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Market impacts of *E. Coli* vaccination in U.S. Feedlot cattle

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Abstract

Immunization through vaccination has been a commercially available pre-harvest intervention to reduce *E. coli* shedding in cattle for about five years. Despite demonstrated substantial improvement in human health that vaccine adoption offers, it has not been widely adopted. This highlights the need for understanding the economic situation underlying limited adoption. Using an equilibrium displacement model, this study identifies the economic impact to U.S. feedlots implementing this vaccination across a series of alternative scenarios. Producers face $1 billion to $1.8 billion in welfare losses over 10 years if they adopt this technology without any associated increases in demand for fed cattle. Retail beef demand increases of 1.7% to 3.0% or export demand increases of 18.1% to 32.6% would each individually make producers economically neutral to adoption. Retail or packer cost decreases of 1.2% to 3.9% would likewise be sufficient to make producers neutral to adoption.

Keywords: Adoption incentive; Beef; Cattle; Cost savings; Demand increases; *E. coli* O157; Economic impacts; Food safety; Vaccination

Shiga toxin producing *E. coli* (STEC O157) is a serious human health hazard in the United States. STEC-related bacteria cause more than 175,000 illnesses (Scallan et al. 2011) with an annual direct economic cost ranging from $489 million (USDA, ERS 2010) to $993 million (Scharff 2010). STEC O157 is naturally occurring in cattle and, through presence in fecal material, threatens food safety if meat contamination occurs during processing.

Because of the human health threat of *E. coli*, considerable beef industry and public health official efforts have targeted pathogen reduction in beef processing plants including development of extensive hazard analysis critical control points (HACCP) and intensive testing of beef for *E. coli* presence (Ferrier and Buzby 2013). Pre-harvest interventions to reduce pathogens in live cattle have arisen as one strategy to lessen chances of post-harvest bacterial contamination of beef. If pathogen presence can be reduced prior to slaughter, the probability of meat contamination during carcass processing will likewise decline (Dodd et al. 2011; Hurd and Malladi 2012).

Vaccines can reduce shedding of *E. coli* in ruminants (Snedeker et al. 2012; Varela et al. 2013; Vogstad et al. 2013). A recently developed commercially available pre-harvest intervention to reduce *E. coli* shedding in cattle is immunization through vaccination (Cull et al. 2012). Despite recognition of the potential reduction in foodborne illness that could result from use of cattle *E. coli* vaccination, adoption is very limited (Callaway et al.

2013; Matthews et al. 2013). Perry et al. (2007) suggest feedlot profits are not directly associated with *E. coli* O157:H7 prevalence as cattle feeding efficiency is not hindered. Furthermore, a well-established market that compensates producers for vaccinating for STEC 0157 has not developed. Thus, an externality exists because feedlots will not implement the socially optimal level of intervention without directly visible economic incentives. Doing so adds costs without directly visible offsetting increases in revenue. The fact that producers do not have direct incentives to employ *E. coli* vaccination, even though doing so would increase beef food safety, led a recent USA Today article to claim "the economics are backwards" (Weise 2011).

Despite the obvious importance to food safety and human foodborne illness, the economic feasibility and impacts of producer adoption of cattle immunization against *E. coli* have not been determined. The purpose of this study is to evaluate the economic impacts of incorporating animal vaccination into *E. coli* pre-harvest control practices. Specifically this study estimates direct producer costs associated with use of a vaccine in cattle feeding, referred to here as an *E. coli* vaccine. Direct costs include vaccine cost, costs of administering, and potential animal feeding performance impacts associated with the vaccination. Potential benefits include reduced packer or retailer costs associated with lower risk of pathogens, reduced food safety concerns, and potentially increased domestic consumer or export demand associated with safer beef. To estimate market level impacts of the vaccination, we use an equilibrium displacement model (EDM) that incorporates supply and demand shifts associated with the cattle immunization to determine economic impacts of the food safety technology across a series of alternative scenarios.

Estimating economic impacts of *E. coli* vaccines being adopted by feedlot operators is important for several reasons. First, feedlot operators need additional information to make sound adoption decisions. Secondly, understanding broader market impacts of possible adoption highlights how net benefits are distributed throughout the industry. Third, society's ongoing interest in food safety and associated desire for regular improvements in risk mitigation protocols further motivates interest from those outside the beef production chain. Given the apparent market failure of *E. coli* vaccination adoption, an assessment of economic impacts and sensitivity to various market reactions has important policy implications.

Background

Vaccination against *E. coli* O157:H7 and fecal shedding has been available in the United States for over five years with the first licensed vaccine approved in February 2009. The vaccine is a siderophore receptor and porin (SRP®) protein exclusively marketed by Zoetis[a]. The vaccine is administered to feedlot cattle during the feeding phase of production with two or three doses[b].

