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Value of Arrival Metaphylaxis in U.S. Cattle Industry

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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.

Key words: antimicrobials, cattle, EDM, metaphylaxis, policy evaluation

Introduction

Use of antimicrobials in livestock production is facing intense public scrutiny. Although most consumers agree that medicating sick animals is appropriate, opinions diverge on acceptable use of antimicrobials administered to food-producing livestock (Landers et al., 2012). Producers use antimicrobials to kill or inhibit the growth of bacteria that damage health, production efficiency, and welfare of livestock (Key and McBride, 2014). 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).

Medical and disease-monitoring organizations have claimed that inappropriate use of shared-class antimicrobials is occurring in livestock production. These groups have urged the U.S. Congress to take action, stating “the misuse of important antibiotics in food animals must end, in order to protect human health” (Pew Health Group, 2011, p. 3). These concerns, in part, have prompted state and federal legislators to increase regulation and veterinary oversight of shared-class antimicrobials

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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.”

in animal production (American Veterinary Medical Association, 2016; California Legislature, 2015; Food and Drug Administration, 2012, 2013; Maryland Legislature, 2017).

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 (U.S. Department of Agriculture, 2013). Cattle 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, the European Union (2015) has explicitly announced an EU-wide strategy to minimize metaphylaxis as a health treatment protocol in livestock production. The World Health Organization (2017) has strongly recommended an overall reduction in the use of shared-class antimicrobials for disease prevention without individual animal diagnosis The U.S. Veterinary Feed Directive (VFD) regulation does not regulate metaphylaxis; current debate centers on whether to include metaphylaxis in future U.S. regulation. 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).

We estimate the value of metaphylactic use in U.S. cattle feeding and determine implications for consumer and producer surplus of eliminating its use. Determining net return and social surplus impacts enables producers, animal health consultants, and policy makers to make informed decisions surrounding metaphylaxis use. Assessing policy options surrounding antimicrobial use in livestock requires predicting animal health impacts, quantifying uncertainty, and determining distributional impacts of net returns. The resulting estimates address this need by quantifying the impact of a hypothetical policy prohibiting metaphylaxis use or voluntary elimination by the cattle industry.

Net return impacts of alternative animal health treatment strategies have not been adequately quantified due to limited access to representative livestock feeding data. This article presents a fed cattle industry simulation model developed to estimate net returns under alternative market conditions, policies, and animal production technologies. 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 arrival in the feedyard on cattle feeding profitability and producer and consumer surplus. The fed cattle simulation incorporates veterinary costs associated with metaphylaxis, changes in cattle performance parameters, and mortality distributions conditioned on metaphylaxis use. The simulation estimates producer net returns across livestock placement categories and treatment groups. Results from the cattle return simulation 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.

Metaphylaxis Use in U.S. Cattle Feeding

Metaphylactic intervention reduces mortality and morbidity risk, may reduce medication costs, reduces days on feed, and can improve carcass and offal quality (Schumann, Janzen, and McKinnon, 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; U.S. 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 (U.S. Department of Agriculture, 2013).

The primary health management alternative 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 for feedlots to use on cattle where 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 (Babcock et al., 2009; Cernicchiaro et al., 2013). Hence, pull-and-treat is rarely used as the primary approach for high-health-risk cattle, which are often more effectively managed using metaphylaxis followed by selective pull-and-treat.

The use of 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, account for 74% and 22% of total sales, respectively. However, no data exist to quantify the use of antimicrobials in livestock production, and sales data likely overestimate administration in a given time period.

Impact assessments have primarily focused on removing the larger relative proportion of antimicrobials in feed and water for hogs, broilers, and cattle. Recent consumer surplus estimates reflect relatively modest short-run losses associated with fully banning antimicrobials in feed and water: $885.64 million for beef (Mathews, 2002), $41.87 million to $209.14 million for pork (Wade and Barkley, 1992; Brorsen et al., 2002), and $235.47 million for broilers (Sneeringer et al., 2015). Reductions in producer surplus are likewise small: $280.55 million for beef (Mathews, 2002), between $45.36 million and $291.24 million for pork (Wade and Barkley, 1992; Brorsen et al., 2002; Sneeringer et al., 2015), and $189 million for poultry (Sneeringer et al., 2015).[3] However, 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.

