A Farm-to-Fork Stochastic Simulation Model of Pork-borne Salmonellosis in Humans: Lessons for Risk Ranking

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Abstract: For food safety researchers with an interest in assisting public health and agricultural officials design and target effective and efficient policy responses to the risks posed by food-borne pathogens, a food systems view offers many appealing analytic features. These features include the ability to examine comparative questions such as whether it is more efficient to target food safety interventions on-farm or in the food processing plant. Using the example of a farm-to-fork stochastic simulation model of *Salmonella* in the pork production and consumption system, this paper argues the feasibility of such a food systems approach or farm-to-fork model for food safety risk assessment and policy analysis. The paper presents an overview of the farm-to-fork model and highlights key assumptions and methods employed. Lessons from our experience in constructing a farm-to-fork stochastic simulation model are derived for consideration of other food safety risk assessment efforts and for researchers interested in developing “best practice” benchmarks in the area of food safety risk assessments.

Key words: microbial risk assessment, burden of disease, *Salmonella*, salmonellosis, pork, food safety

1. Introduction

Food safety researchers estimate that foodborne pathogens generate billions of dollars of costs to society. This development of an understanding of the general sources and magnitude of the burden of illness due to foodborne pathogens is an important first step in addressing the risk to public posed by food borne disease. Nonetheless, comparative information about the efficiency and effectiveness of specific public health measures designed to reduce the burden of disease associated with food borne illnesses is not readily available. With the push in public health circles for evidence-based public health measures and with potentially significant costs associated with either food safety measures mandated by regulatory bodies or with monitoring programs, a need exists for the development of common food safety risk assessment practices and methodologies. A common approach to food safety risk assessment and analysis will lead to the development of study results that can be compared and that would guide policy makers interested in questions such as: for a given budget of prevention resources, where can society obtain the greatest return in terms of QALYs saved or cost-of-illness averted? Or, on the margin, should public decision makers be investing scarce public funds into food safety measures rather than in HIV/AIDs prevention or treatment programs or in obesity prevention programs.

In this paper we overview our food safety research on the farm-to-fork production and consumption chain and our development of a stochastic simulation of the risk and hazard posed by *Salmonella* in the pork chain. We examine *Salmonella* in pork for several reasons. USDA researchers have estimated that (annually) the costs of human illness for six foodborne pathogens ranges from $2.9 and $6.7 billion (1993 dollars), with meat and poultry accounting for 80 percent.[1] In pork, *Salmonella* is an important pathogen, with outbreak data from the Centers for Disease Control (CDC) showing that 40 percent of the pork-associated outbreaks were due to *Salmonella*.[2] Retail level monitoring data reported in one study indicate that 10 percent of U.S. retail pork products are contaminated with *Salmonella*.[3] Nonetheless, gaps remain in our understanding of the risk posed by *Salmonella* in pork. However, our understanding of the nature of the salmonellosis risk posed by pork products is not definitive. For example, how robust are the assumptions employed in extrapolating from outbreak data, upon which burden of disease estimates rest, to the overall salmonellosis burden?[4]

As an alternative means to understanding the risk posed by pork-borne salmonellosis derived from outbreak data, we employ a farm-to-fork simulation modeling approach. This general method has been applied in other food safety risk assessment contexts including studies of *Salmonella* Enteritidis for shell eggs and egg products, as well as for *Escherichia coli* 0157:H7 in hamburgers made from ground beef.[5,6]

Our model is designed to improve both our understanding of the pork-borne salmonellosis risk and the effectiveness and economics of possible food safety interventions. We construct our model using @RISK software, basing the model parameters upon research reported in the food safety, animal science, veterinary pathobiology, and related literatures. A critical contribution of the stochastic simulation modeling methodology is the explicit treatment of uncertainty, whether the uncertainty arises from differences in reported parameter estimates, or scientific unknowns, or in testing and monitoring procedures. A second important contribution of the method applied here is that the model itself provides a summary of the knowledge concerning the biological and economic system for the food safety risk of interest. That is, a review of our model's documentation can provide an in-depth summary of the key literature related to pork-borne salmonellosis.

