A dynamic model of U.S. beef cattle

by

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DEDICATION

I dedicate my dissertation work to my parents, siblings, and loved ones. I also dedicate this dissertation to my younger self, who has decided to embark on this incredible journey.

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ABSTRACT

The primary purpose of this dissertation is the development of an economic framework for the U.S. beef cattle industry that incorporates its dynamic production process. The economic model is conceived upon a bottom-up framework, where the optimizing behavior of a representative producer, the biology, age, and gender composition of cattle, evolving changes in the U.S. cattle structure, and micro-foundations of consumers are incorporated. The model is derived on a consistently measured set of data, and the data are collected and compiled from various U.S. Department of Agriculture (USDA) sources. The economic model is calibrated to fit the observed data appropriately and to replicate the historical evolution of the industry. The calibrated model is then utilized to project beef cattle prices and quantities several years into the future. To validate the model projections, the projected prices and quantities are compared with USDA and Food and Agricultural Policy Research Institute (FAPRI) long-term projections.

The value of the dynamic model developed in this dissertation is demonstrated by estimating the potential economic impacts of a hypothetical Foot-and-Mouth Disease (FMD) outbreak on the U.S. beef cattle industry. The exogenous shocks to the beef cattle industry such as supply, trade, and consumer shocks due to the disease outbreak are incorporated within the model to generate price and supply counterfactuals. Along with the economic impacts, the evolution of inventory levels determined by the model will be of interest to policymakers, industry stakeholders, and researchers. The framework developed in this dissertation proves to be a valuable tool for analyzing the introduction of exogenous shocks such as various production and policy changes in the beef cattle industry.

The first chapter of the dissertation provides an overview of the beef industry, a literature review, and the purpose of the dissertation and its contribution to the literature. In the second chapter, a conceptual model framework is presented, along with an analytical solution, a numerical solution algorithm, and a framework to conduct projections. This chapter also includes a discussion of the data used to solve the model, as well as the numerical solution of the model which includes estimated parameters, fitted results, the model fitted errors and replication of cattle inventories. Also included in Chapter 2 are the model projections and the comparisons of the model projections to USDA and FAPRI projections. The third chapter demonstrates the developed model by estimating the economic impacts of a hypothetical FMD outbreak. The exogenous shocks assumed because of the FMD outbreak are described in this chapter. The scenarios designed to simulate the model, the algorithm used to generate counterfactuals, and the results of the scenarios are also presented in the third chapter. Finally, the fourth chapter serves as a conclusion to the dissertation.

CHAPTER 1. INTRODUCTION

1.1 Topic overview

Agriculture, food, and related industries contributed $1.26 trillion to the U.S. gross domestic product (GDP) in 2021, which is 5.4% of overall GDP [USDA-ERS (2023b)]. Cattle production in the U.S. is crucial to the economy and is a major contributor to the agriculture industry. With its diverse agricultural resources and unique production practices, the United States has developed a beef industry that is separate from the dairy sector. The production of high-quality beef makes the United States competitive in international beef markets. The United States has the world's largest fed cattle industry and produced 28 billion pounds of beef in 2021 and exported 3.4 billion pounds which was valued at $9.9 billion [USDA-ERS (2022b)].[1] The domestic cash receipts from cattle marketed for slaughter, including on-farm slaughter in 2021 were $72.9 billion [USDA-ERS (2022b)]. Figures 1.1 and 1.2 illustrate the export value and domestic cash receipts of U.S. beef from 2002-2021 respectively. In addition to being the largest producer of beef, the United States is also the world's largest consumer of beef, mainly consuming high-quality, grain-fed beef.

[1] The United States is the largest beef producer in the world, but the second largest importer and fourth largest exporter of beef [USDA-FAS (2022)]. Most of the beef exported from the United States is of high quality and is marketed as such.

Figure 1.1 Value of the U.S. beef exports

Figure 1.2 Domestic cash receipts from beef production in the United States

Beef production in the United States is divided into several stages—primarily cow-calf, backgrounding, feedlot, and harvest facilities. Producers move cattle through these production stages to increase profits and minimize costs. The majority of U.S. calves are born in the spring [Schulz et al. (2016); USDA-NASS (2016)]. The newborn calves spend the first few months of their lives with the dam in a cow-calf operation. At around six months of age, a majority of young calves are weaned and sent to backgrounding where they are fed dry forage, silage, and grains for about four to six months. A share of the calves, mostly female, are not sent into backgrounding. They are kept on the farm for replacement breeding stock. The calves in backgrounding are then sent to feedlots where they are fed high-energy grain feed until they reach harvesting age which is typically between 12 and 24 months. Calf-feds typically are 12 to 16 months old at harvest, depending upon the length of the finishing period. Most cattle fed as yearlings or long-yearlings are harvested between 16 and 24 months of age [Stuttgen (2019)]. Ultimately, production timelines for different regions depend on the availability and costs of feed and other resources. For example, in regions with more access to pastureland, cattle often spend more time and gain more weight on pastureland than in feedlots.

For producers, cattle are both capital and consumption goods [Rosen et al. (1994)]. A calf destined for slaughter as a fed animal is a production good, since it will be sold at the market price. In contrast, a calf that is kept on the farm and added to the breeding stock is a capital good because it will contribute to future production for up to 10 years. In the literature, this process is recognized as a *dynamic* process [Rosen et al. (1994); Rosen (1987); Jarvis (1974)]. The dynamic process involves the biology of the female breeding cow, a one-year birth delay and a two-year maturation lag, and the decisions made by the producer about adult cows (whether to consume or breed the cow) and young calves (whether to consume or add the female calves to the breeding stock). The population mechanics in flow chart 1.3 are simplified but depict the general dynamic process of beef cattle production.[2] Once born, every surviving calf enters the production line and stays in the line for two years before joining the mature stock. Then, a representative producer makes a decision about which animals are sent for consumption (includes young steers and heifers and older, mature cows) and production (replacement heifers and mature cows).[3]

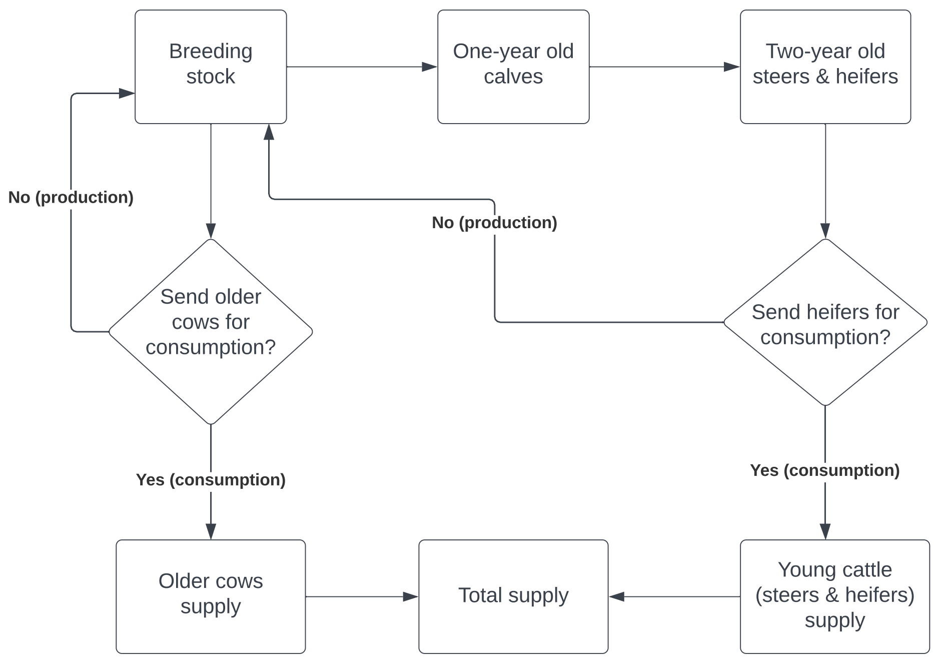

Figure 1.3 Beef cattle production population mechanics

The biology of a mature cow, specifically the gestation and birth delays encapsulates a natural *time-to-build* [Kydland and Prescott (1982)] feature in the age structure of beef cattle. This natural time-to-build feature creates cyclical feedback between current consumption and future production. Any exogenous shock can have persistent effects and can naturally alter the production and investment decisions about beef cattle made by the producers. Ultimately, these decisions change the age distribution of the breeding

[2]The flowchart assumes a closed system. For simplicity, the imports and exports of live animals are not included. The flowchart is inspired by Rosen et al. (1994).

[3]A representative producer makes these decisions annually.

inventories and cause a cyclical response as the cattle approach equilibrium [Rosen et al. (1994)]. This process leads to an expansion and contraction of the cattle inventories. The breeding stock inventory decisions, and the result of the decisions, give rise to *cattle inventory cycles*. Figure 1.4 illustrates the occurrence of cattle cycles in the United States from 1970 to 2021. A typical cattle cycle averages between eight and twelve years [USDA-ERS (2022a); Aadland (2004)] with the latest cattle cycle being ten years (2004-2014). Along with the biology of cattle and the decisions of producers, dry pasture lands and feed supplies may also alter a cattle inventory cycle's length.

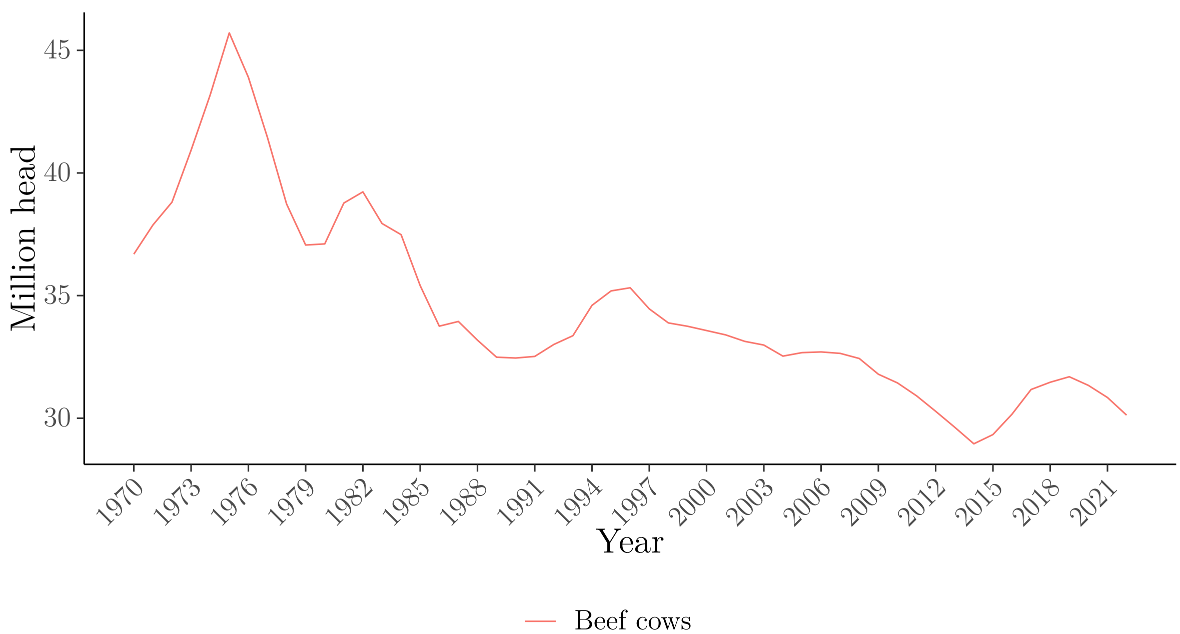

Figure 1.4 Total U.S. beef cow inventories

Even with the existence of natural cattle inventory cycle phenomena, a representative producer makes decisions such that profits are maximized at every stage of the cycle. This is due to expectations made by the producer. In particular, expectations about future prices play an important role in determining the movement of cattle through production stages. Especially, expectation about the price of a young animal and an adult cow is crucial in a producer's decision-making process. A representative producer observes the present price, supply, and demand for beef and cattle, makes expectations about the price of the cattle in the future, leading to a dynamic decision process (on whether to retain the animal for production or use it for consumption). A high expected price leads to building inventories by adding more replacement heifers to the breeding inventory, and a low expected price leads to shrinking inventories by sending older cows to harvest facilities and adding fewer replacement heifers to the breeding stock eventually looping back to the cattle inventory cycle phenomena.

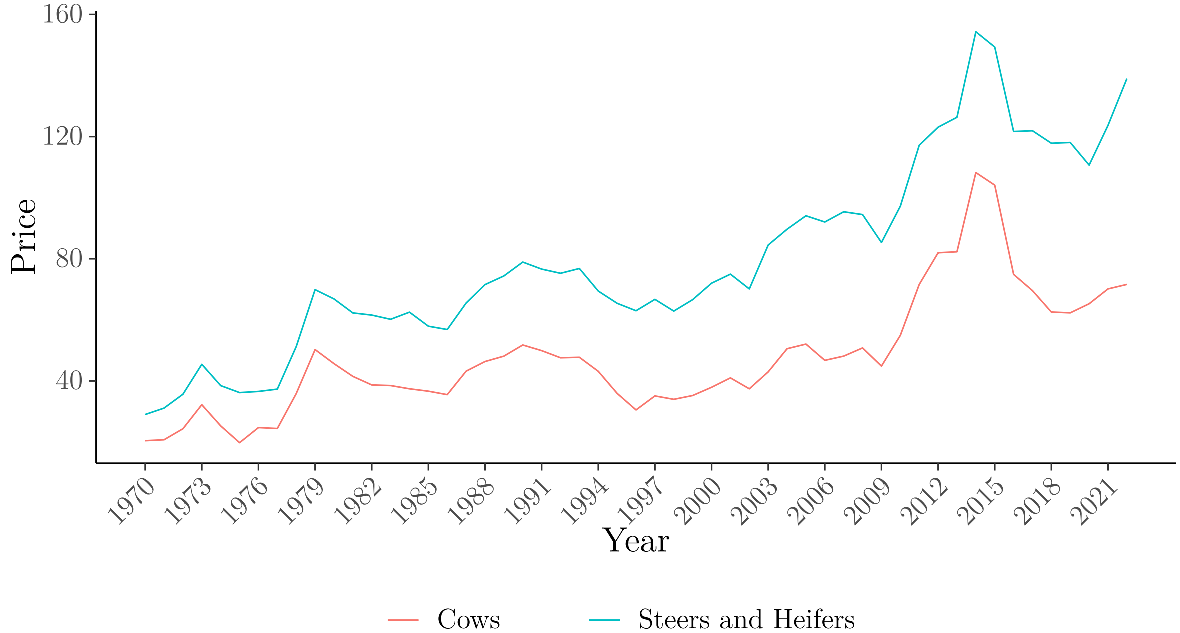

Figure 1.5 Price received by U.S. producers ($/cwt)

The prices received by the producer reflect the cattle inventory cycle phenomena. From Figure 1.5, it is evident the prices received by producers for both young cattle (steers & heifers) and adult cows are trending upwards with occasional peaks and troughs. These peaks and troughs in price are associated with cattle inventory cycles. For example, from the detrended beef cow inventories and prices in Figures 1.6 and 1.7 respectively, the cattle inventory reached trough in 2014 (end of the latest cattle cycle) with a peak observed in the prices in the same year.

Figure 1.6 Detrended U.S. beef cow inventories

Figure 1.7 Detrended prices received by U.S. producers

The persistence of periodical cattle inventory cycles, price cycles (not as pronounced as cattle inventory cycles), and the dynamic process itself in the beef cattle industry, poses some unique and intriguing questions from a theoretical standpoint. In order to fully understand these phenomena, to make important policy recommendations, and to analyze any exogenous shocks on the beef cattle industry, a detailed economic model that considers the biology of cattle, the dynamic optimizing decisions of producers, and the evolving changes in the beef cattle industry is required. This dissertation aims to provide such an economic model. In particular, a structural dynamic economic model of the U.S. beef cattle industry is developed. The dynamic model is built upon a bottom-up framework, where the fundamentals of producers' behavior, biological constraints of beef cattle, age distribution and gender composition of cattle, and micro-foundations of consumers are incorporated. The data-driven structural model is calibrated to adequately capture the dynamics observed in the U.S. beef cattle industry and replicate the historical evolution of the industry. The calibrated model is then used to project beef cattle prices and quantities into the future. In addition to studying the beef industry structure and the dynamics of beef cattle, the dynamic model is shown to be a valuable tool to conduct counterfactual simulations to analyze policy impacts or exogenous shocks within the beef cattle industry and to make important recommendations, making the model of interest to policymakers, industry stakeholders, and beef cattle producers.

1.2 Literature review

The review of the literature on beef cattle industry is divided into three categories. One line of literature aims to explain the expansion and contraction of cattle inventories, the price expectation formation among producers, and the dynamic processes in beef cattle production. The second line of literature aims to study policies affecting U.S. livestock, particularly quantifying the economic impacts of policies, trade bans, and disease outbreaks using static economic models. The third area of literature aims to investigate the market power in the beef packing industry.

1.2.1 Price expectations

Price expectation formation in economics is widely studied and applied in various sub-disciplines of economics. Muth (1961) originally suggested the rational expectations hypothesis and explained the outcome of an economic phenomenon depends on the decisions made by economic agents, and to a certain extent, on what economic agents expect to happen. The rational expectations hypothesis postulates that the economy does not ignore information and expectations depend on the systems involved in the economy.

Rational expectations formulation in agricultural economics has been used and applied in different settings. In the context of U.S. agriculture, Cooley and DeCanio (1977) showed that the producers' price expectations (in aggregate) were consistent with rational expectations theory. Using a simultaneous equation model, Goodwin and Sheffrin (1982) tested the existence of the rational expectations hypothesis in agricultural markets. When applied to the broiler industry, the concept of rational expectations (according to Muth (1961)) was present in producer behavior. Furthermore, Eckstein (1984) developed a dynamic linear rational expectations model to study the impact of price changes on production decisions and land allocation in agricultural settings under exogenous price assumptions. These studies provide evidence that U.S. producers indeed make expectations about prices. In particular, their price expectations are consistent with the rational expectations hypothesis postulated by Muth (1961).

1.2.2 Economic models with price expectations in cattle industry

The seminal work by Jarvis (1974) was the first to coin the phrase "cattle are capital goods and producers are portfolio managers" (p.489). In order to explain producer behavior, using Argentine beef cattle data, Jarvis (1974) analyzed the producer's decision-making process in a microeconomic setting. Rosen (1987) developed a dynamic rational expectations equilibrium model for cattle to explain producer behavior. However, the model does not consider the age and gender composition of cattle. By mathematically modeling U.S. cattle inventory, Rosen et al. (1994) was the first to explain the *cattle cycle* phenomena in the U.S. cattle industry. The simple and straightforward model by Rosen et al. (1994) fit the U.S. cattle inventory data and explained for the first time the expansion and contraction of cattle inventories. Mundlak and Huang (1996) showed that even under different economic settings and different technologies, cattle cycles were observed in Argentina and Uruguay, indicating that regardless of economic conditions, technologies, or location, the decision process of a producer depends on the biology of cattle and price expectations.

Nerlove and Fornari (1998) however, developed a quasi-rational expectations model as an alternative to rational expectations to explain producers' behavior. Using both published and constructed quarterly and monthly data, Nerlove and Fornari (1998) explained the dynamic optimizing behavior of U.S. cattle producers. In contrast, Chavas (2000) showed rational expectations indeed exist in producers' behavior. The empirical results in Chavas (2000) indicate the presence of heterogeneous price expectations, where a large proportion of producers simply use the most recent data ("naïve") to make their production decisions. Although the number of producers with forward-looking price expectations was less compared to naïve expectations, Chavas (2000) provided evidence of the existence of Muth's rational expectations hypothesis [Muth (1961)] among beef cattle producers. Additionally, Chavas (2000) concluded it is costly to access and analyze market information and the cost varies among different market participants. In a related study, Baak (1999) developed a bounded rationality model to test for the existence of different price expectation formations of U.S. beef cattle producers and found the existence of bounded rationality among one-third of producers.

Recognizing the existence of heterogeneous price expectations formation and the criticism of Nerlove and Fornari (1998) about rational expectations, Aadland and Bailey (2001) examined the response of beef cattle producers to changes in beef prices using an economic model with rational expectations. By separating the fed cattle and breeding stock and the corresponding decisions of the producer, the model predicted that, in the short-run, the producers' supply response would be positive to higher prices. Aadland and Bailey (2001) emphasized the importance of separating the fed cattle and breeding cows beef markets when modeling the U.S. beef cattle industry. In related work, Foster and Burt (1992) developed a dynamic model of investments in U.S. beef cattle. The model suggests that incorporating the age distribution of the herd is critical in explaining producers' choices or investment decisions. Schmitz (1997) studied the dynamics of the beef cow herd size using an inventory approach. The study included the age distribution of cattle and by using a simulation strategy, the study estimated the short-run and long-run impacts of shocks on the retention and harvesting of cattle. However, the model abstracted away from price expectations.

In order to explain the recurring cattle cycle, Aadland (2004) developed a forward-looking economic model that takes into account heterogeneous expectations and the age distribution of animals. By allowing two different types of producers (i) fully rational, where producers treat the future variables as endogenous and forecast them, (ii) boundedly rational, where producers use naïve expectations, Aadland (2004) replicated U.S. cattle cycles.

Almost all previous work on the economics of beef cattle has focused on finding evidence for the existence of different expectation formations, explaining the cyclical nature of cattle inventories, determining what the dynamic processes are, and understanding the response of cattle producers to price changes through rational price expectations. The economic models mentioned above do not facilitate the inclusion of age distribution, gender composition, and price expectations of beef cattle, simultaneously. Although the economic models in these studies are constructed to explain producers' behavior in the event of temporary or permanent changes in demand or price, they abstracted away from policy recommendations. These studies, by their construction, often do not have direct applications to investigating impacts of policies affecting the beef cattle industry. An economic model of beef cattle that not only explains producer behavior, but also assists policymakers to develop and assess policies impacting the beef cattle industry is needed.

1.2.3 Policy studies of the U.S. beef cattle industry

There is a host of studies that analyze policy impacts on the beef cattle industry. Traditionally, studies that analyze policy or disease or trade impacts on the beef cattle industry have deviated from the dynamic process and have relied heavily on static Equilibrium Displacement Models (EDMs), Input-Output (I-O) models, and partial equilibrium models.

In order to study the effects of non-governmental costs of mandating an animal identification system on livestock prices, quantities, and producer and consumer surplus, Blasi et al. (2009) developed an EDM. Using different simulation scenarios on animal identification adoption rates, the study quantified the annual costs for beef, pork, lamb, and poultry sectors. In a similar study, using a multi-market EDM, Pendell et al. (2010) examined the impact of animal identification and tracing on U.S. meat and livestock industries. The multi-market EDM facilitates all the stages in the supply chain (farm, wholesale, and retail), and quantifies the short-run impacts on the prices and quantities. Pendell et al. (2013) used EDM to quantify the economic impacts of changes in the source and age verification requirements and related adjustments in the international trade of U.S. beef. To quantify the economic impacts, Pendell et al. (2013) simulated the EDM by assuming the loss of exports to South Korea. The study quantified producer surplus and consumer surplus in the short-run and in a 10-year period.

EDMs have been widely used to study the implementation of mandatory country of origin labeling (MCOOL) in the United States. Brester et al. (2004) employed EDM to estimate short-run and long-run changes in equilibrium quantities and prices in the beef, pork, and poultry industries resulting from implementation of MCOOL. The study simulated two different scenarios (no demand increase, beef and pork demand increase) and found that producer surplus declined (absence of demand increase) by $647.80 million and $220.40 million in beef and pork industries, respectively. The study also reported that a one-time permanent increase of 4.05% beef demand and 4.45% pork demand would be required to offset the losses and gains in the feeder cattle and hog production industries, resulting in a net present value of zero. In a similar study, Tonsor et al. (2015) estimated the economic impacts of the 2009 MCOOL rule and 2013 amendments to the 2009 MCOOL rule on the U.S. livestock industry. The study reported that the implementation of the 2009 MCOOL rule would result in welfare losses of $405 million in the beef industry in the first year, and short-run gains of $105 million and $405 million in the pork and poultry industries respectively. The impacts of the 2013 amendments to the MCOOL rule would increase the economic welfare losses additionally by $494 million for beef and $403 million for the pork industry over the first 10-years. Lusk and Anderson (2004) developed an EDM for retail, wholesale, and farm-level markets for beef, pork, and poultry to study the impact of MCOOL on producers and consumers. The empirical results from the study indicate that, after implementing MCOOL, the costs are shifted from producers to processors and then to retailers. Lusk and Anderson (2004) also concluded, with the adoption of MCOOL, producers are made better off and consumers are made worse off.

EDMs have also been used to study the welfare impacts of trade bans and meat recalls. Mutondo et al. (2009) used an EDM to evaluate the welfare impacts of trade bans by Japan and South Korea in 2003. The analysis included domestic meat, imports, and exports. Using a simulation strategy, the study found that with the Japanese ban on U.S. beef, the welfare of U.S. producers and retailers decreases, and the welfare of Australian and Japanese beef producers and retailers increases. The same phenomenon is observed with a South Korea ban on U.S. beef. Using an EDM, Shiptsova et al. (2002) evaluated the effects of food safety recalls on beef, pork, and poultry industries. The study found that the producer surplus change is always negative for the beef, pork, and poultry industries when there are no substitution effects. Shiptsova et al. (2002) concluded that meat recalls had the largest negative impact on the beef industry and benefited the broiler industry in aggregate.