Cattle Procurement and Metaphylaxis Decision

Cattle feeders make trade-offs when searching for cattle that will perform well in feedlot environments. General cattle characteristics—including animal gender, origin, weight, condition, and perhaps health background—are known to feedlots upon purchase. 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 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. Low- and high-health-risk cattle are often simultaneously available for purchase across different weight classes.

[3] All values have been adjusted to 2017 price levels.

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 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 (U.S. Department of Agriculture, 2013).

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.

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.[4] 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 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.

Cattle experience varying degrees of morbidity due to stress of transport, weather, diet, and comingling with other cattle (Nickell and White, 2010). Historical data on morbidity are not generally available 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 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. 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 characteristics—such as breed, arrival weight, and health treatment practice—on 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).

[4] 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.

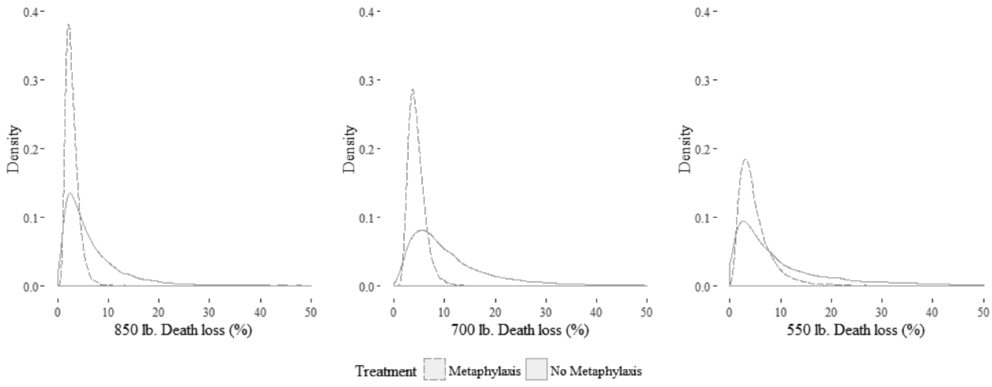

Figure 1. Mortality Distributions across Cattle Placement Weight Categories and Metaphylaxis Use Category

Notes: 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).

Cattle Feeding Simulation Model

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. The cattle feeding simulation estimates changes in net returns distributions for cattle sold on a live-weight basis. Net returns from cattle feeding are translated into short-run producer and consumer surplus changes with and without the use of metaphylaxis in treatment of high-health-risk cattle.

Simulation Framework

Producers select a vector of cattle characteristics ($\boldsymbol{\alpha}$) that includes gender, placement weight, and expected harvest weight. In the simulation, feedlots purchase cattle from three different weight categories (w) where $w =$ calves (550 lb.), middle-weights (700 lb.), or yearlings (850 lb.).[5] Once cattle are purchased, $\boldsymbol{\alpha}$ is fixed and cattle are categorized as either low or high health risk. Low-health-risk cattle have low production and mortality 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 $\boldsymbol{\alpha}$, w, and τ, a producer faces a random cattle death loss ($\varphi_{w,\tau}$). The primary driver of feedlot profitability in our simulator is cattle mortality ($MORT$). We calibrate a unique lognormal death-loss distribution, based on Babcock (2010), 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

[5] 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.

Table 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%	Heifer	54%
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%	Heifer	45%
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.

metaphylaxis were based on estimates from Abell et al. (2017).[6] Figure 1 displays the distributional assumptions and generated mortality distributions across cattle types and health treatments ($\varphi_{w,\tau}$).

In feedlot data, 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 $k = \{\text{dead, alive}\}$ broad groups of cattle purchased by producers: i) animals that survive feeding and sold and ii) animals that die. Given $\boldsymbol{\alpha}$, the kth group death loss assumption, and a vector ($\boldsymbol{\gamma}_k$) 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.

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

[6] 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.

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 1 displays summary statistics for the feedlot data.