Our farm-to-fork model includes six modules: on-farm; transport and lairage; slaughter; fabrication and retail; cooking; and, burden of disease. The next section is drawn directly from our paper "The Burden of Human Salmonellosis in the US Attributable to Pork: A Stochastic Farm-to-Fork Analysis" (McNamara, Liu, and Miller, 2004) and it provides a description of our farm-to-fork economic model. After a discussion of the estimates of the model for the burden of disease attributable to pork-borne salmonellosis, the paper closes with lessons learned that might be useful to other food safety risk modelers.

2. Farm-to-Fork Model Design

[Section 2 of this paper is drawn from McNamara, Liu, and Miller, 2004.] Figure 1 displays a flow chart depicting an overview of the simulation model's structure. The critical model inputs consist of the parameter values, probability distribution assumptions, and process assumptions built into the model design. The model inputs are based upon the published research literature concerning food safety in the pork system and upon previous quantitative risk assessments of foodborne diseases. Table 1 lists constants employed in the model and their source. Table 2 lists the primary probability distributions included in the model as well as the reference providing a justification for their inclusion.

2.1 On-Farm Stage

The farm level is the first stage of the farm-to-table model. *Salmonella* prevalence at this stage becomes important because of the high propensity for *Salmonella* transmission across animals at later stages, and because of the possibility of lengthy survival times and the ability of *Salmonella* to live not only on hides and in the gut, but also in the lymph nodes and in other parts of the animal. The model is based upon the US hog herd in 2000. The total number of hogs slaughtered in both nonfederal inspected slaughter plant and federally-inspected slaughter plants is 97,975,900 head in 2000, including 93,114,900 head of barrows and gilts in federally-inspected slaughter plants, and 3,005,000 head of sows and 315,700 head of stags and boars.[7]

We portray the shedding rate of *Salmonella* for barrows and gilts as a Pert distribution where the left side is constrained to be at least 3%, the most likely value is 6%, and the maximum value is estimated to be 6%. We base this description upon apparent prevalence estimates reported in the literature, where estimates range from 3% to 6% prevalence US farms.[8,9,10] For cull sows we represent prevalence as a Pert distribution with a minimum value of 3.0%, a mode of 7.8%, and a most likely value of 7.8%.[11] The reported shedding rates represent apparent prevalence, and these estimates are likely to overestimate or underestimate the true prevalence do to weaknesses in the testing procedures to detect the presence of *Salmonella*. To represent the uncertainty present in the testing regime, we estimate true prevalence based upon apparent prevalence and other information by using formula:

$$\text{True prevalence} = \frac{\text{apparent prevalence} + \text{specificity-1}}{\text{sensitivity} + (\text{specificity-1})}$$

In most cases, we cannot obtain sensitivity and specificity from each specific paper or test, and they are assumed to be prior information. The specificity is assumed to be constant with value of 0.998. Sensitivity varies with factors such as sample size (e.g. fecal volume) used in the laboratory test. We define a range for the likely sensitivity values for the testing procedures as 0.325 to 0.688.[12] Applying the formula leads estimates of a lower and higher level of true prevalence for market hogs of 0.04 and 0.18, respectively. We represent this uncertainty in the model through a triangular distribution, and assume that the midpoint of the range is the prevalence with the highest possibility. We construct a similar distribution for the cull sows.

2.2 Transport and Lairage Stage

While animals remain in the transport and lairage period for a short duration, evidence suggests that this stage, with its concomitant animal stress and exposure to vehicles and environments used with many different herds, can lead to significant increases in the prevalence of *Salmonella* in pigs. The transportation stage facilitates the mixing of pigs and, hence, the cross-contamination of pigs from different regions, different farms or even from different pens of the same operation. The increase parameters for *Salmonella* prevalence during the transportation and lairage are based upon results from three recent monitoring studies, whose results are used to fashion a triangular distribution for the increase factor of prevalence during transport and lairage (see Table 2).[9,10,13] Although the rate of increase in prevalence for market hogs and sows both follow a triangular distribution, the parameters for sows are higher than the parameters for market hogs.