Static partial equilibrium models, I-O models, and EDMs have been heavily employed to study the impacts of animal vaccination and foreign animal diseases on the U.S. economy. Pendell et al. (2007) used a partial equilibrium and I-O approach to estimate the economic impacts of a foot-and-mouth disease (FMD) outbreak in southwest Kansas. Pendell et al. (2007) simulated the models under different scenarios such as introducing the FMD outbreak at a cow-calf operation, a medium-sized feedlot, and simultaneously at five large feedlots. For each scenario, the study reported producer surplus losses for the beef industry. Tonsor and Schroeder (2015) studied the market impacts of E. Coli vaccination in U.S. feedlots using an EDM and estimated the economic impacts of adopting the vaccination program by the feedlot operators. In particular, the study illustrated the costs associated with the use of a vaccine in fed cattle and reported the economic welfare loss of producers with adopting the program.

The economic models used in all the aforementioned policy studies did not consider dynamics and were simplified significantly (a common theme among all the studies is employing static EDMs to quantify economic impacts). Some of the simplifying assumptions include linear supply and demand curves and parallel shifts in supply and demand. Simplified static models are useful for informing policies and can provide fairly accurate predictions in the short run. However, dynamics are an essential feature in beef cattle production and markets. The use of static models in this setting can be imprecise when trying to predict several years into the future. The inclusion of dynamics can yield more realistic estimates not only in the short run, but also in the long run and show how the estimates vary over time.

1.3 Purpose and contribution to literature

Although dynamics is an important driver of beef cattle markets, current policy analysis discounts its importance and relies heavily on simplified static models. The calibration of these static models uses relatively old and fragile estimates; hence, there is potential to significantly improve beef industry policy analysis by using a dynamic model that calibrates directly from the data rather than relying on static counterfactuals and parameter estimates from the literature. Policies such as restricting the movements of cattle or requiring traceability, identification, vaccination, mitigation of greenhouse gas emissions, and foreign animal disease management strategies routinely reappear in policy discussions of the beef cattle sector. The recurrence of discussions about these policy issues reflects technological improvements that lower costs and open new approaches to old problems, new knowledge, pressure from trading partners, and environmental concerns.

The primary purpose of this dissertation is to develop an economic framework to more appropriately quantify the economic impacts of numerous policy proposals in the U.S. beef cattle sector. To accomplish this, a dynamic economic model that will yield more realistic estimates of the economic impacts of policies affecting the beef cattle sector, and how these impacts vary over time is developed. Using extensive beef cattle industry data, the model is calibrated to capture the dynamics of the U.S. beef cattle industry, replicate the historical evolution of the industry, project prices and quantities into the future, and showcase the models' ability to more realistically estimate the economic impacts of exogenous shocks to the U.S. beef cattle industry.

The structural dynamic model is modeled with naïve and rational price expectations. There are mixed results and beliefs in the literature on the formation of the price expectations and fully rational expectations are highly unlikely among all producers. Some past studies disputed the fully rational expectations formation. In particular, Nerlove and Fornari (1998) used quasi-rational expectations as an alternative to fully rational expectations and used time-series model forecasts to replace future exogenous and endogenous variables. However, Rosen et al. (1994) used fully rational expectations and their model is widely recognized as the leading study to formally explain cattle cycles and made a significant contribution to research on cattle cycles in general. Also, the Rosen et al. (1994) model is simple and easy to navigate. The dynamic model developed in this dissertation is inspired by previous studies, and model terminology is borrowed from Aadland and Bailey (2001), Chavas (2000), and Rosen et al. (1994).

This dissertation complements the existing literature in several ways. First, the economic model extends the existing models explaining beef cattle inventories by modeling producer behavior and price expectations. Contrasting the existing beef cattle models, the dynamic model incorporates both the age distribution and the gender composition of cattle. The inclusion of age distribution and gender composition can complicate the model, but previous research [Foster and Burt (1992)] suggested that they are crucial. In addition to decision-making for young heifers and steers (hereafter referred to as fed cattle), the model also accommodates decision-making for older animals, thus adding another layer to a producers' decision-making process. Using previous research [Powell and Ward (2009); Aadland (2004); Trapp (1986)] and observed data, an assumption that younger cows (six years and less) in the breeding herd are never culled and slaughtered as they are productive is maintained in the model. The possibility of cows exiting the breeding herd due to natural causes or premature death is also incorporated into the model. The model distinguishes the type of cattle and include various age groups of cattle (2-year-old heifers and steers, 3 to 10-year-old cows) to determine the production of fed cattle and adult cows in a given year. The exogenous assumption of prices and quantities (widely made in the literature) is relaxed in the model. By applying micro-foundations on consumer preferences for beef, the share of consumers' purchases of fed cattle and older cow beef are determined separately. Equilibrium conditions are then employed to solve for prices and quantities.

Second, and more importantly, the model can be applied to study a variety of policy impacts, animal disease impacts, and any other exogenous impacts affecting the U.S. beef cattle industry. Knowing not only the short-run impacts, but also knowing the long-run impacts and how the impacts change over time is crucial when policymakers are designing, debating, and deploying any policy that may impact the beef cattle industry. The model allows for counterfactual simulations to better comprehend the short-run and long-run impacts of a policy change or implementation, enabling policymakers to make necessary adjustments to the policies in question.

Third, numerical methods are used to find a solution to the model. Numerical methods are rarely used in models of the beef cattle production process. The equilibrium system for the model is non-linear, so a full closed-form analytical solution cannot be achieved, hence numerical methods are used to find a solution. Solution methods that widely appear in competitive storage literature are borrowed and applied to the cattle model. To the best of my knowledge, this is the first cattle model that utilizes a variety of data (multiple sources are used to collect and compile data), carefully tracks and accounts for observed changes in the beef cattle industry (such as dressed weights of cattle), and uses machine-based algorithms which were developed and programmed by me) to find a solution for the model.

The novelty of the model comes in different features. The presence of both fed cattle and older cows is one of the most important novelty in the model. The solution algorithm of the model can be adapted to different species with biological lags. For example, inspired by the biological constraints and the production lags in the beef industry, Asche et al. (2017) developed a partial equilibrium model for the production of fish when subjected to environmental shocks. This indicates, with slight adjustments, the dynamic framework developed in this dissertation can be adapted to other industries with similar biological lags as those in beef cattle production.

CHAPTER 2. CONCEPTUAL MODEL FRAMEWORK AND SOLUTION TO THE MODEL

2.1 The model

The breeding and inventory modeling approach is inspired by Aadland and Bailey (2001), Chavas (2000), Rosen et al. (1994), and Jarvis (1974). A representative cattle producer is assumed to maximize the discounted future stream of profits for cows of all ages individually. The optimizing behavior of a producer is subject to market and biological constraints. Beef production is modeled to include both fed cattle (steers and heifers) and cull cows (older adult cows). Total cattle numbers and beef supply are determined by producer decisions on slaughtering fed cattle, culling cows, and adding younger breeding stock.[1] Ultimately, the production decisions of a producer depend on market conditions, the age distribution of the herd, biology, and consumer demand for beef from fed cattle and cull cows.

The temporal arbitrage conditions are specific to the age of cattle and are detailed in the following pages. But first, we introduce the notation and the assumptions that underpin the model.

2.1.1 Notation

- $V_{j,t+1}$ is the value of a cow of age j.
- $p_{s,t}$ is the price of fed cattle for slaughter.

[1] Although low in number, bulls play a role in supplying beef. On average bulls made up about 1.8% of the total federally inspected (FI) cattle slaughter in 2021 [USDA-NASS (2021)].

- $p_{c,t}$ is the value of culling[2] a cow at time t. All cows have the same culling value.

- h_t is the unit holding cost of an animal. We assume that it is exogenous, stochastic and depends on the price of corn.

- γ_0 and γ_1 are proportional factors for the cost of holding respectively new-born and one-year-old calves.

- β is the discount factor.

- g is the breeding rate.

- $k_{j,t}$ is the inventory of cows of age j at time t.

- $K_t = \sum_{j=3}^{9} k_{j,t}$ is the total breeding stock.

2.1.2 Assumptions

- Cows can have a calf every year.

- Use the word slaughter for fed cattle and the word cull for cows.

- Once a cow is ten-years old it is culled and has a value $p_{c,t}$.

- A cow is first bred when it is two years old.

- We assume that a cow must survive to the next period for her calf to survive as well. Thus, the size of the calf crop is proportional to the inventory of cows in the next period.

- A cow of age j survives to the next period with a probability δ_j.

[2]Culling is defined as the departure of cows from the herd because of sale, slaughter, salvage, or death [Fetrow et al. (2006)].

- Half of the calves are steers and they are all slaughtered when they are 2 years old. The number of steers at time t is $0.5gK_{t-1}$.
- We ignore the bull population because it is small.
- Heifers are either slaughtered or added to the breeding stock. The number of heifers at time t is $0.5gK_{t-1}$.
- The number of fed cattle slaughtered equals consumption and is written as $q_t = gK_{t-1} - k_{3,t+1}$, where $k_{3,t+1} \leq 0.5gK_{t-1}$.

2.1.3 Holding costs

The discounted cost of holding cows for one more year is given by:

$$z_t = h_t + \beta g \gamma_0 h_{t+1} + \beta^2 g \gamma_1 h_{t+2}. \tag{2.1}$$

The Equation 2.1 states that if a producer retains a cow for another year, the producer commits to the cost of feeding that cow for the next year and its progeny for the next two years. Rosen et al. (1994) specify holding costs in the same way.

The unit holding cost, h_t, depends in large part on the price of feed, mainly the price of corn and on the price of forage, in varying proportions depending on the region. Here, we will take holding costs based on the price of corn, assuming that the price of forage and other feeds are correlated with the price of corn and assuming that other costs are fixed [Suh and Moss (2017)].[3] We calibrate the parameters β, g, γ_0, and γ_1 with information from the literature and from existing cattle models [Aadland (2004); Aadland and Bailey (2001); Baak (1999); Rosen et al. (1994)].

[3]Historical holding costs are estimated from the equilibrium conditions. Then, a linear model is used to establish a relationship between the estimated historical holding costs and historical corn prices. The estimated parameters from the linear model are utilized in the projection framework to determine projected holding costs.

2.1.4 Arbitrage conditions by cohort

The temporal arbitrage conditions are specific to the age of the cattle. These equations take a similar form but it is important to understand timing, in particular for older and younger cows. As such, we derive all the conditions.

Producers with nine-year old cows can either breed them for another year or cull them in the current period. If a producer breeds a nine-year old cow for one more year, the producer will naturally cull the cow, within the context of the model in the next period.

2.1.4.1 Nine-year old cows

The value of a nine-year old cow is

$$V_{9,t} = \max\Big\{p_{c,t}, \mathrm{E}_t[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t]\Big\}, \tag{2.2}$$

where $p_{c,t}$ is the value of culling the cow this year and $\mathrm{E}_t[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t]$ is the net value of breeding the cow this year, culling the cow next year, and capturing the slaughter value from the calf.

If $\mathrm{E}_t\left[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > p_{c,t}$, then a producer keeps the cow for one more year such that $k_{10,t+1} = \delta_9 k_{9,t}$ where δ_9 is the survival rate of nine-year-old cows. That is, if that inequality holds, the producer maximizes profit by breeding all of the nine-year-old cows. Conversely, if $\mathrm{E}_t\left[\beta p_{c,t+1} + g\beta^3 p_{t+3} - z_t\right] < p_{c,t}$, a producer culls all of the nine-year old cows such that $k_{10,t+1} = 0$. Finally, if $\mathrm{E}_t\left[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t\right] = p_{c,t}$, then the producer will cull only a fraction of the cows such that $k_{10,t+1} \in (0, \delta_9 k_{9,t})$.

2.1.4.2 Eight-year old cows

The arbitrage condition for an eight-year old cow is similar. Producers with eight-year old cows can either breed them for one more year or cull them in the current period. A producer would only cull an 8-year cow if the producer had already culled all of the 9-year cows.

If a producer breeds a cow for one more year, they expect to earn $\mathrm{E}_t V_{9,t+1}$ in the next period. Therefore, we write the value of an eight-year old cow as

$$V_{8,t} = \max \Big\{ p_{c,t}, \mathrm{E}_t[\beta V_{9,t+1} + g\beta^3 p_{s,t+3} - z_t] \Big\}. \tag{2.3}$$

At equilibrium, $V_{8,t} \geq V_{9,t}$ because the lowest value it can take is $p_{c,t}$ and $\mathrm{E}_t \left[\beta V_{9,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > \mathrm{E}_t \left[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t\right]$. The value for the 8-year old cow contains the expected value for a 9-year old cow which we write as

$$\mathrm{E}_t V_{9,t+1} = \max \Big\{ \mathrm{E}_t p_{c,t+1}, \mathrm{E}_t[\beta p_{c,t+2} + g\beta^3 p_{s,t+4} - z_{t+1}] \Big\}. \tag{2.4}$$

Substituting 2.4 in 2.3 yields

$$V_{8,t} = \max \Big\{ p_{c,t}, \mathrm{E}_t \Big[\beta \max\{p_{c,t+1}, \beta p_{c,t+2} + g\beta^3 p_{s,t+4} - z_{t+1}\} + g\beta^3 p_{s,t+3} - z_t \Big] \Big\}. \tag{2.5}$$

2.1.4.3 Cows between 3 and 7 years old

For cows between 3 and 7 years old, the arbitrage conditions are analogous to the arbitrage condition for 8-year old cows. We will not fully expand upon all these conditions as they are repetitive and grow in complexity rapidly.

The value of a seven-year old cow is

$$V_{7,t} = \max \Big\{ p_{c,t}, \mathrm{E}_t[\beta V_{8,t+1} + g\beta^3 p_{s,t+3} - z_t] \Big\}. \tag{2.6}$$

We can iteratively substitute for $V_{8,t+1}$ and then $V_{9,t+2}$ to find an expression containing the observed and expected prices.

Producers rarely cull younger cows as they will cull older and lower-performing cows first, so culling cows that are six years old or younger is an unlikely event. The main reason is that the conditions that would lead producers to cull younger cows are quite extreme and in practice, we do not expect such conditions to occur regularly. Younger cows have many years of useful life ahead and a producer would need to have dire expectations about the future to cull a young cow. Another reason is that risk-loving producers may prefer to maintain a sufficiently large breeding herd even though market conditions indicate otherwise. Producers may also have positive outlooks on the future despite the market signaling the opposite.

Based on this observation, we assume that producers never cull cows that are six years old or younger [Powell and Ward (2009); Aadland (2004); Trapp (1986)].[4] The assumption has to do with the comparison of the expected future value and their value for culling. For $k \in \{3, 4, 5, 6\}$, we can write

$$V_{k,t} = \mathrm{E}_t[\beta V_{k+1,t+1} + g\beta^3 p_{s,t+3} - z_t] \geq p_{c,t}. \tag{2.7}$$

The implication is that for younger cattle the annual transition is determined by the survival rate of each cohort such that we can write $k_{4,t+1} = \delta_3 k_{3,t}$, $k_{5,t+1} = \delta_4 k_{4,t}$, $k_{6,t+1} = \delta_5 k_{5,t}$, and $k_{7,t+1} = \delta_6 k_{6,t}$.

2.1.4.4 Two-year old heifers

Producers with two-year old heifers have the choice to either send them to slaughter or add them to the breeding stock. The value of a heifer is

$$V_{2,t} = \max\left\{p_{s,t}, \mathrm{E}_t[\beta V_{3,t+1} + g\beta^3 p_{s,t+3} - z_{t+1}]\right\}, \tag{2.8}$$

where $p_{s,t}$ is the slaughter price. For model simplicity and given the very small number of bulls retained for breeding, the model only considers heifers to be kept in the breeding herd,

[4] In practice, producers will cull sick or injured or underperforming cows. We consider these cases as natural mortality using the parameter for the survival rate, δ_k.

therefore putting an upper limit to the number of heifers bred given by $k_{3,t+1} \leq 0.5gK_{t-1}$. In practice, it is never the case that $k_{3,t+1} = 0$, i.e., no heifers are added to the breeding herd. Thus, we only consider the interior solution where $k_{3,t+1} \in (0, 0.5gK_{t-1})$ such that

$$p_{s,t} = \mathrm{E}_t \left[\beta V_{3,t+1} + g\beta^3 p_{s,t+3} - z_{t+1} \right]. \tag{2.9}$$

2.1.5 Demand for beef and cattle

Beef products from fed cattle and from cows are imperfect substitutes, with fed cattle meat being of higher quality. Only a few higher value cuts such as ribeyes, select loin cuts, and round and chuck cuts are saved from cows, and the rest of the meat and trim is ground. Fed cattle, on the other hand, produce many well-trimmed muscle cuts (e.g., steaks) that are case-ready for grocers [Steiner Consulting Group, DLR Division, Inc. (2021)]. Prices for fed cattle and cull cows reflect the difference in the quality of meat products from cattle of different ages.

The model recognizes the quality difference between beef products from fed cattle and cull cows. The demand for cattle is derived from the demand for beef. Accordingly, we proceed in two steps. We begin by modeling consumer demand for beef products, assuming that distinct products are made out of fed cattle and cull cows. We then turn to beef packing production technology, which allows us to derive an expression for the demand for fed cattle and cull cows.

2.1.5.1 Consumer demand for beef products

Beef from fed cattle is considered a higher quality product than beef from cows. In practice, this means that if prices for beef from fed cattle and beef from cows are the same, consumers will choose beef from fed cattle. This is a simplification because an animal yields many cuts with a wide range of values.

The intensity preference for beef will vary across consumers depending on their intrinsic characteristics. We model these preferences using a standard choice model where the heterogeneity of preferences is captured using a distribution function. The utility a consumer derives from one unit of beef is

$$\theta_j - w_j, \tag{2.10}$$

where w_j is the retail price of beef for $j \in \{s, c\}$. The parameter θ_j is the utility to a consumer of beef of type j, excluding the purchase cost w_j. A consumer purchases beef from fed cattle if

$$\theta \equiv \theta_s - \theta_c > w_s - w_c \equiv w. \tag{2.11}$$

Equation 2.11 says that a consumer purchases beef that yields the most utility. We can interpret θ as consumer willingness to pay for beef from fed cattle over beef from cows, and we can interpret w as the premium for fed cattle beef over beef from cows.

The parameter θ summarizes consumer preferences. Consumers are not identical, and we expect some to have strong preferences for a steak from fed cattle while others are content with ground beef coming mostly from cows. Let $h(\theta)$ represent the marginal distribution of willingness to pay, defined between a lower bound of $\underline{\theta}$ and an upper bound of $\overline{\theta}$. Consumers who purchase beef from fed cattle over beef from cows are those with a willingness to pay a greater price premium as equation 2.11 shows.

The share of consumers' purchases of beef from fed cattle is

$$\int_{w}^{\overline{\theta}} h(\theta) d\theta = 1 - H(w). \tag{2.12}$$

The share of consumers' purchases of beef from cows is

$$\int_{\underline{\theta}}^{w} h(\theta) d\theta = H(w). \tag{2.13}$$

Because the cumulative distribution function $H(w)$ is increasing, the share of beef derived from fed cattle purchased by beef packers decreases as the price premium w increases. Conversely, the share of beef derived from cull cows purchased by packers increases as the price premium w increases.

Equations 2.12 and 2.13 give the consumption shares for a given premium w. We multiply these shares by the total consumption of beef. The total consumption of beef is defined as

$$Q_b(w_s, w_c) = Q_s(w_s, w_c) + Q_c(w_s, w_c), \tag{2.14}$$

where we can write $Q_s(w_s, w_c) = \Big(1 - H(w)\Big)Q_b(w_s, w_c)$ and $Q_c(w_s, w_c) = H(w)Q_b(w_s, w_c)$. The total demand for beef, $Q_b(w_s, w_c)$, depends on prices for the beef categories. The specification of $H(w)$ is discussed in the next section.

We simplify by assuming that the aggregate demand for beef is inelastic to price [Aadland (2004); Aadland and Bailey (2001); Capps et al. (1994); Marsh (1991)] in the short run such that $A = Q_b(w_s, w_c)$. The reason for this assumption is that it will make the calibration of the model much simpler. Although we assume an inelastic demand in the short run, we can allow the value of A to change over time to adjust for trends and to vary according to changes in the price of beef relative to other meat products. We can also introduce stochasticity in demand through the demand parameter A or by using an additive stochastic parameter to the demand equation. In the calibration, we use observed data to determine A.[5]

In what follows, it is useful to work with inverse demand equations. We write the inverse demand functions as $w_s(Q_s, Q_c)$ and $w_c(Q_s, Q_c)$.

[5]Federally inspected slaughter data of fed cattle and older cows is used to determine the total beef disappearance.

2.1.5.2 Derived demand by packing plants

The beef supply chain is as follows: beef packers purchase cattle from producers, the cattle are then processed in slaughter facilities, the beef is then sold to wholesalers, then to retailers, and the meat finally reaches consumers. At the retail to consumer level the complexity certainly increases because of the number of different products involved and alternative market outlets. The retail to consumer level includes grocery store, food service, internet on-line shopping, and export sales. We simplify the supply chain by assuming beef packers purchase cattle from producers and sell meat to consumers.[6] Therefore, the beef packers demand cattle from producers and supply meat to consumers. We derive these supply and demand curves based on the packer's production technology.

We focus on packers who process both fed cattle and cull cows. In practice, most packers specialize in the processing of fed cattle or the processing of cull cows. We do not expect these plants to switch to cattle of another age category unless there is a large change in their relative prices. Some plants do accept both fed cattle and cull cows. These plants will typically accept fed cattle on certain days of the week and cull cows on other days of the week. The number of days dedicated to each age category depends on their relative profitability. Plants that can arbitrage between cattle of the two age categories are the ones that matter at the margin.[7] This is why we focus on the profit of a plant that can process animals of the two age categories.

[6] This simplification is done as we do not model the wholesalers and retailers which decreases the complexity of the model, focusing the model on consumers and producers.

[7] This assumes no corner solution where the capacity to process cattle of a certain age category is binding.

The production technology of transforming live cattle into meat is straightforward. Live cattle carcass yield is on average about $62-64\%$.[8] The yield varies by cattle weight and cattle breed, as well as cattle age.[9]

We assume that packers have Leontief production technology where the total quantity of beef produced by a plant n is given by

$$q_n = q_{ns} + q_{nc} = \min(\phi_s X_{ns} + \phi_c X_{nc}, m), \tag{2.15}$$

where ϕ_i is meat yield, X_{ni} is the quantity of cattle of category $i \in \{s, c\}$ and m is the quantity of other inputs. The literature provides evidence of increasing returns to scale in meatpacking [Xia and Steven (2002); Azzam and Anderson (1996); Ball and Chambers (1982)]. However, assuming constant returns to scale simplifies the model and is consistent with fixed processing capacity in the short run.

We write the profit of a packing plant as

$$\Pi_n = w_s \phi_s X_{ns} + w_c \phi_c X_{nc} - p_s X_{ns} - p_c X_{nc} - (\phi_s X_{ns} + \phi_c X_{nc}) p_m, \tag{2.16}$$

where p_m is the price of other inputs. Taking the first order conditions and assuming perfect competition yields

$$\phi_s w_s - p_s - \phi_s p_m \leq 0, \tag{2.17}$$

$$\phi_c w_c - p_c - \phi_c p_m \leq 0. \tag{2.18}$$

[8] Penn State Extension; Understanding Beef Carcass Yields and Losses During Processing - December 18, 2022. For more information, see https://extension.psu.edu/understanding-beef-carcass-yields-and-losses-during-processing.

[9] The meat yield is lower, as not all bones and fat are sold to consumers at retail. For example, fat rendering is used as an input in the production of biodiesel. Out of 750 pound fed steer carcass, about 450 pounds is boneless trimmed beef, 150 pounds fat trim, and 110 pounds bone are captured. See https://extension.sdstate.edu/how-much-meat-can-you-expect-fed-steer (updated July 13, 2022) for more information.

For a competitive packer, the first-order conditions permit three solutions: two corner solutions where the plant processes only either fed cattle or cows and an interior solution where it processes both. The interest here is in a marginal plant that will process both (cattle) categories, such that the two first-order conditions hold with equality. These equations give us that $p_s = \phi_s(w_s - p_m)$ and $p_c = \phi_c(w_c - p_m)$, such that we can write the inverse demand for fed cattle as

$$p_s(X_s, X_c) = \phi_s(w_s(\phi_s X_s, \phi_c X_c) - p_m), \tag{2.19}$$

and for cows as

$$p_c(X_s, X_c) = \phi_c(w_c(\phi_s X_s, \phi_c X_c) - p_m). \tag{2.20}$$

Thus, the demand for fed cattle and cows are proportional to the beef products for the two categories and shifted down reflecting processing costs. Since we are working with beef from fed cattle and cows, and because the beef from these categories has limited substitutability [Coffey et al. (2011)], we are using single-equation demand equations for both types of beef.

For the purpose of calibrating the model to the data, we must specify a functional form for the demand, which requires specifying an expression for $H(w)$. We want a distribution function defined over the positive and negative intervals, capable of capturing a wide range of preferences for beef products and possessing few parameters, so we can more easily calibrate it to the data. One such function is the logistic distribution:

$$H(w) = \frac{1}{1 + \exp\left(\frac{\mu - w}{\sigma}\right)}, \tag{2.21}$$

where μ is the mean and median willingness to pay for beef from fed cattle over beef from cows and σ is a scale parameter. The variance of the logistic distribution is $(\sigma^2\pi^2)/3$.

