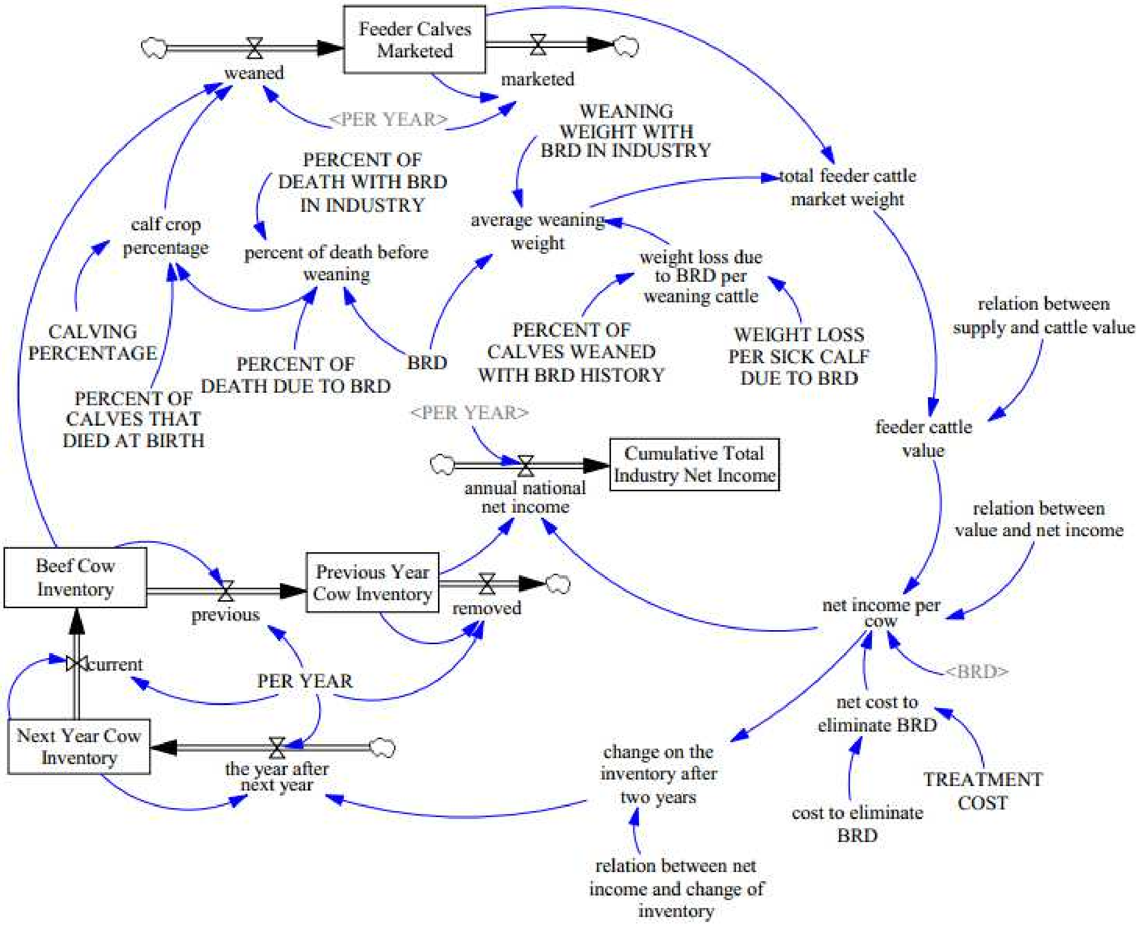

Figure 7.2	Stock-flow diagram for a system dynamics model of the effects of BRD on the net income of the beef cow-calf industry

The first letter of stock names is capitalized; constants are in all capitals, and names of other variables are all lower case.

Data sources

To make sure our model is demographically representative of the US beef cow-calf production system, all the data for simulations were taken from the USDA National Agricultural Statistics Service Quick Stats database, the USDA Economic Research Service website (USDA, 2011, 2017b), the USDA Beef 2007 - 08 survey (USDA, 2009a, 2010a), and a peer reviewed paper conducted in a large herd over multiple years (Snowder, Van Vleck, Cundiff, & Bennett, 2005).

Simulation parameters

In the stock-flow model, there are two kinds of variables: endogenous and exogenous. Endogenous variables are those determined by other variables in the system, and exogenous variables are those independent of the system. Appendix A describes the type, value, and calculation of parameters in the stock-flow diagram. Detailed information for important exogenous and endogenous variables follows:

Endogenous variables—Because each year January inventory of beef cows reported by the USDA represents beef cows and heifers that have calved in the previous year (USDA, 2017a), the year January beef cow inventory is adjusted to correspond to the model year. The number of calves born the subsequent year is limited by the current year's cow inventory due to the time delay of calving. Number of feeder calves marketed is restrained by beef cow inventory (endogenous variable) and calf crop percentage (exogenous variable). Total feeder cattle weight in the market is calculated based on the number of feeder calves marketed (endogenous variable) and average weaning weight (exogenous variable).

The relations between supply and cattle value, value and net income, and net income and change of inventory were defined based on USDA historical data from the year 1990 to 2016. The commercial statistical analysis software, SAS, was used to analyze these historical data. Separate cubic regression models using PROC ORTHOREG were performed on feeder cattle value, net income per cow, and the change on the inventory after two years with a fixed variable of total feeder cattle weight in the market, feeder cattle value, and net income per cow, respectively. The beef cow inventory after year 2003 was significantly affected by bovine spongiform encephalopathy cases that occurred at the end of 2003 (USDA, 2017c). Therefore, only data from 1990 to 2000 was used to model change in the beef cow inventory. Data from 1990 to 2016 were used to model cattle value and net income. Manual backward selection was utilized to determine the final models. The omnibus F test for the regression model and R-square were used to assess model fit. An alpha level of 0.1 was used to determine statistical significance for all the regression analyses.

Exogenous variables—Calving percentage (USDA, 2009b), percent of calves that died at birth (USDA, 2010b), and percent of calves born alive but died due to BRD before weaning (USDA, 2010a) are exogenous variables, and they collectively determine calf crop percentage (Reiling, 2011).

Weaning weight loss per sick calf due to BRD (Snowder et al., 2005), percent of calves weaned with BRD history (USDA, 2010a) , and the weaning weight of calves with BRD in the industry (USDA, 2009b) are also exogenous variables that determine the average weaning weight in the market.

Simulated scenarios

Several scenarios were performed. Scenario 1 assumes that BRD continues to exist in the beef cow-calf system and exogenous parameters do not change over time. Scenario 2 assumes elimination of pre-weaning BRD in the beef cow-calf system without any cost. Other scenarios assume elimination of pre-weaning BRD in the beef cow-calf industry at a cost of $10, $20, $30, $40, and $50 per cow, respectively. The initial value of the beef cow inventory, next year cow inventory, and the change on the inventory after two years are based on the USDA data from 1990 to 1992. The modeling process allowed a 40-year burn-in period to allow the model to stabilize. The scenarios were initiated after another 10-year period and followed for 150 years.

Sensitivity analysis

To identify the most influential factors and quantitatively evaluate the effects of inputs on the annual national net income in the beef cow-calf industry, Monte Carlo simulations were performed in two types of situations. When BRD exists in the industry, simulations evaluate the effects of parameters by ± 1 SD deviation from the default value. When BRD is eliminated from the industry, simulations evaluate those parameters not associated with BRD by ± 1 SD deviation from the default value and the cost to eliminate BRD ($0 to $50 with an interval of $5). The parameters included in the sensitivity analysis are summarized in Table 7.1.

The sensitivity analysis was conducted using 2,000 iterations and a specific simulation seed. Based on the results of the sensitivity analysis in Vensim Professional, the standardized coefficients as direct measures of sensitivity were calculated by regression analyses using SAS PROC GLMSELECT where selection equals NONE and STB included in the statement.

