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The consequences of a human food pathogen vaccine on food demand: a calibrated partial-equilibrium analysis of the U.S. beef market

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Human vaccines against several common foodborne pathogens are being developed and could substantially alter consumer and producer behaviour in the markets for foods commonly afflicted by these pathogens. To understand the possible impacts of such an innovation, we derive and calibrate a partial-equilibrium model using parameters for consumer vaccine uptake from stated-preference work under an array of assumptions concerning industry moral hazard, consumer awareness and alternative preventive effort exercised by consumers. We simulate three scenarios in the U.S. beef sector: the introduction of a vaccine, the tightening of pathogen standards for beef production and the simultaneous introduction of both vaccinations and tighter standards. Our simulation shows that all policies can increase aggregate surplus given most calibrations; though, the largest effects are attributed to vaccine introductions, which reduce expected damages from foodborne illness among vaccinated consumers without shifting firm costs. However, unaware consumers and aware consumers who choose not to vaccinate experience no change in expected damages when a vaccine is introduced but face a higher price of food because of the stronger demand of food from vaccinated consumers.

Key words: beef, cost of ignorance, food safety, partial equilibrium, vaccination.

1. Introduction

The development of human vaccines to protect against food pathogens is progressing rapidly (e.g see Flynn 2009 [*Escherichia coli* vaccine] and Stevens 2009 [*Salmonella* and *Campylobacter* vaccines]). Each vaccine is at a different stage of development. The inventor of the *E. coli* vaccination reports that discussions are underway with pharmaceutical companies to approve the vaccine through clinical trials (Fosmire 2011; MSU 2011). The research team investigating *Campylobacter* vaccines has demonstrated efficacy across several animal species (Monteriro *et al.* 2009), while advances concerning the study of *Salmonella* activation (Crabbe *et al.* 2011) suggest promising pathways to vaccine development.

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This research may produce applications that have important impacts on food markets. Such vaccines would represent a discrete improvement in the technology available to combat foodborne illness. The widespread availability of such vaccines may trigger a cascade of possible actions by consumers and industry that could impact substantially the markets for foods historically affected by foodborne pathogens. However, to our knowledge, there exists no previous work that models how the introduction of such a vaccine might impact the functioning of food markets, and furthermore, there exists little investigation into the role of consumer self-protection on aggregate food demand.[1]

In this study, we develop a partial-equilibrium model that specifically accounts for the introduction of such a consumer vaccine and traces out changes to consumer and producer surplus in the affected food market under a variety of possible consumer and industry responses. Our analysis accounts for several key nuances that would impact aggregate market outcomes, including the possibility that some consumers are unaware of foodborne threats, that aware consumers may alter other self-protection activities, that firms may decrease pathogen-reduction vigilance in response to consumer vaccination and that vaccinations are imperfect in stopping all sources of foodborne illness. We then calibrate the model using parameters from the previous econometric studies of the U.S. beef sector and from the previous stated-preference studies of uptake for such vaccines.

From this calibrated model, we simulate three scenarios. The first is the sale of a vaccine. This intervention leaves firms' marginal beef production costs unchanged (or lower under moral hazard assumptions) and can stimulate beef demand among the vaccinated. However, unaware consumers and aware consumers who choose not to vaccinate experience no change in expected damages (or higher expected damages under moral hazard) but face a higher price of food because of stronger beef demand from vaccinated consumers.

The second policy simulated is the introduction of tighter standards that lower the ambient pathogen level and expected consumer damages (see Unnevehr 2000). This shifts the marginal cost curve upward, while shifting beef demand upward via a reduction in expected damages among aware consumers. Unaware consumers suffer from higher beef prices but suffer a lower cost of ignorance as expected damages diminish with tighter standards. The third policy simulated is the simultaneous introduction of the first two policies.

We find that, under many parameter assumptions concerning vaccine effectiveness, industry moral hazard and consumer response via alternative self-protection activities, vaccinated consumers prefer the vaccine policy to be

[1] Eom (1997) models consumer self-protection from foodborne illness pathogens in an attempt to derive the linkages between information and self-protection activity but does not consider discrete alternatives like vaccines nor the aggregate impact on food supply.

implemented independently. However, the introduction of a vaccine can have disparate effects across consumers as those who fail to adopt the vaccine may be exposed to higher pathogen loads if industry exhibits moral hazard and higher beef prices if industry maintains previous food safety practices. Firms may prefer the joint policy, but the result depends upon the exact magnitudes of vaccine uptake, marginal cost shifts and assumptions concerning consumer beef demand.

Our work differs from the previous food safety work in that it is the first to focus on the market-level effects of a new self-protection technology. The bulk of extant literature in food safety economics focusses on understanding the conceptual and methodological challenges faced in understanding consumer willingness to pay for food safety interventions (Teisl and Roe 2010) or on the costs or market impacts of firm-level food safety regulations (Antle 2000). Our work also differs from the general literature on the economics of vaccines, which largely focus on establishing vaccine demand for communicable diseases (Cropper *et al.* 2004) or the role of public versus private vaccination efforts in disease eradication (Geoffard and Philipson 1997). On the basis of the estimates of consumer willingness to pay for new foodborne pathogen vaccines, the calibration exercise illustrates our contribution with a simple example for showing that the methodology can be used and refined by public authorities for estimating welfare measures of policies. We contribute to the literature by going beyond estimations of willingness to pay for a product, and by generating welfare estimates for different policy scenarios on the beef market indirectly impacted by human vaccines against foodborne pathogens.[2]

From a policy point of view, our work may reignite discussions about the relative roles of consumers and industry in ensuring the safety of a nation's food supply and the distributional consequences of different policies. The literature contains little discussion about the optimal balance of consumer versus industry effort for improving food safety, and the work that exists is either highly theoretical in nature (Roe 2004) or focussed on how the costs of food safety certification should be shared (Crespi and Marette 2001).

In the next section, we develop the partial-equilibrium model. In the following sections, we calibrate a model of the U.S. beef sector using parameters from the literature and then derive market results for the scenarios outlined above. We end with discussion and concluding remarks.