We can express the distribution of willingness to pay as it applies to the derived demand for cattle by a packer. From the first order conditions for a packer's profit maximization, we can write $w_s = \frac{p_s}{\phi_s} + p_m$ and $w_c = \frac{p_c}{\phi_c} + p_m$ such that $w \equiv w_s - w_c = \frac{p_s}{\phi_s} - \frac{p_c}{\phi_c} = \widetilde{p}_s - \widetilde{p}_c \equiv \widetilde{p}$. We must also adjust the units for μ and σ. In the distribution of willingness to pay for beef, μ and σ are measured in dollars per pound of beef. To modify these parameters into dollars per pound of live cattle, we multiply them by ϕ which is measured in pounds of beef per pound of live cattle such that $\widetilde{\mu} = \phi\mu$ and $\widetilde{s} = \phi s$. The distribution function becomes

$$H(\widetilde{p}) = \frac{1}{1 + \exp\left(\frac{\tilde{\mu} - \tilde{p}}{\tilde{s}}\right)}. \tag{2.22}$$

We further adjust the parameter for the demand intensity by writing that $\widetilde{A} = \frac{A}{\phi}$ such that the demand for fed cattle is given by $X_s = \widetilde{A}(1 - H(\widetilde{p}))$ and the demand for cull cows is given by $X_c = \widetilde{A}H(\widetilde{p})$. Where A and $\tilde{A}$ are the estimated total quantities demanded for cattle and total demand for beef respectively.[10]

Calibrating the demand equations will require finding values for the parameters μ, s, ϕ_s and ϕ_c. We find values for μ and s from the observed value for p and other historical data. From equation 2.22, it should be noted that $(1 - H(\widetilde{p}))$ and $H(\widetilde{p})$ can be treated as the share of consumers' purchases of fed cattle beef and cull cow beef respectively. The algorithm to determine the parameters μ and s is provided in appendix A.

2.2 Solving the model

The model comprises several equations and variables. In what follows, we focus on the equations that describe how producers optimize their profits by choosing to breed, slaughter, or cull cattle. After solving these equations, we solve for prices and quantities.

[10]These are estimated using the constructed population distribution of cattle.

The equations of the model are as follows:

$$gK_{t-1} - k_{3,t+1} = \tilde{A}\frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.23}$$

$$k_{10,t} + \sum_{j=7}^{9}(k_{j,t} - k_{j+1,t+1}) = \tilde{A}\frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.24}$$

$$p_{s,t} = E_t\left[\beta V_{3,t+1} + g\beta^3 p_{s,t+3} - z_t\right], \tag{2.25}$$

$$V_{3,t} = E_t\left[\beta V_{4,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > p_{c,t} \implies k_{4,t+1} = \delta_3 k_{3,t}, \tag{2.26}$$

$$V_{4,t} = E_t\left[\beta V_{5,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > p_{c,t} \implies k_{5,t+1} = \delta_4 k_{4,t}, \tag{2.27}$$

$$V_{5,t} = E_t\left[\beta V_{6,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > p_{c,t} \implies k_{6,t+1} = \delta_5 k_{5,t}, \tag{2.28}$$

$$V_{6,t} = E_t\left[\beta V_{7,t+1} + g\beta^3 p_{s,t+3} - z_t\right] > p_{c,t} \implies k_{7,t+1} = \delta_6 k_{6,t}, \tag{2.29}$$

$$V_{7,t} = \max\left\{p_{c,t}, E_t\left[\beta V_{8,t+1} + g\beta^3 p_{s,t+3} - z_t\right]\right\}, \tag{2.30}$$

$$V_{8,t} = \max\left\{p_{c,t}, E_t\left[\beta V_{9,t+1} + g\beta^3 p_{s,t+3} - z_t\right]\right\}, \tag{2.31}$$

$$V_{9,t} = \max\left\{p_{c,t}, E_t\left[\beta p_{c,t+1} + g\beta^3 p_{s,t+3} - z_t\right]\right\}, \tag{2.32}$$

$$V_{10,t} = p_{c,t} \implies k_{11,t} = 0. \tag{2.33}$$

Equation 2.23 says that the supply of fed cattle equals the demand for fed cattle. Similarly, equation 2.24 says that the supply of cull cows equals the demand for cull cows. Equation 2.25 is the arbitrage condition for fed cattle. Equations 2.26-2.29 are the arbitrage conditions for cows between 3 and 6 years of age. Note that we assume producers never cull cows six years or younger which implies that the number of cows for these younger cohorts carries to the next year, adjusting for mortality. Equations 2.30-2.32 determine the choice between retaining cows for one more year or culling cows between 7 and 9 years of age. Finally, equation 2.33 says that all 10-year cows are culled such that there are no 11-year old cows.

The next step is to specify how producers form their expectations about future prices. In fact, the equations 2.23-2.32 imply that producers form price expectations for prices several years into the future. The following subsections present analytical solutions and numerical solution algorithms under naïve and rational price expectations. To simplify the model, we assume $\delta_j \forall j \in [3,9] = \delta$.[11]

2.2.1 Naïve price expectations

We refer to *naïve* expectations as a situation where producers use prices in the current period as the expected prices in all future periods.[12] For example, under naïve expectations, we can write that

$$\mathrm{E}_t p_{s,t+3} = \mathrm{E}_t p_{s,t+2} = \mathrm{E}_t p_{s,t+1} = p_{s,t}, \tag{2.34}$$

and

$$\mathrm{E}_t p_{c,t+3} = \mathrm{E}_t p_{c,t+2} = \mathrm{E}_t p_{c,t+1} = p_{c,t}. \tag{2.35}$$

Assuming naïve expectations simplifies the model quite significantly. Equations 2.23 and 2.24 remain unchanged as they only contain contemporaneous variables. For cohort from $j = 2$ to $j = 9$, we have the following equalities

$$p_{s,t} = \beta \mathrm{E}_t V_{3,t+1} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t \Big(1 + \beta g(\gamma_0 + \beta\gamma_1)\Big), \tag{2.36}$$

$$k_{j+1,t+1} = \delta k_{j,t} \quad \forall j \in [3,4,5,6], \tag{2.37}$$

$$V_{j,t} = max\Big\{p_{c,t}, \beta \mathrm{E}_t \Big[V_{j+1,t+1} + g\beta^3 p_{s,t} - E_t h_t \Big(1 + \beta g(\gamma_0 + \beta\gamma_1)\Big)\Big]\Big\} \quad \forall j \in [7,8,9], \tag{2.38}$$

$$V_{10,t} = p_{c,t} \implies k_{11,t} = 0. \tag{2.39}$$

[11]This assumption is consistent with Aadland (2004), Aadland and Bailey (2001), and Chavas (2000). Relaxing this assumption will not significantly impact the model solution.

[12]We can alternatively use the price in the previous period. This would actually make it simpler to solve the model, but it would be less realistic, as it would assume that producers ignore the information provided by the current price.

We assume that h_t is stationary such that $\mathrm{E}_t h_t = \mathrm{E}_t h_{t+1} = \mathrm{E}_t h_{t+2}$. Under naïve expectations, the model reduces to four cases. We describe the equations for cows aged between 7 and 10 years of age below for these four cases.

2.2.1.1 Case I: Only 10-year old cows are culled

The first case is where producers only cull 10-year old cows. In that situation, the equations for cows aged between 7 and 10 years of age below are:

$$\begin{aligned} k_{j+1,t+1} &= \delta k_{j,t} \quad \forall j \in [7,8], \\ \beta p_{c,t} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t \left(1 + \beta g(\gamma_0 + \beta\gamma_1)\right) > p_{c,t} &\implies k_{10,t+1} = \delta k_{9,t}, \\ V_{10,t} = p_{c,t} &\implies k_{11,t} = 0. \end{aligned} \tag{2.40}$$

Observe that we do not need to solve for $\mathrm{E}_t V_{10,t+1}$, $\mathrm{E}_t V_{9,t+1}$ or $\mathrm{E}_t V_{8,t+1}$ because we assume that producers cull older cows first. Thus, because producers do not cull 9-year old cows, they do not cull 8 and 7-year-old cows either.

2.2.1.2 Case II: Some nine-year old cows are culled

In the second case, producers cull some nine-year old cows. The equations for cows aged between 7 and 10 years of age below are:

$$\begin{aligned} k_{j+1,t+1} &= \delta k_{j,t} \quad \forall j \in [7,8], \\ \beta p_{c,t} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t \left(1 + \beta g(\gamma_0 + \beta\gamma_1)\right) = p_{c,t} &\implies k_{10,t+1} \leq \delta k_{9,t}, \\ k_{11,t} &= 0. \end{aligned} \tag{2.41}$$

Again, we do not need to solve for $\mathrm{E}_t V_{9,t+1}$ or $\mathrm{E}_t V_{8,t+1}$ because we assume that producers cull older cows first. We solve for $k_{10,t+1}$ using the arbitrage equality for 10-year old cows.

2.2.1.3 Case III: Some eight-year old cows are culled

The third case is when producers cull some eight-year old cows. The equations for cows aged between 7 and 10 years of age for that case are:

$$\begin{aligned} k_{8,t+1} &= \delta k_{7,t}, \\ \beta p_{c,t} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t \left(1 + \beta g(\gamma_0 + \beta\gamma_1)\right) = p_{c,t} \implies k_{9,t+1} &\leq \delta k_{8,t}, \\ k_{j+1,t+1} &= 0 \quad \forall j \in [9, 10]. \end{aligned} \tag{2.42}$$

2.2.1.4 Case IV: Some seven-year old cows are culled

Finally, the last case is when producers cull some or all of their seven-year old cows. The equations for cows aged between 7 and 10 years of age below are:

$$\begin{aligned} \beta p_{c,t} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t \left(1 + \beta g(\gamma_0 + \beta\gamma_1)\right) \leq p_{c,t} \implies k_{8,t+1} &\leq \delta k_{7,t}, \\ k_{j+1,t+1} &= 0 \quad \forall j \in [8, 9, 10]. \end{aligned} \tag{2.43}$$

2.2.1.5 Expected return for a two-year old heifer

Equation 2.36 contains $\mathrm{E}_t V_{3,t+1}$, the expected value of a three-year-old cow in the next period. This value contains expectations for the return of a cow for its entire life. We must compute the expression $\mathrm{E}_t V_{3,t+1}$ and assuming naïve expectations significantly simplifies the process. After a few substitutions, we can write the expression for the discounted expected return of a three-year-old cow as

$$\beta \mathrm{E}_t V_{3,t+1} = \beta^5 \mathrm{E}_t V_{7,t+5} + g\beta^4(1+\beta+\beta^2+\beta^3)p_{s,t} - (1+\beta+\beta^2+\beta^3)(1+\beta g(\gamma_0+\beta\gamma_1))\mathrm{E}_t h_t. \tag{2.44}$$

In this expression, we stopped computing expectations for cows that are seven years old or older because we have not described yet how producers form expectations about how long they will retain a cow.

We assume that producers will only cull cows that are seven years or older. This means that a forward looking producer would assign probabilities that they will cull a cow at ages between 7 and 10 years old. In practice, we could assign these probabilities and use them to calculate $\mathrm{E}_t V_{7,t+5}$. However, we will adopt a simpler approach because in practice most cows are culled either at 9 or 10 years old [Aadland (2004); Trapp (1986)]. Therefore, when calculating $\mathrm{E}_t V_{7,t+5}$, we assume that a cow is culled only at the end of its useful life, i.e., 10 years old, and that market conditions do not play a role in early culling. This simplifying assumption does not play an important role in the model because the expected value of older cows is quite heavily discounted.[13]

2.2.1.6 Solution for Case I: Only 10-year old cows are culled

With the assumption that producers expect to keep their cows until they are 10 years old, we can write after a few manipulations that

$$\beta \mathrm{E}_t V_{3,t+1} = \beta^8 p_{c,t} + g\beta^4 \frac{1-\beta^7}{1-\beta} p_{s,t} - \beta\Big(1 + \beta g(\gamma_0 + \beta\gamma_1)\Big)\frac{1-\beta^7}{1-\beta}\mathrm{E}_t h_t. \tag{2.45}$$

We can insert equation 2.45 in equation 2.36 to complete and solve the model under naïve expectations. By plugging in equation 2.45 in equation 2.36 and after some manipulations, the system for Case I becomes

$$k_{11,t} = 0, \tag{2.46}$$

$$k_{j+1,t+1} = \delta k_{j,t} \quad \forall j \in [3,4,5,6,7,8,9,] \tag{2.47}$$

$$p_{s,t} = \beta^8 p_{c,t} + g\beta^3 p_{s,t}\frac{1-\beta^8}{1-\beta} - \Big(1 + g\beta(\gamma_0 + \beta\gamma_1)\Big)\frac{1-\beta^8}{1-\beta}\mathrm{E}_t h_t, \tag{2.48}$$

$$k_{10,t} = \tilde{A}\frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.49}$$

$$gK_{t-1} - k_{3,t+1} = \tilde{A}\frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}. \tag{2.50}$$

[13] The assumption is also consistent with the often optimistic view that producers have regarding their livestock. It might indeed be the case that producers always expect to keep their cows for 10 years [Powell and Ward (2009)].

2.2.1.7 Solution for Case II: Some nine-year old cows are culled

In this case, we assume that producers keep their cows until they are nine years old and then cull them. After a few manipulations $\beta \mathrm{E}_t V_{3,t+1}$ becomes

$$\beta \mathrm{E}_t V_{3,t+1} = \beta^7 p_{c,t} + g\beta^4 \frac{1-\beta^6}{1-\beta} p_{s,t} - \beta(1 + \beta g(\gamma_0 + \beta\gamma_1)) \frac{1-\beta^6}{1-\beta} \mathrm{E}_t h_t. \tag{2.51}$$

Similar to Case I we insert equation 2.51 in equation 2.36 and solve the model under naïve expectations. After some manipulations, the system for Case II becomes

$$k_{11,t} = 0, \tag{2.52}$$

$$\beta p_{c,t} + g\beta^3 p_{s,t} - \mathrm{E}_t h_t (1 + \beta g(\gamma_0 + \beta\gamma_1)) = p_{c,t} \implies k_{10,t+1} \leq \delta k_{9,t}, \tag{2.53}$$

$$k_{j+1,t+1} = \delta k_{j,t} \quad \forall j \in [3, 4, 5, 6, 7, 8], \tag{2.54}$$

$$p_{s,t} = \beta^7 p_{c,t} + g\beta^3 p_{s,t} \frac{1-\beta^7}{1-\beta} - (1 + g\beta(\gamma_0 + \beta\gamma_1)) \frac{1-\beta^7}{1-\beta} \mathrm{E}_t h_t, \tag{2.55}$$

$$k_{9,t} + \sum_{j=7}^{8} (k_{j,t} - k_{j+1,t+1}) = \tilde{A} \frac{1}{1 + \exp\left(\frac{\tilde{\mu} - \tilde{p}}{\tilde{s}}\right)}, \tag{2.56}$$

$$gK_{t-1} - k_{3,t+1} = \tilde{A} \frac{\exp\left(\frac{\tilde{\mu} - \tilde{p}}{\tilde{s}}\right)}{1 + \exp\left(\frac{\tilde{\mu} - \tilde{p}}{\tilde{s}}\right)}. \tag{2.57}$$

For all other cases (cases III and IV), we can solve the model analogously to the previous cases. For brevity, we do not present them here. Once we have analytic expressions, all we have to do is solve for the parameters using the system of equations. We use the observed data and numerical methods to solve for the parameter values. Note that here we always have a boundary condition that is $0.5gK_{t-1} > k_{3,t+1}$. This boundary condition ensures that we calculate realistic quantities and prices.

2.2.2 Rational price expectations

We refer to *rational* expectations as a situation where the producers use all the information available in the economy to make price expectations. The information may include present and past prices, production, and disappearance of fed cattle and cull cows. The system of equations under rational price expectations is as follows:

$$gK_{t-1} - k_{3,t+1} = \tilde{A}\frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.58}$$

$$k_{10,t} + \sum_{j=7}^{9}(k_{j,t} - k_{j+1,t+1}) = \tilde{A}\frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.59}$$

$$p_{s,t} = \beta \mathrm{E_t} V_{3,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t, \tag{2.60}$$

$$k_{4,t+1} = \delta k_{3,t}, \tag{2.61}$$

$$k_{5,t+1} = \delta k_{4,t}, \tag{2.62}$$

$$k_{6,t+1} = \delta k_{5,t}, \tag{2.63}$$

$$k_{7,t+1} = \delta k_{6,t}, \tag{2.64}$$

$$V_{7,t} = max\Big\{p_{c,t}, \beta \mathrm{E_t} V_{8,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t\Big\}, \tag{2.65}$$

$$V_{8,t} = max\Big\{p_{c,t}, \beta \mathrm{E_t} V_{9,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t\Big\}, \tag{2.66}$$

$$V_{9,t} = max\Big\{p_{c,t}, \beta \mathrm{E_t} p_{c,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t\Big\}, \tag{2.67}$$

$$V_{10,t} = p_{c,t}. \tag{2.68}$$

Assuming a producer never culls a cow younger than six years of age, we have a variety of conditions that describe the decisions of the producers about culling older cows. These decisions reduce to four different cases, paralleling the cases under naïve expectations.

2.2.2.1 Case I: Only 10-year old cows are culled

In this case, producers only cull the 10-year old cows. Hence, the equations for cows aged between 7 and 10 are as below:

$$k_{j+1,t+1} = \delta k_{j,t} \forall j \in [7,8], \tag{2.69}$$

$$\beta \mathrm{E_t} p_{c,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t > p_{c,t} \implies k_{10,t+1} = \delta k_{9,t}, \tag{2.70}$$

$$V_{10,t} = p_{c,t} \implies k_{11,t} = 0. \tag{2.71}$$

2.2.2.2 Case II: Some nine-year old cows are culled

In this case, producers cull some 9-year old cows in addition to all 10-year old cows. The set of expressions for cows aged between 7 and 10, in this case, are as below:

$$k_{j+1,t+1} = \delta k_{j,t} \forall j \in [7,8], \tag{2.72}$$

$$\beta \mathrm{E_t} p_{c,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E_t} h_t = p_{c,t} \implies k_{10,t+1} \leq \delta k_{9,t}, \tag{2.73}$$

$$k_{11,t} = 0. \tag{2.74}$$

In Case I and Case II, we don't need to solve for $\mathrm{E_t} V_{9,t+1}$ and $\mathrm{E_t} V_{8,t+1}$. This is because we assume that producers cull all the older cows first. Similar to Case I and Case II, we can also express the equation system for the cases where some 8-year old cows are culled and some 7-year old cows are culled. For brevity, we do not present them here.

2.2.2.3 Expected return for a two-year old heifer

Equation 2.60 contains the expected value of the three-year-old cow $\mathrm{E_t} V_{3,t+1}$. Contrary to naïve expectations where we simply replace the expected price with the price at t, we write the expected price as is and by iterative substitution, equation 2.60 can be rewritten as

$$\mathrm{E_t} V_{3,t+1} = \beta^4 \mathrm{E_t} V_{7,t+5} + g \sum_{i=3}^{6} \beta^i p_{s,t+1+i} - \sum_{i=0}^{3} \beta^i z_{t+1+i}. \tag{2.75}$$

2.2.2.4 Solution for Case I: Only 10-year old cows are culled

Assuming producers expect to keep their cows until they are 10 years old, after some few manipulation equation 2.75 can be written as

$$\mathrm{E_t} V_{3,t+1} = \beta^7 p_{c,t+8} + g \sum_{i=3}^{9} \beta^i p_{s,t+1+i} - \sum_{i=0}^{5} \beta^i z_{t+1+i}, \tag{2.76}$$

where z is the discounted holding costs. By replacing $\mathrm{E_t} V_{3,t+1}$ in equation 2.60 with equation 2.76, we get

$$p_{s,t} = \beta^8 p_{c,t+7} + g \sum_{i=4}^{10} \beta^i p_{s,t+i} + g\beta^3 \mathrm{E_t} p_{s,t+3} - \sum_{i=1}^{7} \beta^i z_{t+i}. \tag{2.77}$$

Finally, by replacing equation 2.60 with equation 2.77, the final solution for Case I is

$$gK_{t-1} - k_{3,t+1} = \tilde{A} \frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.78}$$

$$k_{10,t} + \sum_{j=7}^{9} (k_{j,t} - k_{j+1,t+1}) = \tilde{A} \frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.79}$$

$$p_{s,t} = \beta^8 p_{c,t+7} + g \sum_{i=4}^{10} \beta^i p_{s,t+i} + g\beta^3 \mathrm{E_t} p_{s,t+3} - \sum_{i=1}^{7} \beta^i z_{t+i}, \tag{2.80}$$

$$k_{j+1,t+1} = \delta k_{j,t} \quad \forall j \in [3,4,5,6,7,8], \tag{2.81}$$

$$p_{c,t} = \beta \mathrm{E_t} p_{c,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1)) \mathrm{E_t} h_t. \tag{2.82}$$

2.2.2.5 Solution for Case II: Some nine-year old cows are culled

In this case, we assume producers keep their cows until they are nine years old and then cull them. With some substitution, equation 2.75 can be written as

$$\mathrm{E_t} V_{3,t+1} = \beta^6 p_{c,t+7} + g \sum_{i=3}^{8} \beta^i p_{s,t+1+i} - \sum_{i=0}^{5} \beta^i z_{t+1+i}, \tag{2.83}$$

where z is the discounted holding costs. By replacing $\mathrm{E_t} V_{3,t+1}$ in equation 2.60 with equation 2.83, we get

$$p_{s,t} = \beta^7 p_{c,t+7} + g \sum_{i=4}^{9} \beta^i p_{s,t+i} + g\beta^3 \mathrm{E_t} p_{s,t+3} - \sum_{i=1}^{6} \beta^i z_{t+i}. \tag{2.84}$$

Finally, by replacing equation 2.60 with equation 2.84, the final solution for Case II becomes

$$gK_{t-1} - k_{3,t+1} = \tilde{A} \frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.85}$$

$$k_{10,t} + \sum_{j=7}^{9} (k_{j,t} - k_{j+1,t+1}) = \tilde{A} \frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.86}$$

$$p_{s,t} = \beta^7 p_{c,t+7} + g \sum_{i=4}^{9} \beta^i p_{s,t+i} + g\beta^3 \mathrm{E_t} p_{s,t+3} - \sum_{i=1}^{6} \beta^i z_{t+i}, \tag{2.87}$$

$$k_{j+1,t+1} = \delta k_{j,t} \quad \forall j \in [3,4,5,6,7,8], \tag{2.88}$$

$$p_{c,t} = \beta \mathrm{E_t} p_{c,t+1} + g\beta^3 \mathrm{E_t} p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1)) \mathrm{E_t} h_t. \tag{2.89}$$

The above system is the analytical solution of the rational expectations model (Case I and Case II). The solution system is solved to obtain equilibrium prices and quantities. Note that, the system of equations contains the expected price of the fed cattle three periods ahead and the expected price of the cull cow one period ahead. We must know these expected prices to find the equilibrium solution.[14]

[14] We rely on numerical methods to compute the expected price.

Under rational expectations, producers have the ability to make expectations about prices by using all the information available to them. Forming expectations requires knowing the production (in the number of head) of cattle in future periods. Although it is not possible to know future production with absolute certainty, an approximation of future production is sufficient to make expectations about prices. At time t, a producer knows the total breeding stock $K_t = k_{3,t} + \ldots + k_{10,t}$, the production of fed cattle sl_t, and the production of cull cows cl_t. However, in order to make expectations about prices, the production (or an approximation of the future production) must be used. We rely on the competitive storage model to construct the production of the fed cattle and cull cows into the future. A simple storage type model is specified as $Q_{t+1} = Q_t \epsilon_t + \text{storage}_t$, where Q_{t+1} is the production at $t+1$; Q_t, ϵ_t, storage_t are the production, production shock, and storage respectively at t.[15]

Using the production shocks and the competitive storage model specification, the production of fed cattle and cull cows can be written as follows.

Fed cattle production:

$$
\begin{aligned}
sl_{t+1} &= sl_{t-1}\epsilon^s_{t-1} + \text{storage}_{t-1} && (2.90)\\
&= \Big(gK_{t-2} - k_{3,t}\Big)\epsilon^s_{t-1} + \text{storage}_{t-1} && (2.91)\\
&= \Big(g - gr\Big)K_{t-2}\epsilon^s_{t-1} + \text{storage}_{t-1} && (2.92)\\
&= g\Big(1 - r\Big)K_{t-2}\epsilon^s_{t-1} + \text{storage}_{t-1}, && (2.93)
\end{aligned}
$$

[15]Numerical methods to compute expected prices require integration over random variables. The production shocks in the storage model are used as random variables to compute expected prices.

where g is the breeding rate, and r is the rate of the newborn progeny entering the breeding stock. storage_{t-1} can be further decomposed as:

$$\text{storage}_{t-1} = K_{t-1} - k_{3,t+1} \tag{2.94}$$

$$= (1 - gr)K_{t-1} \tag{2.95}$$

$$= (1 - gr)\delta g\Big[K_{t-2} - sl_{t-2} - cl_{t-2}\Big] \tag{2.96}$$

$$= (1 - gr)\delta g\Big[K_{t-2} - g(1-r)K_{t-3} - (k_{9,t-2} + (1-\delta)k_{8,t-2} + (1-\delta)k_{7,t-2})\Big], \tag{2.97}$$

Cull cow production:

$$cl_{t+1} = cl_t\epsilon_t^c + \text{storage}_t \tag{2.98}$$

$$= \Big[k_{9,t} + (1-\delta)k_{8,t} + (1-\delta)k_{7,t}\Big]\epsilon_t^c + \Big[(k_{9,t+1} - k_{9,t}) + (k_{8,t+1} - k_{8,t} + (k_{7,t+1} - k_{7,t}))\Big] \tag{2.99}$$

$$= \Big[k_{9,t} + (1-\delta)k_{8,t} + (1-\delta)k_{7,t}\Big]\epsilon_t^c + \Big[\delta(k_{8,t} + k_{7,t} + k_{6,t}) - (k_{7,t} + k_{8,t} + k_{9,t})\Big], \tag{2.100}$$

where the production shock of fed cattle ϵ_t^s and the production shock of cull cows ϵ_t^c are random variables following a Gaussian distribution. The production shocks are constructed by taking the ratio of observed historical production to the constructed production from the model specification. Then, the standard deviation of the constructed production shocks is used to define the Gaussian distribution.

