Economic impacts of metaphylaxis use in U.S. feedlots: Producer decisions, policy, and insurance

by

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AN ABSTRACT OF A DISSERTATION

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Abstract

Chapter 1: Net return distributions across antimicrobials used for metaphylaxis to control bovine respiratory disease in high health risk cattle

Net return losses due to cattle mortality and morbidity associated with bovine respiratory disease (BRD) has a substantial impact on the feedlot industry. Metaphylaxis is a common feedlot cattle health management practice used to limit cattle morbidity and mortality attributed to BRD. Efficacy of antimicrobials used for metaphylaxis is known to vary by cattle population. How this differing antimicrobial efficacy translates to net return profitability for heterogeneous cattle populations is less understood. The objective of this article is to measure the net return profitability and uncertainty of Upper Tier and Lower Tier antimicrobials used for metaphylaxis. Using information from 10 feedlots representing a half-million animals and 1500 cohorts between 1989-2015 we find the expected value of administering an Upper Tier (Lower Tier) metaphylaxis treatment compared to no treatment for high health risk steers is \$90.46/head (\$28.06) for 600 lb. and \$118.85/head (\$41.74) for 800 lb. winter placements. Furthermore, the probability or risk of net return losses worsening by at least \$50/head is significantly reduced (from approximately 15% to 4%) when any metaphylaxis antimicrobial is used on high health risk cattle. The expected value and net return risk mitigated by metaphylaxis use on high health risk cattle varies by placement weight, season, and antimicrobial used.

Chapter 2: Value of Arrival Metaphylaxis in U.S. Cattle Industry

Dennis, Elliott J., Ted C. Schroeder, David G. Renter, and Dustin L. Pendell. 2018. “Value of Arrival Metaphylaxis in US Cattle Industry.” *Journal of Agricultural and Resource Economics* 43(2):233-249.

Although several studies have estimated economic impacts of antimicrobials for growth promotion, little is known about economic impacts of the common animal health management strategy known as metaphylaxis: administering antimicrobials to groups of animals to prevent disease. This article develops a new framework to map animal disease to producer profitability and determine societal economic impacts surrounding metaphylactic use of antimicrobials in beef cattle production. Results indicate the direct net return value of metaphylaxis to the U.S. fed cattle industry is at least $532 million. Beef producer surplus losses of $1.8 billion would be associated with eliminating metaphylaxis.

Chapter 3: Why do livestock producers use metaphylaxis? Self-insurance vs. self-protection and an market insurance alternative

Antimicrobial resistance in humans is increasing and there is growing concern that antimicrobials used in livestock production is contributing to this growth. Metaphylaxis, administering FDA approved injectable antimicrobials to high health risk livestock upon arrival at feeding operations, is one animal health strategy producers use to reduce the size or magnitude of livestock morbidity and mortality. International organizations have explicitly aimed to remove metaphylaxis for disease prevention but there is concern that few, if any, alternative health management strategies exist. Likewise, little is known about under what conditions livestock producers use metaphylaxis and if they would be willing to substitute away if a feasible market alternative were available. This article develops a theoretical framework for why metaphylaxis is used in US cattle feedlots. Our results indicate that when no market insurance is available, feedlots use more income for disease prevention than disease treatment. However, producers equalize disease treatment and prevention expenditures when an

actuarially fair market insurance is available. We develop a simple elementary market insurance product that could be used and show that feedlots can improve their wealth position over metaphylaxis when a market insurance product is used.

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Acknowledgments

The ideas generated in this dissertation are in large part the product of countless conversations with professors, livestock producers, veterinarians, and fellow students. As such, it is difficult to attribute which ideas I can solely claim as my own and what have been the product of these conversations. To name just a few persons who have greatly contributed to this work would not give justice to the many others that have provided support, encouragement, and at times piercing remarks. All persons have fostered within me the desire to think, excel, and finish. I will always be grateful for their help. However, I would also like to thank the generous support of Dr. David Renter at the Center for Outcomes, Research and Extension (CORE) in the College of Veterinary Medicine and Dr. Ted Schroeder in the Department of Agricultural Economics for funding and supporting my PhD. Without their support none of this would have been possible.

Dedication

To my wife Tiffany and two girls Audrey and Florence - they bore the burden of this degree.

Preface

In the Summer of 2015 I first met with Dr. Ted Schroeder after arriving at KSU as a new PhD graduate student. As both Drs. Dave Renter and Ted Schroeder would attest, I was very "green" in my understanding of cattle production when I entered K-State. This has both served as a positive and a negative. Positive since it has allowed me to ask simple questions to understand why producers actually make decisions. Negative since it has required an intense amount of effort to learn the required material and has disturbed more than a few people.

These projects have forced me to work in a multidisciplinary environment combining my economic training with my basic understanding of epidemiology. My hesitancy in working on the project has more stemmed from not fully understanding livestock production. Likewise, unforeseen obstacles caused a *major* rewrite in a very short time frame. I am sure this has caused more than just a few disgruntled comments from my colleagues.

I am grateful for this project for facilitating this development within myself and for the patience of my co-authors. More than once I have felt discouraged, embarrassed, frustrated, and depressed. It taught me humility and the importance of reaching out and asking for help and that it is alright to admit that I am at the edge of my knowledge base. This sounds cliche but it is true. I hope that these lessons serve me well in future. They have been no easy task.

People who were instrumental in the idea and writing process were Drs. David Renter, Jesse Tack, and Ted Schroeder. Drs. Glynn Tonsor and Dustin Pendell have more than once offered sound advice, put the project into perspective, and helped me maintain focus, I hope people will recognize the rigour and meticulous process I took to accurately and efficiently identify the main effects and how economics and epidemiology interplay. This sunk cost has been large.

Chapter 1

Net return distributions across tiers of antimicrobials used for metaphylaxis to control bovine respiratory disease in high health risk cattle

1.1 Introduction

Antimicrobials used to improve wellbeing, health, and performance of cattle arriving at feedlots, has received considerable public attention. Metaphylaxis, administration of an antimicrobial, generally via injection, is used selectively by 59% of U.S. feedlots on 20.5% of cattle to reduce adverse effects of bovine respiratory disease (BRD) (United States Department of Agriculture, 2013). Randomized control trials have generally confirmed metaphylaxis can reduce morbidity and mortality in feedlot cattle having high health risk susceptibility (O'Connor et al., 2013; Abell et al., 2017).

When cohorts of cattle arrive at feedlots, producers assess animal health risk and decide whether to employ metaphylaxis. Perceived benefits of metaphylactic treatment to reduce cattle morbidity and mortality are weighed against costs to process, treat, and monitor cattle. If metaphylaxis treatment is utilized, producers must select the type of antimicrobial to administer (Nickell and White, 2010). Selection of the specific antimicrobial to use is based on veterinary consultation, past experience, and duration of action (United States Department of Agriculture, 2013).

While the efficacy and cost of antimicrobials for metaphylaxis varies, how different antimicrobials used for metaphylaxis translates into expected net return distributions for heterogeneous cattle is even less well understood (DeDonder and Apley, 2015; Ives and Richeson, 2015). Realized cattle morbidity and mortality conditional on antimicrobial choice and administration is unknown until after cattle harvest. As such, animal health outcomes are stochastic when a metaphylaxis treatment decision is made.

The objective of this article is to measure expected net return and associated uncertainty of two antimicrobial classes used for metaphylaxis. In particular, we test whether expected net return distributions vary across cattle placement weight, placement season, and antimicrobial administered using data obtained from a panel of 10 Midwestern feedlots. Observational panel data enables us to calibrate net return simulations using observed outcomes. Results contribute to better understanding how alternative metaphylactic antimicrobial options influence expected cattle feeding returns and return risk.

1.2 Materials and Methods

Cattle feeding net returns vary across management, marketing, and animal health protocols. Cattle feeding net return distributions are estimated using a stochastic simulation model developed by Dennis et al. (2018). We modify their model by specifically incorporating cattle and antimicrobial heterogeneity into the simulation.[1] Stochastic[2] net return simulations have

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[1] The primary purpose of Dennis et al. (2018) was to estimate economic value of metaphylaxis for the U.S. fed cattle industry and determine if removing metaphylaxis as an animal health protocol would shift aggregate U.S. beef supply. They accomplished this by assuming an average sex, placement season, and antimicrobial used for metaphylaxis. We modify their simulation method to incorporate heterogeneity into cattle populations and antimicrobials used for metaphylaxis.

[2] Stochastic simulations are distinctly different than deterministic simulations because they incorporate uncertainty via probability distributions obtained from historical data, expert opinion, and/or published literature.

been used to value BRD for dairy, cow-calf, and feedlot cattle (Van der Fels-Klerx et al., 2001; Buhman et al., 2003; Nor et al., 2012; Theurer et al., 2015; Wang et al., 2018) and to value metaphylaxis in feedlot cattle (Dennis et al., 2018). In what follows, we briefly describe the cattle feeding economic decision framework used in our simulation emphasizing how we modify the Dennis et al. (2018) cattle feeding net return simulation model.

1.2.1 Cattle Feeding Net Return Simulation

We consider four types of high health risk steers purchased by producers - two different cattle placement weights (600 or 800 lbs.) and two placement seasons (Oct-Mar (referred to as winter) or Apr-Sept (referred to as summer)). Producers manage high health risk steers by either using or not using metaphylaxis. In our simulation, we consider two different classes of antimicrobials used for metaphylaxis (Upper Tier or Lower Tier[3]). Thus, we consider 8 different metaphylaxis scenarios in our simulation (two placement weights, two seasons, and two antimicrobials for metaphylaxis) and we compare these to 4 no metaphylaxis scenarios for each placement weight - season combination.

Regardless of initial health status and health management strategy, cattle can become sick and/or die. Producers realize final morbidity and mortality only at cattle harvest. All cattle, regardless of initial health risk status, possessing clinical signs of BRD are pulled and treated. Sick cattle incur greater health costs (HC ↑), gain less weight per day during feeding (ADG ↓), and require more feed to gain an additional lb of weight. (AFC ↑).[4] Producers do not sell dead animals (CSW=0) losing the initial cost of the feeder (FDRC) plus costs of yardage (YC), feed (FC), interest (IC), and health treatments (HC). Since final cattle mortality is unknown at purchase, producers effectively face a random draw from a mortality distribution conditional on cattle placement weight, season, and possible antimicrobial used for metaphylaxis. While both morbidity and mortality combine to increase total feeding costs (TC ↑) and decreases total revenue (TR ↓), mortality poses the highest cost to producers

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[3] Upper tier and lower tier antimicrobials are taken from Abell et al. (2017) where they classify antimicrobials conditional on OR confidence intervals.

[4] Increasing feed conversion implies that it requires more feed to obtain one pound of gain. Thus, as morbidity increases some feed conversion increases.

and is the primary driver of net return variation in the simulation.

After initial processing, cattle that survive and reach an expected harvest weight are sold on a live-weight basis. Thus, cattle feeders choose the type of cattle to purchase, initial and supplemental health treatments, and target weight of finished cattle. Given this, cattle feeding net returns (π) per head for a given cohort of cattle can be specified as (Dennis et al., 2018):

$$\pi = \underbrace{\text{TR}}_{\text{Total revenue}} - \underbrace{\text{FDRC} - \text{YC} - \text{FC} - \text{HC} - \text{IC}}_{\text{Total costs}} \tag{1.1}$$

$$\begin{aligned} \underbrace{\text{TR}}_{\text{Total revenue}} &= \underbrace{\text{FP}}_{\text{Fed price}} \times \underbrace{\{ \underbrace{\text{CSW}}_{\text{Finished weight}} \times \underbrace{(1 - \text{SHRINK})}_{\text{Transportation weight loss}} \times \underbrace{(1 - \text{MORT} - \text{CULL}}_{\text{Proportion of animlas sold}} \}}_{\text{Lbs. of animals sold}} \\ &\quad + \underbrace{(\text{CULL} \times \text{CULLW} \times \text{CULLP})}_{\text{Revenue from culled animals}} \end{aligned} \tag{1.2}$$

$$\underbrace{\text{FDRC}}_{\text{Cost to purchase cattle}} = \underbrace{\text{FRP}}_{\text{Feeder price}} \times \underbrace{\text{CPW}}_{\text{Weight of feeder}} \tag{1.3}$$

$$\underbrace{\text{YC}}_{\text{Yardage costs}} = \underbrace{0.30}_{\text{Fixed rate}} \times \underbrace{\text{DOF}}_{\text{Days on feed}} \tag{1.4}$$

$$\underbrace{\text{FC}}_{\text{Feed costs}} = \underbrace{\text{FEED}}_{\text{Price of corn}} \times \underbrace{\{ \underbrace{\text{AFC}}_{\text{Feed conversion}} \times [\underbrace{\text{CSW} \times (1 - \text{MORT} - \text{CULL}) - \text{CPW}}_{\text{Total weight gain while at feedlot}}] \}}_{\text{Total amount of feed consumed while at feedlot}} \tag{1.5}$$

$$\underbrace{\text{IC}}_{\text{Interest costs}} = \{\underbrace{0.5 \times [\text{YC} + \text{FC} + \text{HC}] + \text{FDRC}}_{\text{Entire feeder and half of all other costs}}\} \times \underbrace{\text{DOF}}_{\text{Days on feed}} \times \underbrace{(\text{IR}/365)}_{\text{Interest rate}} \tag{1.6}$$

Table A.1 in appendix A describes each variable in detail.

Our objective is to determine how net return distributions change for high health risk cattle as metaphylaxis treatment protocol varies for different placement weights and seasons. To do this, we calibrate the expected return in the simulation models by using breakeven (π = 0) feeder cattle purchase prices for the Upper Tier antimicrobial used for each season and placement weight. This enables us to compare net return distributions with and without metaphylaxis within season and placement weight.

Cattle Morbidity and Mortality

Metaphylaxis is expected to reduce morbidity and mortality in high health risk feedlot cattle, but expected efficacy varies by cattle placement weight, placement season, gender, and antimicrobial used (Nickell and White, 2010; DeDonder and Apley, 2015; Ives and Richeson, 2015). Historical morbidity in observational data are generally not available. Cattle productivity measures serve as proxies for morbidity. Multivariate Tobit, ordinary least squares, maximum likelihood, and linear mixed models have been used to model variation in average daily gain, veterinary/medication costs, and feed conversion in cattle across different seasons, placement weights, etc. (Miller et al., 2005; Irsik et al., 2006; Belasco, 2008; Belasco et al., 2009; Dennis et al., 2018). We use a linear mixed model to account for the hierarchical nature of cattle feeding data where cohorts of cattle are nested within feedlots. This allows us to capture cohort level animal management practices that can differ across feedlots.

Cattle mortality is conditional on cattle health-risk category, cattle placement weight, and placement season. Metaphylaxis modifies cattle mortality risk. Mortality distributions are right-skewed with long tails, approximated using a log-normal, (zero inflated) negative binomial or a (zero-inflated) Poisson distribution (Babcock, 2010). We model mortality distributions as log-normal conditional on placement risk category, weight, and season.

Mortality distributions of high health risk cattle managed with metaphylaxis are observed in feedlot data. However, mortality of high health risk cattle not managed with metaphylaxis are not observed in feedlot data because feedlots treat all cattle categorized as high health risk upon arrival. Thus, mortality distributions for high health risk cattle not treated with metaphylaxis were approximated using odd-ratios from a mixed treatment comparison (MTC) meta-analysis (Abell et al., 2017). The MTC meta-analysis summarizes published randomized control antimicrobial trials for BRD related cattle morbidity from day 1 to close-out and assesses indirect comparisons across different antimicrobials used for metaphylaxis (O'Connor et al., 2013; Abell et al., 2017).

1.3 Data

Ten large commercial feedlot operations located in several Midwestern states provided two animal health and performance data sets used in this study. Cohorts are the common aggregate unit in commercial feedlot production systems. Cohort-level animal health treatment information is the primary difference between the two data sets. We define cohorts (lots or pens) as animals purchased, assembled, and managed as an observable unit. When finished cattle are marketed, closeouts record cohort-level animal performance and health information.

Observational data used in this study includes a large panel data set comprising 48,341 cohorts of cattle (about 6 million head) placed on feed during 1989-2008. This data set consists of typical closeout information including health costs after feeding has begun excluding costs of metaphylaxis. These data are used to calibrate animal feeding performance over time (i.e., ADG and AFC) which varies by season, location, and animal weight. The second observational data used in this study comprises 1,203 cohorts of cattle (about 264,000 head) placed on feed during 2014-2015. This more comprehensive, but smaller data set, documents both lot and individual animal antimicrobial treatments associated with BRD enabling us to estimate cost of metaphylaxis and facilitates our stochastic simulation around death loss.

1.4 Results

1.4.1 Descriptive Statistics

Cattle performance parameters across the two observational data sets were compared to assess whether the cattle had similar feeding characteristics (feed conversion, daily gain, mortality, placement weight, and days on feed). Table ?? displays summary statistics for the feedlot data. T-tests for each animal feeding attribute indicate cattle from both periods were not statistically different from each other with the exception of more steers placed in the second period. On average [min, max] cattle were placed at approximately 700 lb., gained 3 lb. per day [1.5, 6.0], and had feed conversion of about 6 [3.0, 9.9] over 155 days on feed [128, 229]. Cattle were placed evenly across seasons. Average death loss for period one cattle was 1.24% [0.0, 25.6]. Large variation in death loss is due to initial health status, differing cattle populations, and other factors. Large death losses are associated with cohorts classified as high risk and managed with metaphylaxis.

1.4.2 Estimated Morbidity

Cattle morbidity is not directly observed in our feedlot data but manifests itself in lower average daily gain (ADG $\downarrow$), increased average feed conversion (AFC $\uparrow$), and increased health costs (HC $\uparrow$). The impact of cattle mortality is quantified using a linear mixed model (LMM) with pen- and feedlot-specific fixed and random effects. Specifically, we estimate ADG and AFC using the large panel data set and associated health costs (HC) using the more intensive recent data set. Table ?? displays parameter estimates for the estimated models. ADG and AFC are estimated as a function of the percentage of cohort level mortality (MORT), the natural log of cattle placement weight (lnPWT), whether the cohort were steers (STEER), and whether cattle were placed between October and March (WINTER). Cohort level health costs (HC) are estimated in similar format to ADG and AFC but WINTER is omitted because of the short time horizon of the data and binary variables indicating the class of antimicrobial given for metaphylaxis are included (UPPER TIER or LOWER TIER).

Mortality reduces daily gains (ADG $\downarrow$) and increases feed conversion (AFC $\uparrow$) and health costs (HC $\uparrow$). Higher placement weights are associated with lower daily gains (ADG $\downarrow$), higher feed conversions (AFC $\uparrow$), and lower health costs (HC $\downarrow$) consistent with randomized control trials that indicate lighter weight animals are more susceptible to harmful bacteria (Nickell and White 2010). Steers gain more weight per day on feed and convert feed more efficiently. Cattle placed during winter months are associated with lower cattle performance consistent with literature demonstrating cattle devote more energy to body temperature maintenance during colder months (Mader et al., 2010).