2.4 Slaughter

The slaughter stage actually involves many disparate steps, including stunning, sticking, bleeding, scalding, de-hairing, shaving, head drop, final inspection, trimming, final wash, and chilling. These different steps all involve the potential to decrease or increase the likelihood for *Salmonella* to be present on pork products. For example, researchers have noted the strong effect that scalding the carcasses has on reductions in the prevalence of *Salmonella* on pork carcasses.[14] According to Dickson et al., the scalding operation in a typical US slaughter plant is usually conducted with temperatures 57.7 to 61 C for three to eight minutes and a typical operation would be 58.8 C for six minutes.[14] Dickson et al. state that this "combination of temperature and time would result in greater than a 9 $\log_{10}$ cycle reduction of salmonellae" based on research conducted in a poultry slaughter context.[15] While the experimental work this is based upon was done with chickens, we assume that scalding would have a similarly strong effect in a pork slaughter context. To obtain a parameter estimate for the *Salmonella* reduction in the slaughter stage, we define a triangular distribution based upon a recent USDA FSIS progress report on *Salmonella* testing for pork at the plant level.[16] Based upon the reported values from plant testing in 1998, 1999, and 2000, we assume that the *Salmonella* reduction in the slaughter stage ranges from 87% to 96%, with a most likely value of 91% and is characterized by a triangular distribution.

Another important dimension of the slaughter stage for our model is that change that occurs in the detection and measurement of pork Salmonella contamination. In general, measurement of Salmonella in the on-farm, transport, and lairage stages is done via feces samples, while detection after slaughter and in the fabrication and retail stages is conducted with surface samples. At the slaughter level, the method of detection changes and, hence, an assumption is applied within the model regarding the correspondence between prevalence measured by feces samples and prevalence measured by surface contamination of carcasses. To our knowledge, no study exists providing an estimate of such a correspondence. In this study, we assume the correspondence between changes in prevalence measured by the differing methods is one-to-one.

2.5 Fabrication and Retail

At the fabrication and retail stage, we differentiate between ground pork products and pork cuts, because of the different types of pigs that are used and the associated differences in prevalence. All sows flow into the ground pork product stream and we include trimmings (13% by weight) of market hogs to the ground pork products. To our knowledge, there is no study that connects prevalence of carcass *Salmonella* contamination with the prevalence of pork *Salmonella* contamination. To estimate the change in *Salmonella* prevalence from the fabrication level to the retail level, we rely upon a study at the plant level, which found an average prevalence for *Salmonella* at the plant level of 5.8% in ground pork and pork sausage products.[3] No similar prevalence was reported for pork cuts, and the 5.8% figure is assumed to apply to pork cuts. At the store level, this same study examined pork cuts and found a range of percent positive cuts from 8.3% to 10.4%.[3] We assume that the most likely value is the midpoint of that range, 9.3% and create a triangular distribution of the increase in prevalence (after dividing by 5.8% as the plant prevalence) from plant to retail level with a lower bound of 0.43, a most likely value of 0.60, and a maximum value of 0.78. For ground pork products, we create a similar distribution with the lower bound of 0.26, a most likely value of 0.71, and a maximum value of 1.16, based upon retail level measurements ranging from 7.3% positive to 12.5% positive.

2.6 Cooking

Cooking represents a powerful process of pathogen reduction, especially when meal preparers follow proper food safety practices in the kitchen. Moreover, evidence exists that most people understand well the need to cook foods carefully to reduce the risk of foodborne illnesses.[17] Moreover, Woodburn reports that people "said they would thoroughly cook food contaminated with bacteria to make it safe to eat (56% for *Salmonella* and 59% for E. coli) but 40% responded that the foods either couldn't be made safe to eat or that they didn't know of a way."[17] Writing in 1998 about pathogen reduction post-slaughter, Veeramuthu and Sams indicated that the USDA Food Safety and Inspection Service (FSIS) has proposed to amend cooking regulations to require that any thermal process used for poultry products be sufficient to cause a 70% reduction in *Salmonella*.[18] In addition to the high awareness of many consumers about the need to cook food thoroughly in order to reduce or eliminate pathogens such as *Salmonella*, other consumers, not aware of *Salmonella* risk, may reduce *Salmonella* substantially via adhering to traditional methods of cooking pork products.