2. The partial-equilibrium model

We begin by specifying consumer preferences in the spirit of Polinsky and Rogerson (1983) but with some differences. The demand of consumer i is derived from the following expected utility expression:

[2] See Roosen and Marette (2011) for details about the link between experimental results and welfare analysis.

$$\mathrm{EU}(q_i, w_i, p_i, I_i, \pi_i, e_i) = \{1 - I_i\pi_i\}\left(aq_i - \bar{b}q_i^2/2\right) + I_i\{\pi_i\} \left(aq_i - \bar{b}q_i^2/2 - r_iq_i\right) + w_i - \mu e_i, \tag{1}$$

where a and $\bar{b}$ are the linear and quadratic preference parameters for beef, q_i is the quantity of beef consumed, π_i is the consumer's subjective probability of acquiring foodborne illness, I_i is an indicator variable that equals one if the consumer is aware that beef may contain the pathogens targeted by the vaccine, r_i is the per-unit damage consumer i expects to suffer in the event of foodborne illness, w_i is the amount spent on a numeraire good, μ is the per-unit cost of preventive effort and e_i is the quantity of preventive effort expended by consumer i to avoid the foodborne illness.

The subjective probability of becoming ill $\pi_i \in [0, 1)$ is:

$$\pi_i = \pi_i(S, e_i) = \pi^0(S, e_i) + (1 - V_i(\rho, S, e_i))\Delta\pi, \tag{2}$$

where S is the ambient safety of the food provided by firms, $V_i(\rho, S, e_i)$ is an indicator variable that equals one if the consumer chooses vaccination and ρ is the price of the vaccination. Without vaccination, $V_i(\rho, S, e_i) = 0$, which means the consumer faces a strictly positive probability of illness equal to $\pi^0(S, e_i) + \Delta\pi > 0$. Vaccination implies $V_i(\rho, S, e_i) = 1$, which provides a reduction $\Delta\pi$ in the probability of becoming ill. However, even with vaccination, the consumer may still face a positive probability of becoming ill ($\pi^0(S, e_i) \geq 0$) because of either imperfections in the vaccine or threats from other foods and contaminants that are not eliminated by industry (S) or personal effort (e_i). For instance, someone could take a vaccine against *E. coli* O157:H7 because they like undercooked meat and poultry. This undercooked meat or poultry could easily harbour Salmonella or some other harmful pathogen, making the person sick.

Furthermore, for simplicity, we view beef as an undifferentiated good and assume that all consumers face identical prices (beef, vaccine and preventive effort) and identical expected damages ($r_i = r$). Ambient (average) food safety is public knowledge across all consumers. We also assume that vaccine supply is perfectly elastic and priced at marginal cost. We also assume that preventive efforts other than the vaccination are fixed in the short run and that these costs are rolled into the numeraire expenditure w_i; though, this assumption can be relaxed.[3]

With previous assumptions and Equation (2), we can rewrite (1) as follows:

$$\mathrm{EU}(q_i, w_i, p_i, I_i, e_i, S, \rho) = aq_i - \bar{b}q_i^2/2 - I_i\{\pi^0(S, e_i) + (1 - V_i(\rho, S, e_i))\Delta\pi\}rq_i + w_i. \tag{3}$$

[3] Overall preventative effort towards food safety reflects decisions about many foods and many sources of foodborne illness while we model the market for a single food. Further, broad-based food handling and preparation habits may exhibit substantial inertia. Hence, in the short run, overall effort may change little and may not be cognitively attached to decisions concerning vaccination, which may be influenced by medical advice received by a consumer.

The utility function (3) is maximised via the choice of q_i and subject to the budget constraint of $pq_i + \rho V_i + w_i = y_i$, where p is the price of beef and y_i denotes the income of consumer i. This leads to the following inverse demand function: $p = a - \overline{b}q_i - I_i\{\pi^0(S, e_i) + (1 - V_i(\rho, S, e_i))\Delta\pi\}r$. The demand for consumer i is $q_i(p, I_i, V_i) = [a - p - I_i\{\pi^0(S, e_i) + [1 - V_i(\rho, S, e_i)]\Delta\pi\}r]/\bar{b}$. For consumer i, the discrete decision (0 or 1) to become vaccinated depends upon a simple comparison of the price of the vaccine to the expected damages, including all the sources of contamination and their impacts on different products (recall there may be other sources of contamination in addition to the goods studied in this partial-equilibrium setting). The effort e_i is also fixed for the time being.

Hence, the likelihood of vaccination by consumer i is decreasing in the price of vaccination (ρ), the effort (e_i) and increasing in the per-unit damage (r). Note that, for simplicity, we assume no income effects, for example, you never buy less meat because you have to pay for the vaccine. We assume that the probability of purchasing the vaccine $V_i(\rho, S, e_i)$ is the same for all consumers and, after aggregation, can be shifted in a proportion estimated via the econometric estimation and defined by $\hat{V}(\rho, S, e_i)$ as described in the next section. The function defined by (3) is used to calculate Marshallian welfare linked to the beef market only.

Aggregate demand for the good is obtained by summing individual demand functions over all N consumers. For the vaccinated consumers, we assume $I_i = 1$, which means that consumers are aware that the food may imply a damage r and may contain the pathogens targeted by the vaccine. This assumption means that the ones choosing the vaccine are highly concerned and aware of damages.

Conceptually, total demand can be partitioned into three groups: (i) those who are vaccinated, (ii) those who are not vaccinated and aware of the damage and (iii) those who are not vaccinated and unaware of the damage.

The proportion $\hat{V}(\rho, S, e_i)$ of consumers is vaccinated and has an individual demand denoted as $q_i(p,1,1)$. However, even with vaccination, the consumer may still face a positive probability of becoming ill ($\pi^0(S, e_i) \geq 0$) because of either imperfections in the vaccine or threats from other foods and contaminants. With $b = \overline{b}/N$, the demand over the $\hat{V}(\rho, S, e_i)N$ consumers is defined by

$$Q_1^D(p) = \sum_{i=1}^{\hat{V}(\rho, S, e_i).N} q_i(p,1,1) = \frac{\hat{V}(\rho, S, e_i) \times (a - p - \pi^0(S, e_i)r)}{b}. \qquad (4)$$

The proportion $1 - \hat{V}(\rho, S, e_i)$ of consumers is not vaccinated and may suffer damage equal to r. Among them, a proportion β of consumers are not aware of the damage ($I_i = 0$). This group generates a cost of ignorance in the welfare analysis. A proportion $(1 - \hat{V}(\rho, S, e_i))\beta$ of consumers who are not vaccinated and are not aware of the damage have an individual demand denoted as $q_i(p, 0, 0)$. The demand over the $(1 - \hat{V}(\rho, S, e_i))\beta N$ consumers is defined by

$$Q_2^D(p) = \sum_{i=1}^{(1-\hat{V}(\rho,S,e_i))\beta N} q_i(p,0,0) = \frac{(1-\hat{V}(\rho,S,e_i))\beta(a-p)}{b}. \tag{5}$$

The damage does not impact the demand because of this segment's lack of awareness. The cost of ignorance (or non-internalised damage) $\{\pi^0(S,e_i)+\Delta\pi\}rQ_2^D(p)$ is taken into account in the welfare calculation. It means that the regulator takes into account the subjective probability and damage estimated by consumers in the cost of ignorance and not the one expressed by experts.