UPPER TIER and LOWER TIER are binary variables indicating the class of antimicrobial used for metaphylaxis. If an Upper Tier (Lower Tier) antimicrobial is used for metaphylaxis, a producer incurs an estimated \$30.55 (\$25.65)/head cost for administration. These findings are consistent with results from the National Animal Health Monitoring Survey (NAHMS, U.S. Department of Agriculture, 2013) that reported costs of \$23.50/head to administer metaphylaxis to feeder cattle. Our values are slightly higher since it includes all health cost treatments during the time on feed and not just the cost of the initial cost of metaphylaxis upon arrival.

1.4.3 Mortality Distributions

One important concern is the endogenous choice by the producer to match the type of metaphylaxis to cattle populations. For example, producers may wish to administer a different drug to similar types of cattle based the perceived or observed morbidity and mortality. This decision is not observed in the data and cannot be proxied by variables in our data. Thus traditional assumption of matching on observable is not possible since even after matching cattle are likely to be different.[5]

We multiply the odd ratio by a hypothetical no metaphyalxis death loss to obtain a proposed metaphylaxis death loss. We then iterate through different no metaphylaxis death losses until the proposed metaphylaxis death loss matches the metaphylaxis death loss observed in the proprietary data. This obtained no metaphylaxis death loss can be used to obtain the metaphylaxis that would have been observed in the upper tier metaphylaxis. The upper tier metaphylaxis death loss is obtained by multiplying the odd ratio for the upper tier metaphylaxis by the death loss of no metaphylaxis. This method allows for the death loss distributions, and subsequent net return distributions, to be compared. One can interpret the derived upper tier metaphylaxis as the death loss the would had been observed had the upper tier metaphylaxis been given in place of the lower tier metaphylaxis. [6]

Log-normal distributions are fit using the mean and standard deviation of death for

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[5] The intuition behind this is relatively straightforward. Given that cattle are similar in every respect and a profit maximizing producer, the low metaphylaxis drug would be chosen. Thus, even after matching it is not random chance that certain cattle populations are given a certain metaphylaxis.

[6] The ratio of these death losses represent the relative performance of one metaphylaxis drug to the other. Based on our proposed method, the upper tier metaphylaxis is almost 4 times more effective than the lower tier metaphylaxis. This finding is consistent with the odd ratios found by Abell et al. (2017).

the different tiers of metaphylaxis and no metaphylaxis. Figure 1.1 displays log-normal mortality distributions for high health risk steers conditional on placement weight, season, and antimicrobial used for metaphylaxis.

Four types of high risk steers are considered in our simulation - two different placement weights (600 or 800 lbs.) and two placement seasons (winter or summer). Each cattle type has three alternative animal health management practices (do-nothing, Upper Tier antimicrobial, or Lower Tier antimicrobial).

Both antimicrobials used for metaphylaxis reduce expected death loss and associated variance. Larger death loss is associated with steers placed during winter months at lighter weights. Upper Tier antimicrobials on average reduce mortality by more than Lower Tier antimicrobials. Larger variation in death loss is present across all seasons and placement weights for high health risk steers not managed with metaphylaxis. Thus, metaphylaxis reduces mortality in high health risk steers but varies by class of antimicrobial used.

1.4.4 Net Return Distributions

Figure 1.2 displays net return distributions by cattle placement weight and season across the three alternative animal health treatment protocols. The simulated net returns were generated by randomly selecting mortality from the distributions in Figure 1.1, using the estimated equations reported in Table ??, and calculating net returns using equation 1. This process was repeated with replacement 5,000 times to generate the distributions. No metaphylaxis net return distributions in Figure 1.2 represent high health risk steer cohorts not managed with metaphylaxis upon arrival. The differences in expected net returns per head (averages) between administering an Upper Tier (Lower Tier) to high risk steers compared with not administering metaphylaxis are: 1) \$64.97 (\$16.52) for 600 lb. summer placements; 2) \$58.47 (\$13.73) for 600 lb. winter placements; 3) \$90.46 (\$28.06) for 800 lb. summer placements; and 4) \$118.85 (\$41.74) for 800 lb. winter placements. The difference between the Upper Tier and Lower Tier is the marginal net value benefit of using a certain tier of antimicrobial. For example, the value of administering an Upper Tier compared to a Lower

Tier for 600 lb. summer placements is \$48.45 (58.47-13.73=48.45). On average, Upper Tier antimicrobials are valued at \$58.17 compared to Lower Tier antimicrobials across all placement weights and seasons.

Both antimicrobials used for metaphylaxis increase expected net returns and decrease return variance. Thus, cattle producers are more certain that they will realize greater profit on a high-risk pen of cattle when metaphylaxis is used. Table 1.3 further summarizes the net return distributions displayed in Figure 1.2 reporting percentages of cohorts falling within expected net return ranges conditional on cattle placement weight, placement season, and antimicrobial used. Metaphylaxis administered to high health risk cattle substantially reduces the probability of large losses. For example, for a 600 lb. summer placed high risk steers treated with a Upper Tier, there is an 0.02% (0.00% + 0.02%) chance of realizing a loss of more than \$50 per head, whereas if these high risk steers were not treated, they would face a 27% (4.62% + 22.42%) chance of losing more than \$50 per head. For a 600 lb. winter placed high risk pen treated with a Lower Tier there would be a 21% (1.82% + 19.46%) chance of realizing at least a \$50 per head loss contrasted to not treating this high risk pen with a 31% (8.02% + 23.50%) probability of realizing at least a \$50 per head loss. Taking this result further, large losses in excess of \$250 per head have a 15% (4% to 24%) probability of being realized for high risk 600 lb. placements not treated with any antimicrobial compared to generally less than 5% (0% to 19%) probability of such large losses regardless of season or antimicrobial administered for metaphylaxis treatment.

An interesting result relative to the decision to treat high risk pens with metaphylaxis is that high returns (low death losses) can still, by chance, be realized whether the animals are or are not treated with metaphylaxis. For example, for 600 lb. high risk steers placed, regardless of season or antimicrobial, if they were administered metaphylaxis we would expect more than 43% of the time to realize net returns of at least \$51 per head. However, there is still at least a 23% chance the high risk pen would realize \$51 per head or more even if not treated with metaphylaxis. This is because there is always a chance high risk cattle, even if not treated, will remain sufficiently healthy and not suffer substantial mortality.

Heavier weight placements are less likely to have large negative returns since the proportion of cattle that die is relatively small compared to lighter placements. For example, a 600 lb. summer placed high risk pen administered a Upper Tier would face a 0% (0.00% + 0.00%) chance of realizing a loss greater than $51 per head compared to 25% (0.80% + 23.94%) for an 800 lb. placement at the same time administered the same metaphylaxis treatment. Summer placed high risk cattle are expected to have similar risks of large losses compared to winter placements. For example, 800 lb. summer placed high risk cattle treated with Lower Tier have an 11% (0.00% + 11.36%) probability of realizing a loss of more than $50 per head compared to a winter placement of the same animals of 25% (0.80% + 23.94%).

1.5 Discussion

The decision of whether to treat high risk cattle with metaphylaxis, and if so, which class of antimicrobial to use is a difficult question to answer in part because the decisions are made with incomplete information. Realized health outcomes are only known after cattle are finished feeding whereas metaphylaxis health treatment decisions are generally made at cattle placement. Thus, we must rely on expected return distributions with and without use of metaphylaxis to assess economic viability.

Expected return alone is not sufficient to assess viability of metaphylaxis if return risk also matters. Treating all high risk cattle with metaphylaxis broadly increases expected net return and reduces return uncertainly. This makes the use of metaphylaxis as a health management practice appear obvious. However, the change in expected return as well as the risk mitigated through metaphylactic treatment of all high risk cattle varies by season of placement, type of antimicrobial employed, and cattle placement weight. Lighter-weight high risk cattle are expected to realize greater returns and more return risk mitigation through metaphylaxis regardless of season and drug type (of those investigated here), than heavier-weight placements.

The value of meeting contracting agreements is a value of metaphylaxis not currently captured. Feedlots can use metaphylaxis as a preventative measure to ensure a correct number of healthy cattle reach harvest weight to comply with marketing agreements and contracts. Given this the value of metaphylaxis represents more than just the loss in input costs as currently calculated. Thus, estimated values likely serve as a lower bound to the value of metaphylaxis.

An important issue, not addressed in this study but clearly based on the results deserves much more consideration, is how to identify and categorize high risk cattle. High risk cattle are worth less to the feedlot since they require higher health costs and have greater morbidity and mortality risk. However, often high health risk cattle not treated with metaphylaxis do not realize major net return losses - instead they perform fine in the feedlot. Whether this is from mis-categorization or randomness in animal health outcomes remains unclear. But, we expect with more accurate categorization of cattle into health risk status upon feedlot arrival, health management strategies could be refined. Of course, the cost of acquiring additional information for more accurate animal health status classification may exceed the value.

Fed and feeder cattle price levels impact the value of metaphylaxis for each antimicrobial. The average fed cattle price used in this simulation was $148/cwt (see Table A.1). Higher fed cattle prices create greater value associated with metaphylaxis, ceteris paribus; as cattle prices increase, the cost of animal death loss increases. As such, fed cattle price has important impacts on the value of metaphylaxis because higher fed cattle prices, ceteris paribus, are associated with higher feeder cattle prices and any death loss has a greater economic cost.

1.6 Conclusion

Net return simulation results identified the value of two classes of antimicrobial commonly used for metaphylaxis. The antimicrobials are valued more than not administering antimicrobials but varies by cattle season, placement weight, and gender. Further research is needed to determine the values for specific antimicrobials used for metaphylaxis.

1.7 Tables

Table 1.1: Feedlot Performance Summary Characteristics

January 1989-December 2008[a]	Mean	Std. Dev.	Min	Max.
Feed conversion (lb. feed/lb. gain)	6.07	0.59	3.01	9.91
Average daily gain (lb. gain/day)	2.96	0.56	1.51	5.98
Mortality (%)	1.24	1.76	0.00	25.64
Placement weight (lb.)	683.7	128.99	304.20	1,100.00
Days on feed (days)	154.5	44.17	128.00	229.00
Gender	Steer	46.0%	Heifer	54.0%
Season	Spring	25.1%	Summer	27.4%
	Fall	24.3%	Winter	23.2%
August 2014-December 2015[b]	Mean	Std. Dev.	Min	Max.
Feed conversion (lb. feed/lb. gain)	6.14	0.58	4.29	8.76
Average daily gain (lb. gain/day)	3.24	0.49	1.65	5.18
Mortality (%)	2.54	3.19	0.00	26.78
Placement weight (lb.)	700.8	177.49	301.00	1096.00
Days on feed (days)	192.8	67.20	87.00	443.30
Gender	Steer	55.0%	Heifer	45.0%
Season	Spring	25.8%	Summer	23.2%
	Fall	25.8%	Winter	25.2%

[a] Period one has 48,341 cohorts/pens

[b] Period two has 1,203 cohorts/pens

Table 1.2: Linear Mixed Model (LMM) Estimation for Cattle Performance which serves as a Proxy for Cattle Morbidity

	ADG	AFC	HC
Fixed Effects			
Constant	-4.536 (0.10)[a]	-1.129 (0.14)	13.371 (1.97)
Mortality (MORT)	-0.059 (0.00)	0.050 (0.00)	1.399 (0.08)
Log Placement Weight (LnPWT)	1.147 (0.01)	1.144 (0.02)	0.004 (0.00)
Steer (STEER)	0.238 (0.00)	-0.272 (0.01)	1.294 (0.41)
Oct-Mar (WINTER)	0.009 (0.00)	0.004 (0.01)	
Antimicrobial (Upper Tier)			29.565 (0.80)
Antimicrobial (Lower Tier)			24.750 (0.81)
Random Effects[b]			
Company	0.016	0.016	14.4178
Pen Size	0.002	0.003	0.5008
Placement Year	0.007	0.072	
Observations	48,341	48,341	1,203
REML Convergence	41,637.68	75,791.04	7,998.1

[a] Numbers in parenthesis () are standard errors

[b] Variances are reported for each random effect

Table 1.3: Percentages of Steer Cohorts within Net Return (\$/head) Categories[a]

Net Returns	600 lb. Placement Weight				800 lb. Placement Weight			
(\$/head)	Summer (Apr-Sept)		Winter (Oct-Mar)		Summer (Apr-Sept)		Winter (Oct-Mar)	
	Upper Tier	Lower Tier	Upper Tier	Lower Tier	Upper Tier	Lower Tier	Upper Tier	Lower Tier
Metaphylaxis								
(<-251)	0.00	0.68	0.00	1.82	0.00	0.00	0.00	0.00
(-251, -51)	0.02	16.88	0.08	19.46	0.00	11.36	0.00	11.80
(-50, 0)	1.62	21.08	1.64	16.84	0.10	29.16	0.00	32.34
(0, 50)	42.20	39.46	20.08	29.28	57.20	51.84	1.74	48.88
(>51)	56.16	21.90	78.20	32.60	42.70	7.64	98.26	6.98
No Metaphylaxis								
(<-251)	4.62	4.62	8.02	8.02	0.80	0.80	0.80	0.80
(-251, -51)	22.42	22.42	23.50	23.50	23.94	23.94	39.94	39.94
(-50, 0)	15.38	15.38	12.56	12.56	22.90	22.90	30.28	30.28
(0, 50)	25.04	25.04	18.92	18.92	34.96	34.96	23.14	23.14
(>51)	32.54	32.54	37.00	37.00	17.40	17.40	5.84	5.84

1.8 Figures

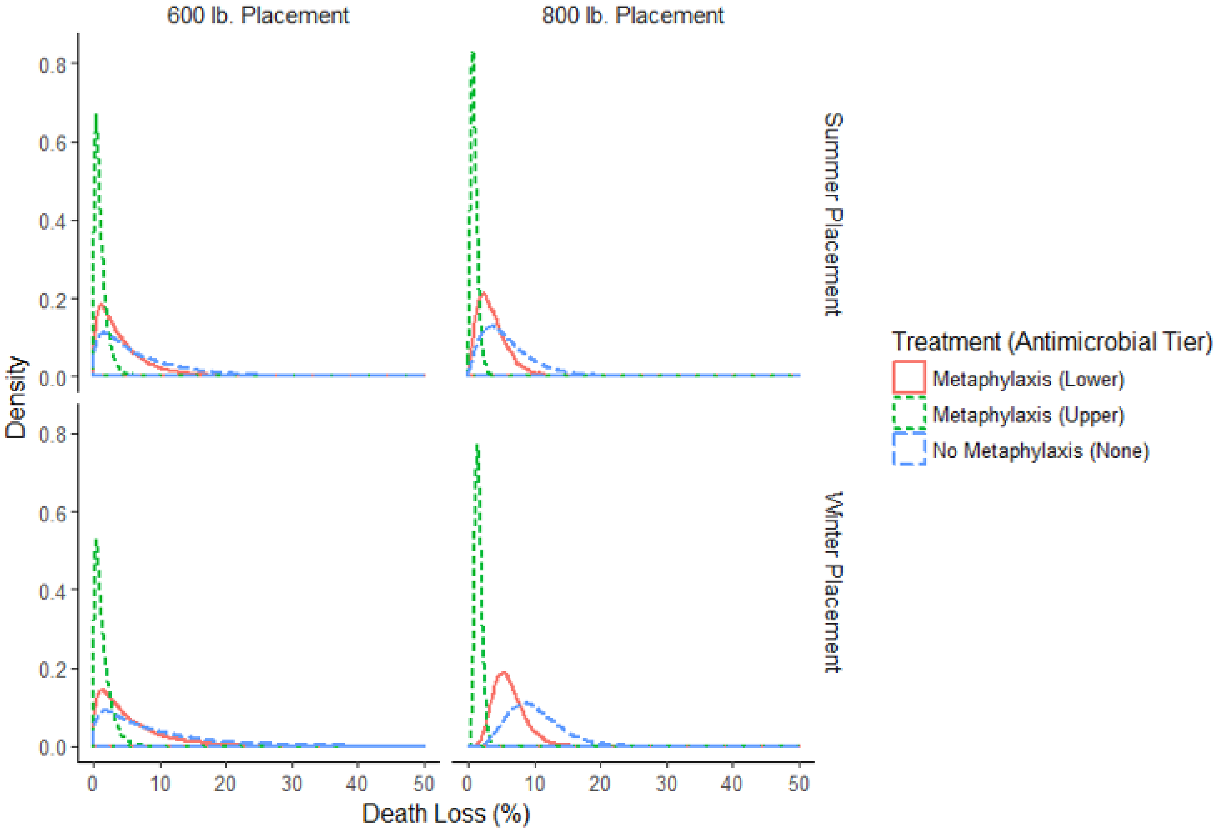

Figure 1.1: Death Loss Distributions for High Health Risk Steers by Placement Weight, Placement Season, and Type of Antimicrobial used for Metaphylaxis