A couple of particularly noteworthy studies have examined the effectiveness of the vaccine in reducing fed cattle fecal concentrations of *E. coli* O157:H7 and in its impact on cattle feeding performance. Thomson et al. (2009) found use of the SRP® vaccine reduced fecal shedding concentrations in fed cattle by up to 98% and cattle feeding performance was unaffected. Cull et al. (2012) found that two doses of SRP® reduced shedding by more than 50% and reduced high shedders by more than 75%. However, Cull et al. (2012) identified a small, but statistically and economically important, reduction in cattle feeding performance associated with vaccinating. In particular, average daily gain declined by 2.7% and feed conversion increased by 2.1% for vaccinated relative to unvaccinated cattle. The reduction in animal performance was hypothesized to be associated with the second vaccination where the vaccinated animals were processed in a chute an additional time relative to the control non-vaccinated cattle. In Thomson et al. (2009) the control cattle were vaccinated with a placebo each time, so the numbers of chute processes were the same for the control and *E. coli* vaccinated cattle. Running cattle through a chute can result in cattle shrink that may not be fully recaptured when placed back on feed and can temporarily disrupt cattle feed intake (Blasi et al. 2009).

Given the differences in experimental results relative to cattle feeding performance impacts associated with administration of an *E. coli* vaccine, we allow for alternative assumptions in our economic analyses. In particular, we consider two alternatives, one assuming no reduction in animal performance and a second assuming a 2.7% reduction in average daily gain and a 2.1% increase in feed conversion (pounds of feed per pound of gain) as a result of the vaccination.

Important to also consider are possible demand improvements or cost savings that could potentially follow implementation of *E. coli* vaccine programs at the feedlot level. Moghadam et al. (2013) estimate that *E. coli* O157:H7 recalls by the USDA Food Safety Inspection Service (FSIS) have a rapid and important economic impact on live cattle futures markets amounting to approximately $6/head for all cattle slaughtered in the United States. Domestic beef demand has been harmed by past FSIS recall events (Marsh et al. 2004; Piggott and Marsh 2004; Tonsor et al. 2010). Furthermore, export market demand for U.S. beef is highly sensitive to food safety (Bailey 2007). As such, domestic retail beef demand and wholesale export beef demand could improve with *E. coli* vaccine programs that reduce *E. coli* prevalence.

Extensive research has examined the cost impacts of additional food safety programs and protocols being introduced into the U.S. beef industry (Antle 1999; 2000). Costs include direct production costs such as additional labor requirements, slowing down processing line speed, investing in food safety technologies, modifying processing procedures or facilities, and expenses of more intensive product sampling and food safety testing (Ferrier and Buzby 2013). In face of a recall, costs of plant down-time, clean up, physical product losses, costs of completing a food recall, and loss of firm customers and reputation can collectively be substantial. Important expenses also include possible litigation costs associated with foodborne human illnesses that have proved expensive in cases where meat food safety breaches have occurred (e.g., Gabbett 2010; Scott 2012).

Given the sizeable costs involved to downstream firms in light of a food safety event, substantial incentives are present to reduce the probabilities of such events including the possibility of feedlots implementing *E. coli* vaccine programs. In essence, use of an *E. coli* vaccine by cattle producers could result in notable benefits to downstream firms but direct benefits to producers that incur the costs of adoption are currently elusive, limiting adoption.

Given the economic importance of identifying the economic impact *E. coli* vaccine program introduction could have on stakeholders throughout the meat and livestock chain we first directly estimate market impacts in the absence of incentivizing demand improvements or possible downstream cost savings. Given the unknown nature of possible demand or cost improvements we then proceed to estimate market impacts under alternative market scenarios to identify the specific beef demand improvements or cost savings that would be needed to make feedlot operators in aggregate indifferent to adoption.

Estimating and discussing these demand or cost improvements that may lead to feedlot adoption is important for several reasons. First, as the levels of demand or cost adjustments that could be experienced elsewhere in the supply chain are realized, having critical thresholds identified is valuable. Second, cattle producers would adopt vaccine programs if they received offsetting benefits which reinforces the value in identifying necessary demand or cost improvements further upstream to encourage adoption (Smith et al. 2013). Finally, from a policy perspective, any cost-benefit analysis of alternative beef food safety enhancing interventions requires the information provided in this study regarding market impacts of these interventions.

Methods

The methodological approach can succinctly be described as using estimates of costs increases incurred by feedlots implementing *E. coli* vaccination programs and estimating changes in prices and quantities at market levels spanning the vertically linked beef industry as well as connected pork and poultry markets. The initial exogenous market shock is feedlot level production costs increasing leading to an inward shift in fed cattle supply. To estimate the market level impact of *E. coli* vaccination on prices and quantities throughout the livestock and meat industry we employ an equilibrium displacement model (EDM). The EDM utilized here is similar to that used by Schroeder and Tonsor (2011) and is documented in the appendix.

The EDM is composed of four sectors in the beef industry: 1) retail (consumer), 2) wholesale (processor/packer), 3) fed cattle (cattle feeding in feedlots), and 4) farm (feeder cattle from cow-calf producers). To capture interactions between retail meat substitutes for beef we also include the pork and poultry markets. Reflecting the higher degree of integration relative to the beef industry, the economic model includes three pork marketing chain sectors (retail, wholesale, and fed cattle) and the poultry marketing chain is composed of two sectors (retail and wholesale). International trade is explicitly incorporated in the model at the wholesale level for all three species. The resulting framework is consistent with existing research and follows the recent work of Brester et al. (2004) and Pendell et al. (2010).