Eventually, a proportion $(1-\hat{V}(\rho,S,e_i))(1-\beta)$ of consumers who are not vaccinated and are aware of the per-unit damage r will have an individual demand denoted as $q_i(p,1,0)$. The demand over the $(1-\hat{V}(\rho,S,e_i))(1-\beta)N$ consumers is:

$$\begin{aligned} Q_3^D(p) &= \sum_{i=1}^{(1-\hat{V}(\rho,S,e_i))(1-\beta)N} q_i(p,1,0) \\ &= \frac{(1-\hat{V}(\rho,S,e_i))(1-\beta)(a-p-\{\pi^0(S,e_i)+\Delta\pi\}r)}{b}. \end{aligned} \tag{6}$$

The damage is internalised and there is no cost of ignorance. The overall demand is:

$$\begin{aligned} Q^D(p) &= Q_1^D(p)+Q_2^D(p)+Q_3^D(p) \\ &= \frac{a-p-\hat{V}(\rho,S,e_i)\pi^0(S,e_i)r-(1-\hat{V}(\rho,S,e_i))(1-\beta)\{\pi^0(S,e_i)+\Delta\pi\}r}{b}, \end{aligned} \tag{7}$$

which is a relatively simple expression that can be calibrated for given values of β and $\hat{V}(\rho)$.

The respective inverse demands are:

$$\begin{cases} p_1^D(Q) = \mathrm{Max}\left[0, a-\pi^0(S,e_i)r-\frac{bQ}{\hat{V}(\rho,S,e_i)}\right] \text{ vaccinated consumers} \\ p_2^D(Q) = \mathrm{Max}\left[0, a-\frac{bQ}{[1-\hat{V}(\rho,S,e_i)]\beta}\right] \text{ non}-\text{vaccinated and unaware consumers} \\ p_3^D(Q) = \mathrm{Max}\left[0, a-\{\pi^0(S,e_i)+\Delta\pi\}r-\frac{bQ}{[1-\hat{V}(\rho,S,e_i)](1-\beta)}\right] \text{ non}-\text{vac./aware cons.} \end{cases} \tag{8}$$

The proportion $\hat{V}(\rho,S,e_i)$ influences the balance between demands. Note that a value of $\hat{V}(\rho,S,e_i)$ tending towards 0 leads to $p_1^D(Q)=0$ (the same effect is valid for other inverse demands).

On the supply side, a perfectly competitive industry with price-taking firms is assumed regardless of any policy intervention. There are M firms. Firms' cost functions are quadratic in output, and they choose output to maximise profits:

$$\pi_i = pq_j - fq_j - (1/2)cq_j^2 \quad \text{for} \;\; j = \{1, \ldots, M\}, \tag{9}$$

where f and c are parameters defining the variable cost.[4] The profit maximisation yields individual firm supply functions that can be added up to yield overall industry supply:[5]

$$Q^S = \frac{M(p-f)}{c}. \tag{10}$$

The parameters c and f will vary with the food safety policies chosen. In particular, $c_H > c$ means that firms confronted with tighter food pathogen regulations incur higher marginal cost than firms with looser standards.

For both simplicity and ease of exposition, the profits and surpluses are described graphically. Figure 1 represents the baseline scenario with the quantity on the horizontal axis and the prices on the vertical axis.

With the baseline scenario, there is no vaccine (equivalent to $\rho \rightarrow \infty$ leading to $\hat{V}(\rho) \rightarrow 0$) and standards are at a baseline level. As a result, $\hat{V}(\rho, S, e_i)$ is 0 and $p_1^D(Q)$ defined in (8) is equal to 0. For the unaware consumers, the demand $p_2^D(Q)$ with $\hat{V}(\rho, S, e_i) = 0$ is represented by D_2, and for the aware consumers, the demand $p_3^D(Q)$ with $\hat{V}(\rho, S, e_i) = 0$ is represented by D_3. In Figure 1, the baseline scenario is represented by the equilibrium price p^E that equalises the overall demand $D_2 + D_3$ and the overall supply S based on

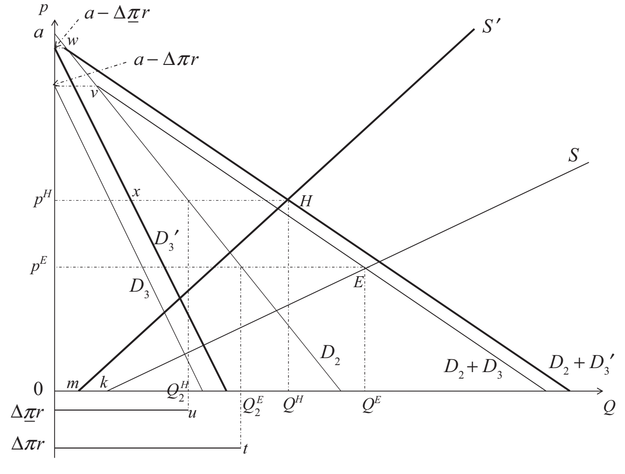

Figure 1 Baseline and tighter standards scenarios.

[4] A complete analysis should consider the impact that sunk costs have on the entry and exit of producers.

[5] Individual supply functions are only defined for prices exceeding average costs, because otherwise firms would obviously cease production.

Equation (8). For unaware consumers, the demand $p_2^D(Q)$ is represented by D_2 and implies a cost of ignorance because of the absence of internalisation of the expected damage r. The value of the overall cost of ignorance is $\{\pi^0(S, e_i) + \Delta\pi\} r Q_2^E$, where Q_2^E is the consumption by the proportion β of unaware consumers at the price p^E. For simplicity, we assume that $\pi^0(S,\, e_i) = 0$, which means that the cost of ignorance is $\{\pi^0(S, e_i) + \Delta\pi\} r Q_2^E = \Delta\pi r Q_2^E$. The consumer surplus with the cost of ignorance for the unaware consumers is defined by the area $p^E Eva$-$0\Delta\pi rt Q_2^E$ in Figure 1. The producer profit is defined by the area $OkEp^E$.