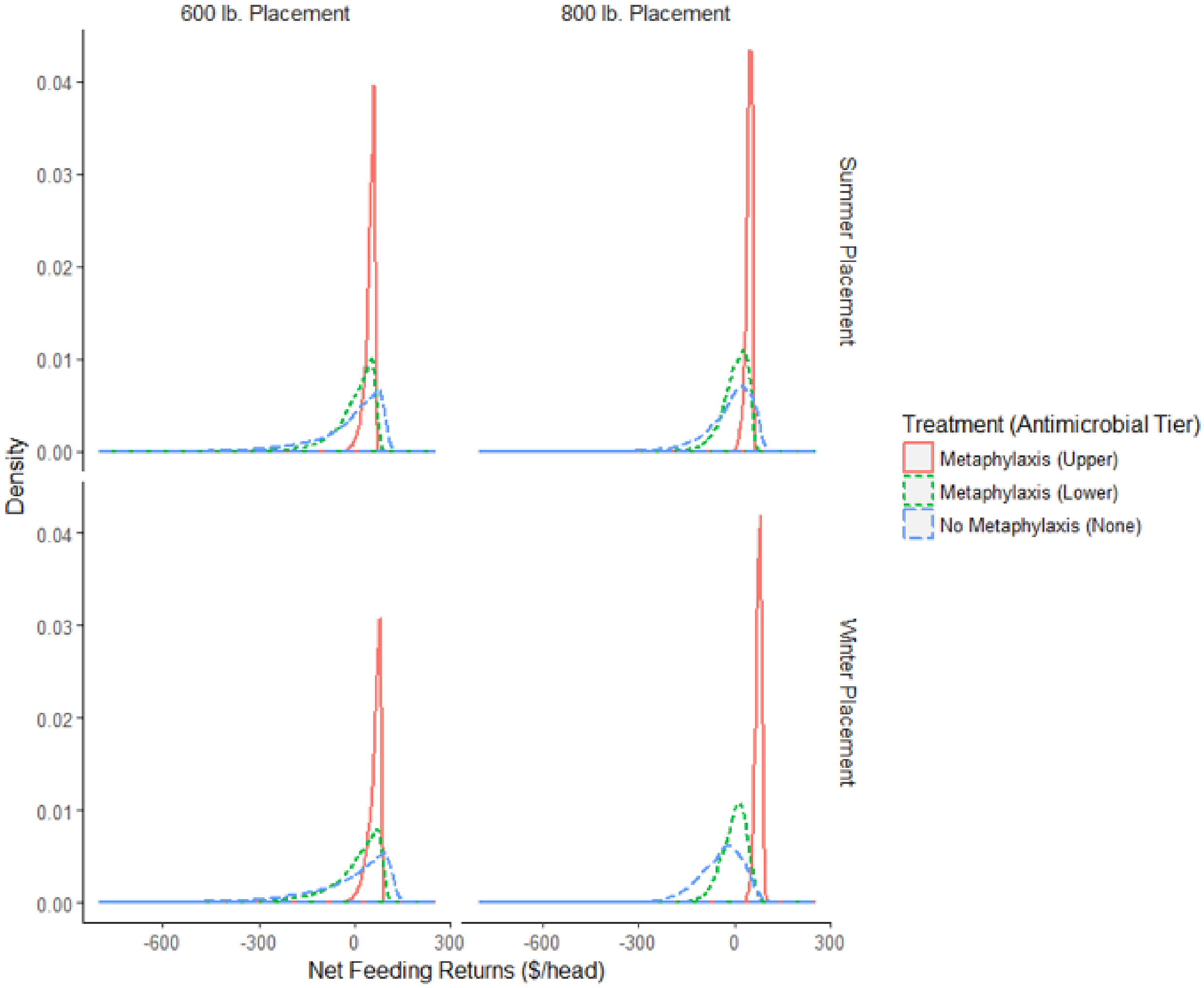

Figure 1.2: Net Return Distributions for High Health Risk Steers by Placement Weight, Placement Season, and Type of Antimicrobial used for Metaphylaxis

Chapter 2

Value of Arrival Metaphylaxis in U.S. Cattle Industry

2.1 Introduction

Public concern over use of shared-class antimicrobials in animal feeding operations, antimicrobial resistant bacteria, and potential antimicrobial residuals in meat has escalated in recent years.[1] Major restaurants, food service companies, food processors, and supermarkets have pledged to reduce or eliminate antimicrobial use in meat production (Pew Charitable Trusts, 2016). Federal and international organizations have expressed growing concerns that the use of shared-class antimicrobials in livestock production for growth promotion[2] and disease prevention is linked to increased health risks and antimicrobial resistance in humans (Centers for Disease Control and Prevention, 2013; World Health Organization, 2012).

Metaphylaxis is an animal health management practice that administers FDA-approved antimicrobials, generally via injection, to groups of high-risk animals in order to eliminate or minimize acute onset of a disease (United States Department of Agriculture, 2013). Cattle

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[1] Antimicrobials are classified by their production use. Shared-class antimicrobials are medically important to both human and animal health.

[2] "Production purposes" refers to products that are used with the intent to enhance growth or improve feed efficiency rather than treat disease. Growth-promotion antimicrobials are commonly referred to as "sub-therapeutic."

producers selectively use this tool to reduce beef cattle health risks when cattle first arrive at feeding facilities and occasionally during feeding. While scientific evidence linking metaphylaxis use in animal production to negative impacts on human health is sparse, select countries and international organizations have strongly recommended an overall reduction in the use of shared-class antimicrobials for disease prevention without individual animal diagnosis (World Health Organization, 2015, 2017). Current debate centers on whether to include further regulate metaphylaxis in the United States. Since metaphylaxis reduces bovine respiratory disease (O'Connor et al., 2013; Abell et al., 2017), the most common cause of morbidity and mortality in beef cattle, livestock producers are concerned that removing such a widely used production technology would be detrimental to animal health and result in substantial animal deaths, reduced animal welfare, increased production risk, and reduced profitability (Fears, 2015).

This paper estimates the value of metaphylactic use in U.S. cattle feeding and determine implications for consumer and producer surplus of eliminating its use. First, we develop a fed cattle industry simulation model to estimate net returns under alternative market conditions, policies, and animal production technologies. Second, using 20 years of proprietary data from 10 large commercial Midwestern feedlots, we obtain short-run estimates of the effect of banning the use of metaphylaxis upon recently arrived cattle. Third, these results are used to estimate changes in producer and consumer surplus at major market levels to determine economic impacts of eliminating metaphylaxis.

Several studies have estimated the economic impacts of banning antimicrobials in livestock production used in feed and water (Hayes et al., 2001; Brorsen et al., 2002; Miller et al., 2005; MacDonald and Wang, 2011; Key and McBride, 2014). In contrast, little economic research has evaluated metaphylactic antimicrobial use in animal production. Antimicrobial use in feed and water and the health management practice of metaphylaxis have distinct purposes, uses, animal outcomes, and producer profitability. Antimicrobials administered in feed and water balance beneficial and harmful bacteria to improve nutrition and create homogeneous animal populations (Cromwell, 2002). Antimicrobials administered during metaphylactic treatment strive to reduce clinical and subclinical morbidity and mortality caused by actual or prospective illness. While both are production technologies used to manage animal health, antimicrobials in feed and water are often used to increase animal efficiency, whereas metaphylaxis specifically treats groups of animals with elevated health risk. This important distinction requires a new framework to map animal disease and health treatment strategies to producer profitability and estimate societal economic impacts surrounding metaphylactic use in beef cattle production.

In what follows, we first describe alternative health management practices in United States feedlots with primary focus on metaphylaxis. Next, we incorporate metaphylaxis into a feedlot producer decision framework accounting for how metaphylaxis modifies animal health and subsequently producer profitability. Main findings and how sensitive these results are to model calibration are presented in the next section. We conclude with how the cost of removing of metaphylaxis as a health management practice in beef feedlots is passed both within and between different meat markets.

2.2 Background

Metaphylactic intervention reduces mortality and morbidity risk, may reduce medication costs, reduces days on feed, and can improve carcass and offal quality (Schumann et al., 1990, 1991; Van Donkersgoed, 1992; Duff et al., 2000; Encinias et al., 2006; Cernicchiaro et al., 2012; Tennant et al., 2014). Metaphylaxis is used to reduce the risk or impacts of an outbreak of bovine respiratory disease (BRD), the most common cause of morbidity and mortality in U.S. beef cattle production, affecting 97% of feedlots, 16% of cattle, and costing the beef industry an estimated $6 billion annually (Griffin, 1997; United States Department of Agriculture, 2013). Metaphylaxis is selectively used by 59% of U.S. feedlots on 20.5% of cattle placed on feed across all cattle placement weights (United States Department of Agriculture, 2013).

The primary alternative health management to metaphylaxis is to only treat clinically observed sick animals, commonly referred to as “pull-and-treat”. Compared to metaphylaxis, targeted pulling and treating animals is costlier when disease risk is high. Metaphylaxis and pull-and-treat are commonly used jointly to manage high-health-risk cattle. However, as the number of times an animal is pulled and treated increases, medication costs rise, carcass and offal quality decline, and mortality and culling rates increase (Belasco et al., 2009; Cernicchiaro et al., 2013). Hence, pull-and-treat is rarely used as the primary approach for managing high-health-risk cattle, which are often more effectively managed using metaphylaxis followed by selective pull-and-treat.

Injectable antimicrobials, to which the metaphylaxis protocol is a major contributor, accounted for 4% of total U.S. antimicrobial sales and distribution for livestock and other animals (Food and Drug Administration, 2016). Use of antimicrobials in feed and water, to which the metaphylaxis protocol is a minor contributor, is much more prevalent. Antimicrobials in feed and water account for 74% and 22% of total antimicrobial sales, whereas injectable antimicrobials, to which the metaphylaxis protocol is a major contributor, accounted for 4%. Hence, impact assessments have primarily focused on removing the larger relative proportion of antimicrobials in feed and water for hogs, broilers, and cattle. Since metaphylaxis impacts cattle performance parameters and reduces mortality and morbidity as well, producer and consumer surplus losses are likely more pronounced. To our knowledge, no prior research has estimated the value of metaphylaxis on the beef cattle sector and its associated economic surplus impacts on society.

2.3 Data

Proprietary data were collected from 10 large commercial feedlot operations located in Midwestern states. The datasets encompass two periods: 1989-2008 and 2014-2015. The first period comprises 48,341 pens of cattle (about 6 million head) over 20 years. Period 2 comprises 1,321 pens of cattle (about 264,000 head) over 1.5 years. Data for period 1 are typical feedlot closeout data and are used to calibrate animal feeding performance (ADG and AFC) variation conditioned on season, location, and animal weight. Health costs reported exclude arrival health treatments, capturing only total animal health cost after feeding began; thus, health costs for this dataset exclude possible costs associated with metaphylaxis. Data for period 2 contain similar animal feedlot performance variables for the same companies but, because of the shorter period, are not well suited for making inferences across time, season, and location. The data from period 2 detail health costs documenting metaphylaxis use, individual animal costs associated with BRD, and their impact on cattle performance, none of which are available in period 1. Specifically, the more recent data enable us to identify costs associated with metaphylaxis in our cattle feeding risk simulation. Table ?? displays summary statistics for the feedlot data.

2.4 Methods

2.4.1 Simulation Framework

A cattle feeding simulation model is developed to incorporate how metaphylaxis conditions cattle morbidity and mortality. Variation in cattle morbidity and mortality influences net return distributions under alternative health management scenarios for heterogeneous at-risk fed cattle. Net returns from cattle feeding, sold under a live-weight basis, are translated into short-run producer and consumer surplus changes with and without the use of metaphylaxis in treatment of high-health-risk cattle.

Producers first select a vector of cattle characteristics (α) that includes gender, placement weight, and expected harvest weight.[3] In the simulation, feedlots purchase cattle at three different weight categories (ω) where ω = calves (550 lb.), middle-weights (700 lb.), or yearlings (850 lb.).[4] Once cattle are purchased, α is fixed and cattle are categorized as either low- or high-health-risk.[5] Low-health-risk cattle have low production and mortality

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[3] Feedlots make feeder cattle purchase decisions based on feeder cattle supplies, feed costs, and season and adjust their cattle price offers in accordance with perceived animal health risk. Prospective buyers categorize cattle into economic risk groups conditional on expected mortality and morbidity risk, cattle performance and characteristics, feeding location, and time of year. Higher transaction prices are generally associated with healthier animals with lower probabilities of morbidity and mortality.

[4] Younger cattle have less-developed immune systems and are more susceptible to infection and disease. Few cattle purchased in the United States have a verified age. The weight categories selected reflect cattle purchase weights commonly used by producers.

[5] Low- and high-health-risk cattle are often simultaneously available for purchase across different weight classes. Producers mitigate health risk in high-health-risk cattle through health management practices such as metaphylaxis. Animal health-risk assessment for cattle purchased by feedlots is based on cattle weight and

risks and are never prescribed metaphylaxis but are individually treated when clinical signs of morbidity are manifest (i.e., pull-and-treat). High-health-risk cattle are prescribed metaphylaxis upon arrival at the feedlot and individually treated for clinical signs of morbidity and mortality.

Producers, with veterinarian oversight, select a health management strategy (τ) that maximizes expected animal well-being, performance, and ultimately profit. Given α, ω, and τ, a producer faces a random cattle death loss ($\phi_{\omega,\tau}$). Death loss distributions for each $\omega \times \tau$ high-health-risk cattle combination are calibrated using feedlot data and metaphylaxis multipliers from Abell et al. (2017). Appendix B describes in more detail how these distributions were generated. Thus, the primary driver of feedlot profitability in our simulator is cattle mortality (MORT). Mortality distributions are displayed in figure 2.1.

The impact of mortality on cattle performance parameters, γ, is estimated from feedlot data using linear mixed model (LMM) regressions, which are commonly used in epidemiologic studies. Appendix B describes in more detail the estimation and results of said LMMs. Performance parameters for cattle are measured for aggregate groups of animals that either live and are marketed as fed cattle at harvest or die during feeding. As mortality rates increase, pen performance parameters become skewed downward, often to irrational values. To overcome this, net returns are calculated for $k =$ dead, alive broad groups of cattle purchased by producers: i) animals that survive feeding and sold and ii) animals that die. Given α, the kth group death loss assumption, and a vector (γ_k) of expected values, we calculate three cattle performance parameters (ADG, AFC, and HC) using proprietary feedlot data. ADG is the average weight (in lb.) gained during the feeding period, AFC is the average amount of feed (in lb.) consumed for an additional pound of weight gain, and HC is health costs associated with feeding.

The variables ADG, AFC, and HC are known to be correlated with each other and vary by risk category and health intervention. To make these variables individually stochastic,

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age, whether cattle have been comingled from multiple sources, distance cattle traveled prior to placement, season, and prior health treatments that may have been administered. In this study, we define high-risk cattle as those entering the feedlot where metaphylaxis was used as the initial health management practice (United States Department of Agriculture, 2013) yet correlated, we model the joint distribution using Iman and Conover (1980) algorithm for 10,000 iterations. We assumed cattle performance parameters (ADG, AFC, and HC) are distributed $N_k \sim (\gamma_k, \sigma)$, where σ is a vector of variances from the estimated LMM residuals and γ_k is the previously specified estimates of ADG, AFC, and HC for the kth group, given a linear dependency structure. This produces simulated cattle parameters (ADG, AFC, and HC) with mean, variance, and dependency structure of cattle performance variables identical to those observed in feedlot data.

We use simulated ADG, AFC, and HC values, random cattle death loss, fixed prices, and exogenous feedlot characteristics to calculate cattle feeding net returns, $\rho_{\omega,k,\tau}$, defined as

$$\rho_{\omega,k,\tau} = TR_{\omega,k,\tau} - FDRC_{\omega} - YC_{\omega,k,\tau} - FC_{\omega,k,\tau} - HC_{\omega,k,\tau} - IC_{\omega,k,\tau} \tag{2.1}$$

$$\begin{aligned} TR_{\omega,k,\tau} =& FP \times CSW_k \times (1 - SHRINK) \times (1 - MORT_{\omega,k,\tau} - CULL) + \\ & (CULL \times CULLW \times CULLP) \end{aligned} \tag{2.2}$$

$$FRDC_{\omega} = FRP_{\omega} \times CPW_{\omega} \tag{2.3}$$

$$YC_{\omega,k,\tau} = 0.30 \times DOF_{\omega,k,\tau} \tag{2.4}$$

$$FC_{\omega,k,\tau} = FEED \times [AFC_{\omega,k,\tau}[CSW_{\omega,k,\tau} \times (1 - MORT_{\omega,k,\tau} - CULL) - CPW_{\omega}]] \tag{2.5}$$

$$IC_{\omega,k,\tau} = [0.5 \times [YC_{\omega,k,\tau} + FC_{\omega,k,\tau} + HC_{\omega,\tau}] + FRDC_{\omega}] \times DOF_{\omega,k,\tau} \times (IR/365) \tag{2.6}$$

Table 2.2 displays and explains the simulated and fixed feeding net return variables used in equations 2.1 - 2.6.

A weighted-average net returns of cattle feeding ($\pi_{\omega,\tau}$) is recovered using the matrix of calculated cattle feeding net returns ($\rho_{\omega,k,\tau}$) from equations 2.1 - 2.6. Given the stochastic mortality ($\phi_{\omega,\tau}$) and a representative pen size of 120 head, $\phi_{\omega,\tau} \times 120$ number of net returns from the $\rho_{\omega,dead,\tau}$ distribution are included while the remaining $(1 - \phi_{\omega,\tau} \times 120)$ cattle net returns are selected from $\phi_{\omega,alive,\tau}$. This is done 10,000 times, taking the mean of each iteration and thus obtaining a weighted-average net return distribution $\phi_{\omega,\tau}$.

A weighted-average net return $\phi_{\omega,\tau}$ for each weight-by-treatment category, where $\omega =$

(500,700,850 pound placement weight) and $\tau =$ (metaphylaxis, no metaphylaxis) is used to calculate the industry net return value of metaphylaxis and the value of metaphylaxis as a proportion of industry gross revenue to high-risk cattle. The latter is calculated as

$$\theta = \frac{\sum_{\omega=1}^{3}(v_\omega \times c_\omega \times x_\omega)}{\xi} \tag{2.7}$$

where the value per head of health management strategy (v_ω) is obtained by taking the difference in expected values from the health intervention (i.e., metaphylaxis). The number of cattle placed on feed in a given year in each weight class is c_ω, x_ω is the proportion of cattle administered metaphylaxis, and ξ is the fed cattle industry total revenue calculated as pounds produced multiplied by dollars per pound for fed cattle.

2.4.2 Producer and Consumer Surplus Impact

A multimarket partial equilibrium that allows for shocks in the fed cattle industry to be transmitted from beef to pork, lamb, and poultry is framed using an equilibrium displacement model (EDM). The EDM is used to estimate changes in producer and consumer surplus that would be incurred by fully eliminating the use of metaphylaxis in the fed cattle industry. EDMs have frequently been used in the livestock and meat sector for determining the impacts of exogenous shocks along and across marketing chains. Lusk and Anderson (2004) and Brester et al. (2004) used EDMs to estimate the effects of country-of-origin labeling on meat producers and consumers. Schroeder and Tonsor (2011) constructed an EDM to estimate economic impacts of removing a cattle feeding production technology. Pendell et al. (2013) employed an EDM to assess impacts of international trade for requirements of cattle age and source verification.

The EDM we use in this study is an updated version of the multimarket partial equilibrium model documented in Pendell et al. (2010). Market parameters-including supply, demand, and quantity transmission elasticities as defined in Pendell et al. (2010) were retained, with updates to selected elasticity estimates (see online supplement).[6] The EDM

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[6] Demand elasticities were updated to reflect more current demand elasticity estimates. The updated

is composed of four sectors for the beef and lamb industries: retail (consumers), wholesale (packers), fed (cattle/lamb feeding), and farm (cow-calf/lamb producers). Pork and poultry markets are highly integrated and thus we model them using three sectors: retail, wholesale, and producer. Each sector explicitly models international trade at the wholesale sector. The base year price and quantity were updated to reflect 2015 prices and quantities. Changes in consumer and producer surplus can be calculated from changes in prices and quantities from the EDM model. Equation 2.7 represents the one-time, 1-year exogenous shock to the fed cattle sector of removing metaphylaxis.