Table 7.1 Ranges and distributions of parameters used for sensitivity analysis

Parameter	Mean	SD	Range	Distribution
Situation 1: with BRD in the industry				
Calving percentage	0.915	0.006	(0.824, 1.000)	Random_uniform (0.824,1.000)
Percent of death with BRD in industry	0.036	0.002	(0.032, 0.040)	Random_uniform (0.032, 0.040)
Weaning weight with BRD in industry	240.404	0.907	(216.364, 264.444)	Random_uniform (216.364, 264.444)
Percent of calves that died at birth	0.029	0.007	(0.026,0.032)	Random_uniform (0.026,0.032)
Percent of death due to BRD	0.160	0.018	(0.144, 0.176)	Random_uniform (0.144, 0.176)
Percent of calves weaned with BRD history	0.025	0.004	(0.023,0.028)	Random_uniform (0.023,0.028)
Weight loss per sick calf due to BRD	6.760	1.02	(6.084,7.436)	Random_uniform (6.084,7.436)
Situation 2: without BRD in the industry				
Calving percentage	0.915	0.006	(0.824, 1.000)	Random_uniform (0.824,1.000)
Percent of death with BRD in industry	0.036	0.002	(0.032, 0.040)	Random_uniform (0.032, 0.040)
Weaning weight with BRD in industry	240.404	0.907	(216.364, 264.444)	Random_uniform (216.364, 264.444)
Percent of calves that died at birth	0.029	0.007	(0.026,0.032)	Random_uniform (0.026,0.032)
Cost to eliminate BRD	—		(0,50)	Vector (0,50,5)

SD = standard deviation

Validation

The simulation model was validated by the dimensional consistency, extreme condition, and behavior reproduction tests. Dimensional consistency ensures unit consistency of model parameters. Extreme condition assesses whether the model behaves appropriately by changing the value of the cost to eliminate BRD from 0 to \$100 by \$5 increments. Behavior reproduction compares the dynamic behavior of the model to the expected real beef cattle system with an approximate 10 year oscillation in the beef cattle inventory (Sterman, 2000, pp. 859-881). Boundary adequacy, structure assessment, and parameter assessment were not conducted because plausible information was unavailable.

Results

Table 7.2 summarizes regression results of feeder cattle value, net income per cow, and the change on the inventory after two years. There is a quadratic relationship between total feeder cattle market weight and feeder cattle value, and cubic relationships between feeder cattle value and net income per cow and between net income per cow and the change on the inventory after two years.

Scenario outcomes indicate the effects of occurrence or elimination of BRD on the beef cow inventory (Figures 7.3 and 7.4), total feeder cattle market weight (Figures 7.5 and 7.6), feeder cattle value (Figures 7.7 and 7.8), annual national net income (Figures 7.9 and 7.10), and cumulative total industry net income (Figures 7.11 and 7.12) from the year 51 to 200. A summary of these values is provided in Table 7.3. Because the net income per cow and annual national net income have similar patterns, the results of net income per cow for different scenarios are not shown. For all scenarios, beef cow inventory, total feeder cattle market weight, feeder cattle value, net income per cow, and annual national net income display a typical ten-year cycle.

With BRD and elimination of BRD at no cost

Compared to the current situation with BRD in the industry, the model predicts that beef cow inventory would decrease slightly with the elimination of BRD without any cost (Figure 7.3). No differences were observed in the patterns and trends of total feeder cattle market weight (Figure 7.5), feeder cattle value (Figure 7.7), and annual national net income (Figure 7.9) with BRD eliminated with no cost compared to the system in which BRD occurs. The cumulative total industry net income is lower in the scenario where BRD is eliminated without any cost than the current situation with BRD existing in the system (Figure 7.11).

Eliminating BRD at a cost of $10, $20, $30, $40, and $50 per cow

Removing BRD from the industry at a cost of $10 to $50 per cow results in a decrease in US beef cow inventory (Figure 7.4) and a corresponding reduction in the total feeder cattle supply on the market (Figure 7.6). Lower supply and consistent demand increases the average value of feeder cattle as the cost per cow to eliminate BRD increases (Figure 7.8). Elimination of BRD may lead to milder fluctuations in the beef cow inventory, total feeder cattle market weight, feeder cattle value, and annual national net income in the industry as elimination costs increase from $10 to $40 per cow. Fluctuations of these variables subsequently increase as prevention costs increase from $40 to $50 per cow. Paradoxically, spending more money to eliminate BRD may result in more profit to the industry compared to having BRD or eliminating BRD at no cost (Figure 7.12).

Sensitivity analysis

The annual national net income has a substantial variation when BRD is removed from the system compared to the current situation with BRD. Standardized coefficients demonstrate calving percentage and percent of calves that died at birth are most sensitive to the annual national net income in the industry no matter whether BRD exists or not. Those factors associated with BRD, including percent of death due to BRD, percent of calves weaned with BRD history, and weight loss per sick calf due to BRD, by ± 1 SD variation from the default value have limited or no significant effect on the annual national net income (Table 7.4).

Validation

The units check confirmed consistency in units throughout the model except two warnings due to using the lookup function which uses one variable to determine the value of another variable with different units. The warnings do not indicate a problem that would influence the model results. The results of the extreme condition test indicate that the model may not correctly predict the system when cost to eliminate BRD increases above $60 per cow. Figures 7.3 to 7.12 illustrate simulation results of the model for the scenarios. The oscillation in US beef cow inventory, total feeder cattle market weight, feeder cattle value, and annual national net income follow the previously described ten-year cattle cycle (USDA, 2016). Also, cattle inventory and feeder cattle value move in opposite directions, as previously documented for the US cattle inventory and feeder calf price (Prevatt, 2015).

Discussion

This model demonstrates system dynamics underlying the effects of BRD in the beef cow-calf system. Our model is not proposed for precise quantification of the system's elements, but instead to reveal trends and interrelationships under alternative scenarios in the beef cow-calf system.

Currently, there are no estimates of the effect of BRD using a system dynamics modeling approach. Several scenarios were conducted in our study including the current occurrence of BRD in the industry, BRD elimination from the system without cost, or elimination at a cost of $10 to $50 per cow. Elimination of BRD means there are no costs due to death loss, production loss, or treatment of BRD.

A cattle cycle represents a period of time in which the number of cattle is alternately expanded and reduced for several years corresponding to the changes in profitability of production. This cycle is approximately 10 years in the US beef cattle industry (USDA, 2016). The model oscillation in US beef cow inventory, total feeder cattle market weight, feeder cattle value, net income per cow, and annual national net income followed this cattle cycle. Therefore, the dynamic behavior of the model seems reasonable compared to the cattle cycle in the US beef industry (Schulz, 2013; USDA, 2016).

The model oscillation amplitude is similar in the scenarios with BRD and when BRD is eliminated without cost. The model outputs have minimum fluctuations at the elimination cost of $40 per cow. The further away from this cost there is greater amplitude in the oscillations. This might be explained by the use of cubic functions in the model. Cubic functions have been used widely in market structure analysis (Corcoran, 2007; Nikutowski, Leis, & von Weizsäcker, 2013). In our model, there are cubic relationships between feeder cattle value and net income per cow and between net income per cow and the change on the inventory after two years. The cubic function shows feeder cattle value close to 85 to 95 index value has less impact on the net income and the net income's effect on the change of inventory after two years. Values further from 85 to 95 index value have a larger impact on the system. In our model, at the cost of \$40 per cow to eliminate BRD, the feeder cattle value stabilized at an index value of 90 after several years of oscillation. This probably explains the minimum fluctuations in the model outputs at the cost of \$40 per cow to eliminate BRD.