Tightening pathogen standards for all firms leads to an upward supply (S) shift linked to the cost increase, with the new supply curve represented by the bold line S' in Figure 1. Implementing tighter standards decreases the subjective probability to $\Delta\underline{\pi}$ with $\Delta\underline{\pi} < \Delta\pi$. The cost of ignorance decreases for the unaware consumers because the expected per-unit damage $\Delta\underline{\pi}r$ is lower because of the standard with $\Delta\underline{\pi}r < \Delta\pi r$. The aware consumers increase their demand to D_3' because the expected per-unit damage $\Delta\underline{\pi}r$ is internalised in this demand. Under tighter standards, the new equilibrium H leads to a price p^H and a quantity Q^H. The consumer surplus with the cost of ignorance for unaware consumers is defined by the area $p^H Hwa$-$0\Delta\underline{\pi} ru Q_2^H$ in Figure 1. The aware consumers' surplus is equal to $(a - \Delta\underline{\pi}) p^H x$ and the producer profit is defined by the area $OmHp^H$. The welfare effect of tighter standards implementation characterised by the comparison of welfare in E and H depends on the relative change of the supply curve and the probability of contamination. If the proportion of unaware consumers β is large relative to other parameters, the equilibrium quantity Q^H in H is lower than the equilibrium quantity Q^E in E because of the supply shift.

We now turn to the case where the vaccine is introduced. Figure 2 represents the impact of the vaccine (with $\hat{V}(\rho, S, e_i) > 0$) on the market allocation compared with the baseline scenario in point E (with the demand represented by the dashed curves). For the vaccinated consumers, the demand defined by Equation (6) is $p_1(Q)$ and represented by D_{1v} in Figure 2. Compared with the baseline scenario E, the curves of unvaccinated consumers decrease with $D_{2v} < D_2$ and $D_{3v} < D_3$ because $\hat{V}(\rho, S, e_i) > 0$. The number of aware consumers with a demand depending on the damage decreases when the number of vaccinated consumers increases.

With the vaccine, the new equilibrium V leads to a price p^V and a quantity Q^V. The proportion $[1 - \hat{V}(\rho, S, e_i)]$ of unvaccinated consumers influences the cost of ignorance of the unaware consumers defined by the area $0\Delta\pi rn Q_2^V$. The consumer surplus, including the cost of ignorance, is defined by the area $p^V Vza$-$0\Delta\pi rn Q_2^V$ in Figure 2. The producer profit is defined by the area OVp^V. As the vaccine purchase and its demand are not detailed in our framework, we do not integrate the vaccine cost in our analysis of the welfare variation. Clearly, the effects on firms or consumers are different under tighter pathogen standards and vaccine policies. To explore these differences, we parameterise the model in an attempt to calibrate the U.S. beef market.

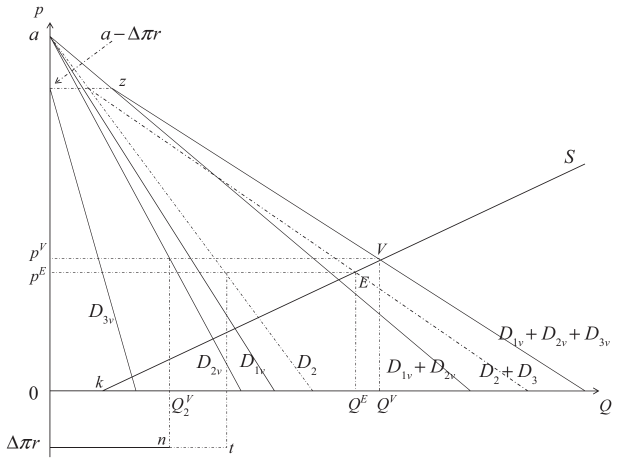

Figure 2 Baseline and vaccination scenarios.

3. Model parameterisation

Calibration of the model requires fundamental supply and demand parameters for the U.S. beef market as well as information concerning vaccine uptake, consumer expected damages, consumer awareness and marginal cost shifts owing to tighter pathogen standards. We consider the beef market for the year 2006. The consumer demand parameters a and b as defined in the baseline scenario can be determined by standard calibration methods using existing data on price elasticity of beef demand and equilibrium prices and quantities of beef (see Table 1).

Using existing data on the quantity $\hat{Q}_E$ of beef during 2006, the average price $\hat{p}^E$ observed during 2006, and the direct price elasticity $\hat{\varepsilon} = (\mathrm{d}Q_E/\mathrm{d}P^E)(P^E/Q_E)$ obtained from time-series econometric estimates, the calibration of $Q^D(p)$ given by (5) leads to estimated values for the demand equal to $1/\tilde{b} = -\hat{\varepsilon}\hat{Q}_E/\hat{p}^E$ and $\tilde{a} = \tilde{b}\hat{Q}_R + \hat{p}^E + (1-\beta)\{\pi^0(S, e_i) + \Delta\pi\}r$. The value $\{\pi^0(S, e_i) + \Delta\pi\}r$ is determined by experimental results as explained in the following paragraph. The calibration of the demand is made for initial situations where the vaccine does not exist, so $\hat{V}(\rho, S, e_i) = 0$.

Table 1 Values of parameters for the calibrated model of beef in 2006 in the USA

	Value
Beef consumption in 2006 (million lbs)*	8248.6
Beef price in 2006 (US $)*	2.73
Own-price elasticity of demand*,†	−0.504
Own-price elasticity of supply‡	0.9

Source: *Lusk and Marette (2010). †Bryant and Davis (2008). ‡Authors' assumptions. Notes: We abstract away from quality differences linked to the leanness because, to the best of our knowledge, there are no data on quantities differing by fat content at the retail level – only prices varying by fat content. As a percentage of beef purchases, 43% are of lower fat and remaining 57% is of higher fat products. Thus, the weighted average price would be $0.43 \times 3.26 + 0.57 \times 2.34 = 2.73$.

For estimating the per-unit damage r, we take results given by experimental economics. Hayes *et al.* (1995) found respondents willing to pay 15–30 per cent more for food that is essentially completely safe from five pathogens found in ground beef (with realistic probabilities linked to these risks revealed to consumers). This experiment measured the participants' bids to exchange a real (and relatively risky) hamburger similar to those participants could buy in fast food stores for a riskless hamburger. This willingness to pay is often used as the social value of non-contamination and is widely cited.[6] This experiment did not include *Listeria* and participants were students. We take into account the relative change in the willingness to pay equal of 30 per cent given by Hayes *et al.* (1995). The 30 per cent represents in relative terms what they are willing to pay to go from a subjective probability $\{\pi^0(S, e_i) + \Delta\pi\}$ to 0 risk (recall that there is no vaccine with $V_i(\rho, S, e_i) = 0$). Despite flaws, we use this relative change in the willingness to pay to calibrate $\{\pi^0(S, e_i) + \Delta\pi\}r$.