2.5 Results

We selected feeder cattle prices to use in the simulation so that comparisons could be made across treatment groups for each specific placement weight. For example, net returns for 550 lb. feeder cattle can be compared with and without metaphylaxis administered. Figure 2.2 depicts the simulated net returns of metaphylaxis use on high-risk cattle across the three placement weight categories. Negative values indicate the losses conditioned by metaphylaxis treatment. All reported results are on a per head live-weight basis for a weighted-average gender and season.

Overall, using metaphylaxis reduces mean occurrence and extreme death loss, resulting in greater net returns with reduced variability. Metaphylaxis is most profitable when administered to high-risk cattle with lighter placement weight. On average, high-risk 550 lb. placements lose \$104.46/head when not treated with metaphylaxis, high-risk 700 lb. cattle lose \$99.26/head, and high-risk 850 lb. cattle lose \$63.36/head relative to treated cattle.

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elasticities used in the EDM are retail beef -0.420 (Tonsor et al., 2010), fed cattle -0.66 (Marsh 1992), feeder cattle -0.62 (Marsh, 1992), retail pork -0.7396 (Tonsor et al., 2010), and retail poultry -0.099 (Tonsor et al., 2010).

2.5.1 Impact of Removing Metaphylaxis

The percentage of cattle administered metaphylaxis and the number of cattle placed on feed by weight category were used to translate the simulated return distributions into an industry-wide valuation of metaphylaxis. The Livestock Marketing Information Center (2017) reports placements of cattle by year and weight category from USDA data. Weight categories comparable to those used in our simulation were obtained by aggregating cattle into three placement weight groups: 500-625 lb., 626-775 lb., and 776-925 lb.. Roughly one-third of cattle placed on feed in 2015 were in each calculated category with slightly more placements in heavier weights.

The NAHMS intermittently monitors and surveys health management practices in the cattle industry. In 2011, feedlots with more than 1,000-head capacity reported metaphylaxis administration rates of 2.81%, 18.01%, and 68.01% for 850 lb., 700 lb., and 550 lb. cattle placed on feed, respectively (United States Department of Agriculture, 2013). Using these assumptions and equation (10), we calculated the value of metaphylaxis as a percentage of the U.S. fed cattle industry.

Table 2.3 summarizes the results. Metaphylaxis is worth $532.18 million to the cattle feeding industry. That is, if metaphylaxis were eliminated in the feedlot sector, not allowing cattle producers to substitute into other health management or procurement practices, net returns to the cattle feeding sector would decline by $532.18 million annually, equivalent to a 0.92% reduction in gross feedlot revenue.

Several important differences were revealed when comparing the percentage of cattle given metaphylaxis reported by NAHMS in 2011 and proprietary feedlot health data from 10 large commercial Midwestern feedlots analyzed in 2014-2015 (period 2 data). Feedlot data indicate metaphylaxis health management changes by weight category. Heavier-weight cattle are administered metaphylaxis less often than lighter cattle. The proprietary feedlot data indicated that metaphylaxis was administered to 86.85% of 550-625 lb. placements, 23.10% of 626-775 lb. placements, 3.59% of 776-925 lb. placements, and 26.00% of all cattle placed. These estimates are higher than those reported by NAHMS of 68.01%, 18.01%, 2.81%, and 20.50%, respectively, for each of the three placement weight categories and overall cattle treatment. Using the more intense metaphylaxis use from the feedlot data, we estimated an alternative value of metaphylaxis to the fed cattle industry. If metaphylaxis were administered in the United States at the same rate as in our feedlot sample, eliminating metaphylaxis would reduce net returns to the cattle feeding sector by $679.56 million annually, equivalent to 1.17% of industry gross revenue (see Table 2.3).

Several limitations are important to mention before interpreting the reported estimated values of metaphylaxis. First, the estimated valuation is likely an upper estimate because the simulation model does not enable producers to switch to another health management strategy if metaphylaxis use were eliminated. No substantial alternative presently exists that could effectively replace metaphylaxis, so how much our estimate overstates the impact is debatable. However, it provides an estimate for how much an alternative health management technology could cost and still incentivize producer adoption. Short-term solutions would likely revolve around changes in cattle procurement strategies by weight and season rather than switching to other technologies, which would imply that industry losses would be similar to those estimated here but shifted upstream to feeder cattle suppliers.

Second, the net return simulation depends on calibrating the death-loss distributions, particularly how they differ with and without metaphylaxis. No large-scale randomized trial of the impacts of metaphylaxis (versus negative control cattle) exists. Our death loss distribution is calibrated from a mixed treatment control meta-analysis that examined 29 randomized control studies, which are the most reliable estimates available. In the following section, we evaluate how sensitive our results are to this calibration.

Third, the percentage of cattle given metaphylaxis in each group affects the total value of the health management strategy. Larger placements of 550 lb. animals increase the shock magnitude.

Fourth, fed and feeder cattle price levels impact the value of metaphylaxis. Higher fed cattle prices create greater value associated with metaphylaxis, ceteris paribus; as cattle prices increase, the cost of animal death loss increases. How much this affects our estimates is discussed in the following section.

Fifth, metaphylaxis is only eliminated from cattle production. This implies pork and poultry producers would not change antimicrobial use practices. This simplification allows us to obtain a cattle-specific value of metaphylaxis without other compounding effects.

Sensitivity Analysis

The two important drivers of results in the simulation model are feeder and fed cattle prices and the death loss distributions of fed cattle. The average fed cattle price used in this simulation was \$148/cwt (see Table 2.2). To illustrate the sensitivity of results to cattle prices, we compared results with two different fed cattle prices, \$171.00/cwt and \$125.24/cwt, which correspond to high and low prices observed between Fall 2011 and Fall 2017. These represent prices approximately 15% above and below the base simulation price. Results reveal that, if cattle were prescribed metaphylaxis at the rate specified by NAHMS, the net return value of metaphylaxis would be \$639.83 million (19.11% higher) if the fed cattle price were \$171.00/cwt and \$424.71 million (20.19% lower) with \$125.24/cwt. As such, fed cattle price has important impacts on the value of metaphylaxis because higher fed cattle prices, ceteris paribus, are associated with higher feeder cattle prices and any death loss has a greater economic cost.

The median odds ratio estimates proposed by Abell et al. (2017) were used to calibrate the death loss distributions used in the base simulated model. The authors calculated 95% confidence intervals for two common macrolides, Tilmicosin and Tulathromycin. Using this information, we estimated death loss calibrations for the 2.5^{th} and 97.5^{th} percentiles. Results are sensitive to death loss distributions. Given the metaphylaxis application rates reported by NAHMS, removing metaphylaxis would result in feedlot net return losses of \$91.01 million at the 2.5^{th} percentile and \$1,119.56 million at the 97.5^{th} percentile.

2.5.2 Surplus Implications

We quantify short-run societal impacts of removing metaphylaxis. Column 3 of table 2.3 are used as the shocks to the fed cattle industry.[7] Table 2.4 presents surplus estimates of a complete removal of metaphylaxis using both the NAHMS survey data and proprietary feedlot data with the associated 0.92% and 1.17% losses in net returns to the cattle feeding industry. Feedlots ultimately pass costs downstream to feeder cattle producers, resulting in higher losses in the feeder cattle sector. Feedlots would lose from $924.86 million to $1,179.85 million, and feeder cattle producers would lose $1,060.78 million to $1,354.22 million in producer surplus in year 1 if metaphylaxis were eliminated. Higher beef retail prices induce consumers to substitute into other meat products, leading to gains for pork, poultry, and lamb producers.

The wholesale beef market would lose $206.97 million to $267.45 million, while retailers would experience a short-run surplus gain of $377.45 million to $476.70 million. Overall, beef producer surplus would decline by $1,809.52 million to $2,322.44 million. Total consumer surplus would decrease by $1,074.23 million to $1,370.51 million.

2.6 Conclusion

Antimicrobial use in livestock production is an increasingly important societal concern. All animal drug use is regulated, and we will continue to see more stringent regulationsthe VFD and state-mandated antibiotic-use policies are recent examples. In addition, consumers and retailers are becoming more health conscious, demanding more traceability, restrictive farming practices, and no antibiotic use in meat production. These demands and policies will continue to increase costs while offering minimal demand responses, thus reducing both consumer and producer welfare (Saitone et al., 2015).

On the policy horizon is whether metaphylaxis, an integral animal health management strategy administered to high health risk cattle upon arrival at feeding operations, should

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[7] For example, if metaphylaxis is valued at 5% of industry value then removing metaphylaxis would result in a loss of 5% of industry value. Thus, the shock would be -0.05

be more intensively regulated or even eliminated as an animal health management option. To our knowledge, this study is the first to estimate the value of metaphylaxis, an animal health treatment, in any livestock sector, with particular focus on the U.S. beef cattle sector.

Metaphylaxis is uniquely suited to reduce mortality and morbidity in high-health-risk animals. Using industry metaphylaxis data from the National Animal Health Monitoring System surveys and proprietary feedlot production data, the net return value of metaphylaxis to the cattle feeding industry is \$532 million to \$680 million per year. Eliminating metaphylaxis would reduce beef producer surplus by \$1.81 billion to \$2.32 billion and overall consumer surplus by \$1.15 billion to \$1.47 billion per year.

Removing a production technology (such as metaphylaxis) that directly impacts animal mortality risk is costlier than removing a production technology (such as antimicrobials in feed and water) that targets production efficiency. Producer and consumer surplus estimates are larger in comparison to studies that estimated short-run economic impacts of bans on antimicrobials in feed and water (\$280.55 million for beef producers (Mathews, 2002), \$45.36 million to \$291.24 million for pork producers (Wade and Barkley, 1992; Brorsen et al., 2002; Sneeringer et al., 2017), and \$189.00 million for poultry producers (Sneeringer et al., 2017)).

The better we can predict animal health, quantify uncertainty, and determine net return distributional impacts for antimicrobial use practices in cattle production, the more informed specific policy options become. Results also inform industry stakeholders about how much production/marketing practices would need to be offset if alternative treatments are developed. As public scrutiny of antimicrobials used to treat at-risk animals in feeding operations escalates, a body of research assessing economic and societal surplus impacts of eliminating metaphylaxis is essential for making informed policy decisions.

2.7 Tables

Table 2.1: Feedlot Performance Summary Characteristics for Periods 1 and 2

January 1989-December 2008	Mean	Std. Dev.	Min	Max.
Feed conversion (lb. feed/lb. gain)	6.07	0.59	3.01	9.91
Average daily gain (lb. gain/day)	2.96	0.56	1.51	5.98
Mortality (%)	1.24	1.76	0.00	25.64
Placement weight (lb.)	683.7	128.99	304.20	1,100.00
Days on feed (days)	154.5	44.17	128.00	229.00
Gender	Steer	46.0%	Heifer	54.0%
Season	Spring	25.1%	Summer	27.4%
	Fall	24.3%	Winter	23.2%
August 2014-December 2015	**Mean**	**Std. Dev.**	**Min**	**Max.**
Feed conversion (lb. feed/lb. gain)	6.14	0.58	4.29	8.76
Average daily gain (lb. gain/day)	3.24	0.49	1.65	5.18
Mortality (%)	2.54	3.19	0.00	26.78
Placement weight (lb.)	700.8	177.49	301.00	1096.00
Days on feed (days)	192.8	67.20	87.00	443.30
Gender	Steer	55.0%	Heifer	45.0%
Season	Spring	25.8%	Summer	23.2%
	Fall	25.8%	Winter	25.2%

Notes: N = 48,341 for Period 1. N = 1,321 for Period 2.

Table 2.2: Feeding Net Return Variables

Variables	Description	Value/Calculation
Simulated		
$ADG_{\omega,k,\tau}$	Average daily gain during feeding (lb./head/day)	See equation B.1
$AFC_{\omega,k,\tau}$	Average pounds of feed consumed per pound of weight gain (lb. feed/lb. gain)	See equation B.2
$DOF_{\omega,k,\tau}$	Number of days on feed (days)	$\frac{CSW_{\omega,k,\tau}-CPW_{\omega}}{ADG_{\omega,k,\tau}}$
$FC_{\omega,k,\tau}$	Feed cost ($/head)	See equation B.2
$HC_{\omega,\tau}$	Animal health care cost including metaphylaxis, pull-and-treat, vaccinations, labor costs, etc. ($/head)	See equation B.3
$IC_{\omega,k,\tau}$	Interest cost ($/head)	See equation 2.6
$MOT_{\omega,k,\tau}$	Proportion of death loss in purchased group	$\phi_{\omega,\tau}$
$TR_{\omega,k,\tau}$	Total revenue from cattle sales ($/head)	See equation 2.2
$YC_{\omega,k,\tau}$	Yardage cost of feeding cattle ($/head)	See equation 2.4
$\rho_{\omega,k,\tau}$	Net feeding returns ($/head) for each weight ($\omega$), death loss group ($k$), and treatment ($\tau$)	See equation 2.1
Fixed		
CPW_{ω}	Cattle purchase weight (lb./head)	550, 700, 850
CSW_{k}	Finished animal weight (lb./head) if animal reaches maturity (e.g., k = alive), 0 otherwise (e.g., k = dead).	1,350
$CULL$	Proportion chronically ill animals culled from the remaining cohort	0.014
$CULLP$	Price received for culled animals ($/lb.)	$0.75 \times FP$
$CULLW$	Average weight of culled animals (lb./head)	861
$FDRC_{\omega}$	Feeder cattle purchase cost ($/head)	See equation 2.3
$FEED$	Corn price when cattle are placed on feed ($/lb.)	0.0923
FP	Fed cattle sale price ($/lb.)	1.48
FRP_{ω}	Purchase price for CPW 550, 700, and 850 lb. ($/lb.)	1.70, 1.49, 1.39
IR	Annualized interest rate	0.05
$SHRINK$	Proportion shrink in live weight when marketed	0.04

Table 2.3: U.S. Cattle Feeding Industry Annual Net Return Impact of Metaphylaxis, 2015

Data Source	Metaphylaxis Industry Net Return Value (million $)	Value of Metaphylaxis as Percentage of Industry Gross Revenue[b] (%)	Cattle Placed on Feed by Weight Category (1,000 head)			Percent Given Metaphylaxis by Weight Category (%)		
			550 lb.	700 lb.	850 lb.	550 lb.	700 lb.	850 lb.
NAHMS[a]	532.18	0.92	5,700	6,178	8,554	68.01	18.26	2.81
Feedlot Data	679.56	1.17	5,700	6,178	8,554	86.85	23.10	3.59

Table 2.4: Short-Run (1 Year) Producer and Consumer Surplus Estimates of Metaphylaxis Elimination, 2015

Surplus Measure	NAHMS[a] (million $)	Feedlot Data (million $)
Producer surplus		
Beef		
Retail	377.45**	476.70**
Wholesale	-206.97**	-267.45**
Fed Cattle	-924.86**	-1,179.85**
Feeder cattle	-1,060.78**	-1,354.22**
Total beef producer surplus	-1,809.52**	-2,322.44**
Pork		
Retail	117.36**	149.88**
Wholesale	38.84**	49.60**
Fed hog	22.36**	28.56**
Total pork producer surplus	183.03**	233.76**
Lamb		
Retail	1.55**	1.98**
Wholesale	0.21**	0.27**
Fed lamb	0.08**	0.11**
Feeder lamb	0.07**	0.09**
Total lamb producer surplus	1.93**	2.47**
Poultry		
Retail	570.41**	728.52**
Wholesale	250.30**	319.65**
Total poultry producer surplus	829.26**	1,059.14**
Total meat producer surplus	-772.53**	-996.66**
Consumer surplus		
Retail		
Beef	-1,148.77**	-1,465.37**
Pork	58.54**	74.75**
Domestic lamb	-0.37**	-0.47**
Imported lamb	3.81**	4.86**
Poultry	1.44**	1.80**
Total meat consumer surplus	-1,074.23**	-1,370.51**

Note: Double asterisks (**) indicate significance at the 5% level.

[a] National Animal Health Monitoring Survey

2.8 Figures

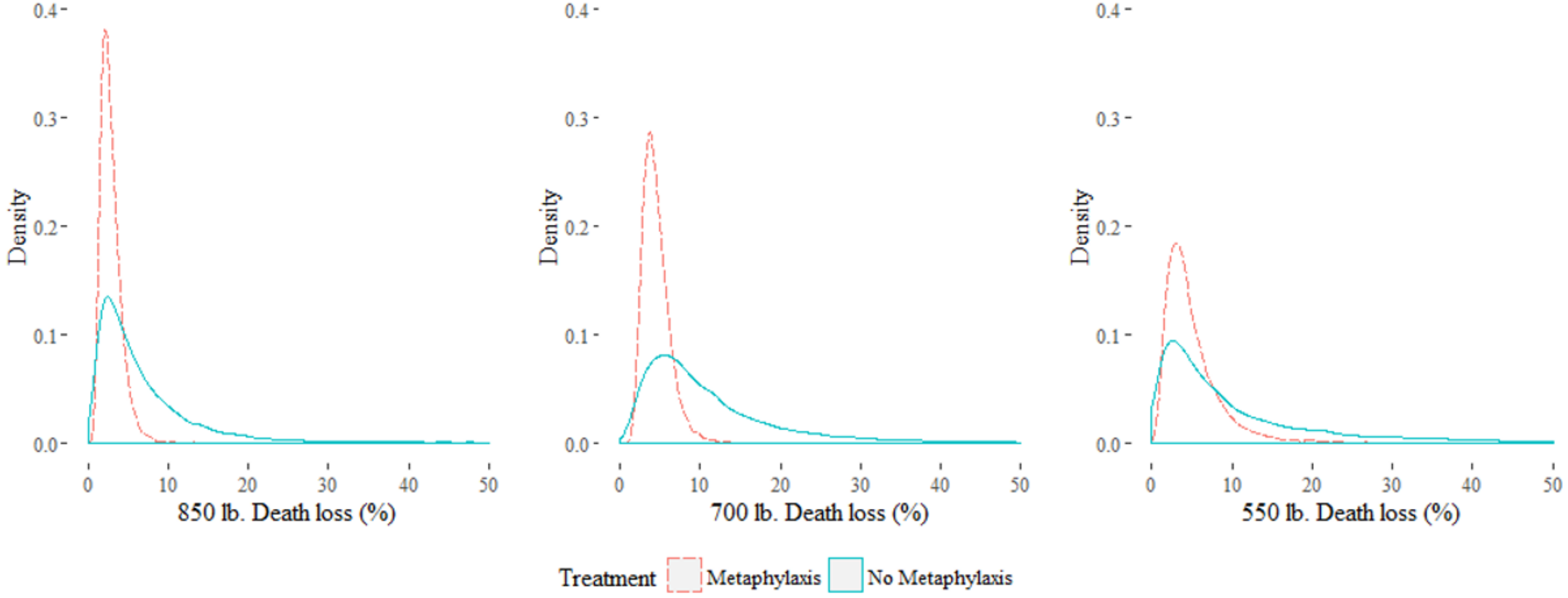

Figure 2.1: Mortality Distributions across Cattle Placement Weight Categories and Metaphylaxis Use Category

Note: Normal mean and standard deviation mortality parameters for metaphylaxis and no metaphylaxis, respectively, are: i) 850 lb. (2.7, 1.3), (6.7, 7.2); ii) 700 lb. (4.5, 1.7), (11.0, 9.3); and iii) 550 lb. (5.0, 3.5) (12.3, 19.6).