Given estimated changes in prices and quantities, producer surplus at the feedlot level where the adoption decision occurs, as well as other levels in the vertically linked supply chain, is calculated as a widely accepted measure of economic welfare impact. As in most EDM applications, direct estimation of elasticities is prohibitive because of the large number of equations and identification problems in jointly estimating supply and demand relationships (Brester et al. 2004). However, given the *E. coli* vaccination results in relatively small aggregate market shifts (in proportional terms), we follow standard EDM procedures and utilize elasticity estimates reported in the published literature to parameterize the model.

We simulate our model annually for ten consecutive years to trace a hypothetical adoption path over time by producers of the *E. coli* vaccination technology. Consistent with historical beef cattle cycles, we assume it takes the marketplace ten years to fully adjust from short-run to long-run relationships. Ten years of market effects were simulated by linearly adjusting all elasticities between short-run (year 1) and long-run (year 10) using elasticity estimates employed by Pendell et al. (2010)[c]. Supply, demand, and quantity transmission elasticities used are equivalent to those used by Schroeder and Tonsor (2011). Similarly, base price and quantity values are necessary to estimate surplus calculations. The market price and quantity values are annual averages for calendar year 2012 as reported by the Livestock Marketing Information Center (LMIC).

Our analysis assumes 10% of fed cattle are vaccinated in year 1, 25% in year 2, 50% in year 3, and 90% in years 4–10. This reflects a typical "S-curve" adoption pattern where adoption increases rapidly upon introduction of the technology with a plateau corresponding to the fact that few technologies are ever completely adopted by all parties in a heterogeneous industry. The employed adoption rate would of course only occur if private market incentives to adopt were widely present and accessible to producers, which currently they are not. As such, the adoption rate is used here for exemplification and estimation of cost impacts and is not a forecast of a probable adoption path given current market conditions.

Results

When feedlot operators implement *E. coli* vaccination protocols one main direct impact serves as the initial shock in our EDM. Specifically, production costs increase leading to an inward shift in fed cattle supply. This initial exogenous shock initiates a ripple-effect through the industry as reflected in multiple endogenous shifts outlined within the EDM.

The change in net returns of finishing cattle for those implementing *E. coli* vaccinations were calculated under alternative assumptions following Lueger et al. (2012). When assuming no animal performance impact, the direct costs are estimated at $6.47/head with the vaccination being administered twice to each animal. The first vaccination occurs upon arrival at the feedlot where cattle are all processed through a chute anyway (so no additional chute charge or animal processing is associated uniquely to the *E. coli* vaccination). For the second vaccination, additional chute and labor charges occur since cattle would not generally be processed through the chute again unless being vaccinated for *E. coli*. One potentially important addition to the direct costs of vaccinating is whether an adverse animal performance outcome occurs from the vaccination. Research includes no impact (Thomson et al. 2009) to an observed animal performance decline (Cull et al. 2012). As such, a second cost scenario is assumed where the direct costs that include vaccination and animal performance losses are estimated at $13.11/head (Lueger et al. 2012). In addition to these base direct costs, adopting feedyards could incur costs associated with third-party verification that *E. coli* vaccinations were indeed implemented if packers were going to pay them for such a verified production protocol. We assume *E. coli* vaccination verification costs of $1.88/head which are based on costs for age and source verification identified by Pendell et al. (2013).

Given the magnitude of the direct costs for feedlots to vaccinate, they generally will not without a clear direct economic incentive. As such, determining the downstream benefits that would need to occur to encourage adoption is essential to understand if adoption is desirable. The $/head implementation costs are presented in Table 1 along with the exogenous supply shifts these cost increases represent in each year within the EDM given an average fed cattle value in 2012 of $1,604/head.

Table 1 Exogenous fed cattle production cost increase of vaccination and verification program adoption

Scenario:	Direct Cost $/hd[a]	Percentage inward supply shift Year 1 10% Adoption	 Year 2 25% Adoption	 Year 3 50% Adoption	 Years 4-10 90% Adoption
No animal performance impact	$8.35	0.052%	0.130%	0.260%	0.468%
Animal performance impact	$14.99	0.093%	0.234%	0.467%	0.841%

[a] Includes $6.47 per head cost of vaccinating plus $1.88 per head verification cost under no animal performance impact and $13.11 per head cost under performance impact plus $1.88 per head verification cost.

The EDM was first applied to identify economic impacts in the case of *E. coli* vaccination program implementation without additional demand or cost benefits occurring elsewhere in the supply chain. This scenario of course would not happen because feedlots will not adopt without clear direct benefits. But having this scenario is necessary to determine the subsequent magnitudes of market events that would need to occur to entice adoption.

Table 2 summarizes the short- (1-year), intermediate- (5-year), and long-run (10-year) changes in prices and quantities estimated by the EDM where animal performance impacts are omitted and considered. Retail and wholesale beef as well as fed cattle, and feeder cattle quantities all decline in each of the 10 years considered. The reduced production volumes reflect the inward shift in fed cattle supply, derived inward shifts in wholesale and retail beef supplies, and derived demand reductions experienced at the feeder cattle level following the increased production costs for feedlots. Retail and wholesale beef prices increase in all 10 years as the increased feedlot costs pass vertically towards consumers. Feeder cattle prices decline in all 10 years as feedlot vaccination costs reduce derived demand for feeder cattle. The fed cattle price path switches signs over the 10 years examined. Specifically, fed cattle prices decline in years 1 and 2 and increase over years 3–10 reflecting long-run supply being more elastic than short-run supply and a multitude of derived demand and supply feedbacks captured by the model. The quantities of wholesale beef exported and imported, as well as the price of imported wholesale beef all decline over the 10 years evaluated. This primarily follows an overall reduction in wholesale beef supplies and increased wholesale beef prices. More broadly, the long-run impacts are smaller as the entire supply chain adjusts to *E. coli* vaccination program implementation over time.

