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Factors affecting cattle producers' willingness to adopt an *Escherichia coli* O157:H7 vaccine: a probit analysis

RESEARCH ARTICLE

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Abstract

E. coli O157:H7 bacteria – a major cause of foodborne illness – occur naturally in the intestine of cattle but do not affect the health or productivity of the animal. A cattle vaccine that significantly reduces the risk of *E. coli* contamination was developed and commercialized in Canada and internationally, however, adoption by cattle producers remained extremely low. Utilizing data from a survey of cow-calf producers in western Canada, this paper examines the factors affecting cattle producers' willingness to adopt the *E. coli* vaccine. Education, prior awareness of the vaccine, perception of who holds primary responsibility for *E. coli* risk reduction, and a producer's external (versus internal) locus of control with respect to their ability to mitigate *E. coli* risks within the production environment are significant determinants of willingness to adopt. Adoption incentives are also evaluated, including policy interventions, market/supply chain incentives, production protocol, and producer reputation incentives. The analysis provides lessons for the development and commercialization of vaccines and other food safety intervention strategies that yield societal and supply chain benefits beyond the individual adopter.

Keywords: binary probit, food safety, risk mitigation, technology adoption, locus of control, beef
JEL code: Q13, Q16, Q18

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1. Introduction

The recognition that the health of humans, animals and the environment are closely linked, so-called 'One Health', is garnering increasing attention across policy, scientific and industry contexts. The relationship between food safety, water quality and livestock production has provided an opportunity for innovations that mitigate human health risks through interventions at the livestock production stage. An example is the prevalence of *Escherichia coli (E. coli)* O157:H7 in the intestine of cattle, creating the potential for foodborne illnesses from *E. coli* O157:H7 contamination at meat processing plants or contamination of irrigation or drinking water supplies by run-off from livestock operations. Recognition of this risk factor spurred scientific research into pre-and post-harvest interventions to reduce the risks of *E. coli* O157:H7 contamination in food supply chains, resulting in the development and commercialization of a cattle vaccine.

E. coli O157:H7 is one of five pathogens identified as the primary causes of foodborne illness in the U.S. (alongside *Campylobacter*, *Salmonella*, *Listeria monocytogenes*, and other strains of *E. coli*), which together account for an estimated US$7.7 billion in annual costs of foodborne illness[1] in the U.S. (Scharff, 2012). *E. coli* O157:H7 (henceforth, *E. coli*) has been associated with a number of high profile incidents of food (and water) borne illnesses internationally. Examples include contamination at the XL Foods beef packing plant in western Canada in 2012 that resulted in the largest beef recall in Canadian history, contamination of organic beansprouts in Germany in 2011 resulting in over 30 deaths and thousands of illnesses and severe disruption to fresh produce supply chains before the source of the contamination was determined, a nationwide recall of bagged spinach in the United States in 2006, and contamination of municipal drinking water supplies in Walkerton, Ontario (Canada) in 2000 resulting in an estimated 2,300 illnesses and 7 deaths (Ochieng' and Hobbs, 2016). In all of these cases, the source of *E. coli* contamination was eventually traced to cattle: through cross-contamination of fecal matter from hides to meat in the case of the Canadian beef packing plant, as a result of contaminated irrigation water in the case of the organic beansprouts in Germany and in the U.S. spinach case, and as result of run-off from a nearby livestock farming operation in the case of the contamination of municipal water supplies in Ontario.

Cattle are asymptomatic carriers of the *E. coli* bacteria, which occur naturally in their intestine. A number of post-harvest interventions exist to reduce the risk of *E. coli* contamination in the food system, including (where permitted), irradiation, organic acid rinses and steam pasteurization. Nevertheless, it is recognized that pre-harvest interventions may also be an effective means by which to reduce the risk of *E. coli* contamination both within food supply chains and in a broader environmental context. One such pre-harvest intervention is a cattle vaccine that reduces the prevalence of *E. coli* in the intestine, therefore reducing the risk of cross-contamination during food processing or through environmental factors (water). An *E. coli* vaccine (Econiche) became available in a number of countries in 2008, beginning with Canada and the U.S., followed by Australia in 2011 and was available on a special certificate system across some Member States of the European Union the same year (Ochieng' and Hobbs, 2016).

Despite the existence of the vaccine, and scientific evidence of its effectiveness (discussed in the next section), levels of adoption by cattle producers were remarkably low, estimated to be in the range of 5% in Canada (Grier and Schmidt, 2009) By February 2015 the vaccine was no longer commercially available after the Canadian company which manufactured the vaccine (Bioniche) sold its animal health division to the French company Vetoquinol, who ceased production of Econiche (NFAN, 2015). As a commercial endeavor, the vaccine suffered from a classic externality problem: the cattle producer incurred the costs of vaccination, yet the direct benefits flowed elsewhere within the supply chain, to downstream meat packers/processors and retailers, and to consumers, or more broadly within the environment, such as users of municipal or irrigation water supplies. The additional costs of vaccination, together with the lack of a strong market incentive

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[1] Estimated annual costs of foodborne illness include direct health-related costs as well as a variety of indirect costs such as quality of life effects, lost productivity, foregone income.

(premiums) for vaccinated cattle, have been identified as significant barriers to adoption of this technology (Ochieng' and Hobbs, 2016; Tonsor and Schroeder, 2015).

The vaccine, and the challenges associated with its adoption, provides a timely opportunity to examine the factors affecting the willingness of livestock producers to adopt technologies with beneficial human health impacts – or 'socially beneficial' technologies. This paper examines these questions within the context of Canadian cattle producers' willingness to adopt the *E. coli* vaccine while it was still available for use. Using data from a survey of cow-calf producers in western Canada the paper uses a probit model to evaluate the factors affecting willingness to adopt. The degree of awareness of the vaccine among cattle producers and their primary sources of information about the vaccine further enriches our understanding of the adoption environment. Actions are often driven by perceptions, and in this case, producers' perceptions with respect to who holds primary responsibility for reducing the risk of *E. coli* contamination, as well as who benefits from the reduced risks can influence willingness to adopt. The relative strength of a set of market, policy, and reputational incentives for adoption are also examined.

The remainder of the paper is organized as follows: the next section provides further context for the focus on *E. coli* and documents the development of the *E. coli* vaccine as a pre-harvest intervention strategy. The Methods section outlines the survey data collection process and the methodological approach (binary probit analysis). Insights from survey data pertaining to producer awareness of *E. coli* problems and the *E. coli* vaccine, perceptions over the distribution of responsibility for *E. coli* risk reduction, the benefits that flow from risk reduction, and barriers to adoption of the vaccine are presented in the section 'The adoption environment: descriptive statistics' and set the scene for the probit regression analysis discussed in the Results section. The paper concludes with a discussion of policy and managerial implications, together with suggestions for further research.