There are some limitations in this model. First, a fixed demand was assumed in the model, which may not accurately represent consumer demands. For example, the price of alternative protein sources and feed prices might affect the demand curve for feeder calves. We choose to use simple model to study the specific question. Also, the constraint of the cost to eliminate BRD is \$60 per cow because the historical data used to get the relationship among variables has restrictions. The dynamic model might not be reliable outside of this range. Despite these limitations, the present work is the first attempt to investigate the effect of BRD in the US beef industry with feedback effects, nonlinearity, and considerations for time delays.

Currently, beef cow-calf producers not experiencing BRD in their calves have an economic advantage over producers with BRD. Assuming no change in demand, eliminating pre-weaning BRD without any cost may benefit previously affected producers, but the additional supply of beef reduces cattle value for the industry as a whole. Eliminating BRD by different costs would benefit calf health and well-being, and would immediately benefit the economic well-being of the owners of affected herds. However, it is paradoxical that, in the long run, having BRD was more profitable for the industry compared to eliminating BRD at no cost. Also, eliminating BRD at some cost offered more benefit the industry due to greater profitability at less annual variability compared to eliminating BRD at no cost.

Table 7.2 Regression results of feeder cattle value, net income per cow, and the change on the next year inventory

Response	**Intercept**	**$W_{FeederCattle}$** **$W_{FeederCattle}^2$**	**$V_{feederCattle}$** **$V_{feederCattle}^2$** **$V_{feederCattle}^3$**	**$N_{IncomPerCow}$** **$N_{IncomPerCow}^2$** **$N_{IncomPerCow}^3$**	**Statistics (R^2, *P*-value)**
$V_{FeederCattle}$	2262.56	-5.94E-07 4.00E-17			0.73, <0.0001
$N_{ProfitPerCow}$	-1119.89		5.19E-09 -7.98E-21 4.37E-33		0.89, <0.0001
$C_{BeefInventory}$	-333213.57			12402.27 244.73 1.00	0.77, 0.012

$W_{FeederCattle}$ = total feeder cattle market weight; $V_{feederCattle}$ = feeder cattle value; $N_{IncomPerCow}$ = net income per cow; $C_{BeefInventory}$ = change on the inventory after two years. R^2 = R-squared statistic.
Regression models for $V_{FeederCattle}$ and $N_{IncomPerCow}$ were based on the USDA history data from 1990 to 2016; the regression model for $C_{BeefInventory}$ was conducted by using USDA data from 1990 to 2000 because $C_{BeefInventory}$ was significantly affected due to bovine spongiform encephalopathy cases happened in the end of 2003.

Table 7.3 Summary of main outputs for scenarios from year 51 to 150

Scenario	Main Output	Mean (SD)	Median (IQR)	Range (min, max)
Scenario 1: With BRD	Beef cow inventory (head)	3.30E+07 (7.70E+05)	3.30E+07 (1.47E+06)	2.21E+06 (3.20E+07, 3.42E+07)
	Total feeder cattle market weight (kg)	6.80E+09 (1.59E+08)	6.80E+09 (3.02E+08)	4.55E+08 (6.58E+09, 7.03E+09)
	Feeder cattle value (dmnl)	69.51 (8.09)	69.12 (15.58)	22.93 (58.84, 81.77)
	Annual national net income ($/year)	2.46E+08 (8.89E+08)	3.93E+08 (1.71E+09)	2.51E+09 (-1.11E+09, 1.40E+09)
	Cumulative total industry net income ($)	4.11E+10 (1.18E+10)	4.07E+10 (2.02E+10)	4.21E+10 (2.05E+10, 6.26E+10)
Scenario 2: Eliminate BRD without cost	Beef cow inventory (head)	3.29E+07 (7.91E+05)	3.29E+07 (1.53E+06)	2.37E+06 (3.18E+07, 3.41E+07)
	Total feeder cattle market weight (kg)	6.81E+09 (1.64E+08)	6.81E+09 (3.18E+08)	4.91E+08 (6.58E+09, 7.07E+09)
	Feeder cattle value (dmnl)	69.13 (8.21)	68.11 (16.01)	23.95 (57.62, 81.57)
	Annual national net income ($/year)	2.22E+08 (9.16E+08)	3.03E+08 (1.81E+09)	2.72E+09 (-1.31E+09, 1.41E+09)
	Cumulative total industry net income ($)	3.87E+10 (1.10E+10)	3.83E+10 (1.88E+10)	3.93E+10 (1.95E+10, 5.88E+10)
Scenario 3: Eliminate BRD by spending $10/cow	Beef cow inventory (head)	3.24E+07 (6.93E+05)	3.24E+07 (1.39E+06)	2.58E+06 (3.15E+07, 3.41E+07)
	Total feeder cattle market weight (kg)	6.73E+09 (1.43E+08)	6.73E+09 (2.86E+08)	5.34E+08 (6.53E+09, 7.06E+09)
	Feeder cattle value (dmnl)	73.19 (8.06)	72.43 (16.42)	27.40 (58.03, 85.43)
	Annual national net income ($/year)	3.36E+08 (7.44E+08)	4.19E+08 (1.49E+09)	2.85E+09 (-1.57E+09, 1.29E+09)
	Cumulative total industry net income ($)	4.56E+10 (1.62E+10)	4.54E+10 (2.88E+10)	5.48E+10 (1.83E+10, 7.31E+10)
Scenario 4: Eliminate BRD by spending $20/cow	Beef cow inventory (head)	3.20E+07 (4.05E+05)	3.20E+07 (4.69E+05)	2.84E+06 (3.12E+07, 3.41E+07)
	Total feeder cattle market weight	6.64E+09 (8.42E+07)	6.64E+09 (9.15E+07)	5.89E+08 (6.47E+09, 7.06E+09)
	Feeder cattle value (dmnl)	78.07 (4.92)	78.53 (6.02)	31.47 (58.03, 89.51)

Table 7.3 (continued)

Scenario	Main Output	Mean (SD)	Median (IQR)	Range (min, max)
	Annual national net income ($/year)	5.01E+08 (4.26E+08)	5.78E+08 (4.21E+08)	3.06E+09 (-1.91E+09, 1.15E+09)
	Cumulative total industry net income ($)	5.48E+10 (2.42E+10)	5.45E+10 (4.37E+10)	8.03E+10 (1.68E+10, 9.70E+10)
Scenario 5: Eliminate BRD by spending $30/cow	Beef cow inventory (head)	3.16E+07 (3.82E+05)	3.16E+07 (7.92E+04)	3.16E+06 (3.09E+07, 3.41E+07)
	Total feeder cattle market weight (kg)	6.56E+09 (8.05E+07)	6.56E+09 (1.66E+07)	6.56E+08 (6.40E+09, 7.06E+09)
	Feeder cattle value (dmnl)	83.44 (4.68)	84.19 (1.19)	36.87 (58.03, 94.90)
	Annual national net income ($/year)	5.18E+08 (4.07E+08)	5.96E+08 (5.87E+07)	3.29E+09 (-2.25E+09, 1.05E+09)
	Cumulative total industry net income ($)	5.54E+10 (2.55E+10)	5.50E+10 (4.49E+10)	8.47E+10 (1.50E+10, 9.97E+10)
Scenario 6: Eliminate BRD by spending $40/cow	Beef cow inventory (head)	3.12E+07 (4.52E+05)	3.11E+07 (1.85E+04)	3.52E+06 (3.05E+07, 3.41E+07)
	Total feeder cattle market weight (kg)	6.47E+09 (9.62E+07)	6.47E+09 (4.24E+06)	7.29E+08 (6.33E+09, 7.06E+09)
	Feeder cattle value (dmnl)	89.90 (5.92)	91.14 (0.33)	43.27 (58.03, 101.30)
	Annual national net income ($/year)	4.94E+08 (4.61E+08)	5.93E+08 (1.31E+07)	3.57E+09 (-2.59E+09, 9.85E+08)
	Cumulative total industry net income ($)	5.25E+10 (2.51E+10)	5.20E+10 (4.43E+10)	8.35E+10 (1.27E+10, 9.62E+10)
Scenario 7: Eliminate BRD by spending $50/cow	Beef cow inventory (head)	3.08E+07 (5.59E+05)	3.07E+07 (8.36E+04)	3.89E+06 (3.02E+07, 3.41E+07)
	Total feeder cattle market weight (kg)	6.39E+09 (1.19E+08)	6.39E+09 (1.78E+07)	8.07E+08 (6.25E+09, 7.06E+09)
	Feeder cattle value (dmnl)	96.96 (7.89)	98.80 (1.60)	50.31 (58.03, 108.34)
	Annual national net income ($/year)	4.56E+08 (5.41E+08)	5.79E+08 (6.19E+07)	3.93E+09 (-2.93E+09, 9.98E+08)
	Cumulative total industry net income ($)	4.76E+10 (2.44E+10)	4.69E+10 (4.34E+10)	8.11E+10 (9.39E+09, 9.05E+10)