In the base situation of no additional demand enhancement or cost savings, the cumulative net present value producer surplus losses over ten years at the feedlot level are $1.00 billion if no animal performance reduction occurred by vaccinating and $1.79 billion if reduced animal performance is considered (Table 3). This substantial difference in welfare, despite small potential impacts on animal performance, clearly illustrates how the economic value of interventions changes if animal productivity is affected.

These substantial losses reflect changes in prices and quantities summarized in Table 2 and occur if the adoption rate we assume and no offsetting benefits materialize. This illustrates why, consistent with Matthews et al. (2013) and Callaway et al. (2013), limited voluntary adoption of *E. coli* vaccination will occur unless recognized direct incentives for implementation arise. Such incentives could occur in the form of derived demand increasing for fed cattle from feedlots with *E. coli* vaccination programs if either domestic retail or wholesale export beef demand increased following program

Table 2 Percentage change in endogenous variables of the equilibrium displacement models with adoption costs but no benefits scenario

	No animal performance impact			With animal performance impact		
Endogenous variables	**Short run**	**Intermediate**	**Long run**	**Short run**	**Intermediate**	**Long run**
Retail beef quantity	−0.27%	−0.04%	−0.01%′	−0.49%	−0.06%	−0.01%
Retail beef price	0.32%	0.04%	0.01%	0.58%	0.06%	0.01%
Wholesale beef quantity	−0.51%	−0.15%	−0.04%	−0.91%	−0.27%	−0.07%
Wholesale beef price	0.40%	0.16%	0.04%	0.72%	0.28%	0.07%
Slaughter cattle quantity	−0.40%	−0.28%	−0.12%	−0.72%	−0.51%	−0.21%
Slaughter cattle price	−0.38%	0.26%	0.14%	−0.68%	0.46%	0.25%
Feeder cattle quantity	−0.23%	−0.21%	−0.09%	−0.42%	−0.37%	−0.16%
Feeder cattle price	−1.06%	−0.15%	−0.03%	−1.91%	−0.27%	−0.06%
Imported wholesale beef quantity	−0.38%	−0.13%	−0.04%	−0.69%	−0.24%	−0.07%
Exported wholesale beef quantity	−0.17%	−0.24%	−0.11%	−0.30%	−0.44%	−0.20%
Imported wholesale beef price	−0.21%	−0.02%	0.00%	−0.37%	−0.04%	−0.01%
Retail pork quantity	0.04%	0.01%	0.00%	0.08%	0.01%	0.00%
Retail pork price	0.02%	0.00%	0.00%	0.04%	0.00%	0.00%
Wholesale pork quantity	0.03%	0.01%	0.00%	0.05%	0.01%	0.00%
Wholesale pork price	0.02%	0.00%	0.00%	0.03%	0.00%	0.00%
Slaughter hogs quantity	0.01%	0.00%	0.00%	0.02%	0.01%	0.00%
Slaughter hogs price	0.03%	0.00%	0.00%	0.06%	0.01%	0.00%
Imported wholesale pork quantity	0.02%	0.00%	0.00%	0.03%	0.01%	0.00%
Exported wholesale pork quantity	−0.02%	0.00%	0.00%	−0.03%	0.00%	0.00%
Imported wholesale pork price	0.01%	0.00%	0.00%	0.02%	0.00%	0.00%
Retail poultry quantity	0.05%	0.01%	0.00%	0.08%	0.01%	0.00%
Retail poultry price	0.04%	0.00%	0.00%	0.08%	0.00%	0.00%
Wholesale poultry quantity	0.05%	0.01%	0.00%	0.09%	0.01%	0.00%
Wholesale poultry price	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Exported wholesale poultry quantity	−0.32%	−0.04%	−0.01%	−0.57%	−0.08%	−0.01%

Note: These percentage changes are relative to 0% vaccination and verification adoption. Short-, intermediate-, and long-run corresponds to years 1, 5, and 10, respectively from the EDM simulated over 10 consecutive years. Percentage changes for each individual year are available upon request.

implementation. Similarly, a derived demand benefit could materialize if production costs at either the retail or wholesale level declined following *E. coli* vaccination program implementation. Given these unknown but important plausible alternatives, we extended our analysis and utilized the EDM to identify demand benefits or cost savings needed to make the feedlot level indifferent to adoption.

Table 4 presents the estimated retail demand increase, wholesale export demand increase, retail cost savings, and wholesale costs savings that result in no changes in producer surplus at the fed cattle (feedlot) level[d]. Note, the estimates in Table 4 are for independent downstream shocks to demand or costs needed to make feedlot producers economically indifferent to adoption. Possible combinations of demand and cost impacts would be smaller than individual shocks necessary to make feedlot producers indifferent. The minimum changes that may lead to feedlot adoption are lower in each case where implementing an *E. coli* vaccination program does not impact animal performance.