Regarding the calibration, the expected per-unit damage is defined *ex ante*, including this perceived probability. The relative change in the willingness to pay given by the experiment is equal to the expected damage $\{\pi^0(S, e_i) + \Delta\pi\}r$ relative to the equilibrium price $\hat{p}^E$, namely $\{\pi^0(S, e_i) + \Delta\pi\}r/\hat{p}^E = 0.3$. From the Foodborne Diseases Active Surveillance Network survey used for the stated-preference data (see the next paragraph and Table 2 for details), the median respondent had a subjective probability that 10 per cent of hamburger found in stores would cause sickness (before any vaccine decision), so we say that the subjective probability $\{\pi^0(S, e_i) + \Delta\pi\} = 0.1$. The per-unit damage r is defined by the following equality: $r = 0.3 \times \hat{p}^E/(0.1)$. This value is used in the baseline scenario. Note that, in the baseline scenario, there is only the subjective probability $\{\pi^0(S, e_i) + \Delta\pi\} = 0.1$, which does not imply any assumption regarding the vaccine efficiency and the related share between $\pi^0(S, e_i)$ and $\Delta\pi$.

To measure the impact of the tighter pathogen standards, we assume that the probability is divided by two with $\underline{\pi}^0(S, e_i) + \Delta\underline{\pi} = (\pi^0(S, e_i) + \Delta\pi)/2 = 0.05$. It is also assumed a cost $c_H = 1.1 \times c$ with c defined in Equation (9) when tighter standards are introduced. The initial proportion of unaware consumers is $\beta = 0.2$, which is consistent with results of the 2001 Food Safety Survey where between 10 and 20 per cent of respondents had reported being unaware of pathogens like *Salmonella* or *E. coli*.

Vaccine uptake is calibrated using stated-preference results (details about the method and data are provided in Marette *et al.* 2012). In it, we use data obtained from the Foodborne Diseases Active Surveillance Network survey to estimate U.S. consumer acceptance of food safety vaccines that would protect the individual from *Salmonella, E. coli* or *Listeria* across various time

[6] This approach differs from the case where we would estimate the magnitude of damage from *ex post* cost of illness estimates. For instance, we could consider ERS estimates in 2006 that the average cost of suffering an *E. coli*-related illness was \$6067 and suffering *Salmonella*-related illness was \$1766. See data available at http://www.ers.usda.gov/data/foodborneillness/.

Table 2 Variables and estimated model coefficients

	Description of variables	Mean (standard deviation)	Probit coefficients: prob (purchase vaccine)
No Illness	= 1 if the respondent believes no illness will occur from the food-pathogen combination proposed in the stated preference question	0.121 (0.326)	−0.660** (0.301)
Severity Illness	Respondent's perception of the severity of possible foodborne illness from the food-pathogen combination proposed in the stated preference question (mild = 1, moderate = 2 or severe = 3)	2.352 (0.724)	−0.104 (0.238)
Cost of Vaccine	Cost of vaccine in survey question	61.948 (28.166)	−0.0088*** (0.0007)
Salmonella	= 1 if the proposed target of the vaccine was *Salmonella*	0.540 (0.498)	0.017 (0.070)
Escherichia coli	= 1 if the proposed target of the vaccine was *Escherichia coli*	0.297 (0.457)	0.248*** (0.075)
Hamburger	= 1 if the food mentioned in the scenario was hamburger	0.247 (0.431)	−0.087 (0.068)
Lettuce	= 1 if the food mentioned in the scenario was lettuce	0.249 (0.433)	0.074 (0.103)
Eggs	= 1 if the food mentioned in the scenario was eggs	0.249 (0.433)	0.054 (0.080)
Vaccine duration	Proposed duration of the vaccine in years	17.979 (23.306)	0.026*** (0.004)
Vaccine duration^2		323.244 (543.170)	−0.0002*** (0.00005)
Age < 25	Respondent < 25 years	0.117 (0.322)	0.208*** (0.068)
Age > 65	Respondent > 65 years	0.159 (0.366)	−0.305*** (0.064)
Female	= 1 if respondent is female	0.582 (0.493)	−0.016 (0.055)
Education	Education level (in years)	14.027 (3.206)	−0.017** (0.007)
Income	Income (in \$10 000)	5.669 (3.666)	0.019*** (0.005)
Insure	= 1 if respondent reports any medical insurance	0.906 (0.292)	−0.067 0.064)
Loss	= 1 if respondent missed work due to illness	0.263 (2.991)	0.010* (0.006)
Intercept		–	0.889* (0.535)

Notes: *, **, ***Denotes the estimated coefficient is significantly different from zero at the 10, 5 and 1% level of significance. Standard errors are presented in parentheses.

periods. We assume an individual's probability of purchasing the vaccine is a linear function of the respondent's subjective assessment of their risk of getting sick, the respondent's subjective assessment of the severity of potential illness without the vaccine, the vaccine's attributes (price, duration of protection) and other respondent characteristics. In Table 2, we reproduce the results of the vaccine uptake model, which details the probability of purchasing the vaccine used in the calibrated partial-equilibrium model, with a description of the variable used. Note that the vaccination choice is already driven by consumers' risk aversion via the *Severity of Illness* variable (in Table 2), so it is already part of our model.

The average vaccine uptake used in Equations (2)–(6) is given by:

$$\hat{V}(\rho, S, e_i) = F[\hat{\theta}_1 \rho + \hat{\theta}_2 \text{ duration} + \hat{\theta}_3 \text{ duration}^2 + \hat{\Theta}^T_{\text{Dummies}} I + \hat{\Theta}^T_{\text{other}} \bar{X}] \tag{11}$$

where $F(.)$ is the standard normal cumulative density function. From the last column of Table 2, $\hat{\theta}_1 = -0.0088$ is the estimated coefficient linked to the vaccine price ρ, and $\hat{\theta}_2 = 0.026, \hat{\theta}_3 = -0.0002$ are the estimated coefficients linked to the *duration*, which is assumed to be a single year. The transposed vector $\hat{\Theta}^T_{\text{Dummies}}$ takes into account the estimated coefficients linked to the vector of dummy variables I, which correspond to the type of disease (*E. coli* in our case) and to the type of products (*hamburger* in our case). The transposed vector $\hat{\Theta}^T_{\text{other}}$ integrates all the other estimated coefficients of Table 2, and $\bar{X}$ is the vector of the average values of the other independent variables used in the estimation. The vaccine price ρ is varied as part of the simulations and different possibilities are considered regarding $\pi^0(S, e_i)$.