The equilibrium system of equations can be solved when the price expectations of fed cattle and cull cows are known. The constructed production from the competitive storage type model is utilized to determine the prices and expected prices of the fed cattle and cull cows. The rational expectations model is a functional equation problem. The solution takes the form of a function rather than a finite-sized vector of prices and quantities. Therefore, the model cannot be solved analytically and requires numerical methods to solve it. The competitive storage model with rational expectations is also a functional equation problem and the solution takes a functional form instead of a finite-sized vector. Therefore, numerical methods from the competitive storage literature are borrowed to find a solution to the rational expectations model.

Collocation methods are widely used in the competitive storage literature [Miranda and Fackler (2002)]. Although there are multiple methods for functional approximation, Miranda (1997) showed that solutions under collocation methods are accurate and efficient. Gouel (2013) provided various fast and precise numerical methods to solve competitive storage models, which include projection methods such as the collocation method. Miranda (1997) and Gouel (2013) compared different numerical methods for solving competitive storage models and presented solution methods that are suitable to use (the collocation method is one of the solution methods presented). Using the collocation method, Miranda and Schnitkey (1995) proposed a solution method to a dairy production model (collocation method is applied for a function that possessed no closed-form analytical solution). Ritten et al. (2010) used the collocation method in their stochastic dynamic model to solve for optimal rangeland stocking decisions under uncertain weather and climate conditions. Miranda and Glauber (2022) used the Chebyshev collocation method to find equilibrium market prices for a production model of global agricultural commodity markets. Hence, to find a solution to the rational price expectations model, we apply the projection method. Specifically, a collocation method is applied to find an equilibrium solution.

Using the collocation method, the following system of equations is solved to determine the equilibrium prices and quantities.

$$gK_{t-1} - k_{3,t+1} = \tilde{A}\frac{\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.101}$$

$$k_{10,t} + \sum_{j=7}^{9}(k_{j,t} - k_{j+1,t+1}) = \tilde{A}\frac{1}{1+\exp\left(\frac{\tilde{\mu}-\tilde{p}}{\tilde{s}}\right)}, \tag{2.102}$$

$$p_{s,t} = \beta^7 p_{c,t+7} + g\sum_{i=4}^{9}\beta^i p_{s,t+i} + g\beta^3 \mathrm{E}_t p_{s,t+3} - \sum_{i=0}^{6}\beta^i z_{t+i}, \tag{2.103}$$

$$p_{c,t} = \beta \mathrm{E}_t p_{c,t+1} + g\beta^3 \mathrm{E}_t p_{s,t+3} - (1 + g\beta(\gamma_0 + \beta\gamma_1))\mathrm{E}_t h_t. \tag{2.104}$$

The above system of equations is non-linear, so to solve the system of equations we need to provide the initial values for the prices and expected prices. First, we determine the cattle price and use it to compute the expected price. We posit that the price of the fed cattle (cull cows) depends on the total supply of fed cattle (cull cows), demand shock, and corn price. Without assuming a functional form of the relationship, we approximate the price function by a linear combination of independent basis functions $\psi_1, \psi_2, \ldots, \psi_n$ of the supply of fed cattle (sl_t) for the fed cattle price, supply of cull cows (cl_t) for cull cow price, demand shock (ϵ_t^D), and corn price (c_t^p).

Specifically, the price of fed cattle is expressed as

$$p_{s,t} = p_{s,t}\left(sl_t, \epsilon_t^D, c_t^p\right) \tag{2.105}$$

$$p_{s,t} = p_{s,t}\left(sl_t, \epsilon_t^D, c_t^p\right) \approx \tilde{p}_{s,t}\left(sl_t, \epsilon_t^D, c_t^p\right) \tag{2.106}$$

$$= \sum_{l_1=1}^{n_1}\sum_{l_2=1}^{n_2}\sum_{l_3=1}^{n_3} C_{l_1 l_2 l_3}\psi_{s1}^{(l_1)}\left(sl_t\right)\psi_2^{(l_2)}\left(\epsilon_t^D\right)\psi_3^{(l_3)}\left(c_t^p\right), \tag{2.107}$$

and the price of cull cows is expressed as

$$p_{c,t} = p_{c,t}\Big(cl_t, \epsilon_t^D, c_t^p\Big) \tag{2.108}$$

$$p_{c,t} = p_{c,t}\Big(cl_t, \epsilon_t^D, c_t^p\Big) \approx \tilde{p}_{c,t}\Big(cl_t, \epsilon_t^D, c_t^p\Big) \tag{2.109}$$

$$= \sum_{l_1=1}^{n_1}\sum_{l_2=1}^{n_2}\sum_{l_3=1}^{n_3} C_{l_1l_2l_3}\psi_{c1}^{(l_1)}\Big(cl_t\Big)\psi_2^{(l_2)}\Big(\epsilon_t^D\Big)\psi_3^{(l_3)}\Big(c_t^p\Big), \tag{2.110}$$

where $\left\{\psi_{s1}^{(1)}, \psi_{s1}^{(2)}, \psi_{s1}^{(3)}, \ldots, \psi_{s1}^{(n_1)}\right\}$ and $\left\{\psi_{c1}^{(1)}, \psi_{c1}^{(2)}, \psi_{c1}^{(3)}, \ldots, \psi_{c1}^{(n_1)}\right\}$ are univariate basis functions of sl_t and cl_t, $\left\{\psi_2^{(1)}, \psi_2^{(2)}, \psi_2^{(3)}, \ldots, \psi_2^{(n_2)}\right\}$ are basis functions of the demand shock ϵ_t^D, and $\left\{\psi_3^{(1)}, \psi_3^{(2)}, \psi_3^{(3)}, \ldots, \psi_3^{(n_3)}\right\}$ are basis functions of corn price c_t^p. And $n_1, n_2,$ and n_3 are the number of univariate basis functions for sl_t and cl_t, ϵ_t^D, and c_t^p respectively. The coefficient vector $C_{l_1l_2l_3}$ contains $N = n_1 \times n_2 \times n_3$ elements. These elements must be solved to determine the price.

With the above specification, equations 2.85 - 2.89 are required to hold at a selected number of collocation nodes $x_0, x_1, \ldots, x_n$. The nodes must cover the range of possible values of the variables included in the approximation and don't necessarily need to be equidistant. The polynomial specification is determined by studying the functional properties of the price. The price must be non-negative indicating that there will be no corner solution and the range will be positive. Therefore a Chebyshev polynomial interpolation is used [Miranda and Fackler (2002); Judd (1998); Miranda (1997); Miranda and Glauber (1995)]. The nodes that are used are Chebyshev nodes (Chebyshev nodes are not evenly spaced and are more concentrated on the boundaries of the interval), over a bounded interval $[a, b]$ and takes the following form

$$x_i = \frac{a+b}{2} + \frac{b-a}{2}\cos\Big(\frac{n-i+0.5}{n}\pi\Big), \forall i = 1, 2, \ldots, n. \tag{2.111}$$

Additionally, the Chebyshev polynomial basis is defined recursively as

$$T_0(y) = 1, \tag{2.112}$$

$$T_1(y) = y, \tag{2.113}$$

$$T_2(y) = 2y^2 - 1, \tag{2.114}$$

$$T_{n+1}(y) = 2yT_{n-1}(y) - T_{n-2}(y), \tag{2.115}$$

where $y_i = \frac{2(x_i-a)}{b-a} - 1, \forall i = 1, 2, \ldots, n$ is the normalized node such that the polynomials are defined on the domain $[-1, 1]$. Alternatively, the chebyshev polynomials can also be formulated using a trigonometric definition $T_n(y) = \cos(\arccos(y)n)$.

The system of equations that needs to be solved contains the expected prices of the fed cattle and cull cows. Determining the expected prices requires numerical integration. A Gaussian quadrature for integration is used to compute the expected prices [Miranda and Fackler (2002); Judd (1998)]. In the Gaussian quadrature for the integration method, the continuous distribution is approximated by a finite number of discrete points. The expected prices are then computed by assigning weights to the Gaussian nodes and then by taking a weighted average of all the nodes. The expected prices for fed cattle and cull cows are specified as below:

$$\mathrm{E}_t\Big[p_{s,t+3}\Big] = \frac{1}{v}\sum_{i=1}^{v}\int\int \tilde{p}_{s,t+3}\Big(sl\left(sl_{t+1}, \mathrm{E}_t(p_{s,t+3})\right)\epsilon^s_{t+1,j} + \mathrm{storage}_{t+1}, \epsilon^D_{t+3,l}, c^p_t\Big)d\epsilon^s d\epsilon^D \tag{2.116}$$

$$= \frac{1}{v}\sum_{i=1}^{v}\sum_{j,l=1}^{N} w_{j,l}\tilde{p}_{s,t+3}\Big(sl\left(sl_{t+1}, \mathrm{E}_t(p_{s,t+3})\right)\epsilon^s_{t+1,j} + \mathrm{storage}_{t+1}, \epsilon^D_{t+1,l}, c^p_t\Big). \tag{2.117}$$

$$\mathrm{E}_t\Big[p_{c,t+1}\Big] = \frac{1}{v}\sum_{i=1}^{v}\int\int \tilde{p}_{c,t+1}\Big(cl\left(cl_t, \mathrm{E}_t(p_{c,t+1})\right)\epsilon^c_{t,j} + \text{storage}_t, \epsilon^D_{t+1,l}, c^p_t\Big)d\epsilon^c d\epsilon^D \tag{2.118}$$

$$= \frac{1}{v}\sum_{i=1}^{v}\sum_{j,l=1}^{N} w_{j,l}\tilde{p}_{c,t+1}\Big(cl\left(cl_t, \mathrm{E}_t(p_{c,t+1})\right)\epsilon^s_{t,j} + \text{storage}_t, \epsilon^D_{t+1,l}, c^p_t\Big). \tag{2.119}$$

The prices of the fed cattle and cull cows must satisfy the equilibrium conditions. In equilibrium, the system of equations is non-linear. Therefore, we provide the estimated prices and expected prices from the above price approximation using the Gaussian quadrature method as starting points to solve the system of equations. Additionally, we provide bounds for the prices so the prices satisfy the equilibrium conditions.

Equations 2.93 and 2.100 are used to compute the fed cattle and cull cow production and corresponding Chebyshev nodes. In order to attain the equilibrium price, a multi-year iterative method is performed using the Chebyshev nodes of fed cattle production, cull cow production, production shocks, and demand shocks. Using the iterative algorithm, the prices are approximated, expected prices are computed, and the results are used as initial values to solve the system of equations 2.85 - 2.89. In particular, we solve equations 2.85, 2.86, 2.87, and 2.89. Where equations 2.85 and 2.86 are the equilibrium conditions (supply equals to demand) for the fed cattle and cull cows respectively. Equations 2.87 and 2.89 contain both price and expected price conditions.

An initial guess of the prices are made and the price coefficients are determined (from the linear price function relationship) as a beginning step before the following multi-year iteration begins. The initial guess of the prices (both fed cattle and cull cows) along with the computed expected prices are used to solve the system of equations simultaneously. A non-linear least squares estimation method is used to solve the system. The prices that solve the system are then used to update the coefficients and are compared with the previous iteration coefficients. A simple Euclidean distance is measured between the updated and previous iteration coefficients. The Euclidean distance is then compared with a predetermined tolerance level. If the Euclidean distance is below the predetermined tolerance level, the iteration stops and the updated coefficient vector is part of the solution. If the Euclidean distance is above the predetermined tolerance level, the guessed coefficient vector is replaced with the updated coefficient vector, and the iteration continues until the tolerance level is met.

2.2.2.6 The iterative algorithm

1. Specification of the Chebyshev nodes and polynomials

   Using equations 2.111 and 2.115, Chebyshev nodes and Chebyshev polynomials are defined. The selection criteria for the number of polynomials depend on the execution time and desired precision. A higher number of polynomials means more precision, but the execution time increases as well. In this work, for both fed cattle and cull cows, $n_1 = n_2 = n_3 = n$ number of independent Chebyshev polynomials for each variable is used to approximate the price function. The variables for fed cattle and cull cows are $(sl_t, \epsilon_t^D, c_t^p)$ and $(cl_t, \epsilon_t^D, c_t^p)$ respectively.[16] Therefore, a total number of $N = n_1 \times n_2 \times n_3 = n^3$ independent Chebyshev polynomials are constructed separately for the fed cattle and cull cow price approximation. The Chebyshev nodes are selected over the domains $[sl_{min}, sl_{max}]$, $[cl_{min}, cl_{max}]$, $[\epsilon^D_{min}, \epsilon^D_{max}]$, and $[c^p_{min}, c^p_{max}]$. Historical data are used to define the domains of each variable that go into the price approximation. Following the Chebyshev polynomial structure, n Chebyshev nodes for each variable are determined. For both fed cattle and cull cow price approximation, a grid of $N = n^3$ interpolation nodes is constructed by using a cartesian product of each univariate interpolation node. The number of nodes is

[16] Note that the state variables for both fed cattle and cull cow price approximations are the same except for the production and the corresponding production shock.

chosen to optimize the accuracy and execution time:

$$\Big\{sl_{l_1}, \epsilon^D_{l_2}, c^p_{l_3} \mid l_1, l_2, l_3 = 1, 2, \dots, n\Big\}, \tag{2.120}$$

$$\Big\{cl_{l_1}, \epsilon^D_{l_2}, c^p_{l_3} \mid l_1, l_2, l_3 = 1, 2, \dots, n\Big\}. \tag{2.121}$$

2. Start with an initial guess for the coefficients

   Using the guessed price, the initial guess for the coefficients is determined. The initial guess of the coefficients is then applied to the price approximation functions

$$\tilde{p}_{s,t} = \sum_{l_1=1}^{n_1} \sum_{l_2=1}^{n_2} \sum_{l_3=1}^{n_3} C_{l_1 l_2 l_3,t} \psi^{(l_1)}_{s1} \psi^{(l_2)}_{2} \psi^{(l_3)}_{3}, \tag{2.122}$$

$$\tilde{p}_{c,t} = \sum_{l_1=1}^{n_1} \sum_{l_2=1}^{n_2} \sum_{l_3=1}^{n_3} C_{l_1 l_2 l_3,t} \psi^{(l_1)}_{c1} \psi^{(l_2)}_{2} \psi^{(l_3)}_{3}. \tag{2.123}$$

   Once the price is approximated, using equations 2.117 and 2.119 the expected prices of fed cattle and cull cow are computed, the Chebyshev node $(sl^1_t, \epsilon^{D1}_t, c^{p1}_t)$, $(cl^1_t, \epsilon^{D1}_t, c^{p1}_t)$ is applied to the system of equations and solved with the approximated prices and expected prices as initial values. This is repeated for all the n^3 Chebyshev nodes to get a complete set of fed cattle prices, expected fed cattle prices, cull cow prices, and expected cull cow prices:

$$\mathbf{p_{s,t}} = \begin{pmatrix} p^1_{s,t} \\ p^2_{s,t} \\ \vdots \\ p^N_{s,t} \end{pmatrix}; \mathbf{p_{c,t}} = \begin{pmatrix} p^1_{c,t} \\ p^2_{c,t} \\ \vdots \\ p^N_{c,t} \end{pmatrix}; \mathrm{E}_\mathbf{t}[\mathbf{p_{s,t+3}}] = \begin{pmatrix} \mathrm{E}_t[p_{s,t+3}]^1 \\ \mathrm{E}_t[p_{s,t+3}]^2 \\ \vdots \\ \mathrm{E}_t[p_{s,t+3}]^N \end{pmatrix}; \mathrm{E}_\mathbf{t}[\mathbf{p_{c,t+1}}] = \begin{pmatrix} \mathrm{E}_t[p_{c,t+1}]^1 \\ \mathrm{E}_t[p_{c,t+1}]^2 \\ \vdots \\ \mathrm{E}_t[p_{c,t+1}]^N \end{pmatrix}. \tag{2.124}$$

3. Update the coefficients

   A $N \times N$ interpolation matrix Ψ (for both fed cattle and cull cow) is determined. Each element in the interpolation matrix is defined by evaluating each Chebyshev polynomial at each interpolation node and the matrix is specified below

$$\Psi_{N\times N} = \begin{bmatrix} \psi_1^{(1)}\psi_2^{(1)}\psi_3^{(1)}\mid_1 & \cdots & \psi_1^{(n_1)}\psi_2^{(n_2)}\psi_3^{(n_3)}\mid_1 \\ \psi_1^{(1)}\psi_2^{(1)}\psi_3^{(1)}\mid_2 & \cdots & \psi_1^{(n_1)}\psi_2^{(n_2)}\psi_3^{(n_3)}\mid_2 \\ \vdots & \ddots & \vdots \\ \psi_1^{(1)}\psi_2^{(1)}\psi_3^{(1)}\mid_N & \cdots & \psi_1^{(n_1)}\psi_2^{(n_2)}\psi_3^{(n_3)}\mid_N \end{bmatrix}. \tag{2.125}$$

In a simpler matrix notation, the above $N \times N$ interpolation matrix can be specified by a tensor product of univariate $(n \times n)$ interpolation matrices as

$\Psi_{N\times N} = \Psi_1 \otimes \Psi_2 \otimes \Psi_3$.

Using the relationship of the prices, the approximation function is:

$$\mathbf{p}_{h,t} = \begin{pmatrix} p_{h,t}^1 \\ p_{h,t}^2 \\ \vdots \\ p_{h,t}^N \end{pmatrix} = \Psi \times C_1, \quad \text{for} \quad h = \{s, c\}. \tag{2.126}$$

The coefficients are computed and updated by simply solving the linear interpolation equation 2.126, as $C_1 = (\Psi_{N\times N})^{-1}\mathbf{p}_{h,t} \quad \text{for} \quad h = \{s, c\}$. Note that, if a higher number of nodes is used, we can avoid having to invert the full $N \times N$ interpolation matrix, which increases the complexity with each additional node, as, we can invert the individual univariate interpolation matrices and multiply them together.

4. Equilibrium conditions

   After the first iteration, using the updated prices, for each node, the differences between the estimated supply and demand are calculated for both fed cattle and cull cows. The computed differences are then used to give prices a specific direction to hold in equilibrium (to avoid local optimum solutions and to increase the precision). At a given node, if the difference between the supply and demand is positive, then the price is reduced and vice versa. The updated prices, along with the expected prices, are used again to solve the model. This is repeated until the prices reach equilibrium and the difference between supply and demand reaches a predetermined tolerance level. The production of fed cattle and cull cows at the equilibrium prices are also determined for each node.

Finally, the equilibrium prices are used to update the coefficients and the iteration is continued with the equilibrium prices and quantities until the coefficients converge.

2.3 Data

The dynamic model depends on data which are measured consistently over time and are publicly available. We use livestock industry data compiled and distributed by various U.S. Department of Agriculture agencies. The data includes total beef cattle inventory, calf crop, inventory of replacement heifers, prices received by producers for fed cattle and cows, number of fed cattle slaughtered, number of culled cows, the dressed weight of slaughtered fed cattle and culled cows, cattle imports and exports, and corn prices.

The National Agricultural Statistics Service (NASS) of the USDA [USDA-NASS (2022b)] compiles beef cow inventory data every year and provides a measure in January and July. January measures of annual total beef cows inventory and replacement heifers are used in the model. With these measures, we construct cattle of all age groups in any year. Knowing the age groups in a given year is important as we use these numbers to determine the annual domestic-fed cattle production and cull cow production. Table 2.1 provides the constructed age distribution of cattle in the United States.[17]

The constructed domestic supply of fed cattle and cull cows is converted from units of number of head to pounds of meat. We use dressed weights of the slaughtered fed cattle

[17] For brevity, we provide data for the latest decade.

Table 2.1 Age distribution of cattle in the United States (in number of head)

Year	K	k_3	k_4	k_5	k_6	k_7	k_8	k_9
2010	31439900	5550200	5364270	5266448	5027218	4592268	4262218	1377278
2011	30912600	5443000	5272690	5096056	5003126	4775857	4362654	959216
2012	30281900	5134600	5170850	5009056	4841254	4752970	4537065	836107
2013	29631300	5280600	4877870	4912308	4758603	4599191	4515321	687408
2014	28956400	5429200	5016570	4633976	4666692	4520673	4369231	320057
2015	29332100	5556300	5157740	4765742	4402278	4433358	4294639	722044
2016	30163800	6086400	5278485	4899853	4527454	4182164	4211690	977754
2017	31170700	6335200	5782080	5014561	4654860	4301082	3973056	1109862
2018	31466200	6363200	6018440	5492976	4763833	4422117	4086028	319606
2019	31690700	6108200	6045040	5717518	5218327	4525641	4201011	0
2020	31338700	5884900	5802790	5742788	5431642	4957411	4299359	0
2021	30843600	5808900	5590655	5512650	5455649	5160060	4709540	0

Note: Here K represents beef cow total inventory (publicly available), k_3 represents the replacement heifers (publicly available), and k_4 to k_9 represents cows from ages (constructed by the model) 4 to 9 years.

and cows to calculate the meat supply in pounds. Using the monthly dressed weights provided by USDA-NASS [USDA-NASS (2022c)], we compute the annual average dressed weights of fed cattle (including steers & heifers) and cull cows.[18] The annual average dressed weights are used to determine the domestic production of fed cattle and cull cow meat in pounds. With changes in the weight of the cattle over time, it is important to use dressed weights (using a constant weight could deviate the model from the trends we observe in the real world).

In addition to the domestic quantities, we also incorporate cattle imports and exports in the model. The USDA Foreign Agricultural Service (FAS) Production, Supply and Distri- bution (PSD) [USDA-PSD (2022)] compiles annual cattle numbers that include production, imports, exports, and more. We utilize the import and export animal numbers

[18] USDA-NASS compiles these data from the reports of the Food Safety and Inspection Service (FSIS) of USDA, along with data from state-administered non-federally inspected (NFI) slaughter plants.

for accuracy purposes. In Tables 2.2 and 2.3 the annual supply of the fed cattle and cull cows are listed in the number of head and in pounds of meat, which are constructed based on age distribu- tion, imports, and exports. Table 2.4 contains the dressing weights with which the supply is converted from the number of heads to the pounds of meat.

Table 2.2 Annual supply of fed cattle

Year	Number of head	Meat in billion pounds
2010	27482786	22.95
2011	26966703	22.67
2012	26942622	23.14
2013	25964843	22.42
2014	25563161	22.30
2015	24442408	21.80
2016	24004737	21.39
2017	24537686	21.54
2018	25527379	22.48
2019	26150014	22.99
2020	26648079	24.17
2021	25859639	23.43

The model also includes the prices received by producers for fed cattle (steers & heifers) and cows. Prices play a key role in the model. From USDA-NASS [USDA-NASS (2022a)] monthly prices, we calculate the average annual price of cows, steers and heifers. Table 2.5 lists the calculated annual average prices. These prices are further converted into $/pound. Table 2.6 lists annual calf crop data in the number of head utilized in fitting the model.

Corn prices are used in the model to estimate a relationship for holding costs. We use the annual corn price data from USDA-NASS [USDA-NASS (2022a)]. Table 2.7 lists annual corn price data used in fitting a linear model with the equilibrium holding costs.

Fixed parameters in the model are compiled from the literature [Aadland (2004); Aadland and Bailey (2001); Baak (1999); Rosen et al. (1994)] and are constant. Table 2.8 lists the fixed model parameters $(\beta, \delta, g, \gamma_0, \gamma_1, \phi)$ for model fitting.

Table 2.3 Annual supply of cull cows

Year	Number of head	Meat in billion pounds
2010	4909893	2.98
2011	4724556	2.82
2012	4923412	2.99
2013	5112631	3.17
2014	4193278	2.63
2015	4260597	2.74
2016	4288690	2.76
2017	4978365	3.20
2018	4626740	2.99
2019	4427294	2.83
2020	4547230	2.92
2021	4967543	3.17

Table 2.4 Annual average dressed weight (in pounds)

Year	Fed Cattle	Cows
2010	835.17	607.25
2011	840.83	596.58
2012	858.75	608.08
2013	863.50	619.83
2014	872.50	627.33
2015	892.00	644.25
2016	891.00	642.75
2017	878.00	642.58
2018	880.50	645.33
2019	879.00	639.50
2020	907.17	641.08
2021	906.08	637.25

Table 2.5 Annual average price (in $/cwt)

Year	Fed Cattle	Cows
2010	97.23	54.93
2011	117.17	71.58
2012	123.08	81.97
2013	126.33	82.29
2014	154.33	108.22
2015	149.33	104.11
2016	121.67	74.89
2017	121.92	69.56
2018	117.83	62.56
2019	118.08	62.29
2020	110.67	65.27
2021	123.67	70.13

Table 2.6 Annual calf crop (in number of head)

Year	Calf Crop
2010	35739800
2011	35357200
2012	34469000
2013	33630000
2014	33522000
2015	34086700
2016	35062700
2017	35758200
2018	36312700
2019	35591600
2020	35495500
2021	35085400

Table 2.7 Annual corn price (in $/bushel)

Year	Corn Price
2010	3.83
2011	6.02
2012	6.67
2013	6.15
2014	4.11
2015	3.71
2016	3.48
2017	3.36
2018	3.47
2019	3.75
2020	3.50
2021	5.40

Table 2.8 Fixed model parameters

Parameter	Value
β	0.98
δ	0.95
g	0.97
γ_0	0.90
γ_1	0.95
ϕ	0.63

2.4 Numerical solution of the model

Using the constructed and available data along with the fixed parameters, the model is calibrated to capture the historical evolution of the U.S. beef cattle industry. The algorithm is written in R programming language and uses a simple sum squared error as the loss function. Since the system of equations is non-linear, a non-linear least squares method is employed in the iterative algorithm 2.2.2.6. The estimated parameters, fitted prices, and quantities are obtained for the model under both naïve price expectations and rational price expectations. The solution of the model under rational expectations is used to project the prices and quantities into the future. Consequently, we present the numerical solution of the model under rational price expectations. In what follows, we present various tables and figures that include estimated parameters ($\tilde{\mu}$ and $\tilde{s}$), fitted prices ($\hat{p_s}$ and $\hat{p_c}$), and fitted quantities ($\hat{sl}$ and $\hat{cl}$). We present the median of the results of the iterative algorithm 2.2.2.6 in the tables.