Table 3 Producer surplus changes from vaccination and verification program adoption ($ millions), no benefits scenario

	No animal performance impact				With animal performance impact			
Beef producer surplus	**Short run**	**Intermediate run**	**Long run**	**Cumulative present value**	**Short run**	**Intermediate run**	**Long run**	**Cumulative present value**
Retail level	294.05	32.58	5.07	654.66	527.41	58.49	9.10	1,174.59
Wholesale level	197.81	76.67	18.49	804.03	354.46	137.58	33.20	1,441.69
Fed cattle level	−224.72	−110.56	−173.92	−1,000.90	−402.86	−198.29	−312.13	−1,795.23
Feeder cattle level	−434.83	−61.77	−12.98	−1,018.27	−780.04	−110.82	−23.30	−1,826.42
Total Beef Industry Producer Surplus	−167.69	−63.08	−163.33	−560.48	−301.02	−113.04	−293.13	−1,005.37

Note: Producer surplus is calculated relative to 2012 quantities and prices for livestock and meat. Cumulative net present value was calculated using a 5% discount rate.

Table 4 Independent changes needed for no change in feedlot sector producer surplus

	No animal performance impact	With animal performance impact
Domestic retail beef demand increase	1.7%	3.0%
Wholesale export beef demand increase	18.1%	32.6%
Retail beef (retailer) cost decrease	2.2%	3.9%
Wholesale beef (packer) cost decrease	1.2%	2.2%

Note: Values are the exogenous responses (demand increases or cost savings) resulting in cumulative net present value of producer surplus not changing at the fed cattle level (feedlots). Demand increases on all beef production were considered while cost savings evaluated corresponded only to the portion of product retailers or packers would receive from *E. coli* vaccination programs reflecting the 10-year adoption path assumed.

When animal performance impacts are considered, either a 3.0% increase in domestic retail beef demand or a 32.6% increase in wholesale export beef demand would provide the derived demand benefits to make feedlot operators indifferent to implementation. The 3.0% domestic retail demand increase is within the range of experienced annual demand shifts in the U.S. (AgManager 2013). However, the finding of Zingg and Siegrist (2012) that a minority of consumers may be willing to consume meat from vaccinated animals casts some doubt on the extent of a positive, aggregate retail demand response. In 2012 Japan and South Korea combined accounted for 30.8% of total U.S. beef exports (LMIC 2013). Accordingly, context on the 32.6% wholesale export increase can readily be made noting how maintaining access to Japan and South Korea by avoiding food-safety related market closures could offset feedlot level vaccination program costs. The identification of thresholds for export demand increases being approximately 10 times those of domestic demand increases reflects the fact approximately 90% of beef produced in the U.S. is consumed domestically. While domestic and export demand responses are unknown, recognizing the demand response thresholds is important for broader industry-wide deliberations and sets the stage for additional future research.

Table 4 also indicates that 3.9% (2.2%) cost savings for retailers or 2.2% (1.2%) cost savings for packers results in no net economic welfare changes for the feedlot segment if animal productivity is (not) reduced through a vaccination protocol. As with the threshold demand values, the precise level of cost savings at retail or wholesale levels are unknown as adjustments that operations may make in *E. coli* mitigation efforts have yet to be directly studied. Hurd and Malladi (2012) concluded that the number of ground beef-related *E. coli* human illnesses in the United States could be reduced by 58% from about 20,000 illnesses to around 8,400 per year under an 80% effective and fully adopted feedlot steer and heifer vaccination program. Smith et al. (2013) found combinations of interventions applied pre-harvest and throughout processing resulted in larger relative *E. coli* risk reductions. If a single and relatively simple intervention such as a vaccination program would have this dramatic of impact on foodborne illnesses, downstream cost savings would certainly be realized. Estimating potential downstream cost savings is an area ripe for future research.

Discussion and Conclusions

This study expands knowledge of economic implications of implementing *E. coli* vaccination programs, highlights key areas of where additional research would be valuable, and provides information that could improve societal response to efficiently mitigating food safety risks. Vaccinations by feedlots could potentially reduce *E. coli* related human foodborne illnesses from ground-beef by 58% (Hurd and Malladi 2012). However, cattle producers will not adopt *E. coli* vaccination programs without offsetting direct benefits because doing so is costly and would reduce their economic welfare by $1 billion to $1.8 billion. Currently, direct benefits of *E. coli* vaccine adoption by cattle producers are elusive as a well-established market premium does not exist despite the vaccine having been commercially available for over five years now.

What might it take for *E. coli* vaccination programs to be successfully implemented? We illustrate the threshold magnitudes of downstream demand improvements or cost savings that are needed to provide producers economic incentives to adopt *E. coli* vaccination programs. Domestic consumer demand increases of 2-3%, export wholesale market increases of 18-33%, retailer cost reductions of 2-4%, or processor cost reductions of 1-2% would each individually be sufficient to make producer adoption welfare neutral.

This study also highlights the need to further examine if human health benefits from implementing *E. coli* vaccination programs are significant enough to consider additional policy adjustments that encourage adoption. This issue is beyond the economics of adoption focused scope of this paper but certainly is an area of importance for future research. Similarly, a valuable area for future research is to consider the demand increase and cost reduction thresholds identified in this study and determine whether and how *E. coli* vaccination adoption incentives might occur and translate incentives back to cattle producers.