2. *E. coli* O157:H7 outbreaks and the development of a vaccine

The Centers for Disease Control and Prevention tracked 390 *E. coli* O157:H7 outbreaks in the U.S. between 2003 and 2012 finding that these outbreaks resulted in 4,928 reported illnesses, 1,272 hospitalizations and 33 deaths (Heiman *et al.,* 2015). Contaminated food was the source of the majority of these illnesses (65% of outbreaks or 255 incidents). Beef (primarily ground beef but also steak) accounted for approximately 21% of outbreaks (Heiman *et al.,* 2015).

Estimates of the costs of illness from *E. coli* infections include the direct costs of seeking medical attention, which can include hospitalization and, in severe cases, long-term medical care as a result of renal failure from hemolytic uremic syndrome, as well as the indirect costs of illness or premature death, including lost productivity and foregone earnings. In a Canadian study, Sockett *et al.* (2014) estimate that around 22,344 cases of primary *E. coli* infections occur in Canada annually. They estimate the mean annual cost of primary infections to be $26.9 million, of which 31% is accounted for by direct medical costs while 69% ($18.6 million) arises from lost productivity. Premature deaths accounted for the majority of the costs from lost productivity at $15.1 million. In addition, Sockett *et al.* (2014) estimate the annual costs of ongoing long-term illness at another $377.2 million per year, resulting in estimated mean costs of *E. coli* infections in Canada of $403.9 million annually.

Additional costs of an *E. coli* contamination, not reflected in these numbers, include the costs to the food industry of product recalls, damage to industry reputation, market access restrictions and loss of consumer confidence (Loader and Hobbs, 1999; Teisl and Roe, 2010). The 2012 *E. coli* contamination at XL Foods Inc. in western Canada, for example, led to the largest beef recall in Canadian history and created short-run disruptions in export market access for Canadian beef products until the source of the contamination was identified. It also created severe disruption to domestic beef supply chains with the temporary closure of a major packing plant (the XL Foods plant represented 35% of Canada's beef processing capacity), reflected in sharply lower cattle prices until the plant eventually reopened and markets stabilized (Lewis *et al.*, 2013).

A number of potential interventions exist at both the pre-harvest and post-harvest stages of beef production as a means of addressing the *E. coli* pathogen. Pre-harvest interventions range from the use of vaccines, microbial probiotics designed to exclude or reduce microbial pathogens within the digestive tract of livestock, to biosecurity and herd management measures to reduce risks within the production environment. At the slaughtering and processing stage, interventions to reduce the risks of *E. coli* contamination within processing plants range from food safety management practices such as the use of Hazard Analysis And Critical Control Points plans, to technological measures such as electron-beam processing, irradiation, ethylene gas processing and steam pasteurization (Teisl *et al.,* 2001).

A wide body of scientific evidence, over a considerable period of time, has pointed to the potential for an *E. coli* vaccine to significantly reduce the risk of *E. coli* contamination within the beef supply chain (Ochieng' and Hobbs, 2016). In early studies using stochastic simulation models, Jordan *et al*. (1999) and Signorini and Tarabla (2002) argue that vaccination is a key pre-harvest intervention strategy, with other post-slaughter measures, such as control of storage temperatures and the use of hide-wash cabinets in slaughterhouses remaining relevant complementary risk reduction measures. Smith *et al*. (2013) find vaccination to be highly effective at reducing both colonization and shedding, reducing the risk of environmental transmission of *E. coli* O157 within commercial farm operations. Withee *et al.* (2009) determine the maximum cost per unit at which a hypothetical *E. coli* vaccination would still be a cost-effective intervention for preventing *E. coli* illnesses in humans, finding that vaccinating the entire U.S. herd at a cost of between $2.29 and $9.14/unit would be a cost-effective intervention. The cost-effectiveness of interventions to reduce human illnesses varies with vaccine efficacy, and the authors suggest that vaccinating only a portion of the herd would be cost-effective for vaccines that are less effective or most costly.

The recognition that cattle are a primary source of *E. coli* problems in both the food system and through environmental contamination of water supplies with cattle feces, along with the potential for a vaccine to reduce the prevalence of cattle shedding *E. coli*, led to research at the University of British Columbia and the Vaccine and Infectious Diseases Organization at the University of Saskatchewan in Canada to develop a vaccine. Building upon this research, a vaccine (Econiche) was licensed by the Canadian company Bioniche Life Sciences Inc., with early trials showing that vaccinated cattle were 92% less likely to be colonized by *E. coli* (Smith *et al.,* 2009).

The vaccine was authorized for use by the Canadian Food Inspection Agency (CFIA) as a three dose regimen for cow-calf operations or feedlots. Typically beef/dairy cattle received two doses of the vaccine within the first 12 months of life, with a recommendation that animals over 1 year receive one dose on an annual basis. The vaccine cost approximately CAD[2] $3 per dose and in Canada was available through veterinarians (Grier and Schmidt, 2009).

Despite the apparent effectiveness of the vaccine, adoption by cattle producers in regions where the vaccine was licensed for use was very low. A major impediment to adoption was the fact that cattle are unaffected by the presence of *E. coli*, which has no impact on the health of the animal or its productivity. Thus, cattle producers may perceive that the benefits of vaccination primarily flow elsewhere: to downstream actors in the beef supply chain, to consumers, to municipal water authorities, and so on. Other issues may have impacted the commercial uptake of the *E. coli* vaccine, including the cost of vaccination, the extent to which the required changes fit within existing practices and the scale of changes needed, lack of knowledge, the availability of veterinary advice, skepticism over the effectiveness of the intervention, financial constraints, human capital constraints, expected impacts on reputation, export market orientation, as well as anticipated government regulation and liability (Cobanoglu, 2012; Ellis-Iverson *et al.,* 2010; Jayasinghe-Mudalige and Henson, 2006; Ochieng' and Hobbs, 2016). A moral hazard risk may also be present if cattle producers anticipate that vaccinating their cattle will result in reduced efforts to mitigate food safety hazards on the part of other firms downstream in the supply chain (Marette *et al.,* 2012; Ochieng' and Hobbs, 2016).

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[2] 1 CAD (Canadian dollar) = 0.76 USD; calculated on the basis of the exchange rate on December 12, 2016

In the absence of incentives in the form of market premiums for vaccinated cattle, vaccination becoming a pre-requisite for securing a buyer, or the risk of direct penalties (market access, reputational or liability penalties) from being identified as the source of an *E. coli* contamination event, there appears to have existed little direct commercial incentive for cattle producers to vaccinate their cattle. Tonsor and Schroeder (2015) discuss the additional costs of vaccination and the absence of market premiums for vaccinated cattle as major impediments to widespread adoption of the vaccine by U.S. cattle producers, while Ochieng' and Hobbs (2016) find market incentives (price premiums for vaccinated cattle or buyers requiring vaccination), along with measures to offset the costs of vaccination, to be attractive adoption incentives for Canadian cattle producers.