4. Results

We simulate three cases. Under case 1, the vaccine price is $\rho = 50$ and the initial proportion of unaware consumers is $\beta = 0.2$. Under case 2, the vaccine price is $\rho = 20$ and the initial proportion of unaware consumers is $\beta = 0.2$. For cases 1 and 2, we assume that the vaccine is completely efficient and perfectly eliminates all risks with $\Delta\pi = 0.1$ and $\pi^0(S, e_i) = 0$. For case 3 (with $\rho = 50$ and $\beta = 0.2$ as with case 1), we consider an imperfect vaccine reducing two-thirds of the risk with $\pi^0(S, e_i) = (1/3) * 0.1$ and $\Delta\pi = (2/3) * 0.1$, which leaves subjective post-vaccination risk of 0.033. In this case 3, the combination of the vaccine and tighter pathogen standards leads to the subjective probability divided by 2 with $\underline{\pi}^0(S, e_i) = (1/6) * 0.1$ and $\Delta\underline{\pi} = (2/6) * 0.1$.

Table 3 presents results for the year 2006 in the United States given these parameter values. Separate welfare calculations are reported for firms and for the three groups of consumers (vaccinated, unaware unvaccinated and aware unvaccinated). Three policies are considered: vaccination, tighter standards and a combination of vaccination and tighter standards.

Table 3 Variation in the U.S. beef market owing to tighter standards and vaccine introduction compared with the baseline scenario (in \$)

	Standard	Vaccine	Standard + vaccine
Case 1: $\beta = 0.2, \rho = 50, \pi^0(S, e_i) = 0$			
Average vaccine uptake (%)	0%	53%	50%
Price variation (\$)	0.46 (16.9%)	0.12 (4.6%)	0.52 (19.2%)
Quantity variation (million lbs)	−205.8 (−2.4%)	342.5 (4.1%)	−50.3 (−0.6%)
Profit variation (million \$)	693.5 (5.5%)	1060.4 (8.5%)	1204.1 (9.7%)
Consumer surplus variation (million \$)	−347.2 (−1.6%)	2756.7 (13.1%)	848.3 (4%)
Vaccinated	—	3219.1 (28.7%)	1266.3 (12.0%)
Non-vaccinated, unaware	−8.1 (−0.1%)	−92.5 (−4.8%)	−53.1 (−2.6%)
Non-vaccinated, aware	−339.0 (−2.0%)	−369.9 (−4.7%)	−364.8 (−4.3%)
Welfare variation	346.3 (1.0%)	3817.1 (11.4%)	2052.4 (6.1%)
Case 2: $\beta = 0.2, \rho = 20, \pi^0(S, e_i) = 0$			
Average vaccine uptake (%)	0%	62%	59%
Price variation (\$)	0.46 (16.9%)	0.14 (5.3%)	0.53 (19.6%)
Quantity variation (million lbs)	−205.8 (−2.4%)	397.4 (4.8%)	−23.4 (−0.2%)
Profit variation (million \$)	693.5 (5.5%)	1234.5 (9.9%)	1293.3 (10.4%)
Consumer surplus variation (million \$)	−347.2 (−1.6%)	3185.4 (15.2%)	1051.3 (5.0%)
Vaccinated	—	3621.9 (27.8%)	1430.8 (11.5%)
Non-vaccinated, unaware	−8.1 (−0.1%)	−87.3 (−5.6%)	−50.8 (−3.0%)
Non-vaccinated, aware	−339.0 (−0.2%)	−349.2 (−0.2%)	−338.6 (−4.7%)
Welfare variation	346.3 (1.0%)	4419.9 (13.2%)	2344.7 (7.0%)
Case 3: $\beta = 0.2, \rho = 50, \pi^0(S, e_i) > 0$			
Average vaccine uptake (%)	0%	53%	0%
Price variation (\$)	0.46 (16.9%)	0.07 (2.6%)	0.49 (18.2%)
Quantity variation (million lbs)	−205.8 (−2.4%)	199.7 (2.4%)	−115.1 (−1.3%)
Profit variation (million \$)	693.5 (5.5%)	613.3 (4.9%)	990.1 (7.9%)
Consumer surplus variation (million \$)	−347.2 (−1.6%)	1968.6 (9.1%)	485.8 (2.3%)
Vaccinated	—	2169.7 (19.3%)	801.8 (7.6%)
Non-vaccinated, unaware	−8.1 (−0.1%)	−54.2 (−2.8%)	−32.7 (−1.6%)
Non-vaccinated, aware	−339.0 (−2.0%)	−216.9 (−2.7%)	−283.2 (−3.3%)
Welfare variation	346.3 (1.0%)	2511.9 (7.0%)	1476.0 (4.4%)

Note: Relative variation (%) compared with the baseline scenario in parentheses.

Table 3 shows that, for the three cases, the total welfare variation is positive under all three policies. However, not all parties gain under all scenarios and different parties would likely prefer different policy options. Within a given row, the vaccine uptake differs between columns 2 and 3, because the improved standards alter vaccine uptake (defined by (11)). The standard increases the 'No Illness' variable defined in Table 2. We assume that the 'No Illness' variable increases from 0.121 to 2 * 0.121, which decreases the vaccine uptake. Note that a standard also impedes firms from slackening their safety effort when consumers are vaccinated.

Let us first consider the consumer point of view. In all three cases, for consumers in aggregate, the vaccine policy (second column) generates greater benefits than tighter standards (first column) because the price increase is much smaller with vaccination than with tighter standards (see the difference between Figures 1 and 2). This is driven by the fact that, under tighter standards, firm costs rise and drive up equilibrium price. That is, the disutility caused by increased prices outweighs the improved utility from diminished expected damages for the set of parameters chosen in this simulation.

While consumer benefits from vaccination are positive in aggregate, not all consumers benefit. In fact, vaccinated consumers are the only group of consumers to benefit under this policy. Non-vaccinated consumers suffer from the price increase linked to the demand shift caused by vaccinated consumers but find no relief from damages as beef continues to contain the same pathogen loads. However, the gains to vaccinated consumers are larger than the losses to non-vaccinated consumers, which leads to large aggregate gains for consumers.

Consumers who would not choose to vaccinate under a vaccination policy prefer tighter standards to a vaccination policy. While tighter standards drive up equilibrium price via an increase in firm costs, these consumers benefit through a reduction in damage provided by the tighter standards.

When considering the consumer point of view regarding the combined policy of both vaccination and tighter standards, we find that it is always the middle option for consumers. Vaccinated consumers prefer a policy of vaccination only because under the combined policy of vaccination and standards they face higher prices owing to increased firm costs; furthermore, those increased firms costs linked to the standard do nothing more for reducing damages as they are already fully protected from all damages.