Endnotes

[a] See: https://online.zoetis.com/US/EN/Solutions/Pages/SRPEcoli/index.aspx

[b] Experiments with both two doses and three doses have been conducted (Cull et al. 2012; Thomson et al. 2009) with three doses showing a trend in efficacy.

[c] Available at: http://ajae.oxfordjournals.org/content/suppl/2010/04/29/aaq037.DC1/aaq037supp.pdf

[d] Demand increases were modelled to impact 100% of production over the 10 year period while cost increases were modelled to impact only the portion of production that aligns with feedlot vaccination adoption. That is, demand increases reflect an assumption of product being undifferentiated downstream to buyers while cost increases reflect an assumption of downstream purchases only experiencing cost savings when product is verified to be sourced from adopting feedyards.

[e] This model follows Pendell et al. (2010) and similar studies in assuming international trade can be succinctly captured by including exchange of meat products while not explicitly incorporating live animal trade.

[f] Available at: http://ajae.oxfordjournals.org/content/suppl/2010/04/29/aaq037.DC1/aaq037supp.pdf

APPENDIX - Details of Applied Equilibrium Displacement Model

To estimate the market level impact of *E. coli* vaccination we employ an equilibrium displacement model (EDM). The EDM utilized here is similar to that used by Schroeder and Tonsor (2011). The EDM is composed of four sectors in the beef industry: 1) retail (consumer), 2) wholesale (processor/packer), 3) fed cattle (cattle feeding in feedlots), and 4) farm (feeder cattle from cow-calf producers). To capture interactions between retail meat substitutes for beef we also include the pork and poultry markets. Reflecting the higher degree of integration relative to the beef industry, the economic model includes three pork marketing chain sectors (retail, wholesale, and fed cattle) and the poultry marketing chain is composed of two sectors (retail and wholesale). International trade is explicitly incorporated in the model at the wholesale level for all three species. The resulting framework is consistent with existing research and most closely follows the recent work of Brester et al. (2004) and Pendell et al. (2010). The structural model (omitting error terms for convenience) is given by the following series of general demand and supply equations of this multi-species model. Superscripts *r*, *w*, *s*, and *f* denote the retail, wholesale, fed cattle, and farm market levels, respectively; subscripts *B*, *K*, and *Y* denote beef, pork, and poultry, respectively; *P* is price; *Q* is quantity; and *Z* and *W* denote demand and supply shifters, respectively. Consistent with existing international trade, the model captures imports (subscript *i*) and exports (subscript *e*) of beef, pork, and poultry[e]. Equations (1) - (25) omit superscripts for demand and supply as market clearing conditions are imposed, requiring demand and supply to equal.

Beef marketing chain

(1) Retail beef primary demand: $Q_B^r = f_1\left(P_B^r, P_K^r, P_Y^r, Z_B^r\right)$,
(2) Retail beef derived supply: $Q_B^r = f_2\left(P_B^r, Q_B^w, W_B^r\right)$,
(3) Wholesale beef derived demand: $Q_B^w = f_3\left(P_B^w, Q_B^r, Z_B^w\right)$,
(4) Wholesale beef derived supply: $Q_B^w = f_4\left(P_B^w, Q_B^s, Q_{Bi}^w, Q_{Be}^w, W_B^w\right)$,
(5) Imported wholesale beef derived demand: $Q_{Bi}^w = f_5\left(P_{Bi}^w, Q_B^w, Z_{Bi}^w\right)$,
(6) Imported wholesale beef derived supply: $Q_{Bi}^w = f_6\left(P_{Bi}^w, W_{Bi}^w\right)$,
(7) Exported wholesale beef derived demand: $Q_{Be}^w = f_7\left(P_B^w, Z_{Be}^w\right)$,
(8) Fed cattle derived demand: $Q_B^s = f_8\left(P_B^s, Q_B^w, Z_B^s\right)$,
(9) Fed cattle derived supply: $Q_B^s = f_9\left(P_B^s, Q_B^f, W_B^s\right)$,
(10) Farm (feeder cattle) derived demand: $Q_B^f = f_{10}\left(P_B^f, Q_B^s, Z_B^f\right)$,
(11) Farm (feeder cattle) primary supply: $Q_B^f = f_{11}\left(P_B^f, W_B^f\right)$,

Pork marketing chain

(12) Retail pork primary demand: $Q_K^r = f_{12}\left(P_B^r, P_K^r, P_Y^r, Z_K^r\right)$,
(13) Retail pork derived supply: $Q_K^r = f_{13}\left(P_K^r, Q_K^w, W_K^r\right)$,
(14) Wholesale pork derived demand: $Q_K^w = f_{14}\left(P_K^w, Q_K^r, Z_K^w\right)$,
(15) Wholesale pork derived supply: $Q_K^w = f_{15}\left(P_K^w, Q_K^s, Q_{Ki}^w, Q_{Ke}^w, W_B^w\right)$,
(16) Imported wholesale pork derived demand: $Q_{Ki}^w = f_{16}\left(P_{Ki}^w, Q_K^w, Z_{Ki}^w\right)$,
(17) Imported wholesale pork derived supply: $Q_{Ki}^w = f_{17}\left(P_{Ki}^w, W_{Ki}^w\right)$,
(18) Exported wholesale pork derived demand: $Q_{Ke}^w = f_{18}\left(P_K^w, Z_{Ke}^w\right)$,
(19) Market hog derived demand: $Q_K^s = f_{19}\left(P_K^s, Q_K^w, Z_K^s\right)$,
(20) Market hog primary supply: $Q_K^s = f_{20}\left(P_K^s, W_K^s\right)$,