3. Methods

Given the costs to the agriculture and food sector and to society as a whole from *E. coli* O157:H7 and the apparent promise of cattle vaccination as a pre-harvest intervention strategy, a deeper understanding of the factors affecting cattle producers' willingness to adopt this type of vaccine is warranted. Using data from a survey of western Canadian cow-calf producers, a clearer picture of the adoption environment is provided, including producers' experience with and awareness of *E. coli* and of the vaccine, their perceptions of who benefits from the vaccine within the supply chain and who bears the primary responsibility for reducing *E. coli* risks. A probit analysis is used to identify the significant factors influencing willingness to adopt the vaccine, including producer characteristics, attitudinal variables, and a set of market, policy, production protocol and reputational incentives for adoption. This section describes the data collection process and provides details of the probit model specification.

Data were gathered through an online survey of western Canadian cow-calf producers drawn from an animal health/producer database managed by Ipsos Agriculture and Animal Health[3]. Cow-calf producers in the three prairie provinces of Alberta, Saskatchewan and Manitoba were surveyed in July 2014. These three provinces represent the largest share of the beef cow population (82%) in Canada at 40.7, 29.8 and 11.6% respectively (CanFax, 2014). A token incentive payment of CAD $20 was provided to participants who completed the survey. Pre-screening questions on location (province) of operation and number of beef cows ensured the survey sample matched the distribution of cow-calf production across the three prairies provinces and was comprised of producers with varying sizes of operations. Before proceeding with the survey, respondents were asked to confirm whether they were the person with overall or joint responsibility for the animal health management practices in use in their cow-calf operation.

The survey gathered data on several aspects of the cattle farming operation, attitudes to and knowledge about *E. coli* risks and interventions including vaccination protocols, familiarity of cattle producers with *E. coli* and with the vaccine, attitudes towards *E. coli* risks, use of management practices/interventions within the cow-calf operation to mitigate *E. coli* risks, the extent to which producers exhibited an internal versus external locus of control with respect to *E. coli* risks within the production environment, barriers to adoption of the vaccine, and demographic information[4]. A more detailed discussion of the insights from the data is provided in the section 'The adoption environment: descriptive statistics'. In analyzing producers' willingness to adopt the vaccine, a binary probit model is developed.

Probit model specification

Survey respondents were asked to indicate their willingness to adopt an *E. coli* vaccine in response to an adoption incentive (discussed below), with three possible responses: yes, no, and don't know/unsure. A standard probit model specification is used (Supplementary Methods S1 for details).

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[3] The survey received research ethics approval from the University of Saskatchewan Behavioural Research Ethics Board (BEH # 14-136) on June 27, 2014.

[4] A copy of the survey instrument is available from the authors upon request.

Adesina and Baidu-Forson (1995) note the need for technology adoption studies to expand the range of explanatory variables beyond broad socio-economic, demographic and institutional determinants by including farmers' subjective perceptions of the characteristics of new agricultural technologies. In this study, willingness to adopt is assumed to be a function of a set of producer and farm characteristics, attitudes, experience and the presence of a set of adoption incentives. The probit model estimation is specified as:

$$\begin{aligned}\mathit{Willingness\ to\ adopt}_i = {} & \beta 0 + \beta 1\ \mathit{Gender}_i + \beta 2\ \mathit{Age}_i + \beta 3\ \mathit{Education}_i + \beta 4\ \mathit{Experience}_i \\ & + \beta 5\ \mathit{Continuity}_i + \beta 6\ \mathit{Sales/revenue}_i + \beta 7\ \mathit{Livelihood}_i + \beta 8\ \mathit{Retain}_i \\ & + \beta 9\ \mathit{Size}_i + \beta 10\ \mathit{Location}_i + \beta 11\ \mathit{Awareness}_i + \beta 12\ \mathit{Responsibility}_i \\ & + \beta 13\ \mathit{Benefits}_i + \beta 14\ \mathit{External\ locus\ of\ control}_i \\ & + \beta 15\ \mathit{Internal\ locus\ of\ control}_i + \beta 16\ \mathit{Individual\ best\text{-}worst\ scores}_i + \varepsilon_i\end{aligned} \qquad (1)$$

where *i* represents the individual and ε_i: is assumed to be a random error with a zero mean and finite variance.

The explanatory variables are described in Table 1 and include socio-demographic and farm-level characteristics to control for the effect of gender, age, level of education, number of years as a principal decision maker (experience), expected continuity as a cow-calf producer (continuity), the percentage of sales/revenues derived from cow-calf operations (revenue), dependence on cow-calf operations (livelihood), retaining ownership of cattle through the feedlot stage of production (retain), size of beef cow herd (size), and location (Alberta and Manitoba, with Saskatchewan omitted as a reference variable). For the most part, these are control variables with no *a priori* expectations as to the effect on willingness to adopt. Three exceptions are for livelihood (dependence on cow-calf operations), revenue, and retained ownership, where there is a weak expectation that producers with greater reliance on the cow-calf operation for their livelihood, or for whom a greater percentage of revenues is derived from cow-calf operations, or who retain ownership through the feedlot stage of production, might be more risk averse with respect to supply chain disruptions, liability or reputational risks from an *E. coli* outbreak that was traced to their cattle, and therefore have a higher willingness to adopt the vaccine.

Other explanatory variables capture psychographic, attitudinal and knowledge variables. These include a variable capturing producer awareness of the *E. coli* vaccine technology and a set of dummy variables controlling for producers' perceptions with respect to who bears primary responsibility for *E. coli* risk reduction between cow-calf producers, feedlots, packers, retailers, consumers, and regulators[5]. It is expected that producers who believe cow-calf producers bear the primary responsibility will be more willing to adopt the vaccine, or conversely those who believe primary responsibility lies elsewhere in the supply chain will be less likely to adopt.

Using the same set of categories, respondents were asked who they perceived to be the primary beneficiaries of an *E. coli* vaccine. *A priori* we expect respondents who perceive cow-calf producers to be the primary beneficiaries will be more likely to express a willingness to adopt. This variable is specified as a dummy variable, with 1 where respondents indicated cow-calf producers as the primary beneficiary, and 0 otherwise.