Table 2.9 lists the estimated parameters of the model. Instead of fixing the parameters to a single value, we keep them dynamic and calibrate them for each year. This is intended to reflect the changes observed in the data in consumer preferences for fed cattle and cull cow beef, and reflect that in corresponding production. This is also one of the novel features of the model. Tables 2.10 and 2.11 provide the model fitted and observed prices and quantities, respectively. Figures 2.1 and 2.2 illustrate the observed and the model fitted (the median of the iteration results) prices of fed cattle and cull cows, respectively. Using the fitted quantities, the cattle inventories are replicated and illustrated in Figure 2.3.

Table 2.9 Estimated parameters

Year	$\tilde{\mu}$	$\tilde{s}$
2010	2.222	0.803
2011	2.080	0.709
2012	2.147	0.742
2013	2.130	0.748
2014	2.073	0.700
2015	2.123	0.734
2016	2.048	0.685
2017	2.058	0.650
2018	2.125	0.657
2019	2.135	0.657
2020	2.089	0.714
2021	2.092	0.654

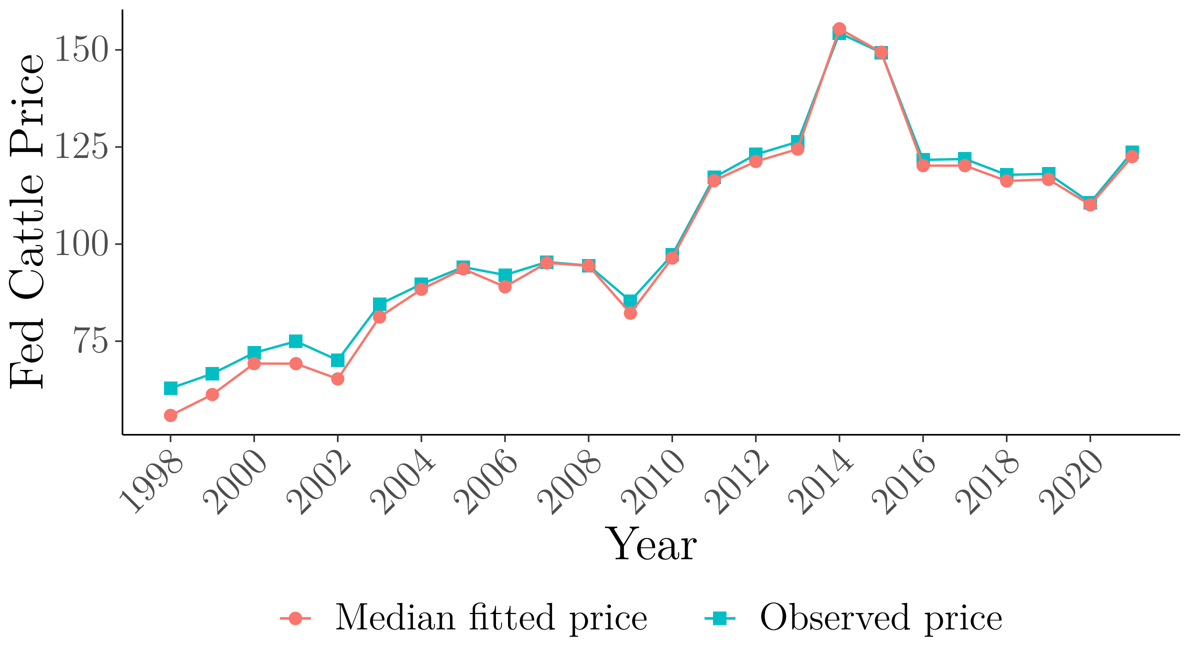

Figure 2.1 Observed and fitted fed cattle price ($/cwt)

Table 2.10 Observed & fitted prices (in $/cwt)

Year	p_s	$\hat{p}_s$	p_c	$\hat{p}_c$
2010	97.23	96.40	54.93	62.05
2011	117.17	116.33	71.58	75.16
2012	123.08	121.28	81.98	85.47
2013	126.33	124.45	82.29	86.67
2014	154.33	155.44	108.22	110.29
2015	149.33	149.41	104.11	106.52
2016	121.67	120.20	74.89	75.82
2017	121.92	120.21	69.56	73.12
2018	117.83	116.26	62.56	69.09
2019	118.08	116.65	62.29	68.81
2020	110.67	110.10	65.27	69.86
2021	123.67	122.52	70.13	76.91

Note: $\hat{p}_s$ and $\hat{p}_c$ denote the fitted fed cattle price and cull cow price respectively. p_s and p_c denote the observed.

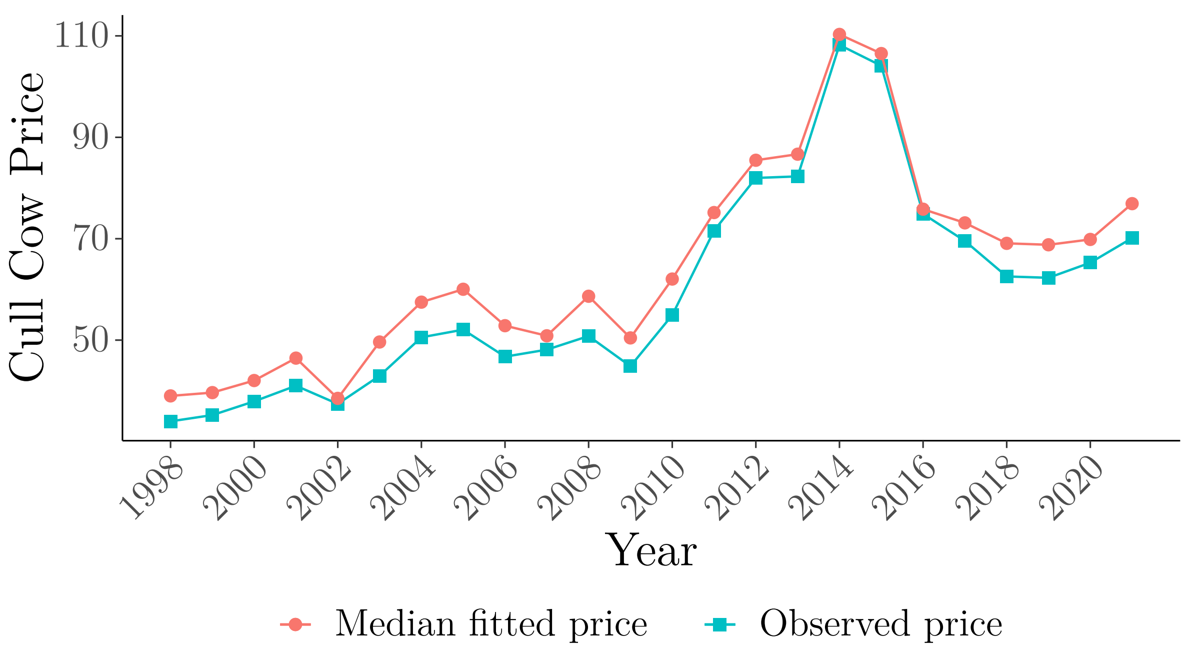

Figure 2.2 Observed and fitted cull cow price ($/cwt)

Table 2.11 Observed & fitted quantities (in billion pounds)

Year	sl	$\hat{sl}$	cl	$\hat{cl}$
2010	21.84	22.18	2.84	2.71
2011	22.29	22.13	2.77	2.70
2012	23.08	21.88	2.99	2.67
2013	21.57	21.71	3.05	2.65
2014	21.74	20.46	2.56	2.48
2015	20.54	20.03	2.59	2.44
2016	20.05	21.33	2.58	2.60
2017	21.87	22.12	3.25	2.70
2018	23.09	22.73	3.07	2.77
2019	23.58	22.99	2.90	2.80
2020	24.73	22.91	2.98	2.79
2021	22.77	23.55	3.08	2.87

Note: $\hat{sl}$ and $\hat{cl}$ denote the fitted fed cattle and cull cow meat respectively. sl and cl denote the observed.

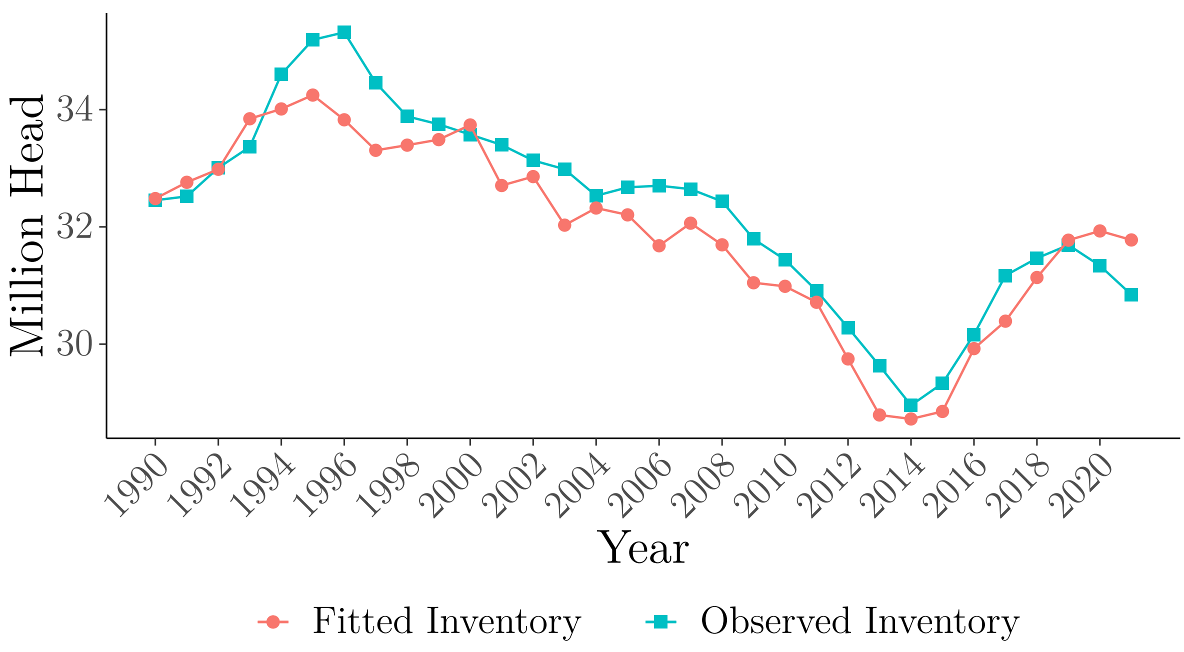

Figure 2.3 U.S. beef cow inventories and model fitted inventories

From the above results, it can be seen that the dynamic model fits the observed data fairly well. To support the claim, a percent error (in unit-free form) is computed using $|e| = \left|\frac{(O-\hat{M})}{O}\right|$, where O and $\hat{M}$ are observed and fitted respectively. The model fits the data with a median error of 2.38%, 10.04%, 2.49%, and 6.66% for fed cattle price, cull cow price, fed cattle supply, and cull cow supply. The replication of the cattle inventories from the fitted results follows the observed inventories and demonstrates the ability of the model to capture the observed dynamics in beef cattle inventories.

2.5 Projection framework

The model equations and parameter estimates from the fitted model are used to project the prices and quantities into the future. Projecting future prices and quantities requires knowledge about replacement heifers. In particular, the number of heifers that will be added to the breeding stock each year in the future.

Let $k_{3,t+2}$ be the number of replacement heifers that need to be determined. A linear relationship $k_{3,t+1} = \gamma k_{3,t} + \eta k_{0,t-3}$, where $k_{3,t+1}$, $k_{3,t}$ are replacement heifers and a lag of replacement heifers, and $k_{0,t-3}$ is the calf-crop at $t-3$ is constructed. Here γ and η capture the proportional relationships among replacement heifers, its lag, and the relevant calf crop. Note that γ is not related to γ_0 and γ_1 in the holding cost equation.

The following system of equations is solved to determine future replacement heifers:

$$sl_{t+1} = gK_{t+1} - k_{3,t+2}, \tag{2.127}$$

$$\begin{aligned} cl_{t+1} &= k_{9,t+1} + (k_{8,t+1} - k_{9,t+2}) + (k_{7,t+1} - k_{8,t+2}) \\ &= \frac{\delta^4}{\gamma^7}\Big[\delta^2 + (1-\delta)\gamma(\delta+\gamma)\Big] \\ &\Big[k_{3,t+2} - \eta\gamma^4 k_{0,t-6} + \gamma^3 k_{0,t-5} + \gamma^2 k_{0,t-4} + \gamma k_{0,t-3} + k_{0,t-2}\Big] \\ &- \frac{\delta^5}{\gamma^2}\eta\Big[\delta\gamma k_{0,t-8} + (\delta + (1-\delta)\gamma)k_{0,t-7}\Big], \end{aligned} \tag{2.128}$$

where sl_{t+1}, cl_{t+1}, K_{t+1} are the fed cattle production, cull cow production, and total breeding stock respectively at $t+1$, and $k_{0,t-i} \forall i \in [2, 8]$ is the calf crop at $t-i$. The proof for equation 2.128 is provided in appendix B.

In order to solve equations 2.127 and 2.128, we must know the total breeding stock in those years. Using the historical data of the total breeding inventory in the United States, we fit a linear model. An Autoregressive Integrated Moving Average (ARIMA) model is selected to fit the breeding stock. To elaborate further, a linear regression model is built with specified lags to breeding stock observations ($K_{t-i} \forall i \in [1, 2]$) with a moving average window ($Z_{t-j} \forall j \in [1, 3]$). The breeding stock data from 1924 to 2021 are used to fit the following linear model.[19]

$$K_t = \sum_{i=1}^{2} \zeta_i K_{t-i} + \sum_{j=1}^{3} \lambda_j Z_{t-j} + Z_t. \tag{2.129}$$

The equation 2.129 model estimates are used to determine future projections of the total breeding stock.

A multi-year algorithm is performed to project production and prices into the future. This is a cyclical algorithm, meaning the result of each iteration is used to project prices

[19] This linear model is consistent with Rosen et al. (1994).

and quantities of the next subsequent year. The breeding stock projections are used as input in the cyclical algorithm.

2.5.1 Multi-year cyclical algorithm for projection of prices and quantities

1. For the first iteration, using the fitted prices $\hat{p}_{s,t}$, $\hat{p}_{c,t}$, demand $\hat{A}_t$, and the model parameter estimates $\tilde{\mu}_t$ and $\tilde{s}_t$, the fed cattle production sl_{t+1} and cull cow production cl_{t+1} are computed (The estimated prices and model parameters are used to obtain the share metric containing the proportion of consumers' purchases of fed cattle meat and cull cow meat separately. This metric is then used along with the estimated demand to determine the corresponding production).

2. sl_{t+1} and cl_{t+1} from step 1, along with the projected breeding stock K_{t+1}, are used in equations 2.127 and 2.128 to solve for replacement heifers $k_{3,t+2}$.

3. Using the estimated $k_{3,t+2}$ (in step 2) along with K_{t+1}, the fed cattle production sl_{t+1}, cull cow production cl_{t+1}, and total demand for meat A_{t+1} is updated.

4. Holding costs h_{t+1} are computed with the corn futures using the parameters estimated from the linear model between historical equilibrium holding costs and historical corn prices.

5. Using the estimated holding costs from the above step, equations 2.41, 2.42, and 2.43 determine the number of older animals (aged 6 and above) in the breeding inventory.

6. The updated production and demand from step 3, the prices and the expected prices from step 1, and the holding costs from step 4 are used as starting values to solve the system of equations 2.101 - 2.104. The result of this step contain projected prices ($\hat{p}_{s,t+1}$ and $\hat{p}_{c,t+1}$), and quantities ($\hat{sl}_{t+1}$, $\hat{cl}_{t+1}$, and $\hat{A}_{t+1}$). This is the end of the first iteration.

7. For the second year in the projection period, the results from step 6 are used together with the model parameter estimates ($\tilde{\mu}_t$ and $\tilde{s}_t$) and the projected total breeding inventory, to repeat steps 2 through 6.

8. Step 7 is repeated for each year in the projection period.

2.6 Model projections

The estimated parameters, fitted prices, and fitted quantities of the model are used to project the prices and supplies into the future. We use the 2021 estimates from the fitted model to initiate multi-year cyclical algorithm 2.5.1. But first, we present the regression estimates of equation 2.129 in Table 2.12. The projections of total breeding stock using the regression estimates of equation 2.129 are presented in Table 2.13.

Table 2.12 Regression estimates of equation 2.129

Parameter	Estimate	Standard Error
ζ_1	0.6097	0.2162
ζ_2	-0.4947	0.1723
λ_1	0.1403	0.2169
λ_2	0.6389	0.0937
λ_3	0.3400	0.1199

Note: $\zeta_i \forall i \in [1, 2]$ and $\lambda_j \forall j \in [1, 2, 3]$ denote the AR and MA parameters.

As stated in the model projection framework, the breeding stock projections in Table 2.13, along with the model estimates from 2021 are used to initiate the multi-year cyclical algorithm 2.5.1 to project the fed cattle price, cull cow price, fed cattle supply, cull cow supply, and total supply. Note that we must determine the age distribution every year following the holding costs and the market prices in the projection period. This is done so to replicate the producers' optimizing behavior.

Table 2.13 Projections of total breeding stock with a 95% confidence interval (number of head)

Year	$K_{L,95}$	K	$K_{U,95}$
2022	28157618	31063066	33968514
2023	26693220	31157824	35622427
2024	25298713	31209654	37120596
2025	24199626	31194386	38189146
2026	23373813	31159438	38945062
2027	22693681	31145681	39597680
2028	22055784	31154580	40253376
2029	21424517	31166811	40909104
2030	20814139	31169867	41525595
2031	20242995	31165680	42088365

Note: K,$K_{L,95}$, and $K_{U,95}$ denote the projected, lower 95%, and upper 95% breeding stock respectively.

Tables 2.14 and 2.15 list the projected fed cattle price, cull cow price, fed cattle production, and cull cow production through 2031. The corresponding plots of the projected fed cattle price, cull cow price, fed cattle production, and cull cow production are illustrated in Figures 2.4, 2.5, 2.6, and 2.7, respectively. To provide a basis for comparison, we compare model projections to the well-recognized USDA long-term projections [USDA (2022)] and FAPRI projections [FAPRI (2022)]. In particular, we compare the total beef production and the fed cattle price projections. Figures 2.8 and 2.9 illustrate the fed cattle price and the total supply of the dynamic model, USDA, and FAPRI projections.

Table 2.14 Projections of fed cattle price and cull cow price (in $/cwt)

Year	Fed Cattle	Cows
2022	131.56	72.00
2023	130.49	71.05
2024	130.32	71.65
2025	129.86	73.17
2026	129.87	73.94
2027	132.95	72.03
2028	135.45	71.48
2029	135.45	71.58
2030	135.49	72.36
2031	135.51	72.55

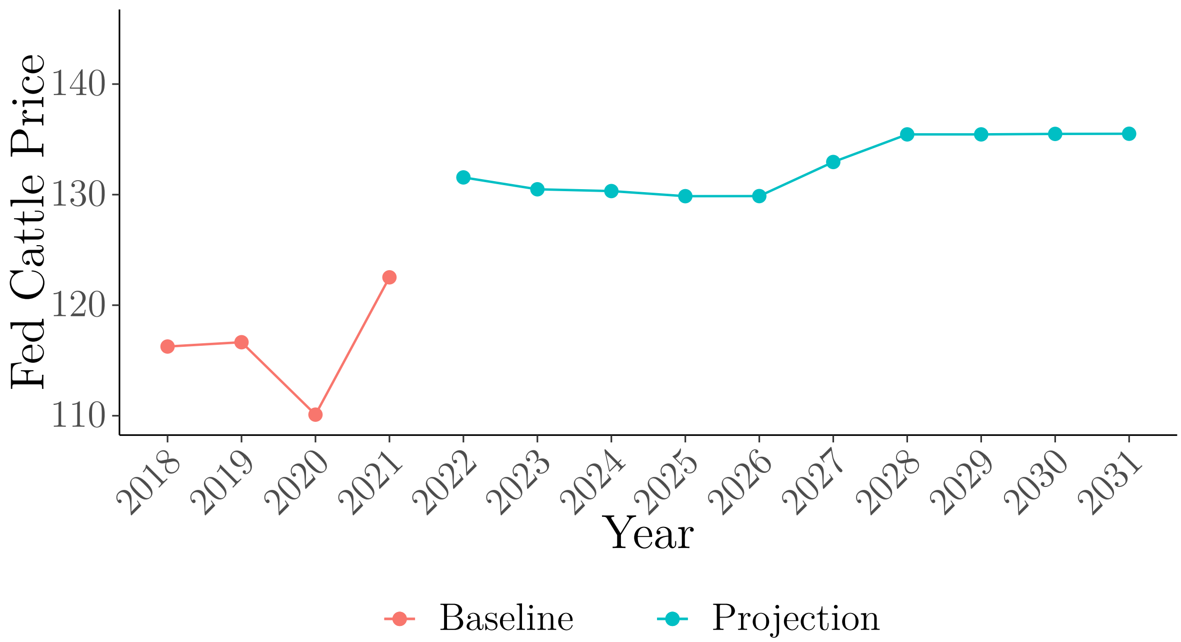

Figure 2.4 Projected fed cattle price ($/cwt)

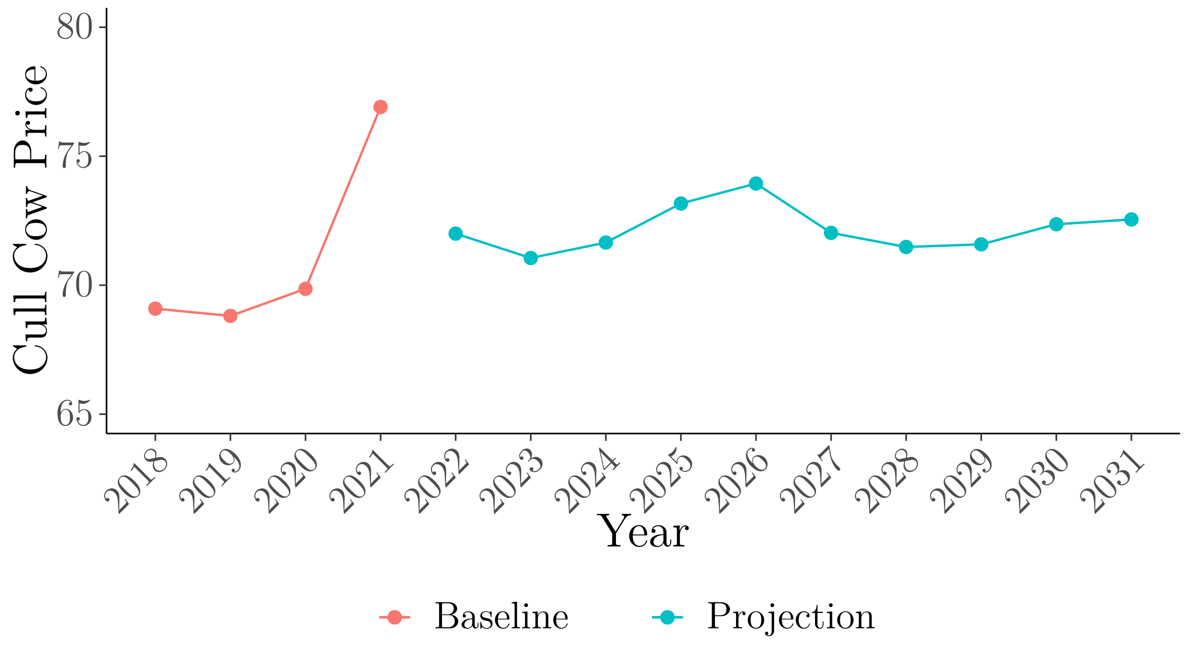

Figure 2.5 Projected cull cow price ($/cwt)

Table 2.15 Projections of fed cattle production and cow production (in billion pounds of meat)

Year	Fed Cattle	Cows
2022	23.98	3.38
2023	23.51	3.30
2024	23.07	3.16
2025	23.60	3.05
2026	23.64	2.99
2027	23.54	3.45
2028	23.51	3.76
2029	23.50	3.75
2030	23.48	3.67
2031	23.44	3.64

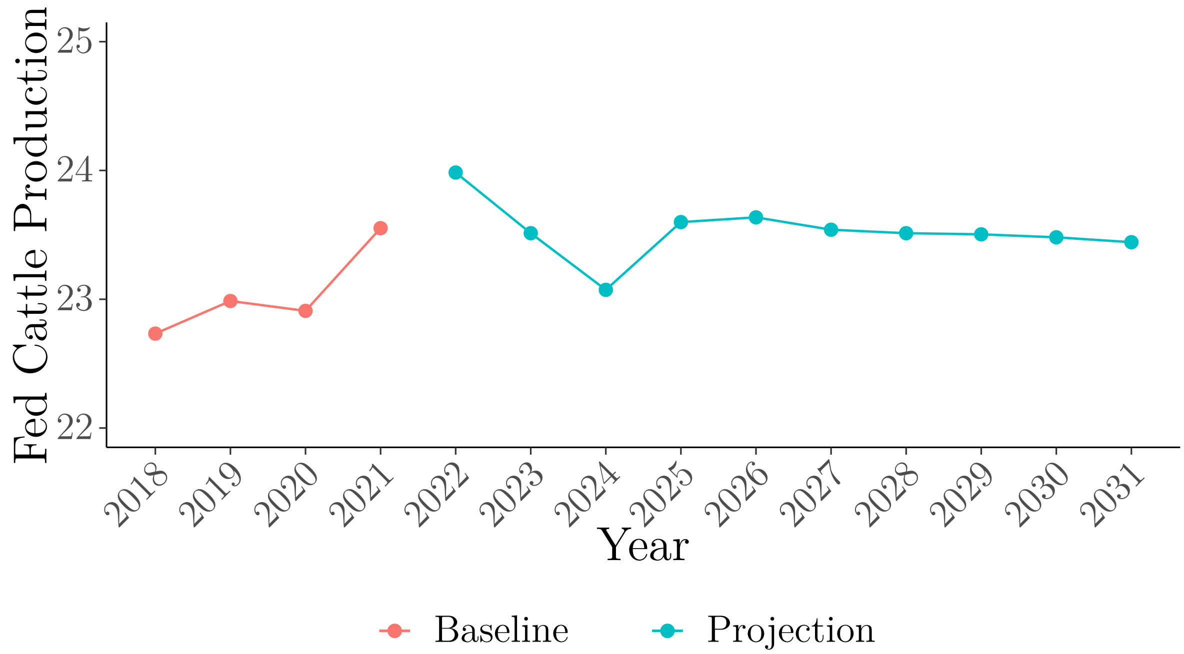

Figure 2.6 Projected fed cattle production (billion pounds)