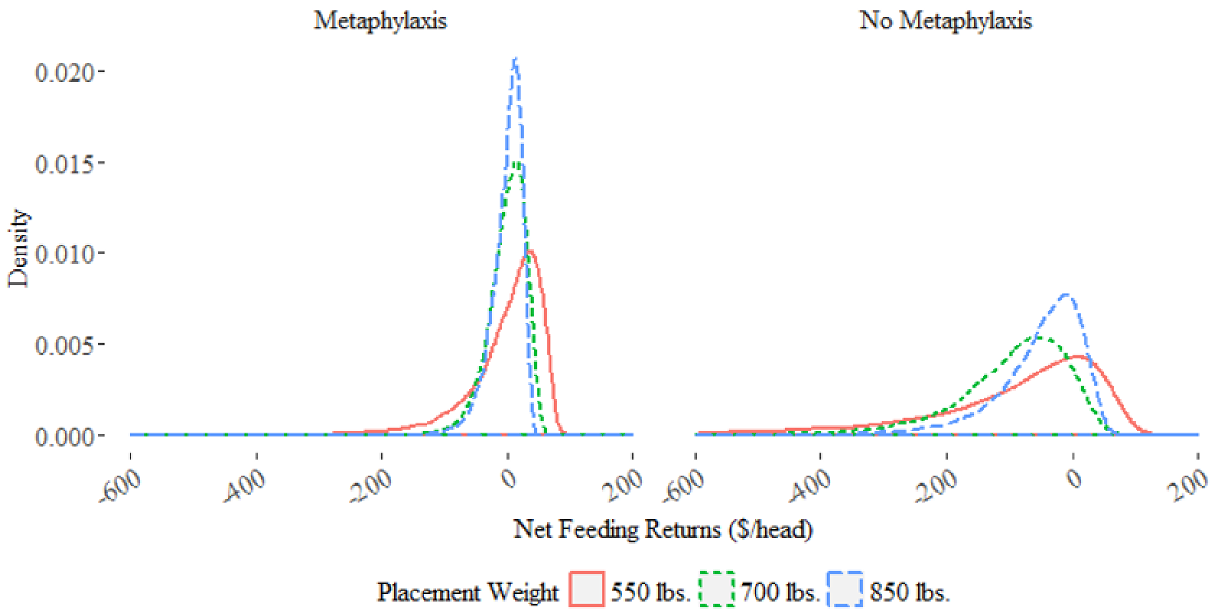

Figure 2.2: Simulated Net Return Distributions by Cattle Health Risk and Placement Weight

Note: 550 lb. high-risk cattle lose $104.46/head relative to treated cattle, 700 lb. high-risk cattle lose $99.26/head, and 850 lb. high-risk cattle lose $63.36/head when not treated with metaphylaxis. Typical cattle feeding returns over a comparable period across all placement weights were -$43.39/head (Focus on Feedlots, 2015).

Chapter 3

Why do livestock producers use metaphylaxis? Self-insurance vs. self-protection and a market insurance alternative

3.1 Introduction

Antimicrobial resistance in humans is a global health concern that causes an estimated 700,000 deaths per year globally (O'Neill, 2016). There is growing public concern from medical and disease-monitoring organizations that inappropriate use of shared class antimicrobials in livestock for disease prevention is directly contributing to antimicrobial resistance in humans (Clifford et al., 2018). Concerns of antimicrobial resistance and antimicrobials used in livestock for disease prevention has prompted international and national organizations to further monitor and regulate antimicrobial use in livestock production.

Monitoring efforts have primarily focused on the quantity of antimicrobials sold as a proxy for antimicrobial use. Antimicrobial sales likely overstate actual production use within a given year. Several studies show that antimicrobial sales are expected to grow in both developed and developing countries (Van Boeckel et al., 2017). It is difficult, if not impossible, to determine through publicly and privately available data if livestock were given antimicrobials for the purpose of disease treatment or prevention. However, livestock producers use antimicrobials for disease prevention on high health risk animals when morbidity and mortality rates are expected to be high but animals have not yet shown clinical signs.

Livestock producers use antimicrobials for disease prevention since there are few alternative animal health practices to reduce morbidity and mortality rates in high health risk livestock during feeding. Current alternative disease detection methods are either too variable, not cost effective or both.[1] Newly developed technologies are likely to be adopted first by more efficient producers who maintain low costs through optimal management and environmental conditions thus using relatively few antimicrobials. New technologies may have little effect on producers who substitute antimicrobial use for improved environmental and management conditions (McBride et al., 2008). Thus, few alternative technologies available to mitigate morbidity and mortality in high health risk livestock meet the World Health Organization's goal to provide new medicines, diagnostic tools, vaccines and other interventions that *optimize* the use of antimicrobials in livestock production (World Health Organization, 2018).

Our findings for this study are summarized as follows. First, we find that when market insurance is not available, feedlots prefer to allocate expenditures towards disease prevention compared to disease treatment. Second, when an actuarially fair insurance product is offered, producers equalize expenditure behavior shifts from disease prevention towards disease treatment. Under the assumption that antimicrobials used for disease prevention increases antimicrobial resistance, market insurance can reduce antimicrobial resistance. Third, we propose an elementary insurance product and estimate indemnity and break even premium rates for various cattle types and producer placement decisions. To our knowledge, this is the first attempt to document the conditions for producer use of injectable antimicrobials upon arrival and provide a market alternative to solve potential concerns of antimicrobial

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[1] For example, Whisper by Merck and REDI by Precision Animal Solutions are available for cattle and ADXL320 in chickens have all shown positive results in randomized control trials over visual observation but rely on calibrated threshold levels that may by livestock population and producer specific.

resistance.

We directly contribute to the animal health economics and insurance literature in several ways. First, we modify existing insurance models and allow metaphylaxis use to enter a damage function for either the use of disease prevention or disease treatment and not production improvement. Then, motivated by the insights that producers prefer self-insurance (i.e. disease prevention), we show that when an actuarially fair market insurance product is available producers change behavior towards greater self-protection (i.e. disease treatment). Finally, we propose and illustrate insights of how an insurance product could be constructed using a simple elementary insurance contract conditional on realizations of farm-level mortality rates. Combined, this illustrates how antimicrobial use and potentially antimicrobial resistance could be reduced by providing a market insurance product to feedlots. To our knowledge, this is the first attempt to document the conditions under which a feedlot uses metaphylaxis and provides a market alternative to solve consumer and international concern surrounding antimicrobial resistance.

The remainder of this paper is organized as follows. Section I summarizes current understanding of injectable antimicrobial use and antimicrobial resistance in cattle feedlots. Section II presents our conceptual model of self-insurance and self-protection and the proper identification of metaphylaxis through a damage function. Section III motivates a market insurance product and provides results based on an elementary insurance contract. Section IV concludes.

3.2 Antimicrobial Use in Feedlots

Considerable attention has focused on monitoring the use and sales of feed, water, and injectable antimicrobials. In 2008, the United States Congress instructed the Food and Drug Administration (FDA) to monitor antimicrobial sales for food producing livestock. Increased monitoring continued when the United States Congress further required livestock operations to obtain a veterinary feed directive (i.e. prescription) from a practicing veterinarian to purchase and use antimicrobials in their operations beginning on January 1st 2017 (United

States Congress, 2015).

In 2017, the share of antimicrobials used in feed and water decreased but the share of medically important injectable antimicrobials and non medically important antimicrobials increased (see figure 3.2). Species specific sales by drug class reveal that cattle producers have reduced tetracycline use, an antimicrobial used in feed and water, by 45% between 2016 to 2017 but increased macrolide use by 41% (Food and Drug Administration, 2018). Fluoroquinolone use across all species increased by 24% for which two of the three drugs available are marketed to treat and control disease in high risk cattle (2018). The animal health practice of metaphylaxis, injecting FDA approved antimicrobials to high health risk cattle upon arrival, is a major contributor to both macrolide and fluoroquinolone use.

Producers use metaphylaxis to manage mortality and morbidity in high health risk cattle. Metaphylaxis is selectively used by 59% of U.S. feedlots on 20.5% of cattle placed on feed across all cattle placement weights (United States Department of Agriculture, 2013). Metaphylaxis is used for two primary purposes: (1) control the amount of morbidity and mortality in clinically diagnosed high health risk cattle and (2) prevent occurrence of morbidity and mortality in high health risk cattle that are at an elevated risk to become sick. Thus, metaphylactic intervention is used to reduce mortality and morbidity risk, may reduce medication costs, reduces days on feed, and can improve carcass and offal quality (Schumann et al., 1990, 1991; Van Donkersgoed, 1992; Duff et al., 2000; Encinias et al., 2006; Cernicchiaro et al., 2012; Tennant et al., 2014).

3.2.1 Antimicrobial Resistance Due to Use Antimicrobial Use in Feedlots

No information is available about how metaphylaxis impacts antimicrobial resistance. As the number of times an injectable antimicrobial increases, the percentage of resistant isolates observed increases linearly (see figure 3.1). Metaphylaxis could increase the number of antimicrobial resistance isolates but by how much depends on prior antimicrobials received and the bacteria present in cattle. For example, Magstadt et al. (2018) show antimicrobial resistance is most likely to occur when combating *Mannheimia haemolytica* - increasing 2.5-8 times from no antimicrobial treatments to three antimicrobials treatments. Resistance to tilmicosin and tulathromycin were present in >75% of *Mannheimia haemolytica* isolates from cattle that had received three or more antimicrobial treatments. Some small percentage of resistant bacteria to Tilmicosin or Tulathromycin are still present even when zero treatments were given during feeding. This could be as a result of previous health treatments or naturally occurring loads of resistance bacteria.

Minimizing antimicrobial resistance is a meaningless objective which is best achieved by not using any drugs at all. Rather the aim should be to cost effectively minimize the total amount of illness or death. This objective considers both treating livestock today and minimizing future resistance levels. Inherent in this premise is that some level of resistance is optimal. Recently, cycling antimicrobial treatments has been talked about extensively as a viable and cost effective way of reducing antimicrobial resistance in livestock feeding. Cycling involves rotating between one or a combination of drugs used simultaneously over various time horizons and aims to reduce selection pressure for resistance bacteria. The key assumption to cycling is the fitness cost of resistance: the evolutionary disadvantage placed on resistant strains in an antibiotics-free environment. When fitness cost is high, resistant bacteria strains dissipate quickly because the evolutionary cost of maintaining resistance is high. Hence, if resistance to a certain antimicrobial is increasing and has a high fitness cost then temporally removing an antimicrobial from active use will restore its effectiveness. If fitness cost is low then antimicrobial effectiveness always decreases and temporally removing an antimicrobial will have little effect on resistance levels making little sense to cycle antimicrobial treatments.

Practicing livestock feeding veterinarians suggest that periodically removing a given antimicrobial reduces livestock retreatment rates (i.e. a potential proxy for resistance) and once reintroduced re-treatment rates are once again low. This tends to suggest that the fitness cost of antimicrobials used in livestock feeding operations is low. If this is correct then cycling antimicrobials or a market alternative that incentivizes producers to temporally stop using antimicrobial could be a viable option to reduce antimicrobial resistance burden.

3.3 Self-Protection vs. Self-Insurance

The motivation behind the use of metaphyalxis has important policy implications due to the elevated nature of increasing antimicrobial resistance in human health. There is growing consumer concern that the use/misuse of antimicrobials in livestock production creates resistant bacteria which are passed on to humans via consumed meat products. Consumer advocacy groups have repeatedly called for the stop of administering antimicrobials to cattle not clinically diagnosed. However, the line between when sick animals that either do or do not manifest clinical signs is extremely blurred. Hence, the duality of reasons for using metaphylaxis.

In Ehrlich and Becker (1972) seminal paper they develop the theory for the demand for market insurance conditional on two risk-shifting activities: self-protection and self-insurance. Self-insurance activities aim to reduce the *size* of a prospective loss. Self-protection activities aim to reduce the *probability* of an unfavorable event occurring. Although many actions affect both the size and probability, people are generally assumed to behave differently under self-protection and self-insurance.

Our previous discussion suggests that U.S. cattle feedlots use the animal health practice of metaphyalxis on high health risk cattle for two distinct reasons: (1) to reduce the probability of morbidity and mortality in cattle that are at-risk to become sick (i.e. self-protection) or (2) to reduce the size of the loss due to morbidity and mortality in cattle that already show clinical signs (i.e. self-insurance). In what follows, we show under what conditions feedlots would use metaphylaxis for disease prevention or disease treatment and whether a market insurance alternative could modify antimicrobial use behavior.

3.3.1 Self-insurance and Self-protection Utility Maximization Problem

We focus on U.S. cattle feedlots management of high health risk cattle using metaphylaxis. We first assume producers are utility maximizers, utility is monotonically increasing in income ($U = U(I), U'(I) > 0$), and producers are risk averse ($U''(\cdot) < 0$).

There are two mutually exhaustive types of high risk cattle that enter feedlots: high risk cattle that become sick and high risk cattle that remain healthy. Pens of high risk cattle that remain healthy enter the feedlot with probability $(1 - p)$ and generate income $I_1^e = P \times Y$ where P is the fed cattle price and Y is total pen level finished cattle weight. High risk cattle that get sick enter with probability p and generate income $I_1^e - L$ where L is the prospective loss of income due to death and loss of cattle performance. Producers can either self-insure or self-protect against loss due to cattle sickness and death. Self-insurance implies that the loss L can be modified through expending some income y with diminishing marginal returns ($L = L(y), L'(y) < 0, L''(y) > 0$). Self-protection implies that p could be modified through expending some income x with diminishing marginal returns ($p = p(x), p'(x) < 0, p''(x) > 0$).

For simplicity, we assume no jointness between self-protection and self-insurance and a linear cost function (e.g. $c(x, y) = x + y$). Lack of jointness ensures metaphylaxis can either be used for self-protection or self-insurance, but not both.[2] Given these assumptions, producers solve their utility maximization problem by selecting the level of income to expend on self-insurance and self-protection given as

$$\underset{x,y}{\text{Max}}\ U = [1 - p(x)]U(I_1^e - x - y) + p(x)U(I_1^e - L(y) - x - y) \tag{3.1}$$

Damage Function

Of importance here is how to define the loss of income $L(y)$ generated from BRD bacterial infections. Animal health strategies are used to limit the magnitude or probability of damages rather than increase production. In such cases, these agricultural inputs should enter a damage function rather than the regular production function (Lichtenberg and Zilberman 1986). This acts to protect rather than increase potential income. These types of damage functions are common in modeling the effects of pesticide, insecticide, and herbicide use on crop yields but have not been incorporated into modeling how antimicrobial use modifies

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[2] We recognize that this is a somewhat strict assumption given that metaphylaxis can often be used for both treatment and prevention.

livestock production.

We specify a production function $Y = Y_0G(\upsilon)$ such that Y is realized total weight gain, Y_0 is potential cattle weight gain, $G(\upsilon)$ is an abatement function, and υ is the bacteria controlling input. We use a two stage process to examine how the control agent affects bacteria levels and how remaining bacteria levels subsequently affects cattle weight gain. In the first stage, magnitude of bacteria infestation (Z) depends on untreated bacteria (Z_0) and the proportion of damage agent controlled by a given level of animal health expenditures used for self-insurance. The control function $C(y)$ is the fraction of maximum bacteria that is abated (i.e. reduced or removed). Thus, the magnitude of bacterial infestation after the control agent has been applied is given as

$$Z = Z_0[1 - C(y)] \tag{3.2}$$

The control function is assumed to follow a cumulative distribution ($C(y) \in (0, 1)$). When $C(y) = 1$, the control agent(s) completely eliminates all bacteria ($Z = 0$). When the control $C(y) = 0$, the control agent has no effect on the bacterial load.

The second stage models the effect of the remaining bacteria on cattle performance given by

$$Y = Y_0[1 - D(Z)] \tag{3.3}$$

where Y is total cattle weight for a given level of damage agent Z, and Y_0 is the level of cattle weight that would be forthcoming if no damage agent were present. The damage function $D(Z)$ represents the fraction of total weight lost due to bacteria. The damage function follows a cumulative distribution where with no bacteria ($Z = 0$), $D(Z) = 0$ and actual cattle performance will be equal to potential cattle performance ($Y = Y_0$).

Substituting the control function, equation 3.2, into the damage function, equation 3.3, we obtain the production function

$$Y = Y_0[1 - D\{Z_0[1 - C(y)]\}] \tag{3.4}$$

We assume that increases in bacteria reduces cattle weight since cattle need to devote more energy to fighting bacteria than growing ($\partial D/\partial Z_0 > 0$) and in extreme cases results in cattle death which completely eliminates cattle to be sold. Control agent expenditures used for self-insurance reduce bacteria populations ($\partial D/\partial C < 0$) and increases the percentage of bacteria controlled ($\partial C/\partial y > 0$).