The modeling process allowed a 40-year burn-in period to allow the model to stabilize. The data used for the above analysis was initiated at year 51.

Table 7.4 Standardized coefficients of separate regression models on the annual national net income for BRD occurrence or absence in the industry

BRD situation	**Parameter**	**Standardized coefficients**	***P*-value***
With BRD	Calving percentage	-1.18E-02	<.0001
	Percent of death with BRD in industry	3.79E-03	<.0001
	Weaning weight with BRD in industry	-8.83E-03	<.0001
	Percent of calves that died at birth	1.29E-02	<.0001
	Percent of death due to BRD	-2.41E-04	0.727
	Percent of calves weaned with BRD history	-2.12E-05	0.976
	Weight loss per sick calf due to BRD	-5.67E-05	0.935
Without BRD	Calving percentage	-1.18E-02	<.0001
	Percent of death with BRD in industry	3.78E-03	<.0001
	Weaning weight with BRD in industry	-8.84E-03	<.0001
	Percent of calves that died at birth	1.29E-02	<.0001
	Cost to eliminate BRD	2.57E-05	0.970

* The first 40 years are considered a burn-in period to allow the model to stabilize. The data used for sensitivity analysis was initiated at year 51. Year was adjusted as a fixed variable in the two models.

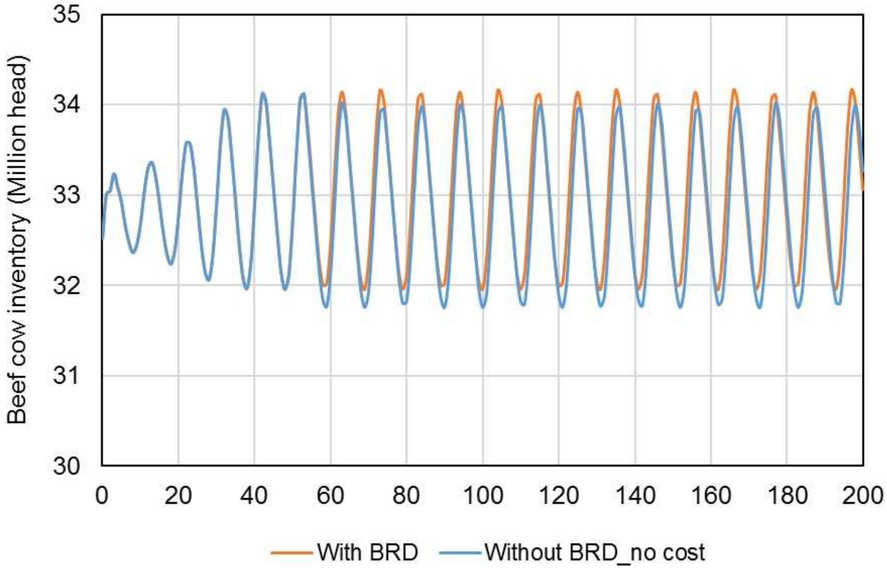

Figure 7.3 Beef cow inventory from year 0 to 200 for the scenarios with BRD and without BRD at no cost in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

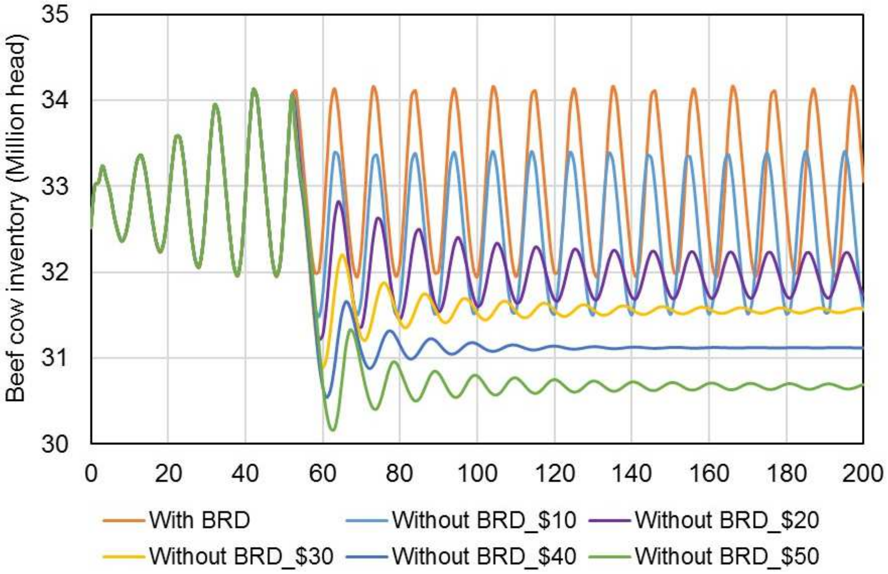

Figure 7.4 Beef cow inventory from year 0 to 200 for the scenarios with BRD and without BRD at different costs in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

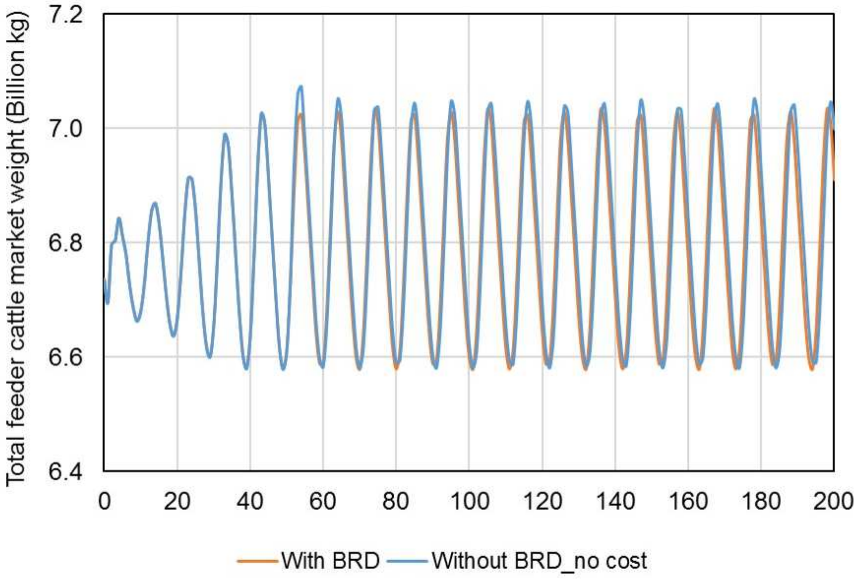

Figure 7.5 Total feeder cattle market weight from year 0 to 200 for the scenarios with BRD and without BRD at no cost in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