Poultry marketing chain

(21) Retail poultry primary demand: $Q_Y^r = f_{21}\left(P_B^r, P_K^r, P_Y^r, Z_Y^r\right)$,
(22) Retail poultry derived supply: $Q_Y^r = f_{22}\left(P_Y^r, Q_Y^w, Q_{Ye}^r, W_Y^r\right)$,
(23) Wholesale poultry derived demand: $Q_Y^w = f_{23}\left(P_Y^w, Q_Y^r, Z_Y^w\right)$,

(24) Wholesale poultry primary supply: $Q_Y^w = f_{24}\left(P_Y^w, W_Y^w\right)$,
(25) Exported wholesale poultry derived demand: $Q_{Ye}^w = f_{25}\left(P_Y^w, Z_{Ye}^w\right)$.

Consistent with Wohlgenant (1993), we incorporate variable input proportions by allowing production quantities to vary across the market levels in the marketing chain. Totally differentiating equations (1) - (25), including variable input proportions, and placing all the endogenous variables on the left-hand side of each equation and isolating exogenous effects to the right-hand side of each equation results in the following EDM. E represents a relative change operator (i.e., $EQ = d\ln Q = dQ/Q$); η_a^m is the own-price elasticity of meat/species a demand at market level m; η_{ab}^m is the cross-price elasticity of demand for meat a with respect to retail prices of meat b; ε_a^m is the own-price elasticity of meat/species a supply at market level m; τ^{lm} is the percentage change in quantity demanded at market level m given a 1% change in quantity demanded at market level l; γ^{lm} is the percentage change in quantity supplied at market level m given a 1% change in quantity supplied at market level l. In this specification, market levels are linked by downstream quantity variables among the demand equations and upstream quantity variables among the supply equations (Wohlgenant 1993).

Beef marketing chain

(1″) Retail beef primary demand: $EQ_B^r - \eta_B^r EP_B^r - \eta_{BK}^r EP_K^r - \eta_{BY}^r EP_Y^r = EZ_B^r$,
(2″) Retail beef derived supply: $EQ_B^r - \varepsilon_B^r EP_B^r - \gamma_B^{wr} EQ_B^w = EW_B^r$,
(3″) Wholesale beef derived demand: $EQ_B^w - \eta_B^w EP_B^w - \tau_B^{rw} EQ_B^r = EZ_B^w$,
(4″) Wholesale beef derived supply:

$$EQ_B^w - \varepsilon_B^w EP_B^w - \gamma_B^{sw}\left(Q_B^s/Q_B^w\right)EQ_B^s - \left(Q_{Bi}^w/Q_B^w\right)EQ_{Bi}^w + \left(Q_{Be}^w/Q_B^w\right)EQ_{Be}^w = EW_B^w,$$

(5″) Imported wholesale beef derived demand: $EQ_{Bi}^w - \eta_{Bi}^w EP_{Bi}^w - \tau_B^{rw} EQ_B^w = \left(Q_{Bi}^w/Q_B^w\right)$ $EZ_{Be}^w + EZ_{Bi}^w$,
(6″) Imported wholesale beef derived supply: $EQ_{Bi}^w - \varepsilon_{Bi}^w EP_{Bi}^w = EW_{Bi}^w$,
(7″) Exported wholesale beef derived demand: $EQ_{Be}^w - \eta_{Be}^w EP_B^w = EZ_{Be}^w$,
(8″) Fed cattle derived demand: $EQ_B^s - \eta_B^s EP_B^s - \tau_B^{ws} EQ_B^w = \left(Q_{Be}^w/Q_B^w\right)EZ_{Be}^w + EZ_B^s$,
(9″) Fed cattle derived supply: $EQ_B^s - \varepsilon_B^s EP_B^s - \gamma_B^{fs} EQ_B^f = EW_B^s$,
(10″) Farm (feeder cattle) derived demand: $EQ_B^f - \eta_B^f EP_B^f - \tau_B^{sf} EQ_B^s = EZ_B^f$,
(11″) Farm (feeder cattle) primary supply: $EQ_B^f - \varepsilon_B^f EP_B^f = EW_B^f$,