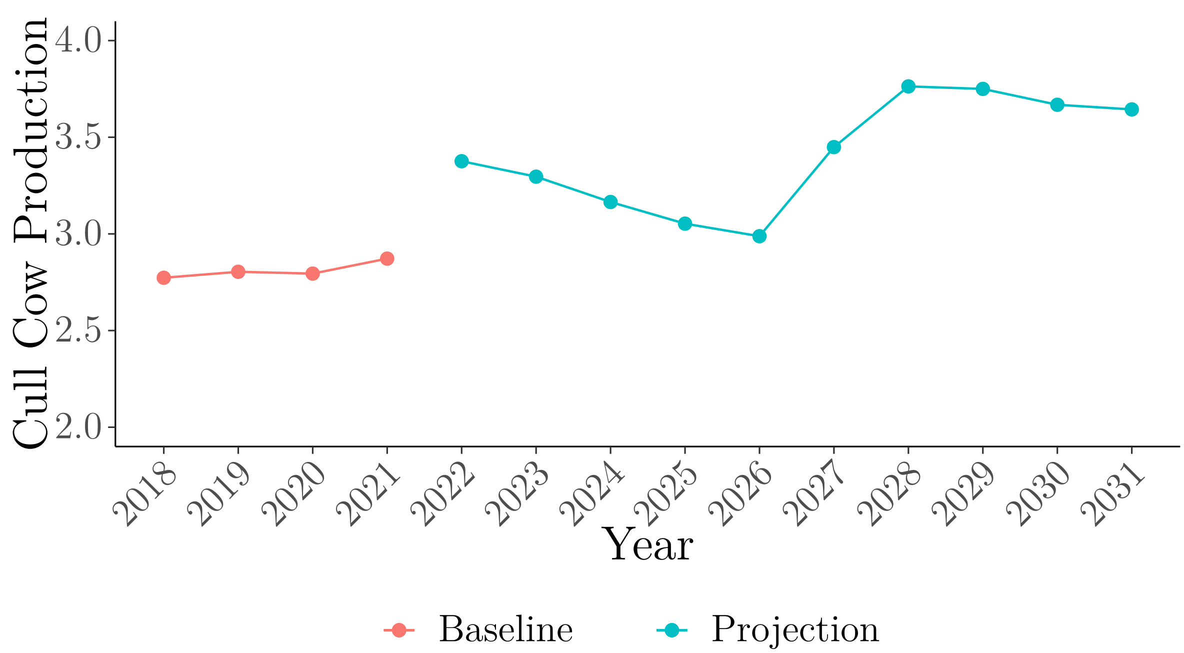

Figure 2.7 Projected cull cow production (billion pounds)

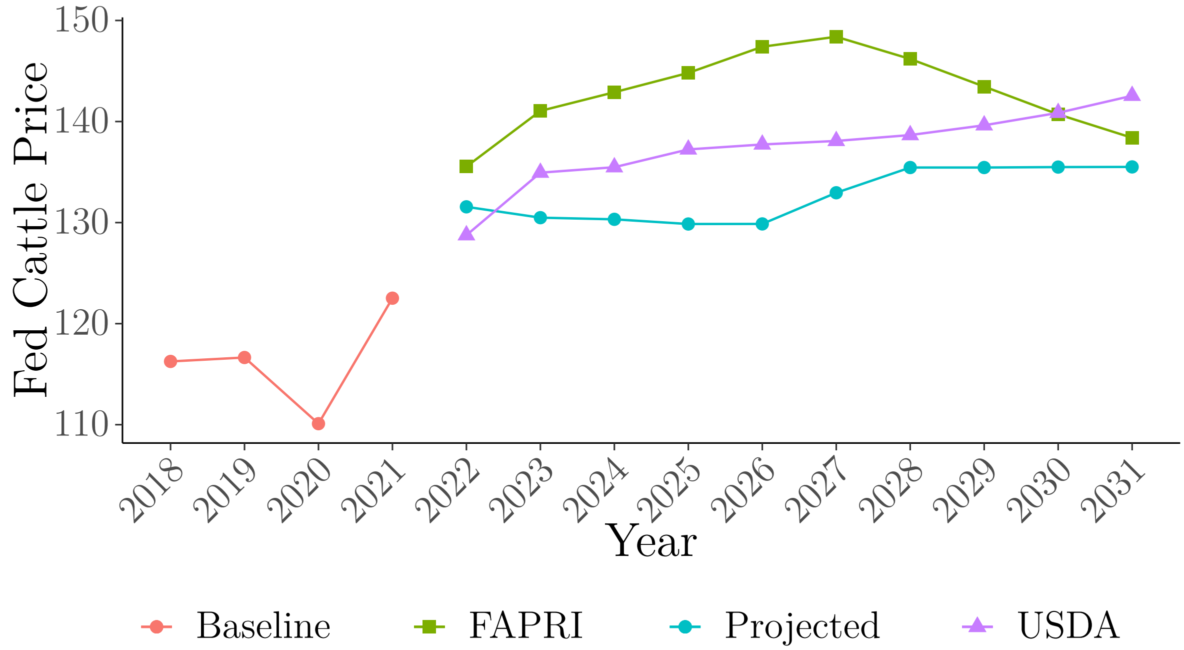

Figure 2.8 Projected fed cattle price vs USDA and FAPRI counterparts

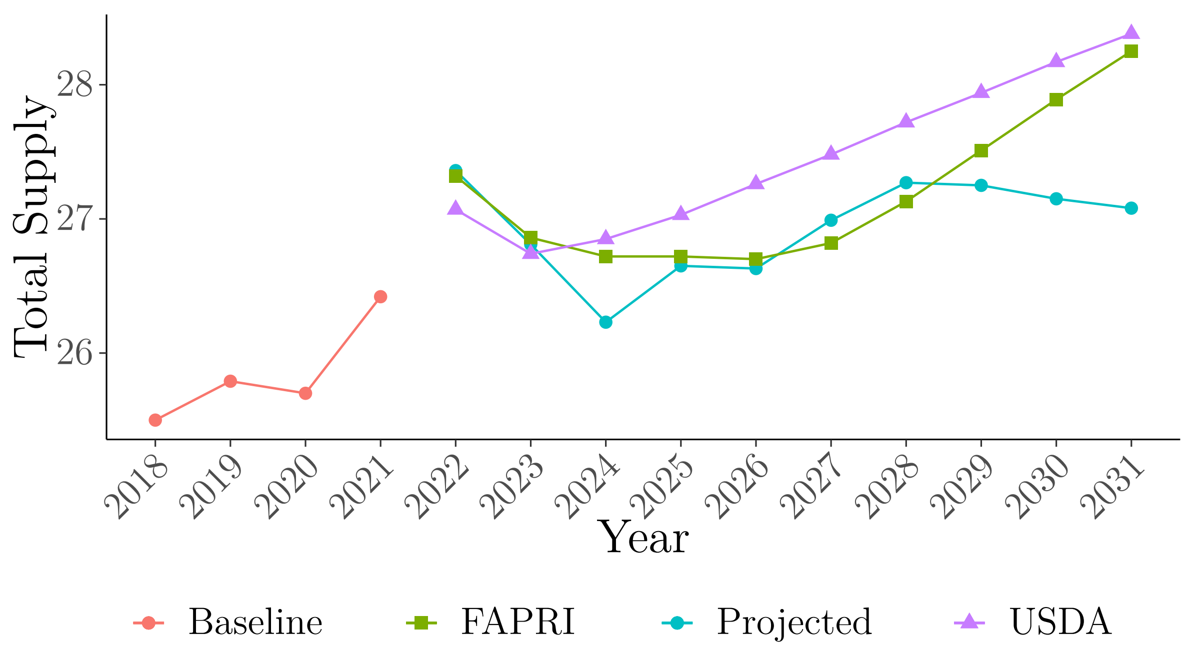

Figure 2.9 Projected total supply vs USDA and FAPRI counterparts

From the comparable projections above, the projected price and quantities are generally consistent with the USDA and FAPRI projections, providing strong evidence that the model is adequately projecting the market as these other models are considered the "gold standard" for agricultural projections. However, the dynamic processes within the model do provide some differences with USDA and FAPRI projections, which could be critical in evaluating policy impacts in the future. Overall, the fitted results and comparable projections further support that the dynamic model fits with the U.S. beef cattle data.

2.7 Summary and implications

A model of the U.S. beef cattle industry is developed and calibrated to appropriately capture the dynamics of the U.S. beef cattle industry. The analytical solution is presented under naïve and rational price expectations. In addition, a numerical solution (iterative algorithm) under rational price expectations is developed and presented. Data from various USDA sources were collected, compiled, and applied in the model to reflect the changes observed in the U.S. beef cattle industry. Numerical methods are used to find an equilibrium solution for the model. In particular, a collocation method is employed in the iterative algorithm to find a solution to the model with rational expectations.

An algorithm for the projection framework is developed. Using the estimated parameters and fitted prices and quantities, beef market prices and quantities are projected for a 10-year period. The model projections are compared with the long-term USDA and FAPRI projections. The long-term projections of the dynamic model are consistent with those of the USDA and FAPRI counterparts, indicating the model adequately captures and projects the market of the U.S. beef industry.

The model's ability to capture the beef cattle prices and quantities makes it valuable for policy analysis of any possible exogenous impact (e.g., foreign animal diseases) on the beef cattle industry. As stated in the first chapter, understanding not only the short-run impacts, but also the long-run impacts is crucial to any beef cattle policy design, or event study. The ability to project future prices and quantities demonstrates the models' potential to estimate the long-run impacts and the variance of these impacts over time provides valuable assistance to policymakers, as they consider policy proposals and modifications or explore potential events, such as disease outbreaks.

CHAPTER 3. AN ASSESSMENT OF THE ECONOMIC IMPACTS OF A FOOT-AND-MOUTH DISEASE OUTBREAK ON THE U.S. BEEF CATTLE INDUSTRY

3.1 Introduction

Foreign animal diseases (FADs) pose a significant threat to the U.S. agricultural economy, as the potential costs of a FAD outbreak would include production losses, the risk of losing access to export markets, and the expenses of eradicating the disease. It's also important to note that indirect costs, such as impacts on the other sectors of the economy like tourism [Thompson et al. (2002)] will be significant. Therefore, consideration of the economic consequences of FADs has become an increasingly crucial factor in the development of animal disease mitigation, control, management, and recovery policies [Schoenbaum and Terry Disney (2003)]. Evidence-based economic decision-making has been an important driver in establishing guidelines for animal disease management and control strategies [Elbakidze et al. (2009); Schoenbaum and Terry Disney (2003)]. The economic impacts due to FAD outbreaks can stem from various avenues, including restrictions imposed by international trading partners [Paarlberg et al. (2005); Paarlberg and Lee (1998)], changes in demand patterns leading to decreased consumption of meat and meat products [Schlenker and Villas-Boas (2009); Paarlberg et al. (2005); Piggott and Marsh (2004); Marsh et al. (2004); Burton and Young (1996)], and decreased productivity and value of livestock depopulated because of infection or mitigation policies [Bates et al. (2003)].

One of the FADs impacting global economies is foot-and-mouth disease (FMD), which, although it carries a low risk, can result in significant economic consequences if an outbreak occurs. The United Kingdom provides an example of this, having been FMD-free since 1967 until a major outbreak in 2001, which lasted 221 days and spread to France, Ireland, and the Netherlands. The repercussions of the outbreak were severe, leading to the depopulation of over six million animals and estimated losses of between £2.7 − 3.2 billion [Thompson et al. (2002)]. FMD outbreaks have also occurred in over 50 countries worldwide since 2000, including the U.K., Argentina, Brazil, Taiwan, and Malaysia.

Although the United States is typically perceived as having a relatively low likelihood of an FMD outbreak, the 2003 Bovine Spongiform Encephalopathy (BSE) outbreak and its subsequent impact on U.S. beef exports highlighted the severe economic implications of animal diseases on the domestic livestock industry.[1] The BSE-related export restrictions resulted in economic losses ranging between $3.2 − 4.7 billion in 2004 [Coffey et al. (2005)].[2] As FMD is not endemic to the United States, an outbreak could be devastating for the country, resulting in trade bans, depopulation of infected animals, decreased productivity, and distortion of the production of animal and animal products threatening the beef supplies, safety and security [Feng et al. (2017); Tozer and Marsh (2012); Nogueira et al. (2011)].

The objective of this chapter is to estimate the potential economic consequences of a hypothetical FMD outbreak on the U.S. beef cattle industry. The dynamic framework developed in this dissertation allows us to generate realistic counterfactuals by incorporating supply, trade, and consumer shocks into the model structure, quantifying the

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[1] FADs possess the ability to spread rapidly across borders and cause considerable economic damages [Pudenz et al. (2019)].

[2] The detection of BSE led to the stoppage of U.S. beef imports by countries including Japan, South Korea, Canada, and Mexico.

impacts on the prices and stocks, and determining the general trajectories of prices and supplies over time. Since the framework incorporates the dynamic processes within the industry, we capture the short-run impacts of production and economic shocks to the industry on the prices, supplies, and inventories as well as long-run impacts and the variability of those impacts over time. Furthermore, the evolution of the inventory levels determined by the model, along with the economic impacts, will be of interest to policymakers, researchers, and industry stakeholders.

Various approaches have been used to investigate the possible economic impacts of the FMD outbreak on the U.S. beef cattle industry. In particular, past studies have heavily relied on static economic models, such as input-output models and partial equilibrium models [Pendell et al. (2015); Pendell et al. (2007); Paarlberg and Lee (1998); Garner and Lack (1995)]. Employing an input-output and partial equilibrium economic model, Pendell et al. (2007) analyzed the impacts of FMD in southwest Kansas. Under different disease introduction scenarios, Pendell et al. (2007) found the total beef industry producer surplus losses due to an FMD outbreak range between $\$43.24 - 706.23$ million. Using a partial equilibrium model for the U.S. beef and veal industry, Paarlberg et al. (2003) found the aggregate producer welfare loss due to a hypothetical FMD outbreak is between $\$138 - 1,772$ million. Paarlberg et al. (2008) estimated the impacts of a hypothetical outbreak of FMD on different livestock species. Under the assumption that all agricultural sectors recover in 16 quarters, the estimated total losses to the livestock industries by the disease outbreak range between $\$2.77 - 4.06$ billion. Schoenbaum and Terry Disney (2003) and Elbakidze et al. (2009) studied the effectiveness of several FMD mitigation strategies and suggested that the best mitigation strategy for FMD depends on the speed of the spread of the virus and the demographics of the population. Elbakidze et al. (2009) further suggested that early detection of the virus can dampen the economic costs of an outbreak.

Zhao et al. (2006) recommend that to minimize the costs associated with an FMD outbreak it is imperative to increase surveillance and traceability of the animals in the United States.

Although the aforementioned static economic models have their advantages, one limitation of these models is that they do not include the dynamic processes inherent in beef cattle production. Given the nature of cattle inventories built into the reproduction process, the decisions made by producers (concerning retaining animals for breeding versus marketing them for slaughter), and the existence of cattle cycles, it is imperative to include dynamics when analyzing animal disease outbreaks. Using the dynamic model for the U.S. beef cattle industry built in this dissertation, we quantify the economic impacts of a hypothetical FMD outbreak.

3.2 Foot-and-Mouth Disease (FMD)

FMD is a highly contagious viral disease and poses a threat to all cloven-hoofed domestic and wild animals such as cattle, pigs, sheep, goats, bison, deer, and elk [USDA-APHIS (2021)]. Common symptoms of FMD include high fever, lesions, and erosions on the lips, tongue, mouth, and feet [USDA-APHIS (2021)]. FMD is not transmissible to humans and is not considered a public health threat. FMD is considered a threat to the agricultural sector, particularly the livestock sector, due to its contagious nature, significant disruptions in the livestock markets, and devastating economic impacts throughout the world.

The transmission of the FMD virus can occur via active subjects (e.g., humans, infected animals) or inactive subjects (e.g., vehicles, clothes, animal byproducts), direct or indirect contact, and air (the virus can transmit up to 100 kilometers by air and can transmit over land and water bodies). An animal that is exposed to an FMD strain can excrete the virus before showing any clinical signs. If undetected, introducing an infected animal carrying the virus into a dense herd can escalate the spread of the disease and infect the entire herd. Although FMD is not fatal to affected adult livestock, it can have negative impacts on the productivity of the animals because the disease makes the animal weak and unable to produce milk.

The FMD virus has the ability to survive for extended periods in uncooked processed meats, frozen products, and dairy products over a broad range of climates and regional conditions. The disease is very common and is endemic in parts of Asia, Africa, the Middle East, and South America [USDA-APHIS (2020)]. FMD was first discovered in the United States in 1870, and there have been several outbreaks since then, with the most recent mild outbreak being reported in California in 1929. [Pendell et al. (2007)]. The United States has been free of FMD (without vaccination) since 1929; however, international travel and trade pose a significant risk of the entry of FMD into the country.

FMD is one of the most difficult animal diseases to control. When detected, aggressive measures must be taken to contain and eradicate the disease. These measures may include limiting animal movement, setting up strict quarantine areas, and eliminating infected animals. Additionally, a vaccination program may be used in conjunction with cleaning and disinfecting FMD areas. To implement any disease management policies, the USDA-APHIS will coordinate with federal, state, tribal, and local partners to control, contain and eradicate FMD in the event of an outbreak.[3] The FMD Disease Response Plan or Red Book [USDA-APHIS (2020)] outlines potential response strategies and disease management policies, which may vary depending on the anticipated economic consequences and the states' and tribal nations' cooperation.

[3]The USDA-APHIS is a federal agency with primary responsibility and authority for protecting animal health, animal welfare, and plant health.

3.3 Hypothetical FMD introduction and exogenous shocks

Below is the description of the exogenous shocks that would be caused by a hypothetical FMD disease outbreak, which are introduced into the model.

3.3.1 Exogenous shock on international trade

Historically, animal diseases have had a significant impact on international trade. Frequent animal disease events over the past three decades have significantly increased the uncertainty in global meat markets through their impact on animal welfare, consumer preferences, and trade patterns [Morgan and Prakash (2006)]. In the event of an animal disease outbreak, strict regulations are often placed on livestock and meat trade. These restrictions depend on the disease and trading partners. In general, countries affected by animal disease outbreaks experience immediate restrictions by their international trading partners until the affected country showed evidence of disease-free status for a pre-determined period of time.

FMD is one of the animal diseases which is transboundary, that is, it can be spread from one geographical location to another. Hence, in an event of a disease outbreak, the export markets will likely be inaccessible to U.S. beef. Therefore, a trade restriction is imposed on all U.S. beef and live cattle exports [Pendell et al. (2015)] as an exogenous shock. Given that the United States has not experienced FMD for more than a century, the plausible duration of the trade restrictions was determined by reviewing the previous literature and by studying the reaction of global markets following the BSE events in the United States in 2003.

Previous studies analyzing FMD imposed different years of trade restrictions depending on the severity of the outbreak. The European Union imposed a one-year trade ban on the U.K. following its 2001 FMD outbreak. In analyzing the trade impacts of a hypothetical

FMD outbreak in Australia, Tozer and Marsh (2012) applied a $1-2$ year trade ban. In another study, Nogueira et al. (2011) imposed a $1-2$ year trade ban in studying a hypothetical FMD outbreak in Mexico. Analyzing the 2000-2001 FMD outbreaks in South America, Rich and Winter-Nelson (2007) concluded that FMD impacts on exports were short-lived. Although previous studies imposed different lengths of trade restrictions, the trade restrictions, in reality, depend on the product, the disease, the last known active case of the disease, the disease management strategy, trade agreements, and countries involved in the trade. For example, the 2003 BSE outbreak severely impacted U.S. beef exports. The major U.S. beef importers, Japan and South Korea imposed various restrictions on U.S. imports. Japan resumed imports of U.S. beef almost two years after the outbreak, followed by some strict regulations [Kenneth H. Mathews et al. (2006)]. South Korea, however, took five years to resume imports. In an extreme case, China resumed importing U.S. beef nearly 13 years after the BSE outbreak. This provides evidence that the duration of export restrictions is uncertain.

Based on the literature and the observed trade bans after the 2003 U.S. BSE outbreak, the scenarios in this chapter cover a $1-5$ year trade ban on U.S. beef exports.

3.3.2 Domestic demand exogenous shock

While the consumption of beef from infected cattle is not considered a health hazard [USDA-ERS (2001)], with respect to perceived food safety, food quality, and health concerns, domestic demand for meat would decline [Schlenker and Villas-Boas (2009); Paarlberg et al. (2008)] in the event of an FMD outbreak. Additionally, public food safety information can have a significant impact on meat consumption which can persist for up to two years [Taylor et al. (2016); Piggott and Marsh (2004)]. In the case of Taiwan, consumers reacted negatively to an FMD outbreak.[4] Thus, an exogenous domestic demand shock is included in the model.

Studies quantifying the impact of animal disease outbreaks on consumer demand in the United States have come to similar conclusions [Schlenker and Villas-Boas (2009); Kuchler and Tegene (2006); Coffey et al. (2005); Piggott and Marsh (2004); Marsh et al. (2004)] that the impacts are small and short-lived but can be large in severe outbreaks. In regards to the impact of FMD on consumer demand, the U.K. experienced a FMD outbreak in 2001, which resulted in a 2.7% decline in domestic demand for meat in the U.K. and the market for meat demand recovered to pre-outbreak levels in 5 years [Pendell et al. (2015)]. Studies on hypothetical FMD outbreaks [Pendell et al. (2015); Schroeder et al. (2015); Zhao et al. (2006)] and the BSE outbreak [Coffey et al. (2005)] in the United States assumed a 5% decline in domestic meat demand.[5] Examining the impact of a hypothetical FMD in the U.S., Paarlberg et al. (2003) assumed a 5% and 10% decline in domestic meat demand. In Mu et al. (2015), by analyzing the observed consumer response in the United States, the impact of BSE and avian influenza on domestic beef demand was found to be less than the impacts established in the literature (less than 5%).

While there are mixed results and views on the extent of the magnitude of the demand shock, following the consensus in the large literature on disease outbreaks and food safety, we use a 5% decline in domestic beef demand in the current analysis. The choice of demand shock in this study is not intended to imply the immediate demand shock in the event of FMD will be 5%. It is merely to quantify the impacts under that magnitude.[6]

[4] Livestock diseases such as BSE have been linked to human diseases and some consumers may not distinguish between the human health risks associated with BSE and FMD.

[5] This is consistent with established literature on consumer response to food safety concerns.

[6] The dynamic model can be simulated under varying levels of demand shocks.

3.3.3 Production exogenous shock

Despite having painful clinical symptoms, animals infected with FMD can make a full recovery in a relatively short period of time (two to three weeks) and most adult animals become productive again. However, in some cases, a permanent reduction in productivity is observed in the infected animals. FMD results in different mortality rates in adult and young animals. The mortality rate in the infected adult animal is between 2% and 5% [Ekboir (1999)]. In young animals, the mortality rate is much higher. The mortality rates of the infected young animal can range from 20% in smaller herds to 90% in dense herds [Ekboir (1999)].

To determine the appropriate depopulation levels (reduction of animals) during a potential FMD outbreak, we reviewed the USDA mitigation strategies. According to the Red Book [USDA-APHIS (2020)], the most likely policies for mitigating and eradicating FMD are (1) stamping-out (depopulation) with emergency vaccination to slaughter, (2) stamping-out with emergency vaccination to live, and (3) a combination of stamping-out modified with emergency vaccination to kill, slaughter, and live. The vaccinated animals will live and can be used for their intended purposes (breeding, slaughter, and other purposes). These strategies could depend on the scale of the outbreak and the immediate availability of a vaccine.[7]

In addition to reviewing the USDA mitigation strategies, we examined the 2001 FMD outbreak in the U.K. to determine the depopulation levels. The FMD outbreak in the U.K. resulted in the depopulation of over six million animals [Thompson et al. (2002)]. In

[7] When administering a vaccine to infected animals, the USDA must consider the trade repercussions of the vaccination. Vaccination of the infected animal could be one of the mitigation strategies. However, it is recommended in rare cases. This is because the FMD vaccine is an inactivated form of the virus and vaccination may prolong the duration of trade bans due to the possibility of vaccinated animals carrying the virus.

analyzing the impacts of a hypothetical FMD outbreak in the U.S., Paarlberg et al. (2002) assumed a 5% exogenous decline in the beef cattle inventories, which was based on the animal losses in the U.K. In this study, past FMD events and studies examining FMD impacts in the U.S. are used to determine the depopulation levels.