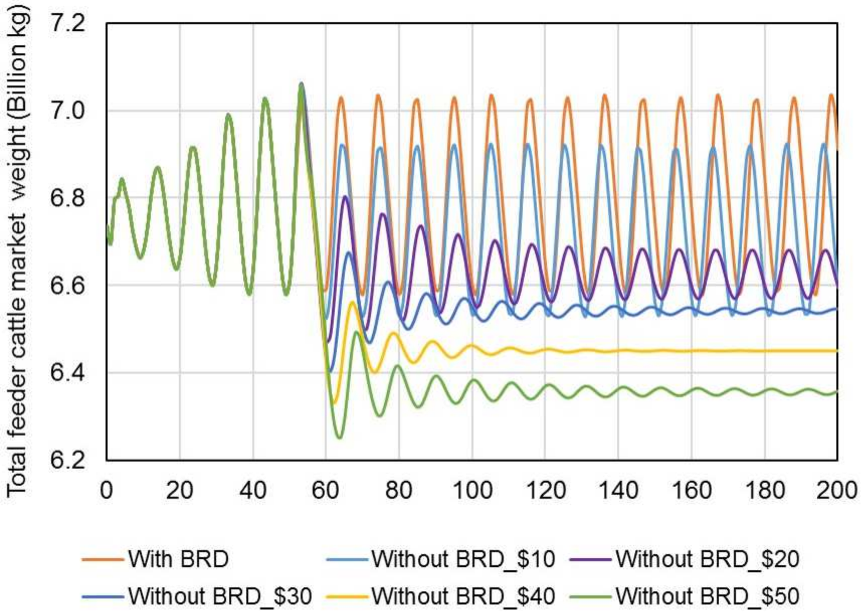

Figure 7.6 Total feeder cattle market weight from year 0 to 200 for the scenarios with BRD and without BRD at different costs in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

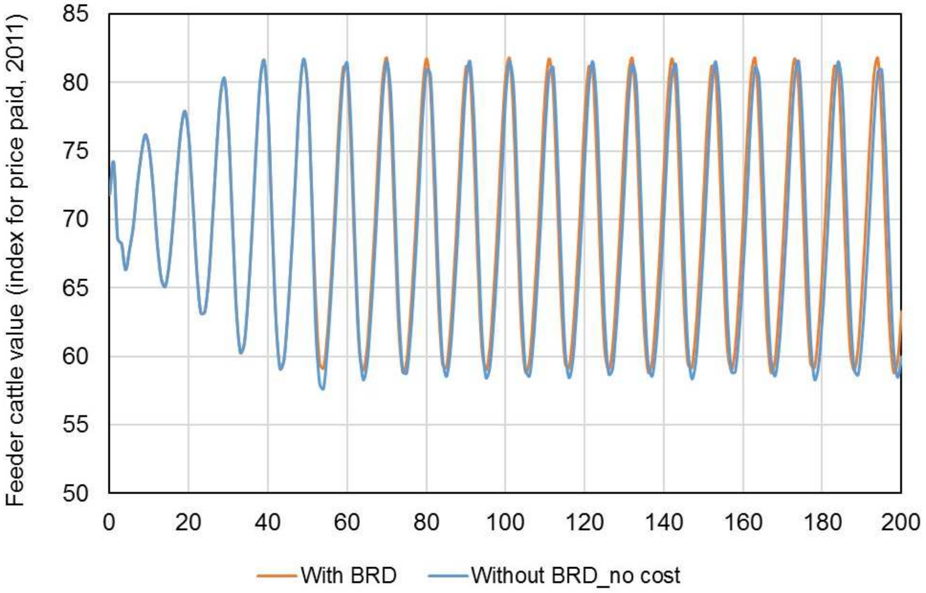

Figure 7.7 Feeder cattle value from year 0 to 200 for the scenarios with BRD and without BRD at no cost in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

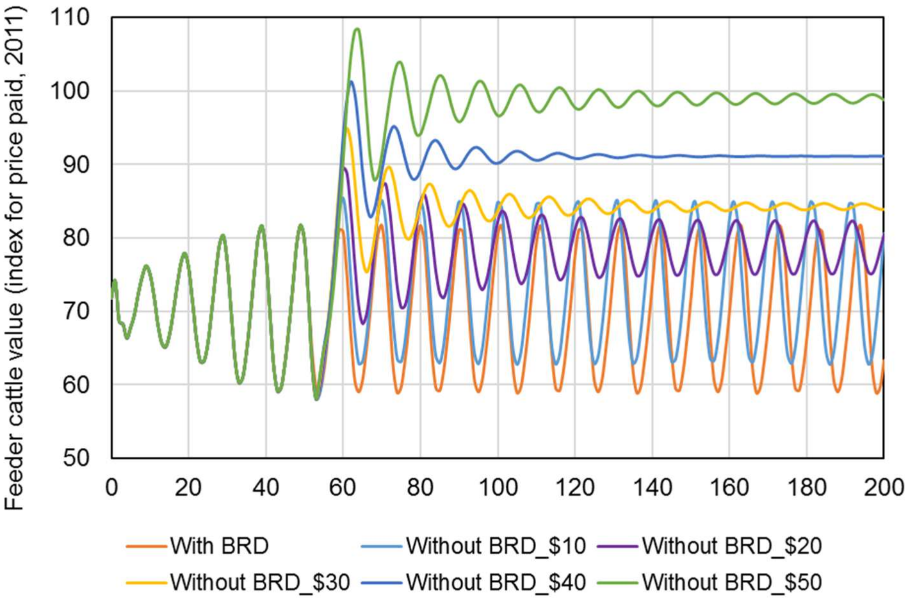

Figure 7.8 Feeder cattle value from year 0 to 200 for the scenarios with BRD and without BRD at different costs in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

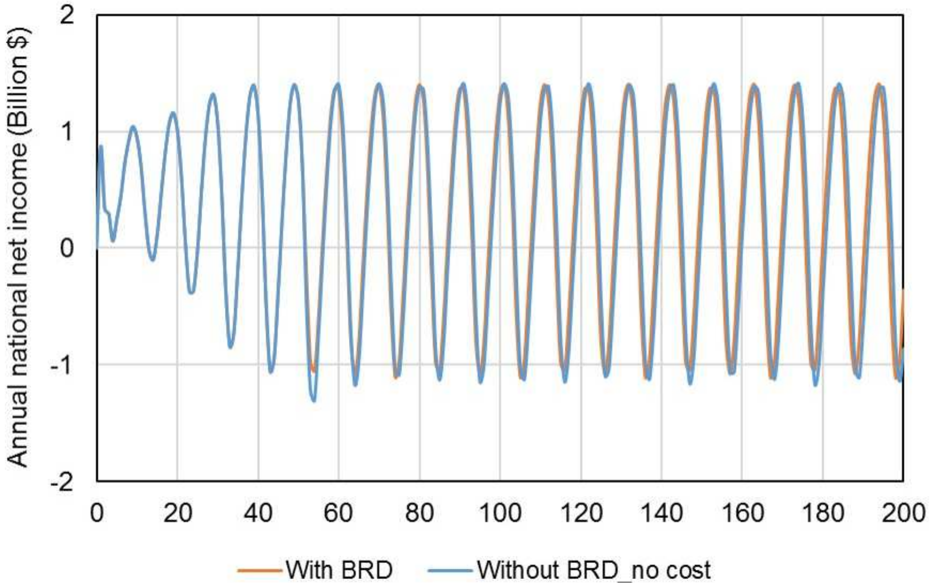

Figure 7.9 Annual national net income from year 0 to 200 for the scenarios with BRD and without BRD at no cost in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