The survey assessed the extent to which respondents exhibited an internal versus an external locus of control with respect to their ability to control *E. coli* risks in their cow-calf operation. It is hypothesized that producers with an internal locus of control (meaning that they believe they can take concrete actions to reduce. *E. coli* risks within their farm environment) will have a higher willingness to adopt the vaccine, while those who believe that *E. coli* risks are largely exogenous to their actions (an external locus of control) are hypothesized to be less likely to adopt. Measured on a 5 point Likert scale from 'Completely disagree' to 'Completely agree' three survey questions reflected an internal locus of control: 'I feel in control of potential *E. coli* contamination due to my existing management practices/interventions'; 'Whether or not I'm successful in

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[5] Perception of primary responsibility for reducing *E. coli* risks is comprised of a set of separate dummy variables for each of the categories given the difficulty of interpreting an aggregated coefficient. To avoid problems of collinearity, 'cow-calf producers' serves as the reference category and is omitted from the estimation. The fifth category dummy variable (retailers) did not receive any responses, hence its omission from the estimated model.

Table 1. Variable descriptions.

Variable	Description
Dependent variable	
Willingness to adopt	Willingness of cow-calf producer to adopt an *E. coli* vaccine, coded 1 if yes, 0 otherwise.
Explanatory variables	
Gender	Coded as 1 if male and 0 if otherwise.
Age	Actual age of respondent in years.
Education	Education level coded as 1, for respondents with an education level at or above college and 0 otherwise.
Experience	Years as principal decision-maker in the cow-calf operation. Mid-points of range: less than 4 years, 5-20 years, 21-35 years, 35 years and over.
Continuity	Years respondent plans to continue as a cow-calf producer. Mid-points of range: <1 year, 1-5 years, 6-10 years, 10-25 years, >25 years.
Sales/revenues	Percentage of revenues derived from cow-calf operations. Treated as a categorical variable with 1 representing 0-24%, 2 representing 25-49%, 3 representing 50-79%, and 4 representing 80-100%.
Livelihood	Importance of cow-calf operations to livelihood, coded as 1 if very important and essential and 0 if otherwise.
Retain ownership	Retained ownership of cattle/calves during the feeding/finishing process, coded 1 if 'yes' and 0 if 'no'.
Size of operation	Number of beef cows in the cow-calf operation.
Location	Province/territory of operation with Saskatchewan as the reference (omitted) variable. Two dummy variables coded 1 if Alberta, 0 otherwise; and 1 if Manitoba, 0 otherwise.
Awareness	Awareness of *E. coli* vaccine, coded 1 if the respondent has heard of an *E. coli* vaccine and 0 otherwise.
Responsibility	Perception of who bears primary responsibility for reducing *E. coli* incidences, with cow-calf producers as the reference (omitted) category. A set of dummy variables each coded 1 if feedlots, 0 otherwise; 1 if packers/processors, 0 otherwise; 1 if retailers, 0 otherwise; 1 if consumers, 0 otherwise, and 1 if regulators and 0 otherwise.
Benefits	Perception of who would benefit the most from an *E. coli* cattle vaccine, coded as 1 if cow-calf producers and 0 otherwise.
External locus of control	External locus of control with respect to *E. coli* risks (average of Likert scale responses to three external locus of control questions): 'My success as a cow-calf operator depends mostly on luck'; 'It is not advisable for me to plan too far ahead by enhancing my current management practices because *E. coli* incidences are such that they cannot be fully prevented'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by factors beyond my control'.
Internal locus of control	Internal locus of control with respect to *E. coli* risks (average of Likert scale responses to three internal locus of control questions): ' I feel in control of potential *E. coli* contamination due to my existing management practices/interventions'; 'Whether or not I'm successful in mitigating/controlling *E. coli* depends mostly on my own ability'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by the management practices I have in place'.
Individual BWS scores	Respondent's best-worst scaling (BWS) scores for each of 13 incentives (see Table 2).

mitigating/controlling *E. coli* depends mostly on my own ability'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by the management practices I have in place'. Three questions reflected an external locus of control: 'My success as a cow-calf operator depends mostly on luck'; 'It is not advisable for me to plan too far ahead by enhancing my current management practices because *E. coli* incidences are such that they cannot be fully prevented'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by factors beyond my control'. Responses to the three internal and external locus of control questions were averaged to give an internal and an external locus of control score for each respondent, each of which represented a separate variable in the analysis. *A priori* expectations suggest that, if significant, the internal locus of control variable will be positive and the external locus of control variable negative.

The final set of explanatory variables capture cattle producers' responses to a set of potential vaccine adoption incentives. The survey featured a set of best-worst scaling (BWS) questions in which respondents were asked to indicate the incentive which would be most likely to influence (best) and least likely to influence (worst) their adoption of an *E. coli* vaccine from a series of repeated choice sets featuring different combinations of thirteen adoption incentives. Each incentive appeared four times across the repeated choice sets, with each choice set featuring four incentives. A detailed discussion of the design and analysis of the BWS experiment is beyond the scope of this paper and is available in Ochieng' and Hobbs (2016)[6]. Table 2 lists the thirteen adoption incentives, which are grouped into government (policy) intervention incentives, market/supply chain incentives, production protocol incentives, and producer reputation incentives.

For each survey respondent, the number of times an incentive was selected as 'worst' in the choice sets is subtracted from the number of times it is selected as 'best' to provide a BWS value. As each of the 13 incentives appeared four times through the repeated choice tasks, the individual level scales for each of the incentives range from +4 to -4. For example, a score of +2 would be obtained if a survey respondent chose

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[6] The analysis presented in Ochieng' and Hobbs (2016) focuses on the Best-Worst Scaling experiment, which produces a preference ranking of the 13 adoption incentives and uses a latent class cluster analysis to identify heterogeneity among producers with respect to their responses to the adoption incentives. The present paper embeds the adoption incentives within a broader analysis of the factors affecting producers' willingness to adopt the vaccine.

Table 2. Adoption incentives.

Government intervention incentives
• Government recommending use of *E. coli* vaccine for cattle.
• Subsidy to compensate the costs of my adoption of the vaccine is available through a government vaccination program.
Market/supply chain incentives
• Premiums for *E. coli* vaccinated cattle are available through various programs (branded beef program) within the supply chain.
• Attraction of a new set of buyers for my vaccinated cattle.
• My buyer requiring use of vaccine as part of the production protocol as a condition for accepting my calves/cattle.
• Feedlots providing an assurance that they will give my cattle a booster of the *E. coli* vaccine to maintain the immunity of my cattle.
• Through vaccination, my farm is less exposed to the effects of *E. coli* outbreaks, such as beef recalls and supply disruptions at packing plants.
Production protocol incentives
• Recommendation from my veterinarian to use the *E. coli* vaccine in my operations.
• I can include an *E. coli* vaccination in my existing vaccination routine.
• Duration of immunity for my calves/cattle is greater than six months.
Producer reputation incentives
• Beef products from my calves/cattle can be traced back to my farm/operations.
• My reputation for a cattle producer is at risk because of higher consumer expectations concerning food safety.
Other
• My neighbors (other cattle producers) are adopting the *E. coli* vaccine.

an incentive as most desirable three times and least desirable once. Respondents' individual BWS scores for each of the thirteen incentives are included as separate explanatory variables in the probit regression model.