Based upon this research, we assume 70% of the population at low risk for salmonellosis cooks their pork thoroughly and effectively eliminates the risk of an exposure to contaminated pork. Furthermore, for the population at high risk for salmonellosis we assume that they take extra care in cooking and that 80% of the high risk population cook their pork thoroughly and thereby eliminate the risk of pork-borne salmonellosis. In addition, for those pork servings not receiving a thorough cooking, the cooking process still reduces the level of Salmonella contamination on the pork (see Table 1 for parameters used for the survival rate after cooking).[19]

2.7 Burden of Disease

The consumption and health stage follows pork from the retail channels to human consumption and some incidence of salmonellosis and the associated economic burden. The following section reviews each of the components of this stage of the analysis.

2.6.1 Population exposure to *Salmonella* contaminated pork

Since not all people consume pork and are exposed to pork and not all exposures will lead to infections with the same likelihood, we divide the population into two groups. The first group, called the sensitive group, consists of infants, the elderly, immuno-compromised persons, and all of these people are at heightened susceptibility to illness from exposure to *Salmonella*. The second group (non-sensitive individuals) consists of all other people and the people in this group exhibit a normal response to microbial contaminated foods. The sensitive group captures 20% of the total population, while the remaining 80% of the population is in the non-sensitive group.[20]

2.6.2 The intensity of exposure

In this model, the effect of *Salmonella* on human infection does not accumulate and the intensity of exposure in our model is only associated with quantity of each serving. We assume an average serving of 3 ounces of pork for the non-sensitive group and 1.5 ounces of pork per serving for the sensitive group.[21] In addition, the quantity of meat serving is assumed to be random variable with a truncated normal distribution.

2.5.3 Dose-Response Model

The dose-response model simulates the relationship between contaminated food intakes and the likelihood of foodborne illness. In the case of *Salmonella* contaminated food, an extensively applied dose-response model is the Beta-Poisson model:

$$P=1-(1+ (dose/beta)^{-alpha}$$

In this study, we use the Beta-Poisson distribution to characterize the possibility of salmonellosis given ingestion of a contaminated serving of pork. The parameters applied here (Table 2) follow those used in the FAO/WHO risk assessment report concerning *Salmonella* in eggs and broiler chicken.[22] At this time, to our knowledge, no dose-response model exists based upon pork consumption and illness data.

2.5.4 Economic Burden of Disease Assumptions

Medical costs and productivity losses from bacterial infection have been previously addressed and, in this model, we rely upon the framework presented by Buzby et al. for the assumptions and parameters used in our cost of illness estimates.[1] We update their 1993 medical costs and values of human life to the year 2000, using the Medical Price Index of the US BLS. For both the low-risk group and the high risk group, we assume that the treatment paths for salmonellosis cases are defined by triangular distributions (see Table 2). To ensure that the sum of the probabilities assigned to the four different treatment paths (no physician visit, physician visit, hospitalization, and death) equals one, for each model iteration the drawn treatment probabilities are standardized by the sum the probabilities for all four treatment alternatives. The cost per case varies by treatment option: no physician visit, $482; physician visit, $1,032; hospitalization, $11,812; and, death, $500,923.

3 Simulation Model Estimates

The simulation model provides output in the form of probability distribution estimates for the annual cost of illness in 2000 for salmonellosis attributable to pork, as well as estimates of the number of cases and deaths. Using Monte Carlo simulation (25,000 iterations) the farm-to-fork model estimates that the mean value for the total cost of illness for salmonellosis attributable to pork is $81.5 million (Figure 2). Note that the 90% confidence interval is estimated to range from $18.8 million to $197.4 million, indicating a ten-fold range in the conventional confidence interval estimate for the cost of illness. While most of the costs ($59.4 million) were associated with the low-risk population, based upon the relative size of their group, the high-risk population is modeled to experience a disproportionate share of the cost of illness burden ($22.1 million).

In terms of salmonellosis cases, the model predicts a mean number of 99,431 cases annually (see Figure 4). Most (83,923) were modeled to have occurred in the low-risk population, while 15,507 affected the high-risk group. The USDA ERS's foodborne illness calculator estimates an annual amount of 1,412,498 cases, and the pork-borne cases modeled here represent about 7.4% of those cases.[23] For salmonellosis cases, the 90 percent confidence interval for the model estimates ranged on average from 20,967 cases to 245,567 cases.