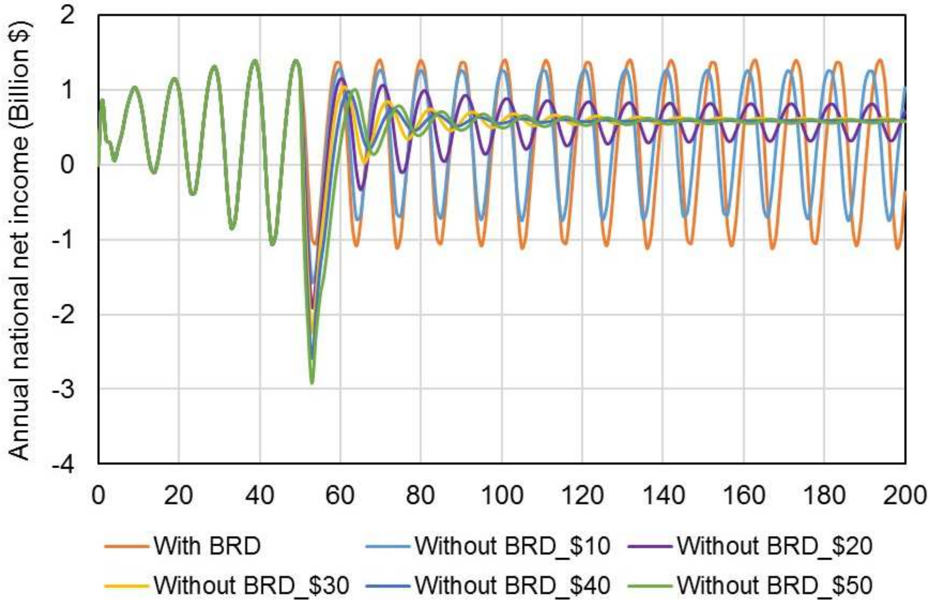

Figure 7.10 Annual national net income from year 0 to 200 for the scenarios with BRD and without BRD at different costs in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

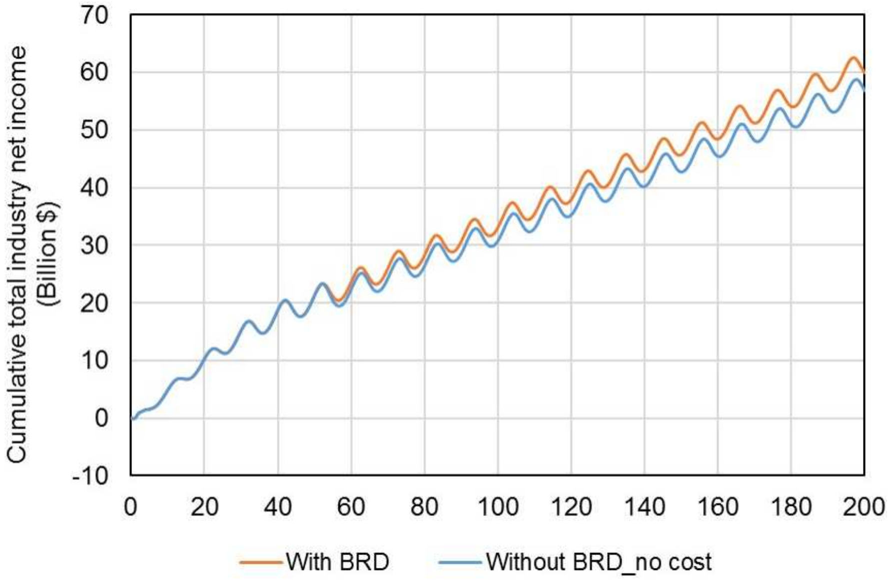

Figure 7.11 Cumulative total industry net income from year 0 to 200 for the scenarios with BRD and without BRD at no cost in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

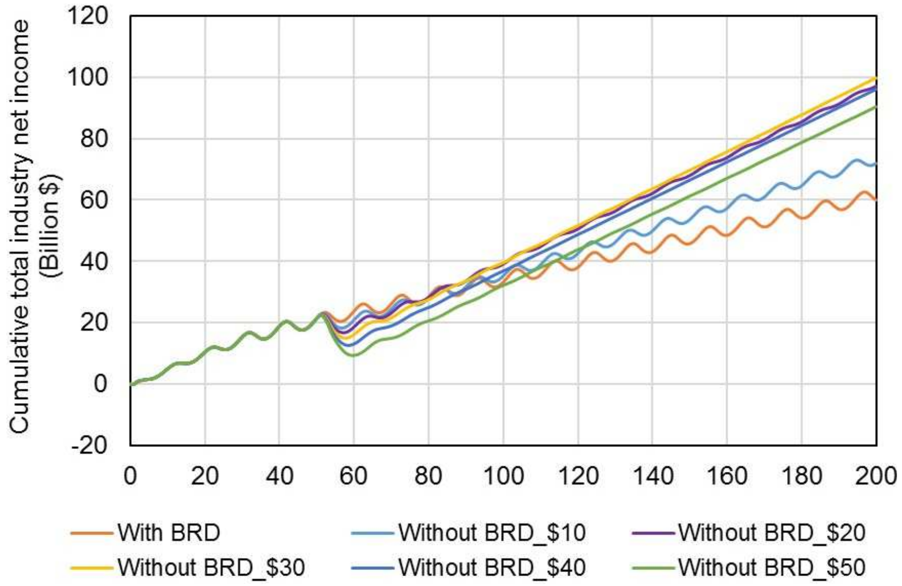

Figure 7.12 Cumulative total industry net income from year 0 to 200 for the scenarios with BRD and without BRD at different costs in the industry

The first 40 years are considered a burn-in period to allow the model to stabilize. The comparison in situations was initiated at year 51.

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CHAPTER VIII

SUMMARY

Bovine respiratory disease (BRD) is an important problem for cattle producers regarding economics and animal health and welfare. It is one of the leading causes of sickness and death in beef calves prior to weaning in the US. Understanding the incidence and impacts of disease, as well as identifying risk factors will assist in the improvement of management in beef cattle system. Understanding the component costs of BRD in beef calves allows us to know where more or less attention should be applied to help decision making of BRD management.

This dissertation is composed of eight chapters. Chapters I and II are literature reviews about BRD and methods to quantitatively estimate risks, respectively. Chapters III to VII are papers describing the research conducted as part of this dissertation. Each paper consists of an introduction, materials and methods, results, and discussion. References cited are located at the end of each section. Chapter VIII is the summary of this dissertation. The detailed information for each chapter as follows.

Chapter I provides a literature review of the pathogenesis, diagnosis, epidemiology, and economic impacts of BRD. Chapter II reviews two methods, risk analysis and system dynamics, which can be utilized to quantitatively evaluate risks.

Chapter III describes research performed to determine if sex, age of dam, or birth weight was associated with the treatment of BRD in beef calves during different age periods prior to weaning. A longitudinal study was conducted on 9,921 calves from 28 cattle management groups within 7 beef cattle ranches in Nebraska, United States. Health records were collected from 2005 to 2014. Separate multilevel multivariable log-binomial regression models were conducted to assess risk factors for BRD in different age periods (< 75 d, 75 d to 149 d, and ≥ 150 d) with explanatory variables of sex, birth weight, and age of the dam and a random effect of management group. Results showed: 1) BRD was treated in 877 of 9,582 (9.2%) calves; and 2) calves born to two-year-old dams were 4.9 times more likely to develop BRD than calves born to cows 3 years or older prior to 75 d. However, calves born to two-year-old dams were 0.6 times less likely to get BRD than those born to older dams between the age of 75 d to 149 d; 3) steers were 1.7 times more likely treated for BRD than heifers between 150 d to weaning. In conclusion, risk factors for BRD are different depending on the age of the calf. The earlier occurrence of BRD among calves born to heifers probably reflects greater risk for failure of passive antibody transfer. Steers are at higher risk to develop BRD in older calves prior to weaning for sex effects on immunity.