From the firms' point of view, they prefer vaccinations in combination with tighter standards for the three scenarios explored in Table 3. The policy of vaccination alone yields the second largest improvement in firm profits, while increased standards alone generate the smallest increase in profits.[7] A combination of vaccination and tighter standards strengthens demand even more; though, it also entails an increase in firm costs. Firm's exact preference between vaccination alone and vaccination in tandem with tighter standards will depend upon the size of the increase in costs and the per cent of aware consumers who will increase demand in the face of tighter standards.

Case 2 shows the positive impact of a decline in the vaccine price on both vaccine uptake and welfare. For case 3, the vaccinated consumer may still face a positive probability of becoming ill with $\pi^0(S, e_i) > 0$, which reduces the private and social benefits of vaccination. The impact of the vaccine's imperfection is illustrated by comparing case 3 with case 1 in Table 3. Welfare variation is higher under case 1 with a perfect vaccine ($\pi^0(S, e_i) = 0$) than under case 3 because of the residual risk. Recall that this probability $\pi^0(S, e_i)$ is difficult to calibrate as it depends on medical characteristics.

[7] Note that a tighter standard alone leads to increased profits owing to the relatively low own-price demand elasticity.

5. Other preventive efforts by consumers

We now turn to the precise study of the consumers' preventive effort and the impact of the vaccine on this effort made before consuming. This takes into account other preventive efforts such as preparation practices and careful refrigeration, as an endogenous variable. That is, we now allow the variable e_i in (1) to be endogenous. Some simplifying assumptions are necessary.

First, for simplicity, we detail the choice of effort when the vaccine choice is already decided. It is also assumed that the effort decision is decided before the purchasing decision. In a previous stage, the preventive effort is determined by taking into account the purchase decision of beef and the estimated surplus determined as in Figures 1 and 2 (the 'game' is solved by backward induction). The estimated surplus coming from the beef purchased now integrates the cost of effort, μe_i.

Second, the choice of effort is discrete (e_i equals 0 or 1), which simplifies the calculation regarding the surplus maximisation. Third, the impact of preventive effort on the probability is linear and given by $(1 - \delta e_i)\{\pi^0(S, e_i) + \Delta\pi\}$. An effort $e_i = 1$ reduces the probability of being sick without vaccination $((1 - \delta)\{\pi^0(S, e_i) + \Delta\pi\} > 0)$ or with vaccination $((1 - \delta)\{\pi^0(S, e_i)\} > 0)$. Fourth, it is assumed that inside each subgroup defined in Equation (8), all consumers take the same decision regarding the preventive effort based on the comparison between the surplus with the effort and the surplus without the effort. It means that all the vaccinated and aware consumers make the same decision regarding preventive effort. Similarly, all the non-vaccinated and aware consumers make the same decision, while unaware consumers make no effort ($e_i = 0$). The incentive constraints for making preventive effort are considered for vaccinated and aware consumers and for non-vaccinated and aware consumers.

Fifth, we used the parameters of case 3 (in Table 3) with $\pi^0(S, e_i) > 0$. As the demand $Q_3^D(p)$ for aware consumers given by (6) is positive under the absence of vaccine (namely for $V(\rho, S, e_i) = 0$), the calibration of the baseline scenario without vaccination depends on the effort made by these consumers. The demand can be rewritten as $Q_3^D(p) = (1 - \beta)(a - p - (1 - \delta e)\{\pi^0(S, e_i) + \Delta\pi\}r)/b$. The calibration without vaccination is made for the case where the effort is made (e equal to 1) and for the case where the effort is not made (e equal to 0). For each case, we check that no deviation brings a better surplus and consider cases consistent with this absence of deviation. With a proportion of $\hat{V}(\rho, S, e_i) > 0$ consumers choosing the vaccination, results are presented in Figure 3 with the impact of the effort on the probability δ on the horizontal axis and the overall cost of the effort $\sum\mu$ over all consumers choosing the effort.

For the chart at the top of Figure 3, all aware consumers select effort in the absence of vaccine (which is valid for areas A and B where no deviation is profitable for consumers). The vaccine introduction leads to the following choices in areas A and B. For a relatively low cost of effort compared with the effort efficiency δ (in area A), all consumers continue making the effort.

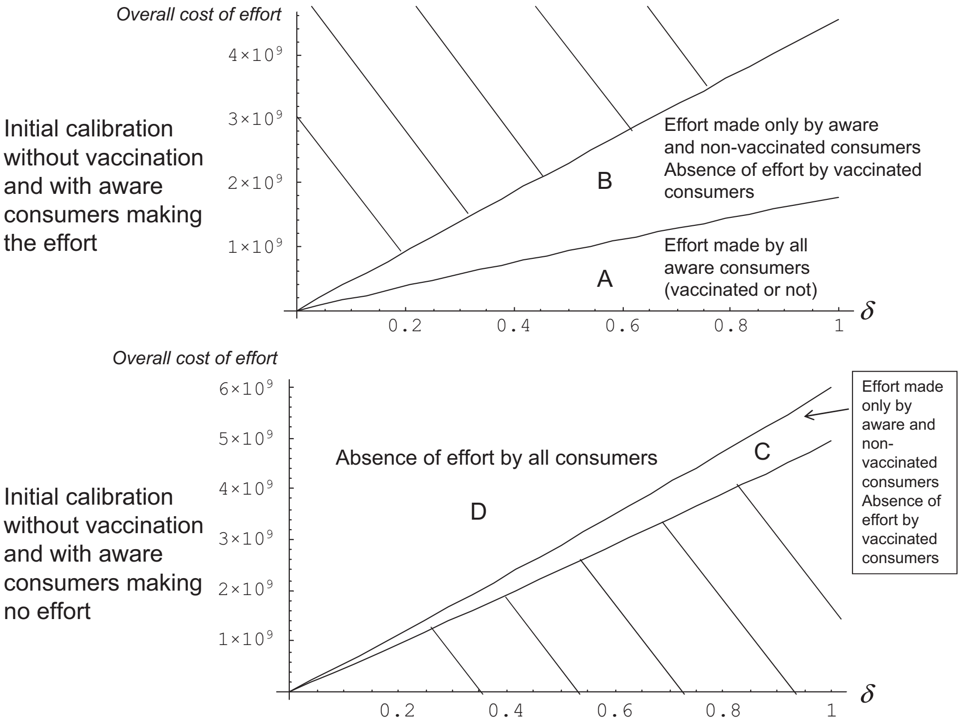

Figure 3 Choice of preventive efforts by vaccinated and non-vaccinated (and aware) consumers.