The farm-to-fork model estimates deaths attributable to salmonellosis from pork for the year 2000 (see Figure 3). An average of 51.1 deaths per year are estimated to have arisen from pork-borne salmonellosis. The 90 percent confidence interval for the estimated deaths ranges from 10.9 to 129.1. In comparison, the USDA ERS foodborne illness calculator reports 582 overall salmonellosis deaths annually.[23]

Detailed sensitivity analyses have been conducted on the model to determine model stability and the relative importance of parameters throughout the farm-to-fork chain. These sensitivity analyses are reported in Miller, Liu, McNamara, and Barber (2004) and McNamara, Liu, and Miller (2004).

4. Lessons for Risk Ranking and Food Safety Risk Assessment

Constructing this model, reporting its cost of illness estimates, and applying it for the economic analysis of food safety interventions represents a first in the area of pork food safety in the US. Like much food safety research, the effort has been necessarily multidisciplinary and interdisciplinary, with insights drawn from the literatures of veterinary pathobiology, animal science and meat science, risk assessment, food safety research, economics, and epidemiology. While in our opinions the model and the several papers that have arisen from it are contributions to our understanding of food safety in the US pork system, the model's existence and documentation can serve as a building block for future food safety research in the pork sector. Moreover, lessons can be drawn from this analysis and modeling approach that might inform the work of other food safety researchers. To that end, here is an incomplete list of challenges and lessons learned from our work to date:

Uncertainty

Our farm-to-fork risk assessment modeling framework quantifies uncertainty, yet there are different types of uncertainty present in the modeling exercise, and the modelers face a question of how to represent these qualitatively different types of uncertainty. For example, the literature may report several estimates of farm level prevalence of *Salmonella* in pigs. We as modelers can make an informed judgement about how to weight the differing estimates and we can represent the variation in the estimates in our model through a probability distribution based upon the reported estimates. However, this type of uncertainty is fundamentally different from the fact that we do not have a dose-response model calibrated specifically for pork-borne *Salmonella*. And, it is fundamentally different from the uncertainty associated with things we simply do not know about and that are not introduced into the model. Balancing these different types of uncertainty is one of the art aspects of food safety risk modeling, and taking care in the interpretation of the model results is necessary to avoid overstating the estimates, given the potential importance of untreated sources of uncertainty.

Model Closure and Calibration

How does a food safety researcher know if his or her model is any good? What sources of information should receive the greatest weight in determining the structure of the model? How to treat different scientific information that is contradictory? What closes the model? How do you rank evidence in terms of importance for building the model? Necessarily, the researchers must answer these questions in building any farm-to-fork simulation model for food safety research purposes. The model building process is fundamentally iterative, with a first cut followed by output that is puzzling and a re-examination of different assumptions employed and model parameters, and then a repeat of the entire process. In the case of our pork farm-to-fork model, we tried to determine which pieces of evidence should receive the greatest weight because they appear to be the best understood. While there is great uncertainty still about on-farm prevalence and the factors associated with it, it appears that our knowledge of food safety risk factors and prevalence within the areas of processing, slaughter and packing plants, the distribution system, and consumption is more limited than our knowledge of on-farm or retail prevalence. We tended to place weight on the scientific knowledge in the literature about on-farm prevalence, the reported prevalence at the retail level, and the comparison of model outputs to other estimates of food safety disease burdens (cost of illness, deaths, and cases). We have communicated our evidence base and assumptions clearly, but just as clearly some other modelers might end up with a different set of estimates.

Untreated Dimensions and Level of Detail

What level of detail should a farm-to-fork food safety model include? The short answer is that we don't know yet. The relative importance of treating dimensions such as spatial disaggregation, farm size disaggregation, slaughterhouse and processing disaggregation, product disaggregation, home/restaurant/food service disaggregation, are all poorly understood. While some evidence suggests that significant variation in food safety risks is distributed spatially, we have not treated that dimension in our model, in part due to a lack of available benchmark information. For each of the dimensions listed, we have modeled things essentially as a black box. Future research that documents significant prevalence variations by farm size or by detailed product type might be considered for as the basis for an expansion of the farm-to-fork model. However, a value ought to be placed on parsimony and model simplicity in areas where prevalence variation is not associated with a variable that policy makers can influence or use to target regulatory efforts.