Following the BWS choice sets, respondents were asked 'Would you consider adopting an *E. coli* vaccine if presented with incentives such as some of those appearing above?' Responses to this question provide data for the dependent variable in the probit regression: 145 (71%) responded 'yes', 8 'no', and 50 'unsure/don't know'. For the purposes of the binary probit model, the dependent variable is coded 1 for 'Yes' and 0 for 'No/unsure'.

4. The adoption environment: descriptive statistics

A final sample of 203 survey responses were received, with the distribution of the sample closely corresponding to the cow-calf population across the three provinces (46.7% of respondents from Alberta, 35% from Saskatchewan, and 17.7% from Manitoba).[7] The mean herd size was 210, ranging from 2 to 11,000. The mean age of respondents was 54, ranging from 29 to 77. Just over one third (34.5%) of the sample had high school level education, with another third (35.5%) having completed trade school/college and around 28% holding a university degree. This sample consists of relatively well-educated respondents which may reflect the mode of recruitment (producer animal health database) and the online nature of the survey. The sample is also comprised of relatively experienced cattle producers, with just over one third (35.5%) having over 35 years of experience as the principal decision-maker in the cow-calf operation, and another third (33.5%) having between 21-35 years of experience, while 27% of respondents had 5 to 20 years of experience. The survey data paint a rich picture of the vaccine adoption environment for this set of survey respondents, providing a useful backdrop to the discussion of the probit regression results that follows.

Cow-calf producers expressed a fairly high degree of awareness of *E. coli*, with 76% of survey respondents indicating that they were either very familiar or somewhat familiar with *E. coli* 0157:H7. Only 5% of respondents were currently using the *E. coli* vaccine and a further 7% had previously used the vaccine but were not doing so at the time of the survey. Just under half of the respondents (46%) indicated that they had heard of the vaccine but had not used it. The remaining 42% of respondents had never heard of the vaccine. Use (either currently or previously) and familiarity with the vaccine were both associated with a higher stated willingness to adopt the vaccine in response to an adoption incentive. All of the producers currently using the vaccine and 86% of respondents who had previously used the vaccine indicated a positive willingness to adopt given the right incentive, while 75% of those who had previously heard of but never used the vaccine and 62% of those who had not previously heard of the vaccine indicated a willingness to adopt if the right incentive was in place.

Primary sources of information on *E. coli* included producer associations (37%), followed by veterinarians (29%), then government agencies such as provincial government ministries (10%). About 11% of respondents indicated having no source of information regarding *E. coli*. A producer's veterinarian was typically the first point of contact regarding *E. coli* for 44% of respondents, followed by government information services (18%), the Internet (17%), producer associations (13%), other cow-calf producers (7%), with only a couple of respondents (1%) indicating consultants.

Asked who bears primary responsibility for reducing the risk of *E. coli* problems in the beef supply chain, the majority (56%) of respondents identified beef processors/packers. Only 15% of respondents indicated cow-calf producers, another 15% indicated feedlots, 8% said consumers and only 5% identified regulators such as the CFIA. Nobody indicated that the primary responsibility lay with food retailers. Conversely, survey respondents were asked who would benefit the most from a vaccine to reduce colonization and shedding of *E. coli* by cattle. The most popular response (41%) was consumers, followed by processors/packers (26%)

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[7] Respondents could exit the survey at any time with incomplete surveys not included in the final sample size, therefore, the final sample includes only fully completed survey responses. Information on the number of incomplete surveys or non-responses is not available.

and cow-calf producers (21%), with the other potential agents (feedlots, retailers, municipal water security agencies) receiving relatively few responses. Responses to these questions – specifically whether or not cow-calf producers hold primary responsibility and are the primary beneficiaries – provide data for two of the explanatory variables in the probit regression.

Figure 1 summarizes responses to the locus of control questions and shows that cow-calf producers within the survey sample on average tended towards an internal locus of control with respect to their perceived ability to control *E. coli* risks in their farm operation, although a larger proportion were neutral with respect to the external locus of control measures.

The extent to which an *E. coli* vaccine fits within the producer's existing vaccination protocol is expected to influence the likelihood of adoption. The vast majority (87%) of respondents vaccinate their calves, with 49% indicating that they did so twice a year, and 39% one a year. The majority of respondents (77%) typically carry out the vaccination themselves (or an employee does the vaccination), with only about 5.4% using their veterinarian. This suggests that an *E. coli* vaccine would need to be reasonably accessible and easy to use to remain consistent with typical vaccination protocols. 27% of respondents indicated they spend between $1 and 4.99 per calf on vaccinations per year, while 30% spend CAD $5 to 6.99 per calf, and 28% of respondents spend more than $7 per calf. At $3 per dose, the *E. coli* vaccine is a non-trivial addition to these costs.

Finally, the extent to which various factors deter respondents from adopting the vaccine was explored (yes/no responses). Focused on barriers to adoption, this set of survey questions differs from the BWS adoption

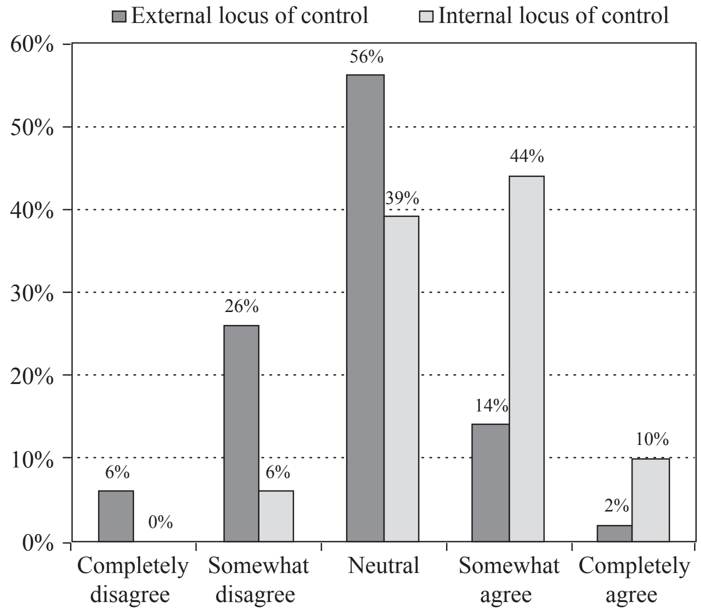

Figure 1. Locus of control for *E. coli* risks: summary of responses (n=203). 'Internal locus of control' measured as average of responses to three Likert scale questions: 'I feel in control of potential *E. coli* contamination due to my existing management practices/interventions'; 'Whether or not I'm successful in mitigating/controlling *E. coli* depends mostly on my own ability'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by the management practices I have in place'. 'External locus of control' measured as average of Likert scale responses to three questions: 'My success as a cow-calf operator depends mostly on luck'; 'It is not advisable for me to plan too far ahead by enhancing my current management practices because *E. coli* incidences are such that they cannot be fully prevented'; 'To a great extent *E. coli* incidences on my cow-calf operation are determined by factors beyond my control'.