Estimated Morbidity

Feedlot data quantify the impact of mortality on $\boldsymbol{\gamma}_k$ 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):

$$\begin{aligned} ADG = \; & \underset{(0.103)}{-4.056} - \underset{(0.001)}{0.056}\, MORT + \underset{(0.012)}{1.086}\, \ln PWT + \underset{(0.004)}{0.245}\, STEER - \underset{(0.005)}{0.021}\, SPRING \\ & - \underset{(0.005)}{0.102}\, SUMMER - \underset{(0.005)}{0.188}\, FALL \end{aligned} \quad (1)$$

$$\begin{aligned} AFC = \; & \underset{(0.135)}{-2.077} + \underset{(0.001)}{0.045}\, MORT + \underset{(0.017)}{1.262}\, \ln PWT - \underset{(0.005)}{0.284}\, STEER - \underset{(0.007)}{0.073}\, SPRING \\ & - \underset{(0.007)}{0.302}\, SUMMER + \underset{(0.007)}{0.284}\, FALL \end{aligned} \quad (2)$$

$$HC = \underset{(7.909)}{30.515} + \underset{(0.086)}{1.606}\, MORT - \underset{(1.152)}{2.180}\, \ln PWT + \underset{(0.708)}{23.811}\, METAPHYLAXIS \quad (3)$$

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 $\ln PWT$ 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*, $\ln PWT$, 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.

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, yet correlated, we model the joint distribution using Iman and Conover's (1980) algorithm for 10,000 iterations. We assumed cattle performance parameters (*ADG*, *AFC*, and *HC*) are distributed $N_k \sim (\boldsymbol{\gamma}_k, \boldsymbol{\sigma})$, where $\boldsymbol{\sigma}$ is a vector of variances from the estimated LMM residuals and $\boldsymbol{\gamma}_k$ is the previously specified estimates of *ADG*, *AFC*, and *HC* for the *k*th 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.

Feeding Net Returns

We use simulated ADG, AFC, and HC values, random cattle death loss, fixed prices,[7] and exogenous feedlot characteristics to calculate cattle feeding net returns, $\boldsymbol{\rho}_{w,k,\tau}$, defined as

$$(4)\quad \boldsymbol{\rho}_{w,k,\tau} = \boldsymbol{TR}_{w,k,\tau} - \boldsymbol{FDRC}_{w} - \boldsymbol{YC}_{w,k,\tau} - \boldsymbol{FC}_{w,k,\tau} - \boldsymbol{HC}_{w,\tau} - \boldsymbol{IC}_{w,k,\tau}$$

$$(5)\quad \boldsymbol{TR}_{w,k,\tau} = \boldsymbol{FP} \times \boldsymbol{CSW}_{k} \times (1 - \boldsymbol{SHRINK}) \times (1 - \boldsymbol{MORT}_{w,k,\tau} - \boldsymbol{CULL}) + (\boldsymbol{CULL} \times \boldsymbol{CULLW} \times \boldsymbol{CULLP})$$

$$(6)\quad \boldsymbol{FDRC}_{w} = \boldsymbol{FRP}_{w} \times \boldsymbol{CPW}_{w}$$

$$(7)\quad \boldsymbol{YC}_{w,k,\tau} = 0.30 \times \boldsymbol{DOF}_{w,k,\tau}$$

$$(8)\quad \boldsymbol{FC}_{w,k,\tau} = \boldsymbol{FEED} \times \{\boldsymbol{AFC}_{w,k,\tau}[\boldsymbol{CSW}_{w,k,\tau} \times (1 - \boldsymbol{MORT}_{w,k,\tau} - \boldsymbol{CULL}) - \boldsymbol{CPW}_{w}]\}$$

$$(9)\quad \boldsymbol{IC}_{w,k,\tau} = \{0.5 \times [\boldsymbol{YC}_{w,k,\tau} + \boldsymbol{FC}_{w,k,\tau} + \boldsymbol{HC}_{w,\tau}] + \boldsymbol{FDRC}_{w}\} \times \boldsymbol{DOF}_{w,k,\tau} \times (\boldsymbol{IR}/365).$$

Table 2 displays and explains the simulated and fixed feeding net return variables used in equations (4)–(9).