Quantitative Risk Modeling as a Means to Identify Gaps in Our Understanding

An important role of risk modeling ought to be the generation of further research questions and the identification of critical gaps in our understanding. Naturally, the modeler and his or her critics will identify the “black boxes” in a simulation model and want to explore whether or not further detail inside the black box might yield insights for food safety. Our model contains a number of black boxes. Many of the important ones would seem to involve human factors and food handling practices, whether in the restaurant, the plant, or in the home. Gathering evidence on food safety practices in these stages of the farm-to-fork chain may highlight areas where public health and agricultural officials could target cost-effective interventions.

Dimensionality

Studying and researching complex systems, like a food production and consumption chain, raises the issue of dimensionality. Most economists and risk analysts tend to think of dimensionality as a difficulty in terms of model construction, and that difficulty appears in the case of the farm-to-fork model. Dimensionality and large scale also pose difficulties for model interpretation and communication. In the case of the farm-to-fork model, the issue of dimensionality includes the difficulty of communicating across disciplines, in covering broad literatures, and in developing knowledge of the system. The detailed system raises challenges for reporting and communicating a large model, replete with specification of model assumptions and documentation of parameter sources. In our opinion, a need exists for the development of specialized peer-reviewed publication (perhaps an on-line peer-reviewed food safety risk assessment annual) that affords an outlet for the type of writing and reporting necessary to document thoroughly a food safety risk assessment.

Incentives for this Type of Food Safety Research

For the academic-based researcher is it wise to invest significant research effort into this type of research effort? A farm-to-fork food safety analysis inherently involves cross-disciplinary work and that poses challenges for publication, if the disciplinary nature of journals is an important aspect of evaluation and promotion. Furthermore, while the funding streams for food safety research have improved over the past several years, obtaining funding for large scale risk assessments remains a challenge. Along with funding, suitable peer reviewed publication outlets for the documentation of rigorous original farm-to-fork food safety research may be needed. If there is a public health and agricultural demand for building the evidence base for food safety policy and practice, it may be necessary to create a food safety research clearing house (refereed website) with links to code for working food safety models and refereed reports that connote peer review and the ability to cite. The attractiveness of such a clearing house or website publication would be increased if it was included in electronic databases such as Medline or Agricola.

5. Conclusions

This paper argues that the farm-to-fork risk analysis of pork-borne salmonellosis represents a model for food safety researchers interested in economic analyses of food safety interventions. In terms of lessons for other food safety researchers, issues such as decisions about dimensions of the phenomenon to model or about the treatment of different types of uncertainty represent the basic modeling decisions that appear to drive the analysis. The modeling exercise also highlights gaps in our knowledge of the risk and hazard posed by pork-borne *Salmonella*. Hopefully, our analyses and the lessons suggested in this paper can help broaden the base of bioeconomic research in the food safety area.

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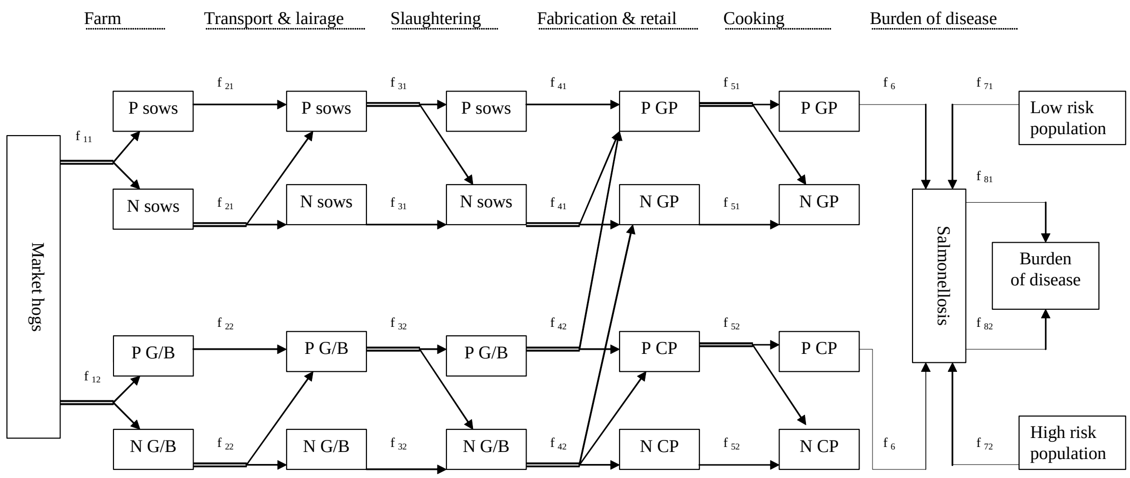
Figure 1. The Farm-to-Fork Pork System