incentives outlined in Table 2 and adds further richness to our understanding of both the incentives and barriers to adoption. Uncertainty over the market benefits of adopting the vaccine and over the efficacy of the vaccine as an intervention measure featured strongly in these responses, as shown in Figure 2.

A number of insights arise from this overview of the adoption environment for the *E. coli* vaccine and provide context for the probit analysis that follows. Although survey respondents exhibited a fairly high degree of awareness of *E. coli* and almost half of respondents had heard of the *E. coli* cattle vaccine, only around 5% were using the vaccine which is consistent with previous assessments of vaccine usage rates (Grier and Schmidt, 2009). A potential disconnect is evident between perceptions of who bears primary responsibility for risk reduction within the beef supply chain and who is the primary beneficiary of the vaccine. Few (15%) of producers believed that cow-calf producers bear primary responsibility for risk reduction or were the primary beneficiaries of an *E. coli* vaccine (21%), suggesting that commercial incentives to adopt the vaccine were weak. There are many potential barriers to adoption, but uncertainty over benefits and over efficacy (in a whole supply chain sense) appear to have resonated particularly strongly across the survey sample. We turn now to a formal consideration of the factors influencing willingness to adopt with the results of the probit analysis.

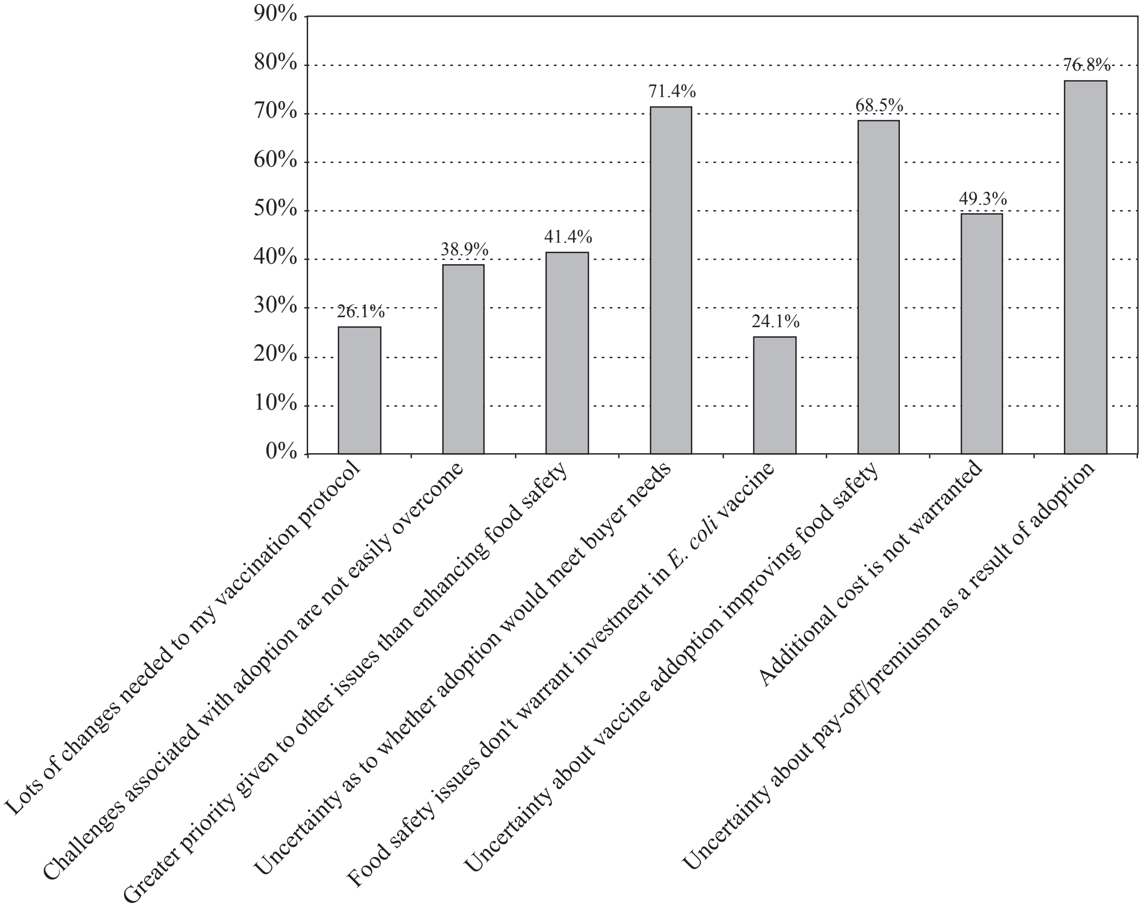

Figure 2. Barriers to adopting an *E. coli* vaccine (percentage of respondents) (n=203). Percentage of respondents answering 'Yes' to the question: 'Please indicate whether the following issues deter you from adopting an *E. coli* vaccine'.

5. Probit regression results

Cow-calf producers were asked whether they would consider adopting the *E. coli* vaccine if presented with the right incentives such as those appearing in Table 2. Responses to this question form the dependent variable in the probit analysis. The full probit model was run on all 32 variables specified in Tables 1 and 2. All estimations were conducted using STATA 2013 (StataCorp LP, College Station, TX, USA). Parameter estimates for the full model are provided in Supplementary Table S1.

The results reveal that 20 of these variables are significant determinants of willingness to adopt, including a producer's level of education, prior awareness of the vaccine, and perceptions of who bears primary responsibility for risk reduction, which is consistent with the assertions of Adesina and Baidu-Forson (1995). An external locus of control with respect to the perceived ability to control *E. coli* risks was also significant, as were all 13 adoption incentives as captured by the BWS scores. Other producer characteristics, such as gender and age, as well as the location (province) of the cow-calf operation, herd size, retained ownership, the relative importance of the cow-calf business to the producer's livelihood, and the length of time the producer anticipating continuing in the business, were not statistically significant[8].