3.3.2 Self-protection and Self-insurance when cattle health insurance is not available

Equation 3.1 can be modified to include how bacteria damages total cattle weight as

$$\underset{x,y}{\text{Max}}\ U = [1-p(x)]U(\underbrace{PY_0[1-D\{Z_0[1-C(y)]\}]}_{I_1^e}-x-y)+p(x)U(\underbrace{PY_0[1-D\{Z_0[1-C(y)]\}]}_{I_1^e}-x-y) \tag{3.5}$$

When high health risk cattle are healthy, bacteria does not cause any damage ($D = 0$) and realized cattle weight equals potential cattle weight ($Y = Y_0$). When high health risk cattle get sick, revenue I_1^e is reduced by some loss ($L(y)$) when bacteria damages potential yields ($D > 0$) resulting in actual yields lower than potential yields ($Y_0 < Y$). Feedlots attempt to control cattle weight loss due to bacteria by y self-insurance expenditures. Thus, loss $L(y)$ is given by $PY_0[1 - D\{Z_0[1 - C(y)]\}]$. Given this, equation 3.5 equation is rewritten as

$$\underset{x,y}{\text{Max}}\ U = [1-p(x)]U(PY-x-y)+p(x)U(PY-\underbrace{PY_0[1-D\{Z_0[1-C(y)]\}]}_{L(y)}-x-y) \tag{3.6}$$

The first order optimality conditions are

$$U_x : p'(x)U(I_1) + (1 - p(x))U'(I_1) - p'(x)U(I_0) + p(x)U'(I_0) = 0 \tag{3.7}$$

$$U_y : (1 - p(x))U'(I_1) + p(x)U'(I_0) + p(x)U'(I_0)L'(y) = 0 \tag{3.8}$$

where $I_1 = I_1^e - x - y, I_0 = I_1^e - L(y) - x - y$ and $L'(y) = Y_0 D'(\cdot) Z_0 C'(y)$. Equating equations 3.7 and 3.8 and rearranging we get:

$$\frac{U(I_1) - U(I_0)}{L(y)U'(I_0)} = -\frac{p(x)L'(y)}{p'(x)L(y)} \tag{3.9}$$

The right hand side represents the reduction in expected loss due to self-insurance relative to self-protection activities. Assuming a risk averse agent ($U''(\cdot) < 0$) implies that the left hand side is less than one.[3] Likewise, this implies that the right hand side must be less than one. Given this, Chang and Ehrling (1986) shows that equation 3.9 can be rewritten as

$$-\frac{\partial L(x,y)}{\partial y} < \frac{\partial L(x,y)}{\partial x} \tag{3.10}$$

where $L(x,y) \equiv p(x)L(y)$ is the expected loss. Equation 3.10 implies that the last dollar spent on self-insurance causes a greater reduction in the magnitude of the expected loss than the last dollar spent on self-protection. This suggests that self-protection causes a greater reduction in the *variance* of expected loss (income) relative to self-insurance where both cause an equal increase in expected revenue. In other words, for a risk averse individual self-protection would have a greater increase in expected utility relative to self-insurance.[4]

This does not imply self-protection is preferred to self-insurance since in equilibrium both are equally preferred. Preferences for self-protection relative to self-insurance would be determined by the functional forms of $p(x)$ and $L(y)$. Given how $L(y)$ is specified via the damage function this suggests that when metaphylaxis is used as an animal health protocol for high risk cattle, producers marginally allocate more expenditure to *prevent* rather than treat disease.

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[3] This can be obtained by using the Taylor series expansion (see Chang and Ehrling 1986), $U(I_1) = U(I_0) + LU'(I_0) + \frac{1}{2}L^2U''(\bar{I})$. This is then rewritten as $\frac{[U(I_1) - U(I_0)]}{L} < U'(I_0)$ and $U''(\cdot) < 0$

[4] Our assumption of jointness (i.e. metaphylaxis is used for either disease treatment or disease prevention) is a critical assumption here.

3.3.3 Self-insurance and self-protection when a market insurance is available

In this section we show how feedlots change their marginal self-insurance and self-protection expenditure behaviors when an actuarially fair insurance product is available to purchase. We define an insurance product s that aims to reduce the gap between incomes generated from high health risk cattle that become sick and those that remain healthy ($s \equiv I_0 - I_0^e$ where $I_0^e = I_1^e - L(y)$) and is sold at a unit price π (Chang and Ehrling 1986). Given a competitive market where self-protection is perfectly observed and no insurance transaction costs exist, the actuarially fair insurance price which reflects true odds of a loss by any producer would be given by $\pi(x) \equiv \frac{p(x)}{1-p(x)}$. Given these assumptions equation 3.6 becomes

$$\underset{x,y,s}{\text{Max}}\ U = (1-p(x))U(PY-x-y-s\pi(x))+p(x)U(PY-\underbrace{PY_0[1-D\{Z_0[1-C(y)]\}]}_{L(y)}-x-y+s) \tag{3.11}$$

The first order optimality conditions are

$$U_x : -(1-p(x))U'(I_1)[1+s\pi'(x)] - p(x)U'(I_0) - p'(x)(U(I_1)-U(I_0)) = 0 \tag{3.12}$$

$$U_y : (1-p(x))U'(I_1) + p(x)U'(I_0)[1-PY_0D'(\cdot)Z_0C'(y)] = 0 \tag{3.13}$$

$$U_s : -(1-p(x))U'(I_1)\pi(x) + p(x)U'(I_0) = 0 \tag{3.14}$$

where $\pi'(x) \equiv \frac{p'(x)}{(1-p(x))^2}$. From equation 3.14 we know that marginal utilities across both states are equal thus making incomes equal across both states when a market insurance is available. Likewise, it follows that equations 3.12 and 3.13 can be combined and simplified to $-p'(x)L(y) = p(x)L'(y)$ which can then be rewritten as

$$-\frac{\partial L(x,y)}{\partial y} = \frac{\partial L(x,y)}{\partial x} \tag{3.15}$$

Comparing equations 3.9 and 3.15 we see that in equilibrium when an actuarially fair insurance is offered it will move expenditure away from self-insurance towards self-protection. This implies that an actuarially fair insurance can cause producers to move away from using metaphylaxis as disease prevention towards using metaphylaxis for disease treatment of high health risk cattle.

3.3.4 Antimicrobial Resistance as a Public Health Externality and Government Subsidies on Insurance

Antimicrobial resistance as a public health externality is the key assumption to justify the use of an insurance product as an alternative to metaphylaxis in high health risk risk feedlot cattle. As the value of this externality increases, so does the potential for government interventions through subsides. Higher government subsidies would result in lower premium rates and thus potential increase in adoption of proposed insurance policies. For example, higher government subsidies are generally thought to have increased crop insurance participation (Coble and Barnett, 2012). As the public externality value decreases, it becomes increasingly difficult to politically justify to use of a government subsidy.[5]

Current public and medical opinion suggests that (1) antimicrobial resistance is a public externality and (2) antimicrobial use in livestock production should decrease. Given these sentiments, acceptance of an insurance policy as a replacement for antimicrobial use seems viable. However given these sentiments some may negate the idea of using an insurance product in favor of a direct tax on antimicrobial use. While this would reduce antimicrobial use by increasing the cost of an antimicrobial, it does little to address producer decision making surrounding metaphylaxis use, namely to manage high health risk cattle upon arrival at feedlots. An insurance product as an alternative directly address this behavior while simultaneously reducing antimicrobial use.

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[5] Our previous derivation has excluded the possibility of a subsidy to incentivize adoption of an insurance policy. Greater subsidies may increase adoption rates as seen in crop insurance.

3.4 Cattle Health Market Insurance

Previous sections supported two facts: (1) in the absence of market insurance cattle producers will marginally expend more income on disease prevention (i.e. self-insurance) compared to disease treatment (i.e. self-protection) and (2) if an actuarially fair market insurance were available producers would marginally shift income away from self-insurance towards self-protection. These two facts establish both the need and demand for cattle health insurance. Further, it directly aligns with the objectives of the World Health Organization that alternatives to antimicrobial use in livestock production should be developed.

Various fed-cattle insurance products are currently offered by private and public agencies. Public forms of fed cattle insurance offered by the United States Department of Agriculture (USDA) include Livestock Risk Protection (LRP) and Livestock Gross Margin (LGM). Livestock Risk Protection offers protection against declining market price. If the actual ending value is below the coverage price, producers receive an indemnity payment for the difference between the coverage price and actual ending value. Livestock Gross Margin protects an expected gross margin rather than a selling price, as is the case with LRP. Both products do not cover losses due to cattle due to morbidity or mortality. Further, no cattle can be insured during the first month of any insurance period making them problematic for producers to use in lieu of metaphylaxis which is given to high health risk cattle upon arrival.

Private forms of herd level fed cattle insurance include both comprehensive coverage for accidents, sickness, disease, and injury and limited coverage for accidents, weather events, natural disasters, and transportation.[6] Comprehensive coverage includes losses due to fed cattle mortality and morbidity but have pre-existing condition clauses. Pre-existing conditions of sickness or impaired health condition make livestock ineligible to be covered. Thus, fed cattle insurance products are used to manage low health risk cattle which have relatively low amounts of mortality and morbidity. There is currently no product that is available for producers to use to manage the mortality and morbidity risk in high health risk cattle.

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[6] For example, Nationwide and Hartford offer various forms of feedlot and pasture insurance products to producers

3.4.1 Cattle Health Insurance Experimental Design

Various combinations of cattle types, health protocols, antimicrobials used, and health outcomes create an enormous number of potential insurance combinations that cannot be comprehensively analyzed here. Rather, we focus on three broad groups of high health risk cattle purchased by feedlots and two animal health protocols - 550lb., 700 lb., and 850 lb. feeder cattle and metaphylaxis or do-nothing (i.e. no metaphylaxis).

For simplicity I assume that an insurance product is written for one producer rather than developing an index product that is more geographically diverse. The primary disadvantage is that this product would be extremely information intensive and more difficult to transfer risk to capital markets. However, it does avoid basis risk which results from imperfect correlation between individual outcomes and insurance indices (Martin et al., 2001; Yu et al., 2019). Additional variations could explore how a Midwestern index insurance product could be developed.

3.4.2 Design and Pricing of Cattle Health Insurance

We restrict our attention to elementary insurance contracts which pay an indemnity based on a realized value and have been used in numerous agricultural studies to price various forms of index insurance (Changnon and Changnon, 1989; Patrick, 1988; Turvey, 1999). Since elementary contracts are quite simple they are convenient for analysis but can be layered to create complex structures of risk protection. We modify the elementary contract proposed by Martin et al. (2001) who created a European call option and whose indemnity function is given as

$$indemnity(x|strike, limit, liability, cattle) = liability \times \underbrace{\begin{cases} 0 & \text{if } x < strike, \\ \frac{x - strike}{limit - strike} & \text{if } limit > x > strike, \\ 1 & \text{if } x \geq limit \end{cases}}_{\text{Loss Cost}} \tag{3.16}$$

where $strike, limit, liability$, and $cattle$ are all choice variables made by the feedlot. $Strike$ is the minimum death loss needed for the contract to pay, $limit$ is the maximum death loss the contract will pay out for, $liability$ is the maximum possible indemnity payment, and 'x' is some pen level realization of BRD related death loss (i.e. % of pen that died). Each call option created is conditional on the type of cattle placed where $cattle$ are the three different cattle placement weights - 550 lb., 700lb., and 850lb. Indemnity values are obtained for a combination of $strike$, $liability$, $limit$, and specific realization of death loss 'x' using equation 3.16.

The loss cost is the portion in the underbrace and equation 3.16 can be rearranged to show that it is equal to indemnities divided by liabilities. Expected loss costs are used by insurance companies to establish insurance premium rates and can be considered as the expected breakeven premium rate (Skees and Barnett, 1999; Martin et al., 2001). We calculate the breakeven premium rate for the proposed call option as the unconditional expectation of the loss cost.

These types of elementary contracts allow feedlots to obtain a unique contract every time a new strike, limit, and maximum liability level is chosen. To illustrate, consider a hypothetical elementary contract written for the total percent of death loss measured for a specific pen located at a specific feedlot. For simplicity assume that the producer is placing a 850 lb. feeder steer with a feeder price of \$1.47 per lb. Suppose the producer selects an insurance contract with strike price of 5 %, 25% limit, and maximum indemnity of \$1000 per head ($(1000/(1.47 \times 850)) \times 100 = 80\%$ of potential income per head). If the pen level death loss during that time on feed was 3% (i.e. below the strike) then the contract would pay nothing. However, if pen level death loss was 27% (i.e. above the limit) then the contract would pay \$1000 per head. Finally, if death loss was 20% then the contract would pay \$750 per head ($1000 \times \frac{20-5}{25-5} = 750$).

3.4.3 Pricing Livestock Health Insurance

In order to price an elementary contract, contract parameters as well as mortality probability distribution should be known. The mortality distribution of high health risk cattle given metaphylaxis can be estimated from data. Previous work suggests that these mortality distributions follow a log-normal or gamma distribution (Babcock et al., 2009). We estimate mortality distribution of high health risk cattle given metaphylaxis as log normal using pen level proprietary data from 10 Midwestern feedlots that placed high health risk cattle between 2014 and 2015 and subsequently administered metaphylaxis. Mortality distributions for cattle that did not receive metaphylaxis are not observed in proprietary data but are obtained by multiplying the mortality distributions of high health risk cattle that received metaphylaxis by an odds ratio. Odd ratio's for high health risk cattle that did not receive metaphylaxis are obtained from Abell et al. (2017).

The objective of the elementary contract is to provide feedlots a market alternative to manage the additional mortality risk incurred by not using metaphylaxis. It does not cover all mortality risk inherent in high health risk cattle. We obtain the probability distribution of this additional mortality risk by differencing the no metaphylaxis and metaphylaxis mortality probability distributions. This differenced death loss distribution is obtained in the following manner. First, approximate the probability density function (PDF) for no metaphylaxis and metaphylaxis as previously discussed. Second, at each value of death loss there is an associated probability. Difference the probability of obtaining a given death for no metaphylaxis and the probability of obtaining that same death loss value for metaphylaxis. What remains is the difference in probabilities at a given death loss. Third, only keep values of death loss where this differenced probability is positive.[7] Fourth, re-scale the death loss values from zero to $D - C$, where D is the maximum loss value for both of the underlying distributions and L is the death loss value where $P(\text{no metaphylaxis}) - P(\text{metaphylaxis}) > 0$.

This new differenced distribution represents the probability of obtaining a death loss over

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[7] We constrain this to be any positive probability where death loss is greater than 1% (i.e. $P(\text{no metaphylaxis}) - P(\text{metaphylaxis}) > 1$). This smooths the distribution by eliminating jumps and discontinuities that generally occur when death loss is less than one.

a pen of cattle that were managed with metaphylaxis. For example, suppose we have a 550 lb. high health risk placement and observe a 1% death loss with probability 0.03 on this new differenced distribution. This would imply that we have a 3% probability of having a death loss 1% higher then we would have had if metaphylaxis had been used. This new differenced distribution is grounded in our previous theoretical model which suggests that producers would be willing to allocate marginal income towards using disease treatment (i.e. pull and treat only those animals which are sick) if a market insurance were available.

Figure 3.3 displays this differenced mortality distribution for high health risk cattle across three different different placement weights. As placement weight increases, we are less likely to obtain differences in death loss between using metaphylaxis and not using metaphylaxis. This is consistent with observed data that finds that the effectiveness of metaphylaxis managing mortality and morbidity increases as cattle placement weight decreases. There is still some probability of obtaining large death losses above metaphylaxis across all placement weights.

After fitting the differenced log-normal distribution by cattle placement weight as shown in figure 3.3, we calculate the expected loss cost by integrating over the loss cost function in equation 3.16. The expected loss cost function for the mortality call option we have described is given as

$$E[\text{Loss Cost}] = \int_{strike}^{limit} (\frac{x - strike}{limit - strike}) f(x)dx + \int_{limit}^{\infty} f(x)dx \tag{3.17}$$

If $x < strike$ then no indemnity is paid out.

3.4.4 Potential Issues with a Mortality Insurance Contract

Additional attention should be given to the amount of information that would be required in order to price such a contract and the differences between developing this contract and crop insurance. First, historical BRD death loss is required on pens of cattle given metaphylaxis. This implies that producers (1) use metaphylaxis, (2) keep pen level animal health information, and (3) have individual death records were deaths are confirmed by a veterinarian. Second, this type of information are privately held and feedlots generally started collecting this information within the past 10 years. This is distinctly different from crop insurance where county level yields are publicly available. No monthly or yearly cattle data are publicly available to use. Combined, these two overarching concerns pose significant constraints on both the implementation and adoption of this any other insurance products.

The insurance product proposed is for three placement weights across an average sex, season, and antimicrobial used. Chapter 1 suggests that the value of metaphylaxis varies by sex, season, placement weight, and antimicrobial used. This implies that estimated premiums represent an “average premium”. To further incorporate this increased amount of heterogeneity in both cattle and producer decisions into insurance premiums would further increase the burden of historical information such as providing antimicrobial specific lot level health information.

While incorporating heterogeneity is beneficial for accurate premium rates it has the potential to impact producer decision making. For example, the insurance contract proposed in equation 3.16 could further include a decision of antimicrobial that *would be used* (i.e. Draxxin, Micotil, etc.). Premium rates conditional on antimicrobial choice, while more accurate, create the potential for adverse selection where producers purposely mismatch antimicrobial and cattle type.[8]. Thus, the trade-off for the insurance provider is whether the gain from accurate premium rates outweighs the added cost from adverse selection which ultimately is an empirical question.

Moral hazard and adverse selection are two significant concerns in designing any insurance contract. Moral hazard occurs when feedlots change behavior after purchasing an insurance contract. Adverse selection occurs when only extremely high risk cattle are enrolled and indemnity payments are likely to be high. Counter-intuitively, the proposed insurance contract potentially encourages the enrollment of cattle to allow producers to substitute away from antimicrobial use. Moral hazard and adverse selection would then be priced into the contract increasing premium rates and potentially requiring the use of government subsidies to offset higher costs. Thus, while the use of government subsidies do not “fix” these prob-

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[8] It is known that producers match the strength of the antimicrobial with cattle health. For example, an upper tier antimicrobial is used on cattle where significant mortality and morbidity is expected.

lems, it does allow sufficient time for insurance contract to be properly calibrated (Coble and Barnett, 2012).

Of these two issues, we believe that adverse selection is the greater problem for several reasons. First, adverse selection is difficult, if at all, observable by the insurance provider. Adverse selection primarily occurs when cattle are initially enrolled. One solution to the potential mismatch of cattle and antimicrobials is to standardize how veterinarians categorize high health risk cattle and which drugs should be administered. Cattle enrolled in a contract would need to meet a certain "numerical score" in order to qualify for contract participation. Based on that numerical score an associated list of antimicrobials that could then be selected.[9] While this would potentially alleviate mismatch concern, creating agreement on a high health risk scale is difficult and categorizing antimicrobials posses significant industry and professional push back. Second, we believe the moral hazard to be a function of innovation and posses a sinusoidal functional form. Given this functional form, moral hazard would then be bound by the chosen strike and limit. Low amounts of moral hazard occur when death loss is below the strike. As death loss increases above the strike, the incentive to increase moral hazard behavior changes, first at an increasing then at a decreasing rate until the limit is reached. As death loss approaches the limit the more producers desire to innovate since indemnities are only paid *up to* the limit and not beyond. These innovations would have a potential spillover effect as producers incorporate this knowledge in managing future high health risk cattle.