Pork marketing chain

(12″) Retail pork primary demand: $EQ_K^r - \eta_{KB}^r EP_B^r - \eta_K^r EP_K^r - \eta_{KY}^r EP_Y^r = EZ_K^r$,
(13″) Retail pork derived supply: $EQ_K^r - \varepsilon_K^r EP_K^r - \gamma_K^{wr} EQ_K^w = EW_K^r$,
(14″) Wholesale pork derived demand: $EQ_K^w - \eta_K^w EP_K^w - \tau_K^{rw} EQ_K^r = EZ_K^w$,
(15″) Wholesale pork derived supply: $EQ_K^w - \varepsilon_K^w EP_K^w - \gamma_K^{sw}\left(Q_K^s/Q_K^w\right)EQ_K^s - \left(Q_{Ki}^w/Q_K^w\right)EQ_{Ki}^w +$ $\left(Q_{Ke}^w/Q_K^w\right)EQ_{Ke}^w = EW_K^w$,,
(16″) Imported wholesale pork derived demand: $EQ_{Ki}^w - \eta_{Ki}^w EP_{Ki}^w - \tau_K^{rw} EQ_K^w = \left(Q_{Ki}^w/Q_K^w\right)$ $EZ_{Ke}^w + EZ_{Ki}^w$,
(17″) Imported wholesale pork derived supply: $EQ_{Ki}^w - \varepsilon_{Ki}^w EP_{Ki}^w = EW_{Ki}^w$,
(18″) Exported wholesale pork derived demand: $EQ_{Ke}^w - \eta_{Ke}^w EP_K^w = EZ_{Ke}^w$,

(19″) Market hog derived demand: $EQ^s_K - \eta^s_K EP^s_K - \tau^{ws}_K EQ^w_K = \left(Q^w_{Ke}/Q^w_K\right) EZ^w_{Ke} + EZ^s_K$,
(20″) Market hog primary supply: $EQ^s_K - \varepsilon^s_K EP^s_K = EW^s_K$,

Poultry marketing chain
(21″) Retail poultry primary demand: $EQ^r_Y - \eta^r_{YB} EP^r_B - \eta^r_{YK} EP^r_K - \eta^r_Y EP^r_Y = EZ^r_Y$,
(22″) Retail poultry derived supply: $EQ^r_Y - \varepsilon^r_Y EP^r_Y - \gamma^{wr}_Y EQ^w_Y = EW^r_Y$,
(23″) Wholesale poultry derived demand: $EQ^w_Y - \eta^w_Y EP^w_Y - \tau^{rw}_Y EQ^r_Y = EZ^w_Y$,
(24″) Wholesale poultry primary supply: $EQ^w_Y - \varepsilon^w_Y EP^w_Y + \left(Q^w_{Ye}/Q^w_Y\right) EQ^w_{Ye} = EW^w_Y$,
(25″) Exported wholesale poultry derived demand: $EQ^w_{Ye} - \eta^w_{Ye} EP^w_Y = EZ^w_{Ye}$.

Balagtas and Kim (2007) note this model can be expressed in matrix form as **RY** = **Z**, where **R** is a matrix of model parameters (i.e., elasticities), **Y** is a column vector of endogenous changes in prices and quantities relative to an initial equilibrium, and **Z** is a column vector of percentage changes associated with vaccination protocol adoption. The model defines proportional changes in equilibrium prices and quantities for each evaluated market level and species in response to exogenous changes corresponding to vaccination introduction. These proportional changes are identified as:

$$(26) \quad \mathbf{Y} = \mathbf{R}^{-1}\mathbf{Z}.$$

We use producer surplus to quantify the net economic impact of vaccination adoption. Changes in producer surplus created by introducing vaccinations can be calculated in terms of changes in prices and quantities identified by the EDM as:

$$(27) \quad \Delta PS^m_a = P^m_a Q^m_a \left(EP^m_a + EW^m_a\right)\left(1 + 0.5EQ^m_a\right).$$

where producer surplus is denoted by *PS* (Lusk and Anderson 2004). The superscript *m* denotes the market level (i.e., *r* = retail, *w* = wholesale (processor/packer), *s* = fed cattle (feeding), and *f* = feeder (farm level)) and subscript *a* denotes the industry/species evaluated (i.e., beef, pork, or poultry). Change in total producer surplus is the sum of the change in producer surplus from each market level for a species, $\Delta PS_a = \sum_m \Delta PS^m_a$.

Solutions to equation (26) require elasticity estimates for the matrix of parameters (***R***). Identifying these estimates by econometrically estimating structural supply and demand equations for the 25-equation EDM is problematic. As in most EDM applications, direct estimation of elasticities is prohibited by the large number of equations and by identification problems in jointly estimating supply and demand relationships (Brester et al. 2004). However, given the *E. coli* vaccination results in relatively small aggregate market shifts (in proportional terms), we follow standard EDM procedures and utilize elasticity estimates reported in the published literature.

We simulate our model annually for ten consecutive years to allow for adoption over time by producers of the *E. coli* vaccination technology. Consistent with historical beef cattle cycles, we assume that it takes the marketplace ten years to fully adjust from short-run to long-run relationships. Ten years of market effects were simulated by linearly adjusting all elasticities between short-run (year 1) and long-run (year 10) using elasticity estimates employed by Pendell et al. (2010)[f]. The supply, demand, and quantity transmission elasticities used are equivalent to those used by Schroeder and Tonsor (2011). Similarly, base price and quantity values are necessary to estimate surplus calculations. The market price and quantity values are annual average values for calendar year 2012 as reported by the Livestock Marketing Information Center (LMIC).

Our analysis assumes 10% of fed cattle are vaccinated in year 1, 25% in year 2, 50% in year 3, and 90% in years 4–10. This reflects a typical “S-curve” adoption pattern where adoption increases rapidly upon introduction of the technology with a plateau corresponding to the fact that few technologies are every completely adopted by all parties in a heterogeneous industry.

Competing interests

The authors declare that they have no competing interests.

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