Chapter IV describes research performed to estimate the costs to prevent or treat BRD in beef calves prior to weaning. A cross-sectional survey was conducted on forty-three beef cow-calf ranchers with a history of pre-weaning BRD in Nebraska, South Dakota, and North Dakota. Both mail and electronic survey methods were used to get a higher response rate. Forty-three (n = 7 mail, n = 36 electronic) completed surveys. The estimated annual median cost for vaccines and labor for vaccination against BRD per cow, per heifer, and per calf were \$2.25, \$4.00, and \$6.25, respectively, and \$4.58, \$3.00, and \$5.00, respectively. The estimated annual median medicine cost and labor cost for treating pre-weaning BRD were \$11.00 and \$15.00 per calf, respectively. The estimated annual median cost of veterinary services (excluding vaccine and drugs) was \$1.25 per calf. The annual least squares mean of vaccine cost per calf (\$7.67 ± 0.66) was significantly higher than per cow (\$3.18 ± 0.75) and per replacement heifer (\$4.48 ± 0.68). Each additional minute spent on vaccination or treatment increased labor cost \$0.31 and \$0.28, respectively. In summary, labor cost for vaccination or treatment was similar or exceeded the cost for vaccines or drugs. Gathering and sorting took most of the time for both vaccination and treatment. It is important to realize the costs associated with time and labor as well as medication when designing BRD prevention and treatment plans.

Chapter V describes research identifying factors affecting the national market price of beef feeder cattle in the US. Two datasets were collected and analyzed to determine the variables affecting average feeder price: 1) USDA Agricultural Marketing Service's weekly weighted average price reports of feeder bulls, steers, and heifers during 2006 to 2015; and 2) USDA National Agricultural Statistics Service US beef cow inventory in January between 2007 and 2016. The average price paid for beef feeder calves during 2006 to 2015 was associated with the US January beef cow inventory from 2007 to 2016 ($R^2 = 0.83$, $P < 0.0001$). An interaction of sex by weight was associated with average price ($P < 0.0001$). For each 22.7 kg increase in live weight, the sale price per 45.4 kg decreased for bulls, steers, and heifers by \$7.93, \$6.22, and \$4.72, respectively. The interaction between frame and muscle scores affected price ($P < 0.0001$). When frame was held constant, heavier muscled cattle had a higher average price than lighter muscled cattle ($P < 0.0001$), but this relationship was not seen in small and medium framed cattle. For cattle with the same muscle score, medium and large framed cattle had a higher average price than cattle with lower frame size ($P < 0.0001$). Spatial analysis showed that clustering of locations with significantly higher or lower prices was dependent upon the year. Understanding the factors that influence market prices can benefit producers in the beef cattle industry by capitalizing on market demands.

Chapter VI estimates the direct cost of BRD in US beef calves prior to weaning during 2011 to 2015. A stochastic simulation model was conducted using computer spreadsheet add-in software. Input data were obtained from USDA, peer-reviewed papers, and a survey of beef cow-calf producers. Results were reported by a median point estimate with 90% confidence interval. Results showed between 2011 and 2015 the estimate of the median total economic cost of BRD in US beef calves prior to weaning was \$165 million (129–246), of which the costs due to death, medical treatment, and weight loss were \$126 million (92–200), \$25 million (20–32), and \$15 million (9–25), respectively. The median costs associated with death due to BRD in calves < 3 weeks and ≥ 3 weeks of age were \$44 million (29–72) and \$84 million (57–138), respectively. Death loss in calves prior to weaning was the largest component cost (76%). Total cost of BRD was most sensitive to deaths in calves ≥3 weeks of age. In conclusion, this model estimates the total and component costs to the US beef industry from BRD in US beef calves prior to weaning. Death loss is the most influential part of the total cost of BRD in beef calves prior to weaning.

Chapter VII develops a system dynamics model to understand the effect of BRD occurrence or absence on the national net income of the US beef cow-calf industry.

Parameter values for simulations were drawn from USDA and peer-reviewed papers. The system dynamics model was developed by using Vensim Professional with feedback effects among variables with annual time effects. Several scenarios were designed: 1) the current situation with BRD in beef calves prior to weaning; 2) elimination of BRD without any cost; and 3) elimination of BRD with a cost of $10, $20, $30, $40, and $50 per cow, respectively. The simulation results were validated to see whether model represents the actual behavior of the beef cattle cow-calf system. Validation was conducted to check whether or not the dynamic behavior may represent reality. Results showed that spending more money to eliminate BRD may result in more profit to the industry compared to having BRD or eliminating BRD at no cost. The oscillation in US beef cow inventory, feeder cattle value, and net income per cow followed the classically described 10-year cattle cycle. Eliminating BRD by different costs would benefit calf health and well-being, and would immediately benefit the economic well-being of the owners of affected herds. It is paradoxical that in the long run having BRD is more profitable for the industry compared to eliminating BRD at no cost. Also, eliminating BRD at some cost has more benefit to the industry due to greater profitability at less annual variability than eliminating BRD at no cost.

APPENDIX A

MAIN VARIABLES AND PARAMETERS IN STOCK-FLOW MODEL

Parameter	Function or Value	Type	Unit	Description
Stock				
Beef Cow Inventory	INTEG (current-previous, 3.25198e+007)	endogenous	head	Number of cows at the start of model
Next Year Cow Inventory	INTEG (next year-current, 3.30068e+007)	endogenous	head	Next year cow inventory compared to the year start of model
Previous Year Cow Inventory	INTEG (previous-removed, 0)	endogenous	head	Previous year cow inventory compared to the year start of model
Feeder Calves Marketed	INTEG (weaned-marketed, 2.802e+007)	endogenous	head	Number of feeder calves marketed
Cumulative total industry Net Income	INTEG (income, 0)	endogenous	$	Accumulation of annual national net income in the beef cow-calf industry over years
Flow				
removed	Previous Year Cow Inventory	endogenous	head/year	Outflow of previous year cow inventory
previous	Beef Cow Inventory	endogenous	head/year	Inflow of previous year cow inventory
current	Next Year Cow Inventory	endogenous	head/year	Inflow of current year cow inventory
the year after next year	Next Year Cow Inventory + change on the after next year inventory	endogenous	head/year	Inflow of next year cow inventory
weaned	Beef Cow Inventory * calf crop percentage	endogenous	head/year	Inflow of feeder calves marketed
marketed	Feeder Calves Marketed	endogenous	head/year	Outflow of feeder calves marketed
annual national net income	net income per cow * Previous Year Cow Inventory	endogenous	$/year	Annual net income of the us beef cow-calf industry at the model year

Continued

Parameter	Function or Value	Type	Unit	Description
Auxiliary variables				
PER YEAR	1	exogenous	year	Per year
calf crop percentage	CALVING PERCENTAGE * (1-PERCENT OF CALVES THAT DIED AT BIRTH) * (1 - percent of calves born alive but died/lost before weaning)	exogenous	dmnl	The percentage of exposed females that weaned a calf
CALVING PERCENTAGE	0.915 (USDA, 2009a)	exogenous	dmnl	Percentage of exposed females that calved
PERCENT OF CALVES THAT DIED AT BIRTH	0.029 (USDA, 2010b)	exogenous	dmnl	Percent of calves died at born
PERCENT OF DEATH WITH BRD IN INDUSTRY	0.036 (USDA, 2010a)	exogenous	dmnl	Percent of calves born alive but died or were lost before weaning for the current situation with BRD problem in the industry
Percent of death before weaning	PERCENT OF DEATH WITH BRD IN INDUSTRY-PERCENT OF DEATH WITH BRD IN INDUSTRY*(1-BRD)*PERCENT OF DEATH DUE TO BRD	exogenous	dmnl	Percent of calves born alive but died or were lost before weaning
PERCENT OF DEATH DUE TO BRD	0.16 (USDA, 2010a)	exogenous	dmnl	Of calves born alive but died prior to weaning, percent of death due to BRD
BRD	0 or 1	exogenous	dmnl	0=without BRD, 1=with BRD