A weighted-average net returns of cattle feeding ($\boldsymbol{\pi}_{w,\tau}$) is recovered using the matrix of calculated cattle feeding net returns ($\boldsymbol{\rho}_{w,k,\tau}$) from equations (4)–(9). Given the stochastic mortality ($\varphi_{w,\tau}$) and a representative pen size of 120 head, $\varphi_{w,\tau} \times 120$ number of net returns from the $\boldsymbol{\rho}_{w,dead,\tau}$ distribution are included while the remaining $(1 - \varphi_{w,\tau}) \times 120$ cattle net returns are selected from $\boldsymbol{\rho}_{w,alive,\tau}$. This is done 10,000 times, taking the mean of each iteration and thus obtaining a weighted-average net return distribution ($\boldsymbol{\pi}_{w,\tau}$).

A weighted-average net return ($\boldsymbol{\pi}_{w,\tau}$) for each weight-by-treatment category, where $w =$ (500, 700, or 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

$$(10)\quad \varnothing = \frac{\sum_{w=1}^{3}(v_w \times c_w \times x_w)}{\xi},$$

where the value per head of health management strategy (v_w) 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_w, x_w 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.

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, Marsh, and Atwood (2004) used EDMs

[7] To compare health interventions and cattle risk category, we calibrate feeder cattle prices so that the expected net returns for metaphylaxis across risk categories are break even.

Table 2. Feeding Net Return Variables

Variables	Description	Value/Calculation
Simulated		
$\boldsymbol{ADG}_{w,k,\tau}$	Average daily gain during feeding (lb./head/day)	See equation (1)
$\boldsymbol{AFC}_{w,k,\tau}$	Average pounds of feed consumed per pound of weight gain (lb. feed/lb. gain)	See equation (2)
$\boldsymbol{DOF}_{w,k,\tau}$	Number of days on feed (days)	$\frac{\boldsymbol{CSW}_{w,k,\tau}-\boldsymbol{CPW}_{w}}{\boldsymbol{ADG}_{w,k,\tau}}$
$\boldsymbol{FC}_{w,k,\tau}$	Feed cost ($/head)	See equation (8)
$\boldsymbol{HC}_{w,\tau}$	Animal health care cost including metaphylaxis, pull-and-treat, vaccinations, labor costs, etc. ($/head)	See equation (3)
$\boldsymbol{IC}_{w,k,\tau}$	Interest cost ($/head)	See equation (9)
$\boldsymbol{MORT}_{w,k,\tau}$	Proportion of death loss in purchased group	$\varphi_{w,\tau}$
$\boldsymbol{TR}_{w,k,\tau}$	Total revenue from cattle sales ($/head)	See equation (5)
$\boldsymbol{YC}_{w,k,\tau}$	Yardage cost of feeding cattle ($/head)	See equation (7)
$\boldsymbol{\rho}_{w,k,\tau}$	Net feeding returns ($/head) for each weight ($w$), death loss group ($k$), and treatment ($\tau$)	See equation (4)
Fixed		
$\boldsymbol{CPW}_{w}$	Cattle purchase weight (lb./head)	550, 700, 850
$\boldsymbol{CSW}_{k}$	Finished animal weight (lb./head) if animal reaches maturity (i.e., $k = alive$), 0 otherwise (i.e., $k = dead$).	1,350
$\boldsymbol{CULL}$	Proportion chronically ill animals culled from the remaining cohort	0.014
$\boldsymbol{CULLP}$	Price received for culled animals ($/lb.)	$0.75 \times \boldsymbol{FP}$
$\boldsymbol{CULLW}$	Average weight of culled animals (lb./head)	861
$\boldsymbol{FDRC}_{w}$	Feeder cattle purchase cost ($/head)	See equation (6)
$\boldsymbol{FEED}$	Corn price when cattle are placed on feed ($/lb.)	0.0923
$\boldsymbol{FP}$	Fed cattle sale price ($/lb.)	1.48
$\boldsymbol{FRP}_{w}$	Purchase price for CPW 550, 700, and 850 lb. ($/lb.)	1.70, 1.49, 1.39
$\boldsymbol{IR}$	Annualized interest rate	0.05
$\boldsymbol{SHRINK}$	Proportion shrink in live weight when marketed	0.04

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).[8] The EDM 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 (10) represents the one-time, 1-year exogenous shock to the fed cattle sector of removing metaphylaxis.