Following the estimation of the full probit model inclusive of all variables, a stepwise assessment of model fit allowed insignificant variables to be dropped one-by-one, with the model re-estimated sequentially as each variable was omitted. The resulting reduced model dampens the effects of the insignificant variables and produces more robust marginal effects estimations. Parameter estimates from the reduced model estimations are presented in Table 3.

For purposes of interpretation, the marginal effects of these parameter estimates are needed. The marginal effect of an independent variable measures the impact of a change in an independent variable (e.g. X_i) on the expected change in the dependent variable (e.g. Y) [9]. Thus, a marginal effect shows the change in probability when the explanatory or independent variable increases by one unit. Alternatively, for a dummy variable, marginal effects measure discrete change or how predicted probabilities change as the binary independent variable changes from 0 to 1. The marginal effects from the reduced model parameter estimates are presented in Table 4.

The estimated marginal effect for education shows that the change from less than college education to at or above college increases the probability of willingness to adopt an *E. coli* vaccine by 20.3%. It is possible that producers with higher levels of education have a better understanding and appreciation of technologies to reduce food safety risks.

Unsurprisingly, prior awareness of the *E. coli* vaccine had a positive and significant ($P \leq 0.05$) effect on stated willingness to adopt the vaccine. The estimated marginal effects show that on average, prior awareness increased willingness to adopt by 16.1%.

The largest marginal effects include several of the 'primary responsibility' variables. Recall that these variables measure the effect on willingness to adopt of a producer's perception that the primary responsibility for reducing risks of *E. coli* problems within the beef supply chain lies with the indicated party rather than with cow-calf producers (the reference category). The negative and significant marginal effect for each of these four variables is consistent with *a priori* expectations, which suggest that cow-calf producers are less likely to be willing to adopt the vaccine if they believe the primary responsibility lies elsewhere in the supply chain. The perception that primary responsibility lay with feedlots, consumers, and regulators were all highly

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[8] The Chi-square value shows the goodness of fit of the data to the model. A value of 51.43 indicates the choice of the explanatory variables in the binary probit model explained the variations in adoption decisions fairly well. An ordered probit model was also estimated, where the dependent variable took the order of the three categories of 'yes', 'don't know/unsure' and 'no' responses. Results of the ordered probit model, which are similar in nature, are not reported here in the interests of brevity but are available in Ochieng' (2015).

[9] Calculation of the marginal effects was as follows: $Y = \phi\,(\beta_0+\beta_1\chi_1+\beta_2\chi_2+\ldots+\beta_n\chi_n)$, thus $\delta Y/\delta\chi_i = \beta_i\,Ø\,(\beta_0+\beta_1\chi_1+\beta_2\chi_2+\ldots+\beta_n\chi_n)$.

Table 3. Binary probit reduced model – parameter estimates.[1]

Variable	**Coefficient**[2]	**Std. err.**	***P*-value**
Level of education	0.639***	0.228	0.005
Awareness of technology	0.522**	0.228	0.022
primary responsibility for *E. coli* risk reduction – feedlots	-1.391***	0.489	0.004
Primary Responsibility *E. coli* risk reduction – processor/packer	-0.807**	0.418	0.054
Primary Responsibility *E. coli* risk reduction – consumers	-1.497***	0.550	0.007
Primary Responsibility *E. coli* risk reduction – regulators	-1.599***	0.611	0.009
External locus of control	-0.379***	0.152	0.013
Beef products can be traced to my farm	0.882***	0.297	0.003
Premiums available through branded programs	0.787***	0.288	0.006
Recommendation from my veterinarian	0.759***	0.290	0.009
Subsidy to compensate cost of adoption available	0.717***	0.284	0.012
Government recommending use of vaccine	0.673**	0.286	0.018
My reputation as producer is at risk	0.766***	0.284	0.007
My buyer requiring use of vaccine	0.785***	0.292	0.007
Feedlots providing assurance for a booster	0.857***	0.293	0.003
Duration of immunity greater than 6 months	0.800***	0.293	0.006
Through vaccination I can reduce supply disruptions	0.841***	0.295	0.004
My neighbors adopting vaccine	0.737***	0.282	0.009
Attraction of a new set of buyers	0.650**	0.279	0.020
I can include vaccine in an existing vaccination routine	0.763***	0.297	0.010
Constant	1.831	0.644	0.004
N	203		
Pseudo R-sq.	0.212		

[1] Dependent variable = willingness to adopt.

[2] ** = $P<0.05$; *** = $P<0.01$.

Table 4. Binary probit reduced model – marginal effects

Variable	**Dy/Dx**	**Std. err.**	***P*-value**
Level of education	0.203	0.074	0.006
Awareness of technology	0.161	0.071	0.024
Primary responsibility for *E. coli* risk reduction – feedlots	-0.499	0.166	0.003
Primary responsibility for *E. coli* risk reduction – processor/packer	-0.232	0.058	0.035
Primary responsibility for *E. coli* risk reduction – consumers	-0.543	0.151	0.002
Primary responsibility of for *E. coli* risk reduction – regulators	-0.576	0.181	0.001
External locus of control	-0.115	0.046	0.012
Beef products can be traced to my farm	0.266	0.088	0.003
Premiums available through branded programs	0.238	0.086	0.006
Recommendation from my veterinarian	0.229	0.086	0.008
Subsidy to compensate cost of adoption available	0.216	0.085	0.011
Government recommending use of vaccine	0.203	0.085	0.017
My reputation as producer is at risk	0.231	0.084	0.006
My buyer requiring use of vaccine	0.237	0.087	0.007
Feedlots providing assurance for a booster	0.259	0.087	0.003
Duration of immunity greater than 6 months	0.242	0.087	0.006
Through vaccination I can reduce supply disruptions	0.254	0.088	0.004
My neighbors adopting vaccine	0.223	0.084	0.008
Attraction of a new set of buyers	0.196	0.083	0.018
I can include vaccine in an existing vaccination routine	0.231	0.089	0.009

significant ($P\leq0.01$) with beef packers significant at $P\leq0.05$ (Table 3). The magnitude of the marginal effect for feedlots in Table 4 suggests that producers who believed feedlots, rather than cow-calf producers, held the primary responsibility were 50% less likely to be willing to adopt the vaccine, 23% less likely for those who believe packers bore the primary responsibility and 54% less likely for those who felt the primary responsibility lay with consumers. The clear inference here is that when cow-calf producers believe the primary responsibility for *E. coli* lies elsewhere in the beef supply chain, they are unlikely to adopt this type of vaccine, regardless of the effectiveness of the vaccine as a pre-harvest intervention strategy within food supply chains. The opportunity for consumers to mitigate the risks of exposure to *E. coli* contamination by properly cooking beef products might also explain the large marginal effect for consumers. As indicated in the discussion of the adoption environment, a slight majority of respondents felt that packers held primary responsibility, with relatively few placing that responsibility with consumers or regulators.