Continued

Parameter	Function or Value	Type	Unit	Description
PERCENT OF CALVES WEANED WITH BRD HISTORY*	0.025	exogenous	dmnl	Percent of feeder calves marketed with BRD history
WEIGHT LOSS PER SICK CALF DUE TO BRD	6.76 (Snowder, Van Vleck, Cundiff, & Bennett, 2005)	exogenous	kg/head	Weaning weight loss due to BRD per sick calf
weight loss due to BRD per weaning cattle	PERCENT OF CALVES WEANED WITH BRD HISTORY * WEIGHT LOSS PER SICK CALF DUE TO BRD	exogenous	kg/head	Weaning weight loss due to BRD per weaning cattle
WEANING WEIGHT WITH BRD IN INDUSTRY	240.404 (USDA, 2009b)	exogenous	kg/head	The average weaning weight per head for the current situation with BRD problem in the industry
average weaning weight	WEANING WEIGHT WITH BRD IN INDUSTRY+(1-BRD)*weight loss due to BRD per weaning cattle	exogenous	kg/head	Average weaning weight
TREATMENT COST†	0.86	exogenous	$/head	Medicine cost and labor cost to treat BRD
cost to eliminate BRD	0, or 10, or 20, or 30, or 40, or 50	exogenous	$/head	Cost to eliminate BRD
net cost to eliminate BRD	cost to eliminate BRD-TREATMENT COST	exogenous	$/head	Net cost to eliminate BRD

Continued

Parameter	Function or Value	Type	Unit	Description
relation between supply and cattle value	[(5.98862e+009, 53.3156)-(7.27204e+009, 136.019)], (5.98862e+009, 136.019), (6.03324e+009, 130.935), (6.10102e+009, 123.515), (6.21107e+009, 112.251), (6.23498e+009, 109.932), (6.36484e+009, 98.1343), (6.42611e+009, 93.0353), (6.47341e+009, 89.305), (6.54628e+009, 83.9076), (6.67819e+009, 75.2159), (6.69576e+009, 74.1636), (6.69812e+009, 74.0237), (6.72137e+009, 72.6733), (6.72759e+009, 72.3194), (6.73337e+009, 71.9929), (6.79119e+009, 68.877), (6.79603e+009, 68.6284), (6.82216e+009, 67.318), (6.86976e+009, 65.071), (6.87662e+009, 64.7623), (6.91302e+009, 63.1861), (6.94913e+009, 61.7271), (6.97685e+009, 60.6782), (7.09481e+009, 56.9005), (7.12466e+009, 56.1208), (7.24561e+009, 53.691), (7.27204e+009, 53.3156)	exogenous	dmnl	Association between total feeder cattle weight in the market and feeder cattle value
relation between value and net income	[(44, -133.2)-(157.2, 379.2)], (44.7, -133.205), (50.9, -82.4167), (55.9, -49.1208), (58.1, -36.423), (59.5, -28.9199), (60.6, -23.3265), (62, -16.578), (62.6, -13.809), (63.9, -8.05503), (65.4, -1.81859), (67, 4.38002), (68.5, 9.78765), (68.8, 10.8242), (69.3, 12.5193), (71.7, 20.1146), (76.4, 32.6502), (80.8, 42.0462), (82.2, 44.6478), (82.4, 45.0061), (83.7, 47.2595), (86.6, 51.8683), (90.3, 57.1058), (94.5, 62.5408), (98.3, 67.3511), (100.1, 69.6942), (104.7, 76.1748), (105.1, 76.7855), (109.2, 83.6518), (115.1, 96.0917), (120.2, 110.136), (125.3, 128.081), (130.4, 150.733), (135.5, 178.897), (140.5, 212.639), (145.3, 251.45), (150.1, 297.231), (156.4, 369.023), (157.2, 379.158)	exogenous	$/head	Association between feeder cattle value and net income per cow

Continued

Parameter	Function or Value	Type	Unit	Description
relation between net income and change of inventory	[(-159.63, -504984)-(392, 1.01928e+008)], (-159.63, -148870), (-140.1, -20063.4), (-130.1, -8904.58), (-120.1, -26942.5), (-110.1, -68170.9), (-100.1, -126583), (-90.1, -196174), (-78.73, -281248), (-71.93, -331669), (-51.02, -461894), (-46.25, -482372), (-43.98, -490465), (-38.55, -504984), (-23.59, -502739), (-22.86, -500800), (-12.65, -452968), (15.28, -82997.3), (18.04, -23955.4), (18.7, -9166.69), (27.15, 203935), (29.37, 267503), (31.11, 319616), (38.97, 581004), (39.79, 610798), (47.07, 897171), (50.34, 1.03898e+006), (79.7, 2.71656e+006), (86.1, 3.18778e+006), (94.97, 3.90935e+006), (107.85, 5.10672e+006), (108.71, 5.19325e+006), (113.1, 5.64818e+006), (118.2, 6.205e+006), (120.1, 6.42038e+006), (125.1, 7.00815e+006), (130.1, 7.62695e+006), (135.1, 8.27751e+006), (140.1, 8.9606e+006), (145.1, 9.67697e+006), (150.1, 1.04274e+007), (155.1, 1.12125e+007), (160.1, 1.20332e+007), (165.1, 1.28902e+007), (170.1, 1.37842e+007), (175.1, 1.47159e+007), (180.1, 1.56862e+007), (185.1, 1.66958e+007), (190.1, 1.77454e+007), (195.1, 1.88358e+007), (200.1, 1.99677e+007), (205.1, 2.11419e+007), (210.1, 2.23592e+007), (215.1, 2.36202e+007), (220.1, 2.49258e+007), (225.1, 2.62766e+007), (230.1, 2.76735e+007), (235.1, 2.91172e+007), (240.1, 3.06084e+007), (245.1, 3.21479e+007), (250.1, 3.37364e+007), (255.1, 3.53747e+007), (260.1, 3.70636e+007), (265.1, 3.88038e+007), (270.1, 4.0596e+007), (275.1, 4.2441e+007), (280.1, 4.43395e+007), (285.1, 4.62923e+007), (290.1, 4.83002e+007), (295.1, 5.03639e+007), (300.1, 5.24841e+007), (305.1, 5.46617e+007), (310.1, 5.68972e+007), (315.1, 5.91916e+007), (320.1, 6.15455e+007), (325.1, 6.39598e+007), (330.1, 6.6435e+007), (335.1, 6.89721e+007), (340.1, 7.15718e+007), (345.1, 7.42347e+007), (350.1, 7.69617e+007), (353.61, 7.89147e+007), (360.1, 8.26109e+007), (365.1, 8.55346e+007), (370.1, 8.85253e+007), (375.1, 9.15838e+007), (380.1, 9.47109e+007), (385.1, 9.79073e+007), (391.24, 1.01928e+008)	exogenous	dmnl	Association between net income per cow and the change on the inventory after two years

Continued

Parameter	Function or Value	Type	Unit	Description
total feeder cattle market weight	Feeder calves marketed * average weaning weight	endogenous	kg	Total feeder cattle weight in the market per year
feeder cattle value	relation between supply and cattle value(total feeder cattle market weight)	endogenous	dmnl	Feeder cattle value
net income per cow	relation between value and net income(feeder cattle value)+(BRD-1)*net cost to eliminate BRD	endogenous	$/head	Net income per cow
change on the after next year beef cow inventory	relation between net income and change of inventory(net income per cow)	endogenous	head	The change on the year after next year beef cow inventory

* PERCENT OF CALVES WEANED WITH BRD HISTORY*: the value was calculated based on the USDA survey (USDA, 2010a).
TREATMENT COST†: the value was obtained based on the beef cow-calf producer survey and simulated data reported in chapter IV and chapter VI, respectively.

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