[8] Demand elasticities were updated to reflect more current demand elasticity estimates. The updated elasticities used in the EDM are retail beef −0.420 (Tonsor, Mintert, and Schroeder, 2010), fed cattle −0.66 (Marsh, 1992), feeder cattle −0.62 (Marsh, 2001), retail pork −0.7396 (Tonsor, Mintert, and Schroeder, 2010), and retail poultry −0.099 (Tonsor, Mintert, and Schroeder, 2010).

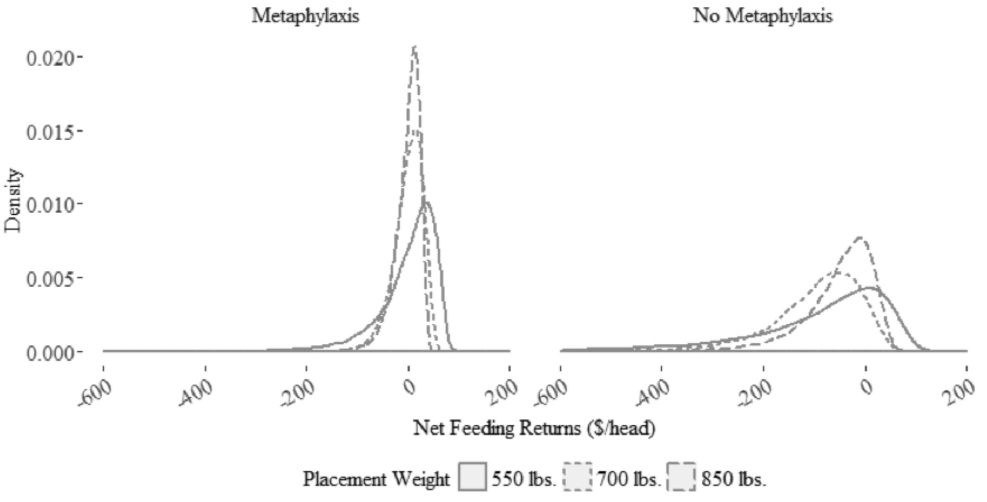

Figure 2. Simulated Net Return Distributions by Cattle Health Risk and Placement Weight

Notes: 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).

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 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.

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 (2015) 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,

Table 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 in 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

Notes: [a] National Animal Health Monitoring System.
[b] Total fed cattle industry is valued at $57.929 billion ($1.4812/lb. × 39.10936 billion lb.).

respectively (U.S. Department of Agriculture, 2013).[9] Using these assumptions and equation (10), we calculated the value of metaphylaxis as a percentage of the U.S. fed cattle industry.

Table 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 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.

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[9] NAHMS categorized Central Region cattle given metaphylaxis as under 700 lb. (37.8%), greater than 700 lb. (4.8%), and overall (20.5%). To obtain comparable cattle weight categories to our study, we calculated metaphylaxis administration rates by scaling metaphylaxis rates from the feedlot data and then multiplying by the number of cattle placed in each group, maintaining the group metaphylaxis administration rate of 20.5%.

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.[10] The average fed cattle price used in this simulation was $148/cwt (see Table 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 2.5th and 97.5th 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 2.5th percentile and $1,119.56 million at the 97.5th percentile.

Surplus Implications

We quantify short-run societal impacts of removing metaphylaxis. Table 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.

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 regulations—the 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, Sexton, and Sumner, 2015).

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[10] Given the number of parameters fixed in equations (4)–(10), explained in Table 2, we also conducted sensitivity analyses to determine how parameter choices influenced results. Changes in interest rate (IR), shrink ($SHRINK$), culling percent ($CULLP$), culling weight ($CULLW$), and yardage cost (YC) increase the size of the impacts by a nominal amount. Cattle finished weight had a small impact. As finished weight increases to 1,500 lb./head, the net benefit of metaphylaxis increases by $0.020/head/lb., $0.033/head/lb., and $0.046/head/lb. for cattle placed at 550 lb., 700 lb., and 850 lb., respectively. Overall, the model is stable to the fixed parameters in the simulation.