3.5 Results

In order to calculate the losses associated with each class of cattle we make some simplifying assumptions. First, we assume that all cattle death occurs within the first day on feed.Thus, feed, yardage, health, and interest costs are negligible. Second, we use a five year average for medium and large frame #1 steers from combined Nebraska auctions (LMIC 2019). We

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[9] This approach is similar to antimicrobial "tiers" proposed by Abell et al. (2017) where antimicrobials are classified based on their respective efficacy to reduce morbidity and mortality in high health risk cattle.

assume these prices are representative of feeder prices for the United States. Prices for 550 lb., 700 lb., and 850 lb. feeder cattle are \$1.8122, \$1.5951, and \$1.4706 per lb., respectively. Losses per head are obtained by multiplying placement weight by the respective feeder cattle price. Estimated per head losses by cattle weight are given in table C.1 in appendix C. Linear losses per head are calculated as \$997, \$1,117, and \$1,250 for 550 lb., 700 lb., and 850 lb. cattle placements, respectively. Higher losses with higher placement weights reflects the increased cost of the feeder cattle.

Each call option measures death loss at the pen level. We use a pen size of 120 head which is the average pen size managed in our proprietary data. To obtain cattle type specific liability levels, we multiply the number of each in each pen by the value of metaphylaxis. The value of metaphylaxis is the average net return per head that producers forgo be choosing not to administer metaphylaxis. The value of metaphylaxis per head is cattle type specific and taken from Dennis et al. (2018). The value of metaphylaxis per head for 550 lb., 700 lb., and 850 lb. feeder cattle placements is \$104.46, \$99.56, and \$63.36, respectively. Thus, we obtain cattle type specific liability levels for 550, 700, and 800 lb. feeder cattle are \$12,535.20 (120×104.46), \$11,911.20 (120×99.26), and \$7,603.20 (120×63.36) respectively. Lower liabilities levels are associated with heavier placement weights reflective of the lower additional risk incurred by not using metaphylaxis. Costs are obtained by multiplying breakeven premium rates by liability. Indemnity values are given for a specific realization of death loss 'x' using equation 3.16.

Table 3.1 displays breakeven premium rates and breakeven costs for a chosen *strike* and *limit* and indemnities for a chosen *strike*, *limit* and realization of 'x'. While numerous combinations are theoretically feasible, we focus on common death loss occurrences across differing cattle placement weights. Breakeven rates are obtained by taking the unconditional probability for each choice of *strike* and *limit* from the differenced distributions in figure 3.3. Breakeven costs (\$) are obtained by multiplying the breakeven premium rate by the maximum liability level. Indemnities (\$) are obtained using equation 3.16. For example, the breakveven costs for *strike* 5 and *limit* 15 (i.e. row 3) is \$3,306 ($26.37/100 \times 104.46 \times 120$). For a death loss realization of 8, the indemnity paid out is \$3,761 ($(8-5)/(15-5) \times 104.46 \times$

120). Breakeven costs (indemnities) range from \$1,433-\$3,468 (\$1,880 - \$12,535), \$819-\$5,256 (\$1,787 - \$11,911), and \$199-\$3,051 (\$1,140 -\$7,603) for 550, 700, and 850 lb. feeder cattle respectively.

Various combinations of strike and limit in conjunction with actual death loss realizations are possible. The benefit of the mortality call depends on these realizations. For example, for 550 lb placement \$3,306 is the breakeven costs for a \$12,535.20 call with a strike of 5 and limit of 15. If the pen realized a death loss of 8 then the call would pay an indemnity valued at \$3,761 ($\frac{8-5}{15-5} \times 12535$). This is below the expected losses of \$7,974 (see table C.1; $1.8122 \times 550 \times 8$) or about 47% of the loss (3306/7974). However, given a call of strike 5, limit 10, and the same death loss realization of 8, the breakeven costs would be \$3,468 and the call would pay \$7,521, nearly 100% of the loss (7521/7974).

In order to spread out the potential mortality liability a feedlot could elect to purchase multiple call options. For example, the feedlot that purchases 850 lb. high risk cattle could purchase a call with strike 5 and limit 20 and a call with strike price 5 and limit 10. This would have a breakeven cost of \$2,398 (see column 9 rows 2 and 4 table 3.1; $[27.67/100 \times 63.36 \times 120] + [23.64/100 \times 63.36 \times 120]$) and offer the feedlot \$6,083 of liability (see column 12 rows 2 and 4 in table 3.1; $[\frac{8-5}{10-5} \times 63.36 \times 120] + [\frac{8-5}{20-5} \times 63.36 \times 120]$) for a death loss realization of 8. This would cover about 60% of the losses. This allows producers to create levels of protection against cattle mortality not possible under traditional forms of insurance.

3.5.1 Expected Utility Analysis

We test the efficiency of our mortality call using an expected utility analysis. We assume a risk averse feedlot that has a 60,000 head one time capacity feedlot, turns its feedlot twice per year, and derives wealth solely from marketing cattle. The feedlot places 1000 pens of cattle with 120 head of cattle in each pen (i.e. this feedlot markets 120,000 head per year (120×1000)). Assuming a feeder price of \$1.8122, \$1.5951, and \$1.4706, initial feedlot wealth is \$4,977,500 ($1.8122 \times 550 \times 5000$), \$6,335,000, and \$7,692,500 if all cattle are 550 lb., 700 lb., or 850 lb., respectively (see panel (a) of table 3.2). We assume the feedlot can take one of three actions: (a) do-nothing which is equivalent to not using metaphylaxis, (b) select a call with strike 5 and limit 10, and (c) select a call with strike 10 and limit 20.

Our wealth simulation is conducted as follows:

1. Draw a death loss for a pen of high risk cattle that received metaphylaxis from the proprietary data;
2. Multiply death loss by the odd ratio to obtain expected death loss of cattle that did not receive metaphylaxis;
3. Difference the death loss obtained in step 2 and step 1;
4. Using this death loss, calculate whether an indemnity that is paid out, if any, based on the producer animal health strategy; and
5. Repeat steps 1-4 1000 times.

The feedlot's expected utility over wealth is assumed to be given by a utility function with constant risk aversion. While many utility functions could theoretically be used, we elect to use the power utility function with constant relative risk aversion where utility over wealth is given as

$$E(U) = \sum_{i}^{j} p_i(-exp^{(-r(X_i+\Omega))}) \tag{3.18}$$

where U is utility, Ω is initial wealth, and r is a risk aversion coefficient. The certainty equivalent of the negative exponential utility function is given as

$$CE = \frac{ln(E(U))}{r} - \Omega \tag{3.19}$$

An $r < 0$ implies risk aversion with larger absolute values inferring a stronger attitude towards risk. The certainty equivalence represents the minimum amount of money that is required to be paid to feedlots to forgo a risky alternative and is the standard for measuring insurance product efficiency.

Mean ending wealth, standard deviation, maximum, and minimum wealth across different cattle placement weights and scenarios is given in panel (b) of table 3.2. On average, ending wealth is higher with less variation in wealth. When either of the mortality calls are used the minimum wealth obtained is greater than under a do-nothing strategy. Thus, the mortality call helps to protect producers from downside risk. Table 3.2 panel (b) display certainty equivalents obtained from equation 3.19 for the negative exponential utility function under the three different scenarios: (a) do-nothing, (b) call with strike 5 and limit 10, and (c) call with strike 10 and limit 20. All certainty equivalents are larger when the feedlot chooses to purchase either of the mortality calls. [10]

3.6 Conclusions

In this study, we investigated the conditions under which livestock producers use antimicrobials for disease prevention or disease treatment. Specifically, we focused on US cattle feedlots and their use of metaphylaxis, administration of injectable FDA approved antimicrobials to sick or at-risk feeder cattle upon arrival. We focused on metaphylaxis since it is one of the only animal health strategies feedlots have to manage high health risk cattle upon arrival and has been targeted to be further regulated by the European Union. Further, metaphylaxis is encompassed under the World Health Organizations goal to reduce or remove the use of shared-class antimicrobials for disease prevention without individual animal diagnosis (World Health Organization, 2018).

The World Health Organization has encouraged the development of new medicines, diagnostic tools, vaccines and other interventions that *optimize* the use of antimicrobials in livestock production. Few products are currently cost effective or reliable to manage morbidity and mortality risk in health health risk livestock. Our study shows that cattle pro-

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[10] Certainty equivalents can vary based upon the utility function used. To verify our finding that for a risk averse feedlot certainty equivalents are higher under our mortality call option we find the certainty equivalents under a power utility function when $r = 1$. The certainty equivalents across the three weights and three strategies are as follows: 550 lbs. (989,191; 994,591; 990,480), 700 lbs. (1,108,987; 1,112,809; 1,111,301), and 850 lbs. (1,244,883; 1,246,476; 1,245,032) for do-nothing, strike 5 limit 10, and strike 10 limit 20, respectively.

ducers will use marginal income towards disease prevention rather than disease treatment but equalize income when an actuarially fair insurance product is offered. We then propose an elementary insurance product that could be marketed to livestock producers. As antimicrobial resistance continues to be a growing human health concern finding alternatives to antimicrobial use becomes elevated. The product we introduced has the potential to reduce antimicrobial resistance if antimicrobial fitness costs are high.

The more market and technology substitutes for antimicrobial use in livestock production the more likely producers can adopt these potentially reducing antimicrobial resistance. These results help inform industry stakeholders and policy makers about potential market insurance contracts that can be created. As concerns over antimicrobial resistance and antimicrobial use in livestock rises greater pressure to provide alternatives will rise. A body of research needs to be developed to provide market alternatives to antimicrobial use metaphylaxis is essential for making informed policy decisions.

3.7 Tables

Table 3.1: Breakeven Premium Rates, Cost, and Indemnity of Various Death Loss Calls with Cattle Type Specific Liability, Annual

Death Loss (%)			Breakeven Premium Rate (%)			Cost ($)			Indemnity ($)		
strike	limit	x	550 Lbs.	700 Lbs.	850 Lbs.	550 Lbs.	700 Lbs.	850 Lbs.	550 Lbs.	700 Lbs.	850 Lbs.
5	5	8	21.82	44.13	40.12	2,735	5,256	3,051	12,535	11,911	7,603
5	10	8	27.67	40.00	18.71	3,468	4,764	1,423	7,521	7,147	4,562
5	15	8	26.37	26.83	14.08	3,306	3,195	1,071	3,761	3,573	2,281
5	20	8	23.64	20.12	12.83	2,963	2,396	976	2,507	2,382	1,521
5	25	8	21.03	16.47	12.20	2,636	1,961	928	1,880	1,787	1,140
10	10	13	27.40	39.73	18.44	3,434	4,732	1,402	12,535	11,911	7,603
10	15	13	24.96	25.41	12.66	3,128	3,026	963	7,521	7,147	4,562
10	20	13	21.65	18.13	10.84	2,714	2,159	824	3,761	3,573	2,281
10	25	13	18.88	14.32	10.05	2,366	1,705	764	2,507	2,382	1,521
15	15	18	21.01	21.47	8.72	2,634	2,557	663	12,535	11,911	7,603
15	20	18	18.52	15.00	7.71	2,322	1,786	586	7,521	7,147	4,562
15	25	18	15.99	11.44	7.17	2,005	1,362	545	3,761	3,573	2,281
20	20	23	15.40	11.87	4.59	1,930	1,414	349	12,535	11,911	7,603
20	25	23	13.61	9.05	4.79	1,706	1,078	364	7,521	7,147	4,562
25	25	28	11.43	6.88	2.61	1,433	819	199	12,535	11,911	7,603

Notes: Death losses are measured at the pen level. We assume a pen size of 120 head. The cattle type specific value of metaphylaxis over no metaphylaxis is taken from Dennis et al. 2018. Liability values are cattle type specific. Lower liabilities levels are associated with heavier placement weights reflective of the lower additional risk incurred by not using metaphylaxis. Cattle type specific liability levels for 550, 700, and 800 lb. feeder cattle are \$12,535.20 (120 × 104.46), \$11,911.20 (120 × 99.26), and \$7,603.20 ($120 \times 7,603.20$) respectively. Breakeven premium rates reflect the difference in the probability of death loss between metaphylaxis and no metaphylaxis animal health protocols. Costs are obtained by multiplying breakeven premium rates by liability. Indemnity values are given for a specific realization of death loss 'x' using equation 3.16.

Table 3.2: Ending Wealth and Certainty Equivalents for Different Mortality Call Scenarios

	Mortality Call Scenario		
	Do-nothing	Strike 5, Limit 10	Strike 10, Limit 20
Panel (a): Inital Wealth ($)			
550 lb.	996,710	996,710	996,710
700 lb.	1,116,570	1,116,570	1,116,570
850 lb.	1,250,010	1,250,010	1,250,010
Panel (b): Ending Wealth ($)			
550 lb.			
Mean	989,200	994,600	990,500
Std. Dev.	5,500	3,143	3,303
Min	956,700	969,200	969,200
Max	996,700	999,300	996,700
700 lb.			
Mean	1,109,000	1,113,000	1,111,000
Std. Dev.	6,796	3,187	3,605
Min	1,089,000	1,101,000	1,105,000
Max	1,117,000	1,117,000	1,118,000
850 lb.			
Mean	1,245,000	1,246,000	1,245,000
Std. Dev.	4,791	2,520	4,449
Min	1,234,000	1,242,000	1,236,000
Max	1,250,000	1,250,000	1,250,000
Panel (c): Certainty Equivalent when $r = 1$ ($)			
550 lbs.	956,663	969,198	969,198
700 lbs.	1,089,353	1,101,264	1,105,553
850 lbs.	1,234,384	1,241,988	1,236,285

Note: Certainty equivalents are obtained for a negative exponential utility function.

3.8 Figures

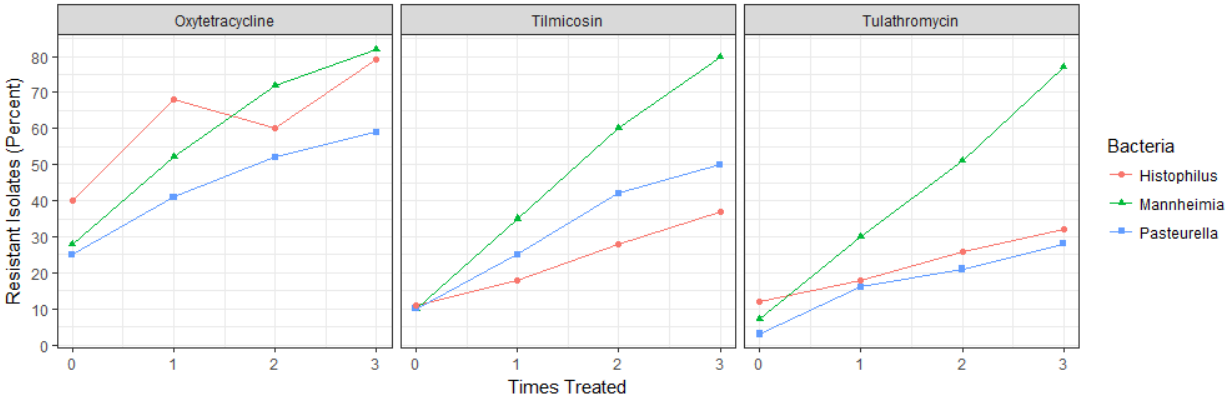

Figure 3.1: Antimicrobial Resistance by Number of Treatments

Source: Magstadt et al. (2008)

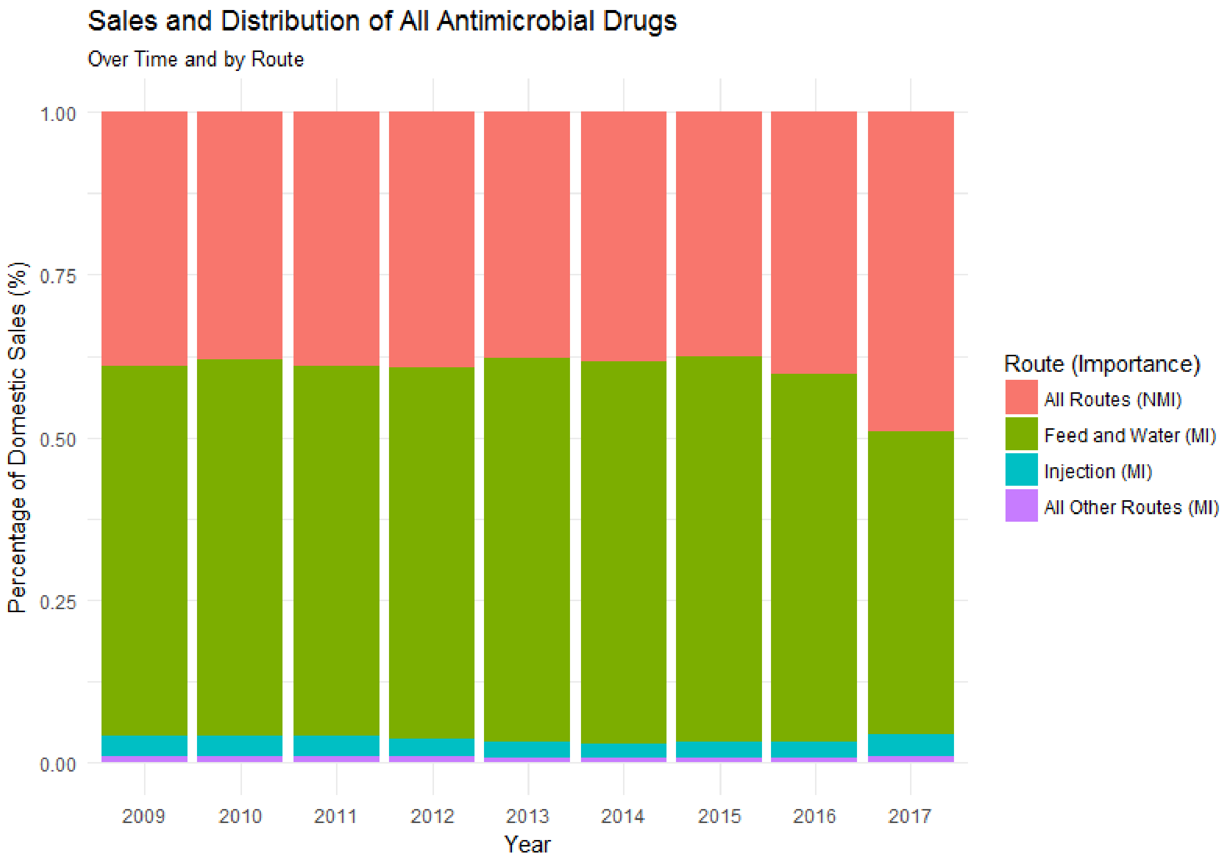

Figure 3.2: Domestic Sales and Distribution of Antimicrobial Drugs Approved for use in Food-producing Animals and Actively Marketed by Route of Administration, 2009-2017

Source: Food and Drug Administration (2009:2017)