In the current study, assuming the infected animals are depopulated, a hypothetical FMD outbreak is inherently treated as a one-time exogenous shock to the cattle inventories with no recurrent FMD outbreaks. We assume two depopulation levels, in particular, depopulation levels of 5% and 10%.[8] In the event of a severe outbreak, we expect the USDA may adopt a vaccination approach rather than depopulating all the infected herds. In the event of vaccine unavailability, we expect the USDA may restrict animal depopulation to specific regions, instead of national depopulation. In reality, depopulating all the infected herds (greater than 15% depopulation) might be counter-intuitive, because the infected animals can recover from the disease and lead productive lives.

3.4 Scenarios

We utilize the dynamic model to examine the impact of a disease outbreak by introducing a hypothetical FMD outbreak into the framework in the year 2021. The resulting exogenous shocks due to the disease outbreak discussed in the previous section are used to simulate the model. In particular, shocks to the cattle inventories, global markets response, and consumer response in the domestic markets are simultaneously included within the model to generate market counterfactuals of an FMD outbreak from 2022 to 2031. In addition, to demonstrate the range of the impacts of an FMD outbreak, we have developed two scenarios: an *optimistic* and a *pessimistic* scenario.

[8]In this study the *depopulation level* is assumed to be a percent decline. For example, a 5% depopulation means a 5% decline in the beef cattle inventories ($K - 0.05K = 0.95K$).

3.4.1 Optimistic scenario

In the *optimistic* scenario, we assume that the exogenous shocks due to the disease outbreak in the domestic and international markets will be short-lived. In particular, the following shocks are introduced into the model:

- Domestic demand for beef falls by 5% for a year,
- Export markets are inaccessible for two years, and
- Account for either a 5% or 10% depopulation of inventory.

The details of the above are as followed: in year one after the disease outbreak, we assume the domestic beef demand declines by 5%, and exports are banned. In the second year, we assume domestic beef demand recovers and export restrictions will remain in place. In the third year post-disease outbreak, we assume the export bans have been lifted and the U.S. resumes beef and live animal exports.

3.4.2 Pessimistic scenario

In the *pessimistic* scenario, we assume that the exogenous shocks in the domestic and international markets are longer-lived. In particular, the following shocks are introduced into the model:

- Domestic demand for beef falls by 5% for three years,
- Export markets are inaccessible for five years, and
- Consider either a 5% or 10% depopulation of inventory.

The further explanation of the *pessimistic* scenario is as followed: for the first three years post-disease outbreak, we assume that domestic beef demand declines by 5% and exports are banned. In year four, we assume domestic beef demand recovers and export restrictions remain in place and continue through year five. In year six post disease outbreak, we assume the export bans are lifted and the U.S. resumes beef and live animal exports.

3.4.3 Exports, imports, and culling decisions

In regards to the magnitude of beef exports in the simulation, we take a conservative approach by using the historical (from 2000 to 2021) beef exports relative to the total production before the FMD outbreak to model the beef exports in the simulation period (from 2022 to 2031).[9] To determine the live animal exports in the simulation period (from 2022 to 2031), the historical live animal exports from 2000 to 2021 are utilized to set the relationship between exports and live cattle supplies. The imports of beef and live animals were also determined in a similar fashion. That is, historical beef and live animal imports are used to determine the beef and live animal imports in the simulation period.[10]

Contrary to the literature, where the culling age of the adult cows is fixed to a specific age, we take current market conditions into consideration to determine the culling age. For example, holding costs and the current market price of a cow are used to determine the culling age of cows. As indicated in the model framework, the holding costs are modeled based on corn futures (sourced from the Chicago Mercantile Exchange) and are used in the simulation period. We model a relationship between the historical equilibrium holding costs and historical corn prices. This relationship is further utilized to estimate the holding

[9] Instead of keeping the beef exports static, we determine the beef exports dynamically where the beef exports depend on the total beef production in the simulation period.

[10] The historical beef exports and imports relative to the total beef production are used to determine the corresponding beef exports and imports in the simulation period. The historical live animal exports and imports relative to the total inventory are used to determine the corresponding live animal exports and imports in the simulation period.

costs in the future with respect to corn futures. Consistent with the literature [Hayes et al. (2011)], these holding costs are further adjusted to reflect the depopulation levels in the scenarios.[11]

3.4.4 Algorithm to generate counterfactuals

We simulate the dynamic model to generate price and supply counterfactuals with the introduction of a hypothetical FMD outbreak based on the scenarios described in the previous sub-sections.[12]

1. A one-time exogenous supply shock is introduced by depopulating the existing stocks.
2. Based on the inventories from step 1, the fed cattle and cull cow supplies are determined.
3. The share metric $1 - H(\tilde{p})$ is determined by using the estimated deep parameters.[13]
4. The demand for fed cattle is calculated from the share metric in step 3.
5. The number of two-year-old heifers, the beef cow inventory of the prior year, and the demand (quantity) for fed cattle from step 4 are used to determine the number of replacement heifers.[14]
6. The replacement heifers from step 5 are used to determine the total inventories of the present period.

[11] Hayes et al. (2011) provide evidence that corn prices react to the FMD outbreak and fall by 20 cents in their simulation period. Consistent with Hayes et al. (2011) findings, we adjust the corn price relative to the depopulation which further changes the holding costs in the algorithm to generate counterfactuals.

[12] Due to the biological constraints in the model, the algorithm can be viewed as a *modified evolutionary algorithm* for the beef cattle industry that generates counterfactuals.

[13] These parameters include $\tilde{\mu}$ and $\tilde{s}$.

[14] The birth rate g and survival rate δ are used to determine the number of mature cattle for decision-making.

7. The replacement heifers and total inventories computed in steps 5 and 6 respectively, are used to generate the number of cows of different age groups (from age 4 to 10).

8. The expected value of a nine-year-old cow is calculated on the basis of the holding costs. The expected value of a nine-year-old cow is then compared to the current market price of the cow and a decision is made on whether the older cows are to be consumed or to retain them in the herd for another year.

9. In this step, the trade and domestic beef demand exogenous shocks are introduced.

10. Once the supplies are determined after the trade shock, the prices of the previous period are used as starting values for solving the equilibrium system. The result of this step contains the equilibrium fed cattle price, cull cow price, corresponding expected prices, and the equilibrium supplies. This is the end of the first iteration.

11. For subsequent years, steps 2 through 10 are repeated with the domestic beef demand and trade shocks described in the scenario.

The above process is performed for both the *optimistic* and *pessimistic* scenarios to generate price and supply counterfactuals and stock evolution. Because the model is calibrated to capture the dynamics at the national level, the simulation assumes the beef industry as one zone. Therefore, the trade impact in the simulation assumes that all international beef trade between the U.S. and trading partners is restricted. In terms of flexibility, the dynamic model can be modified to capture different zones in the United States and appropriate simulations can be run.

3.5 Scenario results and discussion

Due to the inaccessibility of export markets with a uniform trade ban in the scenarios, beef originally destined for the export markets is absorbed into the domestic market, increasing domestic supply. Coupled with a decrease in domestic beef demand, domestic prices decrease compared to the baseline (no disease outbreak).[15] Figures 3.1 and 3.2 illustrate the price impact on fed cattle for the optimistic and pessimistic scenarios, respectively. At higher depopulation levels, the more animals are removed, the more supply is reduced, which drives up the price compared to the price with lower depopulation levels. Over time, however, when domestic beef demand returns to pre-FMD levels and exports resume, domestic prices increase. Specifically, in the optimistic scenario, on average, the higher prices are sustained for about eight years or approximately one cattle cycle. At the end of the simulation period, in the optimistic scenario, the prices approach baseline (for both 5% and 10% depopulation levels), indicating that the market will recover quickly if the exogenous shocks are short-lived.

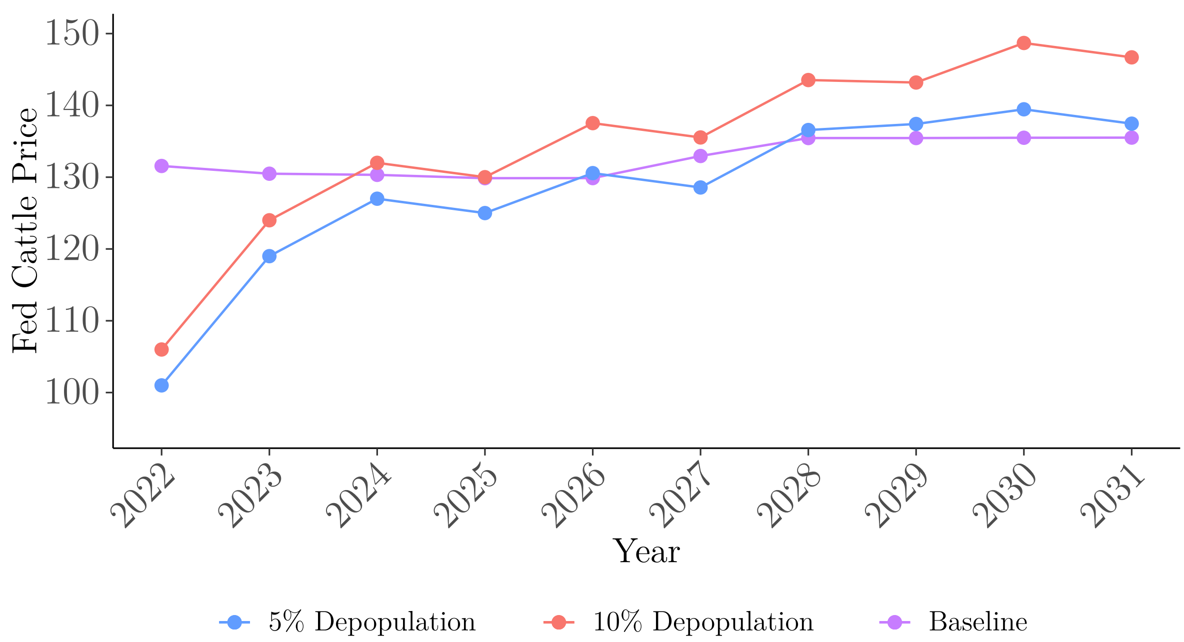

Figure 3.1 Fed cattle price counterfactuals ($/cwt) relative to the baseline – Optimistic scenario

[15]The long-run projections of the dynamic model without the disease outbreak are taken as the baseline.

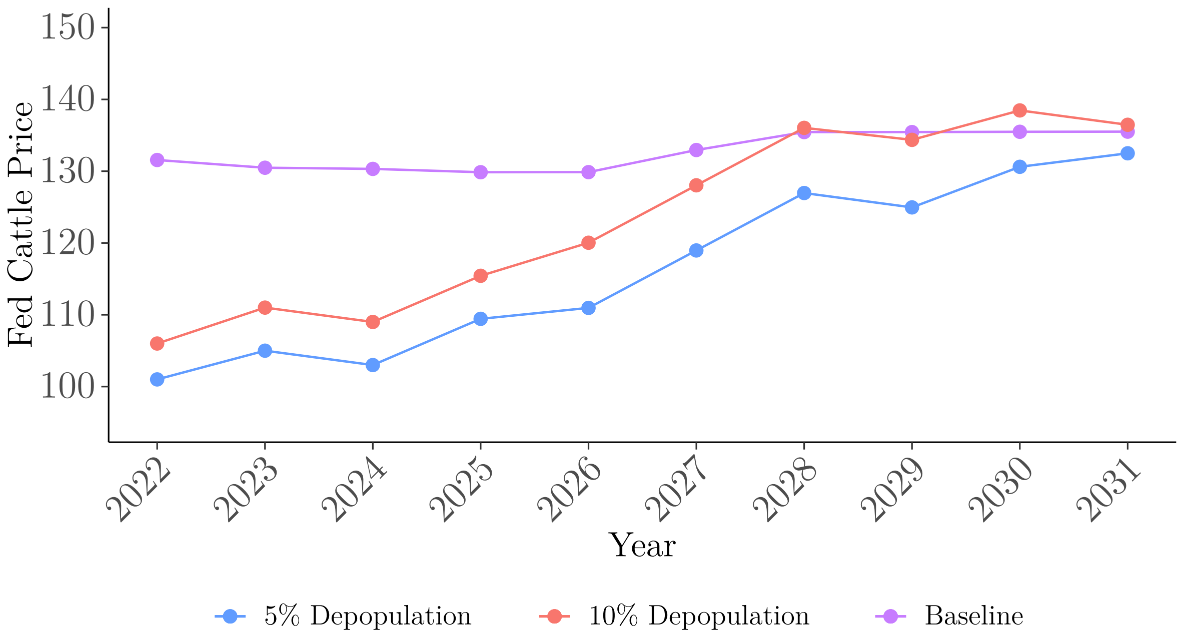

Figure 3.2 Fed cattle price counterfactuals ($/cwt) relative to the baseline – Pessimistic scenario

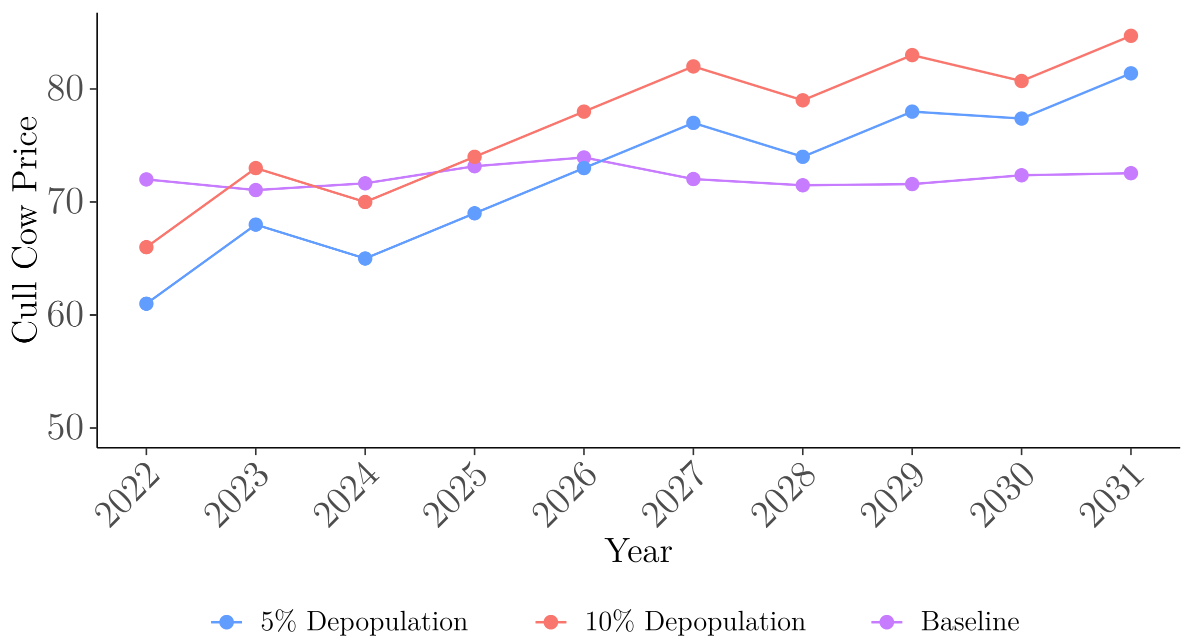

Figure 3.3 Cull cow price counterfactuals ($/cwt) relative to the baseline – Optimistic scenario

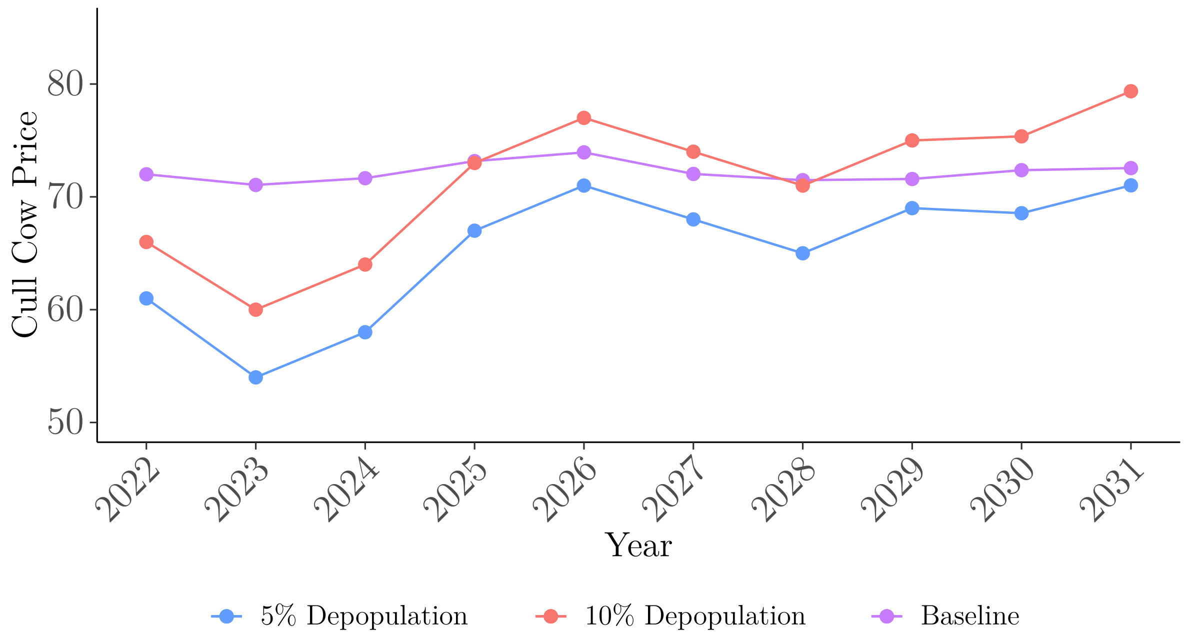

Figure 3.4 Cull cow price counterfactuals ($/cwt) relative to the baseline – Pessimistic scenario

The duration of trade bans assumed in the scenarios impacts the prices and supplies in different ways. In the scenarios with shorter trade bans (optimistic scenario), the impact on prices (Figures 3.1 and 3.3) and supplies (Figures 3.5 and 3.6) is short-lived, while in the scenarios with longer trade bans (pessimistic scenario), the impact on the prices (Figures 3.2 and 3.4) and supplies (Figures 3.7 and 3.8) persist for longer periods. However, in both optimistic and pessimistic scenarios, in the long run, the price trajectories approach the baseline. These findings demonstrate that the market recovery after the disease outbreak ultimately depends on the duration of trade restrictions, domestic beef consumption patterns, and other exogenous shocks incorporated into the model.

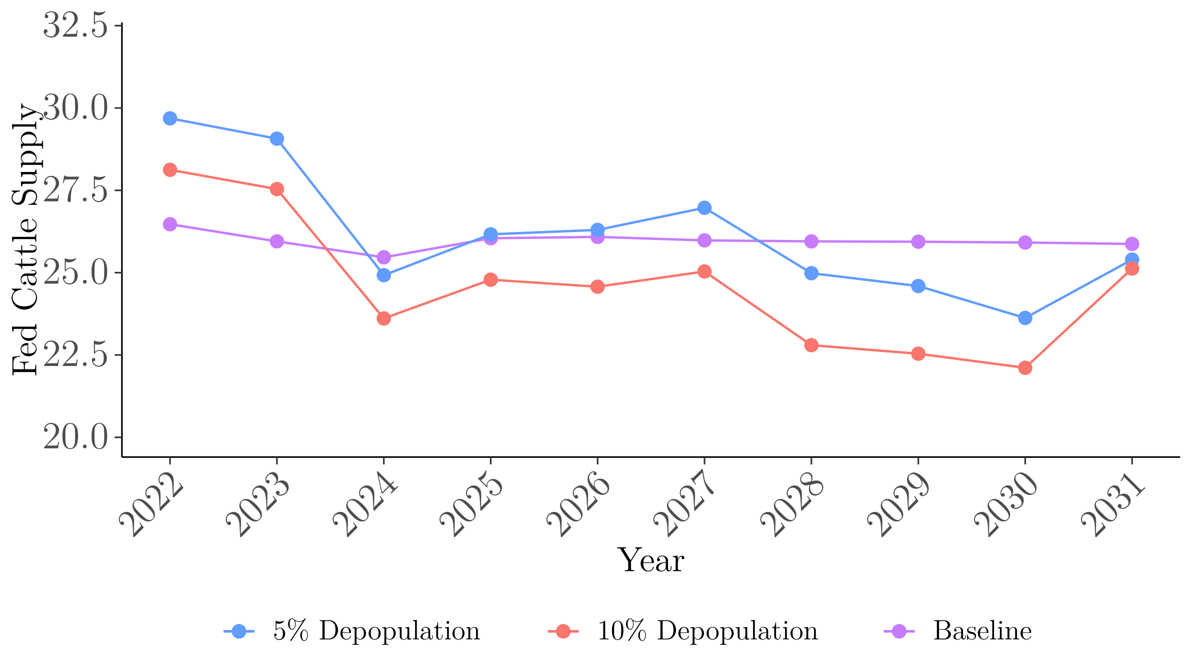

Figure 3.5 Fed cattle supply counterfactuals (million head) relative to the baseline – Optimistic scenario

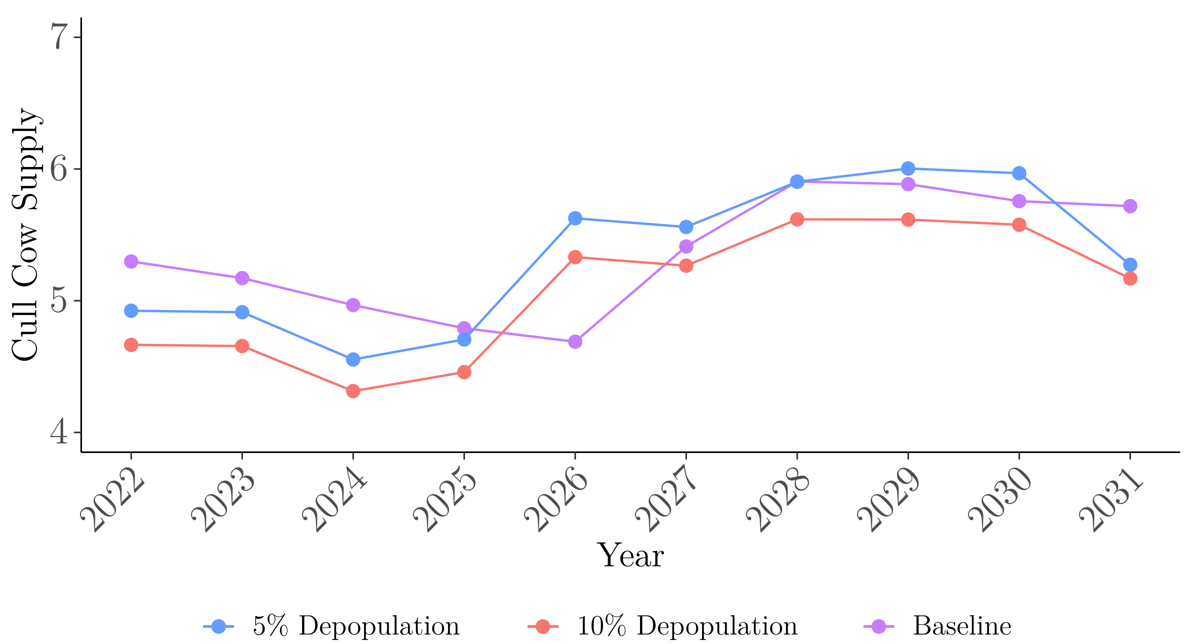

Figure 3.6 Cull cow supply counterfactuals (million head) relative to the baseline - Optimistic scenario

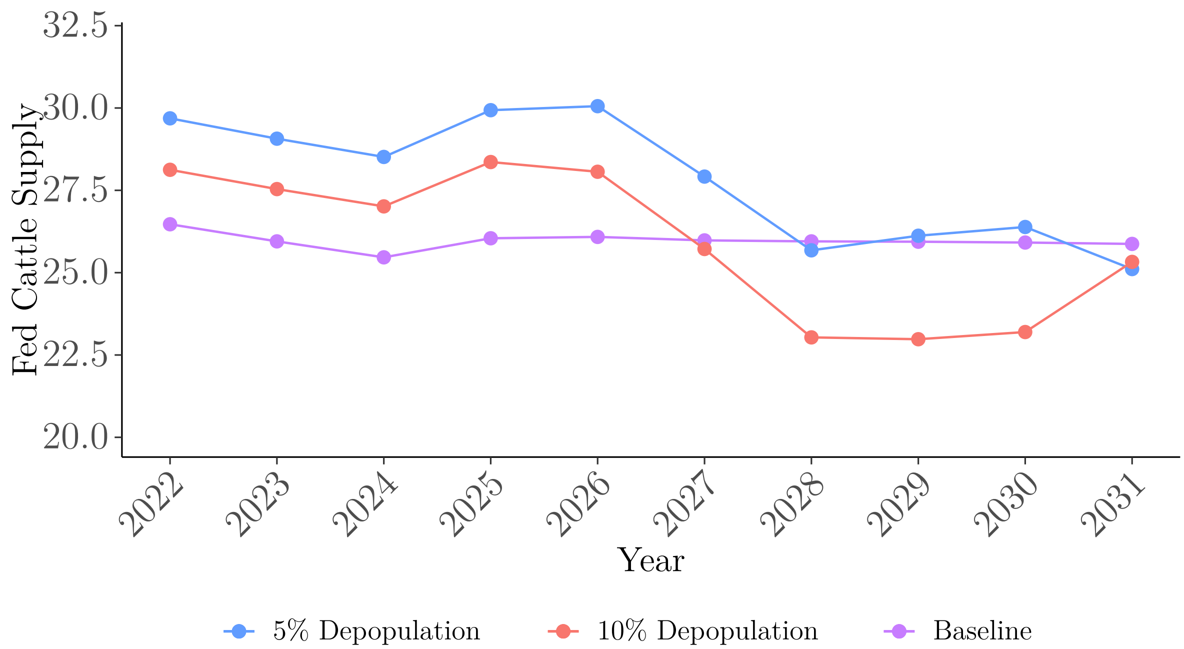

Figure 3.7 Fed cattle supply counterfactuals (million head) relative to the baseline – Pessimistic scenario

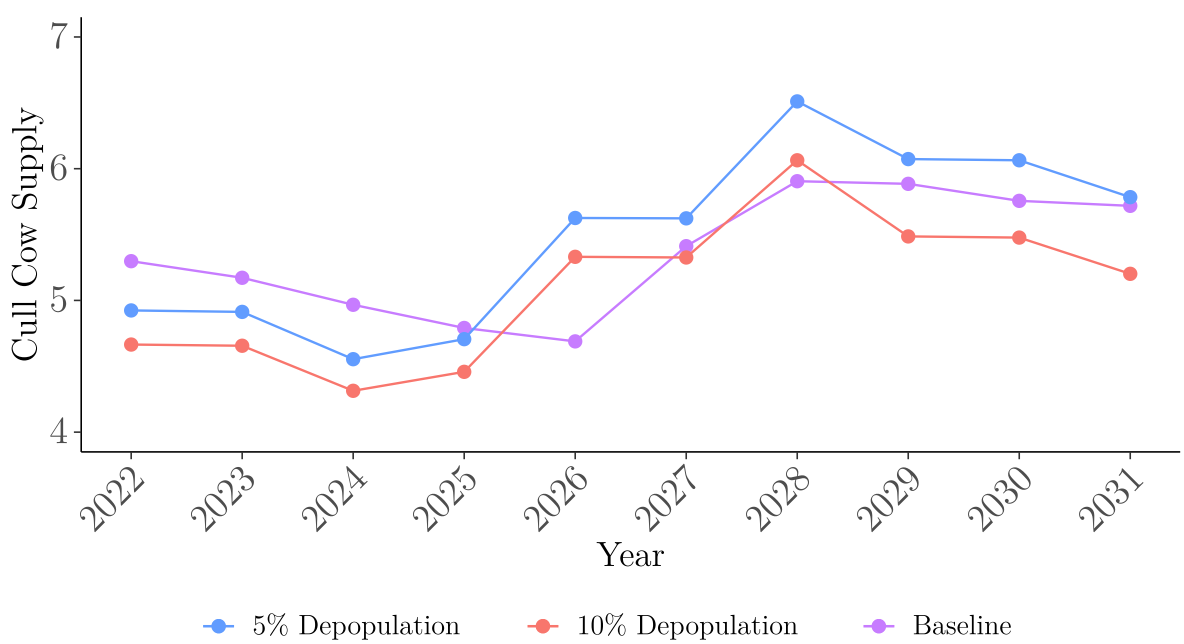

Figure 3.8 Cull cow supply counterfactuals (million head) relative to the baseline – Pessimistic scenario

The price and supply responses determined by the model are consistent with previous studies [Tozer and Marsh (2012); Hayes et al. (2011); Paarlberg et al. (2008)] and economic theory [Aadland and Bailey (2001); Rosen et al. (1994)]. Given the differences in the economic models and methodologies, the magnitude of the results cannot be directly compared to those of past studies. However, the direction of the findings is in line with past studies. Additionally, the model offers value-added features such as stock changes and trade patterns which are discussed below.