Consistent with *a priori* expectations, the external locus of control variable is negative and highly significant ($P\leq0.01$), suggesting that if a producer believes that *E. coli* risks lie beyond his/her control, he/she will less open to adopting this type of vaccine even given the right incentives. Cow-calf producers in this survey sample were 11.5% less likely to adopt the vaccine if they believed that controlling *E. coli* risks lay largely beyond their control.

The remaining 13 variables in Tables 3 and 4 represent the effects of the adoption incentives as captured in the BWS scores. Consistent with *a priori* expectations, each of these variables is positive and significant at $P\leq0.01$ with the exception of 'Government recommending use of the vaccine' and 'attraction of a new set of buyers' which are significant at $P\leq0.05$ (Table 3).

6. Policy and managerial implications

A number of policy and managerial implications flow from the analysis with respect to pre-harvest intervention strategies with the potential to reduce societal food safety risks, as well as informing future product development and commercialization strategies for similar products.

Education and prior awareness of the technology are positive determinants of willingness to adopt, yet almost half of the sampled producers (42%) had not previously heard of the *E. coli* vaccine technology. Furthermore, if a producer believes that primary responsibility for *E. coli* risk reduction lies with other members of the supply chain he/she is significantly less likely to consider using the vaccine. Similarly, if producers believe that there is little they can do within their farm operation to mitigate *E. coli* risks, such that these risks lie largely outside of their control, they are significantly less likely to be willing to vaccinate their cattle. Taken together, these results suggest that steps to inform producers about the vaccine, its potential broader benefits, and the role of producers in mitigating *E. coli* risks will be important components of any strategy to encourage broader adoption of these types of technologies from a commercial perspective for firms in the animal health business or from a policy perspective if this is deemed to be in society's best interest. Producer associations and veterinarians were previously identified as important sources of information and therefore may be particularly influential in the design and implementation of awareness programs for similar vaccines in the future.

Efforts to enhance producer education and awareness regarding management techniques (including but not limited to use of an *E. coli* vaccine) to reduce risk of *E. coli* contamination or cross-contamination within the cow-calf operation, may also be warranted from a societal perspective. This may be particularly pertinent with respect to management practices that reduce contamination of irrigation or drinking water supplies, including removal of farm animals from the proximity of private water supplies (such as wells, boreholes), prevention of ground water contamination or contamination of ready-to-eat crops from farm run-off, or keeping livestock out of ready-to-eat crops using fencing (LeJeune and Wetzel, 2007; Soon *et al.,* 2011). Further work could examine the potential role of information provision in encouraging adoption, including what is communicated, how and by whom.

The low adoption rates for the Econiche vaccine, and its eventual removal from the market, suggest that tangible economic incentives within the beef supply chain are necessary for the adoption of these types of technologies. In this study, willingness to adopt was framed in the context of thirteen potential adoption incentives (Table 2). Some of the adoption incentives take can be viewed as 'carrots', while others are 'sticks'. Reputational effects include adoption incentives that take the form of a threat (the stick), such as the possibility that beef products could be traced to the producer's farm or the producer's reputation being at risk. Incentives related to the practicality of using the vaccine also influence willingness to adopt, including the duration of immunity, the ability to include the vaccination within existing vaccination routines, and a recommendation from the producer's veterinarian. While market-driven incentives appear to dominate, the practicalities of using a new vaccine remain a relevant consideration; indeed Figure 2 shows that 'lots of changes to my vaccination protocol' would deter adoption for a non-trivial portion of respondents. The positioning of new vaccines therefore needs to take into consideration how the vaccine fits within producers' existing vaccination routines in terms of timing, access and availability.

The market-driven incentives (carrots) are of particular interest, reflecting requirements by new or existing buyers for vaccination, price premiums for vaccinated cattle, or an assurance that vaccination protocols are continued through the feedlot stage of production, and their importance is confirmed in other work (Ochieng' and Hobbs, 2016)[10]. These incentives reflect the need for a whole supply chain approach to reducing *E. coli* risks within the food system, with interventions possible at the cow-calf, feedlot and packing plant levels of the chain. Indeed, if cow-calf producers vaccinate their calves but feedlots do not, then the potential societal gain from vaccination may be reduced. If only some cow-calf producers vaccinate their calves and those calves are subsequently mixed with non-vaccinated animals, the potential commercial benefits of reduced exposure to beef recalls and supply disruptions for those who vaccinate is likely to be considerably weakened. If vaccination by cow-calf producers induces beef packers to take less care and attention in mitigating *E. coli* risks during processing – a moral hazard effect – benefits from vaccination may be watered down. Exploration of these broader incentives to adopt risk mitigation interventions at other stages of the beef supply chain, and the extent to which they complement or substitute for risk mitigation actions at the cow-calf producer level lies beyond the scope of the present analysis, but represents a fruitful area for further research.

Finally, this research is relevant for the development of similar livestock vaccinations or other animal health interventions with wider societal benefits for human or environmental health. Despite compelling scientific evidence of the efficacy of a vaccine in reducing *E. coli* colonization and shedding in cattle, adoption rates by cattle producers throughout the period in which the *E. coli* vaccine was commercially available were low, and the vaccine is no longer on the market. Since cattle are asymptomatic carriers of the *E. coli* pathogen, cattle producers receive little direct commercial benefit from the vaccine without stronger market or liability pressures to adopt. Early consideration of the economic incentives to adopt a vaccine could allow more informed research and development decisions into innovations that address food safety risks through pre-harvest interventions, as well as inform commercialization strategies for these products. In the absence of commercial pressure from downstream buyers for cow-calf producers and feedlots to adopt pre-harvest risk mitigation measures such as vaccination, there is little incentive for adoption. Future product development and commercialization strategies for these types of products should incorporate an understanding of the supply chain dynamics within the cattle/beef sectors in which the product is to be commercialized, including the extent to which downstream buyers are likely to require or encourage vaccination by their suppliers.

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[10] Ochieng' and Hobbs (2016) present a detailed analysis of the underlying best-worst scaling experiment, finding the three most influential incentives to be: 'my buyer requiring use of the vaccine', 'subsidy to compensate costs of adoption' and 'premiums available through branded beef programs'. Heterogeneity in producer responses to adoption incentives is explored using a latent class cluster analysis which identifies a market/supply chain oriented cluster, a production protocol cluster and a risk averse producer cluster.

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Supplementary material

Supplementary material can be found online at https://doi.org/10.22434/IFAMR2016.0177.

Methods S1. Standard probit model specification.
Table S1. Binary probit full model – parameter estimates.

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