Table 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**

Notes: Double asterisks (**) indicate significance at the 5% level. [a]National Animal Health Monitoring Survey.

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 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., 2015), and $189.00 million for poultry producers (Sneeringer et al., 2015)).

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.

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Table S1. Elasticity Definitions, Estimates, and Sources for the Log Differential Equilibrium Displacement Model

Definition	Estimated Short Run	Source
Own-price elasticity of demand for retail beef	−0.42	Tonsor and Schroeder (2010)
Cross-price elasticity of demand for retail beef with respect to the price of retail pork	0.10	Brester and Schroeder (1995)
Cross-price elasticity of demand for retail beef with respect to the price of domestic retail lamb	0.05	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for retail beef with respect to the price of imported retail lamb	0.05	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for retail beef with respect to the price of retail poultry	0.05	Brester and Schroeder (1995)
Own-price elasticity of supply for retail beef	0.36	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale beef	−0.58	U.S. Department of Agriculture (2007a)
Own-price elasticity of supply for wholesale beef	0.28	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale beef imports	−0.58	Pendell et al. (2010) best estimate
Own-price elasticity of supply for wholesale beef imports	1.83	Estimated by Pendell et al. (2010)
Own-price elasticity of demand for wholesale beef exports	−0.42	Zhao, Wahl, and Marsh (2006)
Own-price elasticity of demand for slaughter cattle	−0.66	Marsh (1992)
Own-price elasticity of supply for slaughter cattle	0.26	Marsh (1994)
Own-price elasticity of demand for feeder cattle	−0.62	Marsh (2001)
Own-price elasticity of supply for feeder cattle	0.22	Marsh (2003)
Own-price elasticity of demand for retail pork	−0.74	Tonsor and Schroeder (2010)
Cross-price elasticity of demand for retail pork with respect to the price of retail beef	0.18	Brester (1996)
Cross-price elasticity of demand for retail pork with respect to the price of domestic retail lamb	0.02	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for retail pork with respect to the price of imported retail lamb	0.02	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for retail pork with respect to the price of retail poultry	0.02	Brester (1996)
Own-price elasticity of supply for retail pork	0.73	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale pork	−0.71	Brester, Marsh, and Atwood (2004)
Own-price elasticity of supply for wholesale pork	0.44	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale pork imports	−0.71	Pendell et al. (2010) best estimate
Own-price elasticity of supply for wholesale pork imports	1.41	Pendell et al. (2010) best estimate
Own-price elasticity of demand for wholesale pork exports	−0.89	Paarlberg et al. (2008)
Own-price elasticity of demand for slaughter hogs	−0.51	Wohlgenant (2005)
Own-price elasticity of supply for slaughter hogs	0.41	Lemieux and Wohlgenant (1989)
Own-price elasticity of demand for domestic retail lamb	−0.52	U.S. Department of Agriculture (2007b)
Cross-price elasticity of demand for domestic retail lamb with respect to the price of imported retail lamb	0.29	U.S. Department of Agriculture (2007b)
Cross-price elasticity of demand for domestic retail lamb with respect to the price of retail beef	0.05	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for domestic retail lamb with respect to the price of retail pork	0.02	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for domestic retail lamb with respect to the price of retail poultry	0.02	Pendell et al. (2010) best estimate
Own-price elasticity of supply for domestic retail lamb	0.15	U.S. Department of Agriculture (2007b)
Own-price elasticity of demand for imported retail lamb	−0.41	U.S. Department of Agriculture (2007b)
Cross-price elasticity of demand for imported retail lamb with respect to the price of domestic retail lamb	0.78	U.S. Department of Agriculture (2007b)
Cross-price elasticity of demand for imported retail lamb with respect to the price of retail beef	0.05	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for imported retail lamb with respect to the price of retail pork	0.02	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for imported retail lamb with respect to the price of retail poultry	0.02	Pendell et al. (2010) best estimate