Inventory changes (with age groups) after the disease outbreak are shown in Tables 3.1-3.4. The inventory evolution in Tables 3.1-3.4 are consistent with the standard economic theory and intuition. Some years producers keep both 8 and 9-year-old cows, while in other years they do not keep these older animals. This is due to the holding costs and the market price of the cows. As discussed in the previous chapter, within the model, before deciding to cull the older cows, a representative producer computes the expected value of the older cow which depends on the holding costs, and compares the expected value to the current market price of the cow and makes a decision, resulting in dynamic optimizing behavior.[16] These results show a novelty in the model by determining the inventories dynamically with age distribution in a detailed fashion.

Trade patterns, the magnitude of the imports and exports determined in the simulations, are shown in Tables 3.5 - 3.8. During the initial years following the FMD outbreak, it is anticipated that the beef industry will react to the reduced prices by decreasing imports. Moreover, export restrictions will result in more beef being supplied to the domestic market. This phenomenon is captured in both the optimistic and pessimistic scenarios, with 5% and 10% depopulation levels. The magnitude of beef exports and live animal exports are also determined and presented in Tables 3.5 - 3.6.

[16] The conditions that are used for these decisions are specified in the model framework chapter.

Table 3.1 Counterfactual inventory (number of head) distribution under 5% depopulation rate – Optimistic scenario

Year	K	k_3	k_4	k_5	k_6	k_7	k_8	k_9
2022	29995052	6907361	5242532	5045566	4975167	4923723	0	0
2023	30322816	6826104	6561993	4980406	4793288	4726409	0	0
2024	31056546	7248459	6484799	6233893	4731385	4553623	4490088	0
2025	31876000	7370869	6886036	6160559	5922199	4494816	4325942	4265584
2026	31792868	6509256	7002326	6541734	5852531	5626089	4270075	4109645
2027	31016137	5811500	6183793	6652209	6214647	5559905	5344784	4056572
2028	29991855	5525113	5520925	5874604	6319599	5903915	0	0
2029	31244059	7750384	5248857	5244879	5580873	6003619	0	0
2030	31478995	6795726	7362865	4986414	4982635	5301830	0	0
2031	30824267	5917810	6455940	6994721	4737093	4733503	0	0

Note: Here K represents total inventory, k_3 represents the replacement heifers, and k_4 to k_9 represents the cows of ages from 4 to 9 years.

Using the supply and price counterfactuals, the changes in consumer surplus and producer surplus relative to the base model are computed. The change in consumer surplus is computed by summing the change in consumer expenditures relative to the baseline for both fed cattle and cull cow beef markets. The change in producer surplus is computed by summing the changes in producer revenues relative to the baselines for both fed cattle and cull cow markets. Table 3.9 shows the discounted present value of the change in consumer surplus and producer surplus for the optimistic and pessimistic scenarios.

In Table 3.9, under the 5% depopulation level, the present discounted consumer surplus gains are $14.57 billion for the optimistic scenario and $32.79 billion for the pessimistic scenario. The present discounted values of consumer surplus for the 10% depopulation level increase roughly by $5 billion. The decline in price negatively impacts the producers and the present discounted producer surplus losses due to the disease outbreak are $5.05 billion and $18.18 billion for optimistic and pessimistic scenarios, respectively at the 5%

Table 3.2 Counterfactual inventory (number of head) distribution under 10% depopulation rate – Optimistic scenario

Year	K	k_3	k_4	k_5	k_6	k_7	k_8	k_9
2022	28416365	6543816	4966610	4780010	4713316	4664580	0	0
2023	28462525	6465566	6216625	4718279	4541010	4477650	0	0
2024	28937730	6896919	6142288	5905794	4482365	4313959	4253768	0
2025	29365580	6873325	6552073	5835174	5610504	4258247	4098261	4041079
2026	29258213	6359499	6529658	6224469	5543415	5329979	4045334	3893348
2027	28890635	6093920	6041524	6203175	5913246	5266244	5063480	3843068
2028	29074059	6626544	5789224	5739448	5893017	5617583	0	0
2029	30159601	7537832	6295217	5499763	5452476	5598366	0	0
2030	32269244	8616211	7160940	5980456	5224775	5179852	0	0
2031	33969432	8312238	8185400	6802893	5681433	4963536	0	0

depopulation level. The present discounted value of the change in producer surplus at the 10% depopulation level decreases by roughly \$3 billion.

It is important to note that the decline in domestic beef demand and the inability to export to other countries has resulted in higher losses for beef producers in the first few years following the disease outbreak, while consumers have experienced gains. The domestic beef demand shock and export ban shock amplify the price decline, which reduces producers' revenues. The same price decline acts in favor of beef consumers and increases the consumer surplus. However, over time, as domestic demand for beef increases and export restrictions on U.S. beef are lifted, the losses for producers and gains for consumers become smaller and approach the baseline level. All of the welfare results are consistent with the previous literature, in particular, the direction of the changes in the producer surplus and consumer surplus are in line with the past studies [Paarlberg et al. (2008); Pendell et al. (2007); Paarlberg et al. (2002)]. The welfare changes shown in Table 3.9 are purely market-based. These changes do not cover the loss of animal value caused by the depopulation of live animals, disinfection and clean-up costs, government support for

Table 3.3 Counterfactual inventory (number of head) distribution under 5% depopulation rate – Pessimistic scenario

Year	K	k_3	k_4	k_5	k_6	k_7	k_8	k_9
2022	29995052	6907361	5242532	5045566	4975167	4923723	0	0
2023	30300882	6804171	6561993	4980406	4793288	4726409	0	0
2024	31780873	7993623	6463962	6233893	4731385	4553623	4490088	0
2025	32650159	7456917	7593942	6140764	5922199	4494816	4325942	4265584
2026	33229110	7210047	7084071	7214245	5833726	5626089	4270075	4109645
2027	31610106	5041039	6849544	6729868	6853533	5542040	5344784	0
2028	32632151	7601138	4788987	6507067	6393374	6510856	5264938	5077545
2029	32060959	6059003	7221081	4549537	6181714	6073706	6185313	5001691
2030	29950472	4491149	5756053	6860027	4322061	5872628	0	0
2031	31035703	7581342	4266591	5468250	6517026	4105958	0	0

producers, or the implementation of vaccination programs. Incorporating these additional costs would further amplify the losses due to the disease outbreak and would decrease the net welfare impacts.

The results demonstrate that overlooking the dynamic process of beef cattle production can lead to inaccurate long-run estimates and miss the evolution of the industry and the market recovery. By incorporating biological constraints and breeding herd dynamics, we showed not only short-run, but also long-run, trajectories of market response to the FMD outbreak and the nature of the market response.

A number of policy recommendations can be made based on the results. First, restricting the cattle movement, and convincing trading partners to regionalize the United States can sustain some of the export flow, which can significantly reduce the losses from the FMD outbreak. Second, educating consumers about the health consequences of FMD, in particular, raising awareness that *FMD cannot be transmitted to humans through the consumption of red meat* can reduce the losses from the FMD outbreak. The findings about large declines in prices in the initial years post-FMD outbreak also inform that, preventing

Table 3.4 Counterfactual inventory (number of head) distribution under 10% depopulation rate – Pessimistic scenario

Year	K	k_3	k_4	k_5	k_6	k_7	k_8	k_9
2022	28416365	6543816	4966610	4780010	4713316	4664580	0	0
2023	28429279	6432320	6216625	4718279	4541010	4477650	0	0
2024	29454002	7444775	6110704	5905794	4482365	4313959	4253768	0
2025	29718982	6736268	7072536	5805169	5610504	4258247	4098261	4041079
2026	29715092	6480647	6399454	6718909	5514910	5329979	4045334	3893348
2027	27846633	4615883	6156615	6079482	6382964	5239165	0	0
2028	29019848	7564134	4385089	5848784	5775508	6063816	4977207	0
2029	29493092	6922824	7185927	4165834	5556345	5486732	5760625	4728346
2030	29951599	6931750	6576683	6826631	3957543	5278528	0	0
2031	30077238	6621807	6585162	6247849	6485299	3759665	0	0

adverse trading partners' and consumer reactions to the disease outbreak can largely alleviate the negative impacts on prices and revenues.

3.6 Summary

For almost a century, the United States has kept FMD out of the country by imposing strict restrictions on imports of animals and animal products from countries susceptible to FMD. With globalization, increased human mobility, and changes in international trade and travel regulations, the likelihood of the entry of the disease into the United States has increased. The entry of FADs such as FMD into the United States unintentionally or intentionally can have catastrophic economic and animal welfare implications, and the impacts can be significant and persistent.

Using the dynamic model developed in this dissertation, we estimated the potential economic impacts of a hypothetical FMD outbreak on the U.S. beef cattle industry. The findings indicate that the economic consequences of an FMD outbreak in the U.S. beef cattle sector are significant. Although animal losses due to the disease are devastating, the

Table 3.5 Counterfactual trade patterns under 5% depopulation rate – Optimistic scenario

Year	Live Cattle Imports	Live Cattle Exports	Beef Imports	Beef Exports
2022	0	0	0	0
2023	0	0	0	0
2024	0	309619	0	2.12
2025	0	316220	0	2.21
2026	0	306807	0	2.29
2027	0	196852	0	2.33
2028	2442320	192043	0	2.19
2029	0	316009	0	2.17
2030	0	307711	0	2.06
2031	0	194909	0	2.16

Note: Live cattle trade is in number of head and beef trade is in billion pounds.

main drivers of the economic impacts are the changes in export and domestic markets. By designing two scenarios, we simulated the dynamic model to demonstrate how the variation in exogenous shocks such as domestic beef demand, export restrictions, and depopulation levels dictate the economic impacts. Illustrations of the trajectories of prices and supplies, the inventory evolution, and trade patterns highlight the immediate market reaction to the disease outbreak and the time frame for the markets to reach baseline levels.

Because of the nature of beef production, the disease outbreak results in losses for producers, especially when the outbreak is severe. For example, when depopulation rates are high, producers lose valuable breeding inventory in the short run, but as prices rise, the producer surplus increases in the long run. In contrast, consumers are worse off if prices rise in the long run. In the event of a severe FMD outbreak, as mentioned in 3.3.3 stamping out all the infected herds may be counter-intuitive. Although depopulation of the infected herd increases the prices in the long run, producers lose valuable inventory in the short run. Since beef production is a multiyear process, it may take a few years to increase the breeding inventory to baseline levels and supply the desired amount of beef at the same

Table 3.6 Counterfactual trade patterns under 10% depopulation rate – Optimistic scenario

Year	Live Cattle Imports	Live Cattle Exports	Beef Imports	Beef Exports
2022	0	0	0	0
2023	0	0	0	0
2024	0	176232	0	2.01
2025	0	294735	0	2.10
2026	0	181823	0	2.13
2027	0	181158	0	2.16
2028	0	290294	0	2.01
2029	0	306752	0	1.99
2030	0	331605	0	1.94
2031	0	574489	0	2.16

Note: Live cattle trade is in the number of head and beef trade is in billion pounds.

time. In the event of a severe FMD outbreak, vaccinating the infected cattle, zoning and quarantining the infected herds, and limiting cattle movement may reduce losses.

Table 3.7 Counterfactual trade patterns under 5% depopulation rate – Pessimistic scenario

Year	Live Cattle Imports	Live Cattle Exports	Beef Imports	Beef Exports
2022	0	0	0	0
2023	0	0	0	0
2024	0	0	0	0
2025	0	0	0	0
2026	0	0	0	0
2027	2574099	205745	0	2.34
2028	0	323519	0	2.28
2029	0	202049	0	2.29
2030	2438950	198512	0	2.30
2031	0	312910	0	2.11

Note: Live cattle trade is in the number of head and beef trade is in billion pounds.

Table 3.8 Counterfactual trade patterns under 10% depopulation rate – Pessimistic scenario

Year	Live Cattle Imports	Live Cattle Exports	Beef Imports	Beef Exports
2022	0	0	0	0
2023	0	0	0	0
2024	0	0	0	0
2025	0	0	0	0
2026	0	0	0	0
2027	2267629	183987	0	2.21
2028	0	299594	0	2.05
2029	0	296077	0	2.02
2030	0	299157	0	2.03
2031	0	296785	0	2.11

Note: Live cattle trade is in the number of head and beef trade is in billion pounds.

Table 3.9 Welfare changes associated with a hypothetical FMD outbreak for optimistic and pessimistic scenarios ($ billion)

Scenario	Depopulation level	ΔPS	ΔCS
Optimistic	5%	−5.05	14.57
Pessimistic	5%	−18.18	32.79
Optimistic	10%	−8.24	19.54
Pessimistic	10%	−21.10	37.32

Note: ΔPS denote change in producer surplus, and ΔCS denote change in consumer surplus.

CHAPTER 4. CONCLUSION

Livestock production plays a crucial role in the economy of the United States as it contributes significantly to exports, food sources, and nutrition. In 2021, the industry was valued at a staggering $195.8 billion, with the cattle industry accounting for 37% of the total value [USDA-ERS (2023a)]. Due to the importance of the beef industry to the economy and its significance in the international markets, the U.S. beef industry is vital both domestically and internationally. It is crucial that industry leaders and policymakers have access to models that accurately depict the industry and contain the flexibility to investigate both biological and economic factors shaping the industry. The objective of this dissertation was to develop such a model and use it to explore the potential impacts of an animal disease outbreak.

Beef production is a dynamic process. An economic model incorporating the dynamic process can yield realistic short-run and long-run estimates, and reveal the variability of the estimates over time for policy proposals or any exogenous shocks within the beef cattle industry. This dissertation develops a dynamic framework for the U.S. beef cattle industry that is consistent with the economic theory, biology, and decision-making about beef production. The framework developed proves to be a valuable tool for analyzing the introduction of exogenous shocks such as a variety of production and policy changes in the beef cattle industry. The dynamic model is solved using both naïve and rational price expectations. Numerical methods are used to solve the rational price expectations model because a complete analytical solution is not feasible. An iterative algorithm is developed to solve the rational price expectations model. To balance the precision and speed of the execution, a reasonable number of state variables are selected.

The conceptual model is demonstrated by first showing the results from the model in capturing the recent evolution of the U.S. beef cattle industry. The model fits the historical prices and quantities well and replicates cattle inventories. A projection framework is developed to project the market several years into the future. The goodness of the fit of the model is tested by computing an error in a unit-free form (considering the complexity of the model, the errors generated are reasonable), and the projected prices and quantities from the model are validated by comparing them with USDA and FAPRI projections. The projected prices and supplies are consistent with USDA and FAPRI projections. However, the dynamic processes within the model do provide some differences with USDA and FAPRI projections, which could be critical in evaluating policy impacts. After establishing the models' fitness and the potential to project the market several years into the future, the model is further demonstrated by estimating the potential economic impacts of a hypothetical FMD outbreak. The findings of a hypothetical FMD demonstrate how the model can be used to evaluate the potential economic impacts of a disease outbreak and can provide guidance for designing disease control and mitigation policies.

The results of the third chapter, particularly the quantification of short-run and long-run economic impacts of a FMD outbreak and the variation of these impacts over time, demonstrate the ability of the model to capture the evolution of the economic impact of a disease outbreak and response. The exogenous shocks due to the disease outbreak are utilized to develop scenarios. In particular, the production, trade, and consumption shocks were employed to design optimistic and pessimistic scenarios. The model was simulated under the designed scenarios to generate counterfactual price and supply responses to the disease outbreak. The general trajectories of the counterfactuals showcase the reaction of the market to the disease outbreak. In addition to the price and supply counterfactuals, the model also generates changes in the inventory levels. The detailing of the evolution and the age distribution of cows provide greater information on the physical and economic adjustments within the industry. The framework developed is not limited to studying FMD or disease studies, as it can be employed to study various policy proposals affecting the beef cattle industry. As showcased in the third chapter, alternate scenarios of policy proposals can be designed to simulate the model and quantify the economic impacts making the model a valuable tool to effectively design, develop, and deploy policies affecting the beef cattle industry.

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APPENDIX A. ALGORITHM TO ESTIMATE THE PARAMETERS μ AND s

From the observed data, we obtain the disappearance of fed cattle and cull cows respectively. By rearranging the expression $Q_s(w_s, w_c) = \Big(1 - H(w)\Big)Q_b(w_s, w_c)$ and using 2.14, we get

$$\Big(1 - H(w)\Big) = \frac{Q_s(w_s, w_c)}{Q_s(w_s, w_c) + Q_c(w_s, w_c)}. \tag{A.1}$$

After adjusting for pounds in beef and following 2.22, the above equation A.1 becomes

$$\Big(1 - H(\widetilde{p})\Big) = \frac{\widetilde{Q}_s(w_s, w_c)}{\widetilde{Q}_s(w_s, w_c) + \widetilde{Q}_c(w_s, w_c)}, \tag{A.2}$$

where $\widetilde{Q}_s(w_s, w_c)$ is the beef derived from fed cattle and $\widetilde{Q}_c(w_s, w_c)$ is the beef derived from cull cows.

Using the disappearance of the fed cattle and cull cow data and transforming them to beef we obtain the right-hand side of the equation A.2. As stated in the section 2.1.5.2, we consider $\Big(1 - H(\widetilde{p})\Big)$ as the share of consumers' purchases of fed cattle meat and $H(\widetilde{p})$ as the share of consumers' purchases of cull cow meat. Since we know the right-hand side of these share metrics, it is straightforward to solve for $\tilde{\mu}$ and $\tilde{s}$ using a non-linear least squares method and observed prices.

APPENDIX B. PROOF FOR EQUATION 2.128

$$cl_{t+1} = k_{9,t+1} + (k_{8,t+1} - k_{9,t+2}) + (k_{7,t+1} - k_{8,t+2})$$
$$= k_{9,t+1} + (1-\delta)k_{8,t+1} + (1-\delta)k_{7,t+1},$$

Using the relationship $k_{j+1,t+1} = \delta k_{j,t}$ we rewrite $k_{9,t+1}$, $k_{8,t+1}$, $k_{7,t+1}$ in terms of k_3 as below

$$cl_{t+1} = \delta^3 k_{3,t-5} + (1-\delta)\delta^5 k_{3,t-4} + (1-\delta)\delta^4 k_{3,t-3}. \tag{B.1}$$

Using the linear relationship $k_{3,t+1} = \gamma k_{3,t} + \eta k_{0,t-3}$, we rewrite $k_{3,t-5}$, $k_{3,t-4}$, $k_{3,t-3}$ in terms of $k_{3,t+2}$.

$$k_{3,t+2} = \gamma k_{3,t+1} + \eta k_{0,t-2} \tag{B.2}$$
$$= \gamma(\gamma k_{3,t} + \eta k_{0,t-3}) + \eta k_{0,t-2} \tag{B.3}$$
$$= \gamma^2(\gamma k_{3,t-1} + \eta k_{0,t-4}) + \gamma\eta k_{0,t-3} + \eta k_{0,t-2} \tag{B.4}$$
$$= \gamma^3(\gamma k_{3,t-2} + \eta k_{0,t-5}) + \gamma^2\eta k_{0,t-4} + \gamma\eta k_{0,t-3} + \gamma k_{0,t-2} \tag{B.5}$$
$$= \gamma^4(\gamma k_{3,t-3} + \eta k_{0,t-6}) + \gamma^3\eta k_{0,t-5} + \gamma^2\eta k_{0,t-4} + \gamma\eta k_{0,t-3} + \gamma k_{0,t-2} \tag{B.6}$$
$$= \gamma^5 k_{3,t-3} + \eta\gamma^4 k_{0,t-6} + \eta\gamma^3 k_{0,t-5} + \eta\gamma^2 k_{0,t-4} + \eta\gamma k_{0,t-3} + \eta k_{0,t-2} \tag{B.7}$$
$$= \gamma^6 k_{3,t-4} + \eta\gamma^5 k_{0,t-7} + \eta\gamma^4 k_{0,t-6} + \eta\gamma^3 k_{0,t-5} + \eta\gamma^2 k_{0,t-4} + \eta\gamma k_{0,t-3} + \eta k_{0,t-2} \tag{B.8}$$
$$= \gamma^7 k_{3,t-5} + \eta\gamma^6 k_{0,t-8} + \eta\gamma^5 k_{0,t-7} + \eta\gamma^4 k_{0,t-6} + \eta\gamma^3 k_{0,t-5} + \eta\gamma^2 k_{0,t-4} + \eta\gamma k_{0,t-3} + \eta k_{0,t-2} \tag{B.9}$$

by rewriting B.7, B.8, and B.9 in-terms of $k_{3,t-3}$, $k_{3,t-4}$, and $k_{3,t-5}$ respectively, we get

$$k_{3,t-3} = \frac{1}{\gamma^5}k_{3,t+2} - \frac{\eta}{\gamma}\left(k_{0,t-6} + \frac{1}{\gamma}k_{0,t-5} + \frac{1}{\gamma^2}k_{0,t-4} + \frac{1}{\gamma^3}k_{0,t-3} + \frac{1}{\gamma^4}k_{0,t-2}\right) \quad \text{(B.10)}$$

$$k_{3,t-4} = \frac{1}{\gamma^6}k_{3,t+2} - \frac{\eta}{\gamma}\left(k_{0,t-7} + \frac{1}{\gamma}k_{0,t-6} + \frac{1}{\gamma^2}k_{0,t-5} + \frac{1}{\gamma^3}k_{0,t-4} + \frac{1}{\gamma^4}k_{0,t-3} + \frac{1}{\gamma^5}k_{0,t-2}\right) \quad \text{(B.11)}$$

$$k_{3,t-5} = \frac{1}{\gamma^7}k_{3,t+2} - \frac{\eta}{\gamma}\left(k_{0,t-8} + \frac{1}{\gamma}k_{0,t-7} + \frac{1}{\gamma^2}k_{0,t-6} + \frac{1}{\gamma^3}k_{0,t-5} + \frac{1}{\gamma^4}k_{0,t-4} + \frac{1}{\gamma^5}k_{0,t-3} + \frac{1}{\gamma^6}k_{0,t-2}\right), \quad \text{(B.12)}$$

substituting B.10, B.11, and B.12 in B.1 and rearranging gives 2.128

$$\begin{aligned} cl_{t+1} = \frac{\delta^4}{\gamma^7}&\left[\delta^2 + (1-\delta)\gamma(\delta+\gamma)\right] \\ &\left[k_{3,t+2} - \eta\gamma^4 k_{0,t-6} + \gamma^3 k_{0,t-5} + \gamma^2 k_{0,t-4} + \gamma k_{0,t-3} + k_{0,t-2}\right] \\ &- \frac{\delta^5}{\gamma^2}\eta\left[\delta\gamma k_{0,t-8} + (\delta + (1-\delta)\gamma)k_{0,t-7}\right]. \end{aligned}$$