For a medium cost of effort compared with the effort efficiency δ (in area B), consumers choosing the vaccine do not take preventive effort. In this case, vaccinated consumers slacken their effort compared with the initial situation without vaccine. The shaded area above area B indicates that consumers without any vaccination would have an incentive to avoid preventive efforts, which would contradict the assumption of positive effort made for calibrating the baseline scenario.

For the chart at the bottom of Figure 3, all aware consumers were making no effort under the absence of vaccine (which is valid for areas C and D where no deviation is profitable for consumers and not valid for the shaded area). For a medium cost of effort compared with the effort efficiency δ (in area C), non-vaccinated and aware consumers choose preventive effort, while they did not choose effort in the absence of vaccination. In this case, the vaccination influencing the beef price changed the incentive to make the effort for the non-vaccinated consumers. In area D, the vaccine does not change consumer behaviour because the effort is costly.

6. Extensions and robustness checks

To focus on the main economic mechanisms and to keep the mathematical aspects as simple as possible, the analytical framework was admittedly simple. Our aim was mainly to show that we can go beyond the simple WTP estimations by calibrating a model and studying regulatory choices. To fit different problems coming from various contexts, some extensions should be integrated into the model presented here.

Additional data could be collected for refining the model. In particular, additional data about the time spent by households to prevent foodborne illnesses are necessary for calibrating the parameter μ in (1). Part of these data could be collected by a public authority undertaking a cost-benefit analysis. In several extensions, we also considered a nonlinear demand and the related utility function, which leads to close results compared with the results presented in Table 3 (details can be provided upon request).[8]

In particular, a large proportion of vaccinated consumers may induce moral hazard by firms within the food supply chain, where firms could slacken their prevention efforts. In Table 4, we consider a case where the use of the vaccine by many consumers leads to industry moral hazard with a 10 per cent cost decline and to an increase in the subjective probability $\Delta\pi$ from 0.1 to 0.2 (second column, Table 4) or to 0.15 (third column, Table 4). Within a row, the vaccine uptake differs between columns 1 and 2 (or 3), because the moral hazard decreases the 'No Illness' variable defined in Table 2 and influencing Equation (11). It is assumed that the 'No Illness' variable decreases from 0.121 to 0, which increases the vaccine uptake.

For this example, the large increase (2nd column) in the subjective probability leads to a large decline in the demand by the aware and non-vaccinated consumers, which leads to a large decline in the beef price. In this case, firms lose from slackening their safety effort and the resulting moral hazard is not profitable for the industry; though, because of an inability to coordinate privately, no firm would deviate and refrain from slackening standards. In the third column with $\Delta\pi = 0.15$, the moral hazard response does improve industry profits.

7. Conclusion

In this study, we take the first steps towards evaluating the possible indirect welfare impacts of introducing vaccines that can prevent illness caused by foodborne pathogens. Such an analysis requires an understanding of the potential demand both for such vaccines and for the complementary impact of vaccines on the demand for foods afflicted by the foodborne pathogens

[8] The quasi-linear utility function given by (1) can be replaced by the following function: $[(q_i/\bar{A})^{1+1/\varepsilon} - (\sigma/\bar{A})^{1+1/\varepsilon}]/(1+1/\varepsilon) - I_i\{\pi^0(S,e_i) + \Delta\pi^*(1 - V_i(\rho,S,e_i))\}r_i q_i + w_i$ with a parameter σ close to 0 but >0 since the direct price elasticity ε such that $-1 < \varepsilon < 0$ implies $(1 + 1/\varepsilon) < 0$. The parameter $\bar{A}$ is positive and calibrated for representing the demand over a year. The maximization of this new utility function with respect to quantity and subject to the budget constraint detailed above leads to the following nonlinear demand: $q_i^d = \bar{A}(p + I_i\{\pi^0(S,e_i) + \Delta\pi^*(1 - V_i(\rho,S,e_i))\}r_i)^{\varepsilon}$. These demands are aggregated in a similar way to the system (8) and lead to similar results.

Table 4 Comparison between cases without and with moral hazard by firms

	Vaccine $\Delta\pi = 0.1$	Vaccine and moral hazard leading to $\Delta\pi = 0.2$	Vaccine and moral hazard leading to $\Delta\pi = 0.15$
Case 1: $\beta = 0.2$, $\rho = 50, \pi^0(S, e_i) = 0$			
Average vaccine uptake (%)	53%	56.7%	54.7%
Price variation	0.12 (4.6%)	−0.37 (−13.6%)	−0.32 (−11.9%)
Quantity variation (million lbs)	342.5 (4.1%)	−1016.8 (−12.3%)	−887.5 (−10.7%)
Profit variation (million \$)	1060.4 (8.5%)	−169 (−1.3%)	250.7 (2.0%)
Consumer surplus variation (million \$)	2756.7 (13.1%)	4474.54 (21.4%)	5478.3 (26.2%)
Vaccinated	3219.1 (28.7%)	6083.3 (51.3%)	5819.7 (49.0%)
Non-vaccinated, unaware	−92.5 (−4.8%)	−427.8 (−24.1%)	−112.3 (−6.3%)
Non-vaccinated, aware	−369.9 (−4.0%)	−1180.8 (−16.2%)	−228.4 (−3.1%)
Welfare variation	3817.1 (11.4%)	4304.6 (12.9%)	5729.7 (17.2%)

addressed by vaccination. We build a partial-equilibrium model of the U.S. beef sector that addresses this issue in the context of foodborne illness damages created by *E. coli* contamination.

Our calibrated model suggests that introducing a vaccine against foodborne pathogens may improve both consumer and firm welfare in markets for products that can carry these pathogens. For example, we found the vaccine stimulated demand for beef without imposing additional costs on firms. However, the robustness and magnitude of these market-specific impacts must be further explored in the light of the exploratory nature of our model and the difficulty in calibrating key parameters.

In some ways, the introduction of foodborne pathogen vaccines is not that different from other self-protection efforts by consumers, which include thorough cooking of food, attention to food preparation instructions and other forms of care in the handling, storing and preparing of food. However, if vaccines are popular, it may have large impacts on food markets (as shown in Table 3 for the beef market). These impacts should be taken into account by decision-makers.

Nonetheless, these results can instruct qualitative discussions of the impacts of *ex ante* regulatory measures which could streamline debate. This methodology of combining stated-preference calibration of novel demand elements with the pre-existing estimates of supply and demand parameters derived from market data may be systematically mobilised for cost-benefit analyses that can enlighten decision-makers on the best way to improve food safety.

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