Own-price elasticity of supply for imported retail lamb	10.00	U.S. Department of Agriculture (2007b)
Own-price elasticity of demand for wholesale lamb	−0.35	U.S. Department of Agriculture (2007b)
Own-price elasticity of supply for wholesale lamb	0.16	U.S. Department of Agriculture (2007b)
Cross-price elasticity of demand for retail poultry with respect to the price of domestic retail lamb	0.02	Pendell et al. (2010) best estimate
Cross-price elasticity of demand for retail poultry with respect to the price of imported retail lamb	0.02	Pendell et al. (2010) best estimate
Own-price elasticity of demand for slaughter lamb	−0.33	U.S. Department of Agriculture (2007b)
Own-price elasticity of supply for slaughter lamb	0.12	U.S. Department of Agriculture (2007b)
Own-price elasticity of demand for feeder lamb	−0.11	U.S. Department of Agriculture (2007b)
Own-price elasticity of supply for feeder lamb	0.09	U.S. Department of Agriculture (2007b)
Own-price elasticity of demand for retail poultry	0.99	Tonsor and Schroeder (2010)
Cross-price elasticity of demand for retail poultry with respect to the price of retail beef	0.18	Brester (1996)
Own-price elasticity of demand for retail poultry	−0.29	Brester (1996)
Cross-price elasticity of demand for retail poultry with respect to the price of retail beef	0.18	Brester (1996)
Cross-price elasticity of demand for retail poultry with respect to the price of retail pork	0.04	Brester (1996)
Own-price elasticity of supply for retail poultry	0.18	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale poultry	−0.22	Brester, Marsh, and Atwood (2004)
Own-price elasticity of supply for wholesale poultry	0.14	Brester, Marsh, and Atwood (2004)
Own-price elasticity of demand for wholesale poultry exports	−0.31	Estimated by Pendell et al. (2010)
Percentage change in retail beef supply given a 1% change in wholesale beef supply	0.771	Estimated by Pendell et al. (2010)
Percentage change in wholesale beef demand given a 1% change in retail beef demand	0.995	Estimated by Pendell et al. (2010)
Percentage change in wholesale beef supply given a 1% change in slaughter cattle supply	0.909	Estimated by Pendell et al. (2010)
Percentage change in slaughter cattle demand given a 1% change in wholesale beef demand	1.090	Estimated by Pendell et al. (2010)
Percentage change in slaughter cattle supply given a 1% change in feeder cattle supply	1.070	Estimated by Pendell et al. (2010)
Percentage change in feeder cattle demand given a 1% change in slaughter cattle demand	0.957	Estimated by Pendell et al. (2010)
Percentage change in retail pork supply given a 1% change in wholesale pork supply	0.962	Estimated by Pendell et al. (2010)
Percentage change in wholesale pork demand given a 1% change in retail pork demand	0.983	Estimated by Pendell et al. (2010)
Percentage change in wholesale pork supply given a 1% change in slaughter hog supply	0.963	Estimated by Pendell et al. (2010)
Percentage change in slaughter hog demand given a 1% change in wholesale pork demand	0.961	Estimated by Pendell et al. (2010)
Percentage change in retail domestic lamb supply given a 1% change in wholesale lamb supply	0.908	Estimated by Pendell et al. (2010)
Percentage change in wholesale lamb demand given a 1% change in retail domestic lamb demand	0.731	Estimated by Pendell et al. (2010)
Percentage change in slaughter lamb supply given a 1% change in feeder lamb supply	0.864	Estimated by Pendell et al. (2010)
Percentage change in feeder lamb demand given a 1% change in slaughter lamb demand	0.962	Estimated by Pendell et al. (2010)
Percentage change in retail poultry supply given a 1% change in wholesale poultry supply	0.806	Estimated by Pendell et al. (2010)
Percentage change in wholesale poultry demand given a 1% change in retail poultry demand	1.035	Estimated by Pendell et al. (2010)

Table S2. Variable Definitions and Estimates for the Structural and Equilibrium Displacement Models, 2015

	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. (RTC)	46.20
Retail poultry exports, billion lb. (retail weight)	6.99
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, cents/lb. (live weight)	148.12
Feeder cattle, cents/lb.	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, cents/lb. (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, cents/lb. (live weight)	144.00
Feeder lamb, cents/lb.	192.38
Poultry	
Retail poultry, cents/lb.	189.73
Wholesale poultry, cents/lb.	93.64
Wholesale poultry exports, cents/lb.	93.64

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