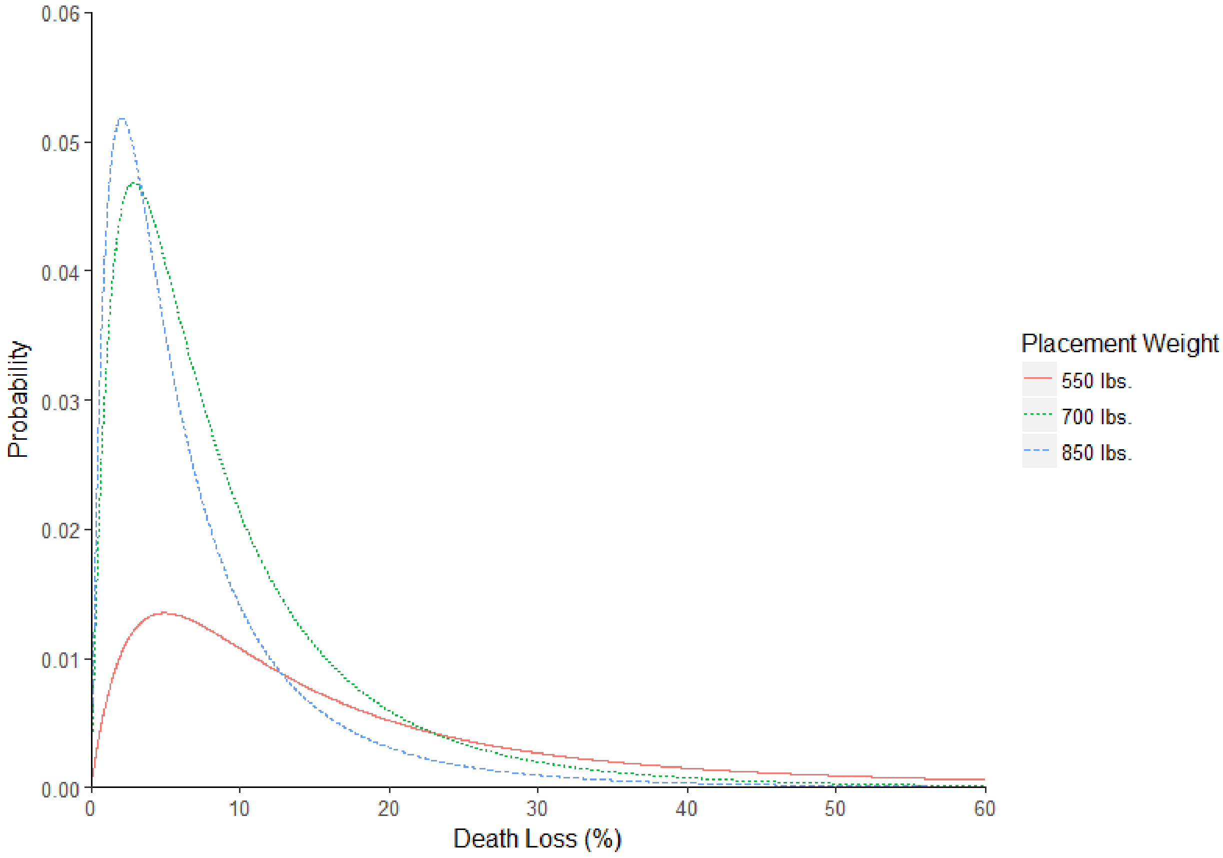

Figure 3.3: Difference in Death Loss Between No Metaphylaxis and Metaphylaxis

Source: Proprietary Feedlot Data (2014-2015)
Note: All distributions can be modeled as Beta distributions and the two shapes are given as: 550 lb (1.19, 273.52), 700 lb. (0.46, 55.37), and 850 lb. (0.36, 55.14)

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Appendix A

Chapter 1 Appendix

Table A.1: Feeding Net Return Variables

Variables	Description	Value/Calculation
Simulated		
$ADG_{\omega,k,\tau}$	Average daily gain during feeding (lb./head/day)	See equation B.1
$AFC_{\omega,k,\tau}$	Average pounds of feed consumed per pound of weight gain (lb. feed/lb. gain)	See equation B.2
$DOF_{\omega,k,\tau}$	Number of days on feed (days)	$\frac{CSW_{\omega,k,\tau}-CPW_{\omega}}{ADG_{\omega,k,\tau}}$
$FC_{\omega,k,\tau}$	Feed cost (\$/head)	See equation B.2
$HC_{\omega,\tau}$	Animal health care cost including metaphylaxis, pull-and-treat, vaccinations, labor costs, etc. (\$/head)	See equation B.3
$IC_{\omega,k,\tau}$	Interest cost (\$/head)	See equation 2.6
$MORT_{\omega,k,\tau}$	Proportion of death loss in purchased group	$\phi_{\omega,\tau}$
$TR_{\omega,k,\tau}$	Total revenue from cattle sales (\$/head)	See equation 2.2
$YC_{\omega,k,\tau}$	Yardage cost of feeding cattle (\$/head)	See equation 2.4
$\pi_{\omega,k,\tau}$	Net feeding returns (\$/head) for each weight (ω), death loss group (k), and treatment (τ)	See equation 2.1
Fixed		
CPW_{ω}	Cattle purchase weight (lb./head)	550, 700, 850
CSW_{k}	Finished animal weight (lb./head) if animal reaches maturity (e.g., k = alive), 0 otherwise (e.g., k = dead).	1,350
$CULL$	Proportion chronically ill animals culled from the remaining cohort	0.014
$CULLP$	Price received for culled animals (\$/lb.)	0.75 × FP
$CULLW$	Average weight of culled animals (lb./head)	861
$FDRC_{\omega}$	Feeder cattle purchase cost (\$/head)	See equation 2.3
$FEED$	Corn price when cattle are placed on feed (\$/lb.)	0.0923
FP	Fed cattle sale price (\$/lb.)	1.48
FRP_{ω}	Purchase price for CPW 550, 700, and 850 lb. (\$/lb.)	1.70, 1.49, 1.39
IR	Annualized interest rate	0.05
$SHRINK$	Proportion shrink in live weight when marketed	0.04

Table A.2: Death Loss Distributional Assumptions for Cattle Type and Antimicrobial Treatment

Antimicrobial	Placement Weight	Season	Mean[a]	St. Dev.[a]
Upper Tier	600	Summer	1.07	0.91
Upper Tier	600	Winter	1.36	1.23
Upper Tier	800	Summer	0.94	0.55
Upper Tier	800	Winter	1.57	0.54
Lower Tier	600	Summer	4.14	3.77
Lower Tier	600	Winter	5.26	5.08
Lower Tier	800	Summer	3.66	2.30
Lower Tier	800	Winter	6.10	2.24
No Metaphylaxis	600	Summer	6.68	6.49
No Metaphylaxis	600	Winter	8.49	8.75
No Metaphylaxis	800	Summer	5.90	3.96
No Metaphylaxis	800	Winter	9.83	3.87

[a] To account for endogenous producer decisions in using specific antimicrobials on specific cattle populations , we use the odd ratios from Abell et al. (2017) for the lower tier antimicrobial and the death loss observed in lower tier antimicrobials to solve for the death loss of the control. We then use this control death loss and the odd ratios for the upper tier antimicrobial to obtain the death loss for the upper tier antimicrobial. This allows us to obtain the death loss of different antimicrobials on different cattle populations. A similar producer was used to find the standard deviations.

Appendix B

Chapter 2 Appendix

B.1 (A) Cattle Mortality

Metaphylaxis is effective in helping reduce feedlot mortality, but efficacy varies by drug, placement weight, location, season, and animal health risk. In randomized-control studies testing the effectiveness of metaphylaxis, using the commonly administered macrolide called Tilmicosin on high-health-risk cattle, mortality has varied considerably across treatment and control groups. For example, in control studies of metaphylaxis, Vogel et al. (1998) realized death losses of 1.65% in the treatment group and 4.18% in the control group; Corbin et al. (2009) found 7.50% treatment, 13.50% control; and Tennant et al. (2014) observed 1.40% treatment, 3.07% control.[1]

In a recent meta-analysis, Abell et al. (2017) reviewed 29 randomized-control trial studies of metaphylaxis use in cattle and estimated odds ratios for various types of metaphylactic drugs. Odds ratio estimates were weighted by U.S. Department of Agriculture (2013) metaphylaxis drug application rates for two commonly used macrolides, Tilmicosin and Tulathromycin, to obtain industry efficacy rates. On average, not administering metaphylaxis to high-risk cattle increased mean mortality (standard deviation) 2.43 (5.57) times. While

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[1] Individual randomized controlled trials are limited in their ability to generalize the magnitude of reduction in mortality associated with metaphylaxis treatments, particularly across season and weights, due to experimental design costs and small sample sizes.

expected mortality distribution of a group of cattle may be approximated, exact mortality risk present at cattle purchase and subsequently modified through a health management practice is only realized after feeding.

Mortality in cattle feeding is directly observed ex post and constitutes the largest observed health-risk cost outcome. Death loss in feedlots is conditional on cattle health-risk category and animal placement weight and can be modified with health management practices. Mortality distributions are generally observed to be right-skewed with long tails, approximated using a log-normal, (zero-inflated) negative binomial or a (zero-inflated) Poisson distribution and conditioned by placement risk category, weight, season, gender, location, and breed (Babcock, 2010). Mortality data used in this article follow a log-normal distribution but can also be adequately modeled using a gamma distribution.

Based on Babcock (2010), we calibrate a unique lognormal death-loss distribution for each of the six weight-by-treatment high-health-risk cattle groups: three cattle types (550 lb., 700 lb., and 850 lb. placement weights) and two health treatments (metaphylaxis or no metaphylaxis). Mortality distributions for high-health-risk cattle treated with metaphylaxis were estimated using feedlot data. Mortality distributions for high-health-risk cattle not treated with metaphylaxis were based on estimates from Abell et al. (2017).[2] Figure 1 displays the distributional assumptions and generated mortality distributions across cattle types and health treatments ($\phi_{\omega,\tau}$).

B.2 (B) Cattle Morbidity

The general state of morbidity is associated with cattle gender, breed, arrival weight, location, health treatment, arrival month, risk classification, pen size, feedlot size, and animal handling practices (Nickell and White, 2010). Historical data on morbidity are not generally available

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[2] Since efficacy varies by drug type, death loss odds ratios reported by Abell et al. (2017) were adjusted to reflect the percentage of cattle administered each type of metaphylatic drug (U.S. Department of Agriculture, 2013). Assuming drug efficacy and treatment administration are constant across weight categories, we calculated a weighted mean and standard deviation odds ratio. Taking the inverse of the odds ratio yields a normally distributed metaphylaxis efficacy multiplier. Multiplying these by the observed feedlot mortality rates for each weight category treated with metaphylaxis provides a normal mean and standard deviation for mortality.

in cattle feedlot data but are discernible in readily available animal performance data. Higher levels of morbidity are associated with lower average daily gain, increased veterinary costs, more frequent lung lesions, less efficient feed conversion, lower offal quality, and poorer meat quality grade (Cernicchiaro et al., 2012; Tennant et al., 2014). Health interventions in arriving animals can reduce the risk of high levels of morbidity during the feeding period.

The hierarchical structure of cattle feedlot performance and cost data consists of cohorts of cattle nested within feedlots. Random effects for feedlots and pen size can be used to model animal performance determinants and account for clustering at the feedlot level and animal management practices that differ across feedlots. The impact of other observable feedlot and cattle characteristicssuch as breed, arrival weight, and health treatment practiceon animal feeding performance is captured through fixed effects. For example, effects of morbidity during feeding can be modeled by changes in animal productivity measures of average daily gain, feed conversion, and veterinary costs. Multivariate Tobit, ordinary least squares, and maximum likelihood have been used to model changes in average daily gain, veterinary costs, and feed conversion in cattle (Miller et al., 2005; Irsik et al., 2006; Belasco, 2008; Belasco et al., 2009).

Using the feedlot data, described in the main text, we quantify the impact of mortality on γ_k in the simulation using linear mixed model (LMM) regressions, which are commonly used in epidemiologic studies. Morbidity in cattle is not directly observed in the data but manifests itself in lower ADG, increased AFC, and increased HC. Estimated regressions relating these performance parameters to death loss are a combination of pen- and feedlot-specific fixed effects and random effects from specific variables, including pen size, breed, specific feedlot, year, placement weight, gender, and quarterly dummies. Specifically, we estimate cattle performance parameters ADG and AFC using data from period 1 and associated health costs (HC) using data from period 2 as follows (standard errors are in parentheses):

$$\begin{aligned} ADG = & \underset{(0.103)}{4.056} - \underset{(0.001)}{0.056}MORT + \underset{(0.012)}{1.086}lnPWT + \underset{(0.004)}{0.245}STEER - \underset{(0.005)}{0.021}SPRING - \\ & \underset{(0.005)}{0.102}SUMMER - \underset{(0.005)}{0.188}FALL \end{aligned} \tag{B.1}$$

$$\begin{aligned} AFC = & \underset{(0.135)}{2.077} + \underset{(0.001)}{0.045}MORT + \underset{(0.017)}{1.262}lnPWT - \underset{(0.005)}{0.284}STEER - \underset{(0.007)}{0.073}SPRING - \\ & \underset{(0.007)}{0.302}SUMMER + \underset{(0.007)}{0.284}FALL \end{aligned} \tag{B.2}$$

$$HC = \underset{(7.909)}{30.515} + \underset{(0.086)}{1.606}MORT - \underset{(1.152)}{2.180}lnPWT - \underset{(0.708)}{23.811}METAPHYLAXIS \tag{B.3}$$

where ADG, AFC, and HC are as previously specified, MORT is the proportion of animals in a pen that died during the feeding period, and lnPWT is the natural log of weight of cattle upon arrival at feedlot. Higher placement weights are associated with lower daily gains and higher feed conversion. STEER is a binary variable equal to 1 if group gender is a steer and 0 otherwise and SPRING, SUMMER, and FALL are quarterly binary variables for placement on feed timing. Steers are associated with higher daily gains and lower feed conversions.

METAPHYLAXIS is a binary variable equal to 1 if an animal was part of a pen of cattle administered antimicrobials upon arrival at the feeding operation and 0 otherwise. If metaphylaxis is used, a producer incurs an estimated \$23.81/head, consistent with results from the National Animal Health Monitoring Survey (NAHMS, U.S. Department of Agriculture, 2013) that reported costs of \$23.50/head to administer metaphylaxis to at-risk feeder cattle. In the simulation, MORT, lnPWT, and METAPHYLAXIS are varied, but we multiplied the proportion of steers placed on feed over the past 10 years to obtain an average gender and multiplied the seasonal coefficients by the proportion of cattle placed on feed over the last 10 years to obtain an average season. Thus, the simulation effects are for the average gender over an average season.

Table B.1: Quantity Definitions and Estimates for the Structural and Equilibrium Displacement Models, 2015

Definition	Mean
Quantity of:	
Beef	
Retail beef, billion lb. (retail weight)	17.40
Wholesale beef, billion lb. (carcass weight)	23.78
Wholesale beef imports, billion lb. (carcass weight)	3.37
Wholesale beef exports, billion lb. (carcass weight)	2.27
Beef obtained from slaughter cattle, billion lb. (live weight)	39.11
Beef obtained from feeder cattle, billion lb. (live weight)	34.30
Pork	
Retail pork, billion lb. (retail weight)	15.94
Wholesale pork, billion lb. (carcass weight)	24.50
Wholesale pork imports, billion lb. (carcass weight)	1.12
Wholesale pork exports, billion lb. (carcass weight)	5.01
Pork obtained from slaughter hogs, billion lb. (live weight)	32.68
Lamb	
Retail domestic lamb, billion lb. (retail weight)	0.13
Retail imported lamb, billion lb. (retail weight)	0.19
Wholesale lamb, billion lb. (carcass weight)	0.15
Lamb obtained from slaughter lamb, billion lb. (live weight)	0.30
Lamb obtained from feeder lamb, billion lb. (live weight)	0.26
Poultry	
Retail poultry, billion lb. (retail weight)	33.56
Wholesale poultry, billion lb. (ready-to-cook)	46.20
Retail poultry exports, billion lb. (retail weight)	6.99

Table B.2: Price Definitions and Estimates for the Structural and Equilibrium Displacement Models, 2015

Definition	Mean
Price of:	
Beef	
Choice retail beef, cents/lb.	628.89
Wholesale Choice beef, cents/lb.	237.48
Wholesale beef imports, cents/lb.	198.10
Wholesale beef exports, cents/lb.	237.48
Slaughter cattle, $/cwt (live weight)	148.12
Feeder cattle, $/cwt	202.92
Pork	
Retail pork, cents/lb.	385.25
Wholesale pork, cents/lb.	78.96
Wholesale pork imports, cents/lb.	149.13
Wholesale pork exports, cents/lb.	78.96
Slaughter hogs, $/cwt (live weight)	50.23
Lamb	
Retail domestic lamb, cents/lb.	769.61
Retail imported lamb, cents/lb.	955.67
Wholesale lamb, cents/lb.	346.70
Slaughter lamb, $/cwt (live weight)	144.00
Feeder lamb, $/cwt	192.38
Poultry	
Retail poultry, cents/lb.	189.73
Wholesale poultry, cents/lb.	93.64
Wholesale poultry exports, cents/lb.	93.64

Appendix C

Chapter 3 Appendix

Table C.1: Financial Losses Due to Cattle Death Loss

Death (head)	Loss ($/head)		
	550 lbs.	700 lbs.	850 lbs.
0	0	0	0
1	997	1,117	1,250
2	1,993	2,233	2,500
3	2,990	3,350	3,750
4	3,987	4,466	5,000
5	4,984	5,583	6,250
6	5,980	6,699	7,500
7	6,977	7,816	8,750
8	7,974	8,933	10,000
9	8,970	10,049	11,250
10	9,967	11,166	12,500
11	10,964	12,282	13,750
12	11,961	13,399	15,000
13	12,957	14,515	16,250
14	13,954	15,632	17,500
15	14,951	16,749	18,750
16	15,947	17,865	20,000
17	16,944	18,982	21,250
18	17,941	20,098	22,500
19	18,937	21,215	23,750
20	19,934	22,331	25,000
21	20,931	23,448	26,250
22	21,928	24,565	27,500
23	22,924	25,681	28,750
24	23,921	26,798	30,000
25	24,918	27,914	31,250
26	25,914	29,031	32,500
27	26,911	30,147	33,750
28	27,908	31,264	35,000
29	28,905	32,381	36,250
30	29,901	33,497	37,500

Note: Assumes that all cattle death occurs within the first day on feed.Thus, feed, yardage, health, and interest costs are negligible. Feeder prices were taken using a five year average for medium and large frame #1 from combined Nebraska auctions (LMIC 2019). Prices for 550 lb., 700 lb., and 850 lb. feeder cattle are $1.8122, $1.5951, and $1.4706 per lb., respectively.