Notice: P sows stands for Salmonella positive sows, N sows Salmonella negative sows, P G/B Salmonella positive gilt & barrow, N G/B Salmonella negative gilt & barrow, P GP Salmonella positive ground pork, N GP Salmonella negative ground pork, P CP Salmonella positive pork cuts, and N CP Salmonella negative pork cuts.

Figure 2   Cost of Illness Estimate for Salmonellosis Attributable to Pork

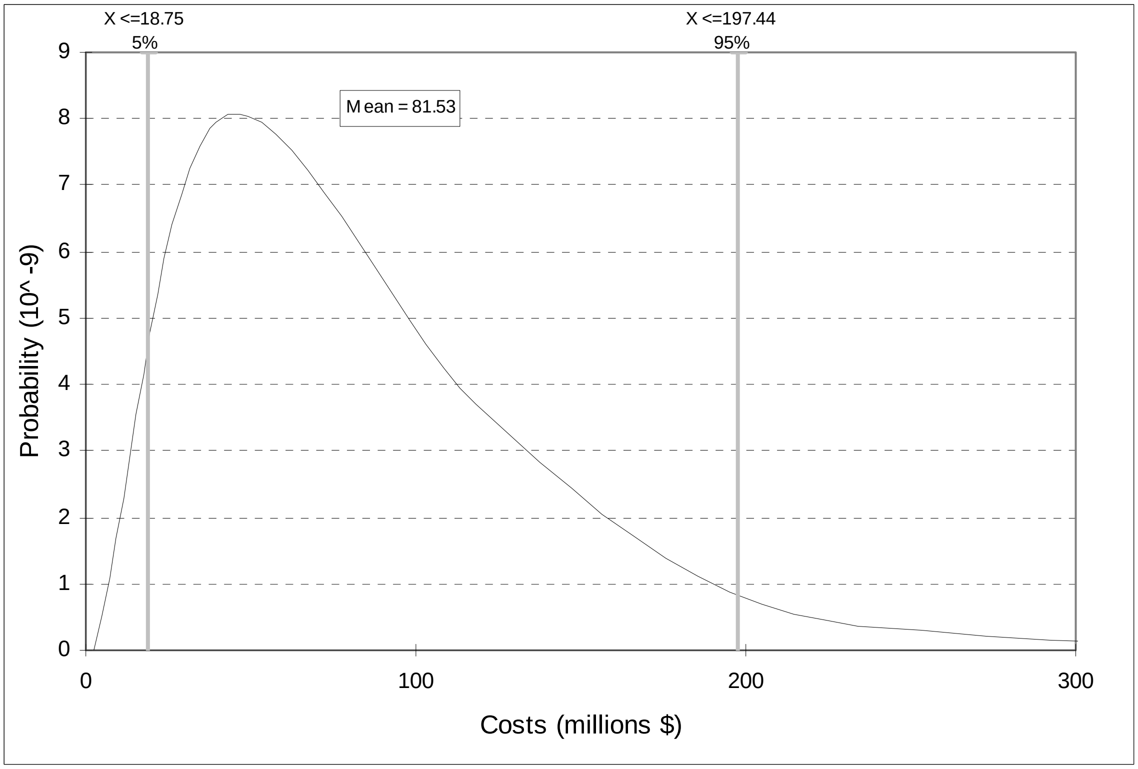


Figure 3   Estimate of Annual Total Deaths Attributable to Salmonellosis From Pork

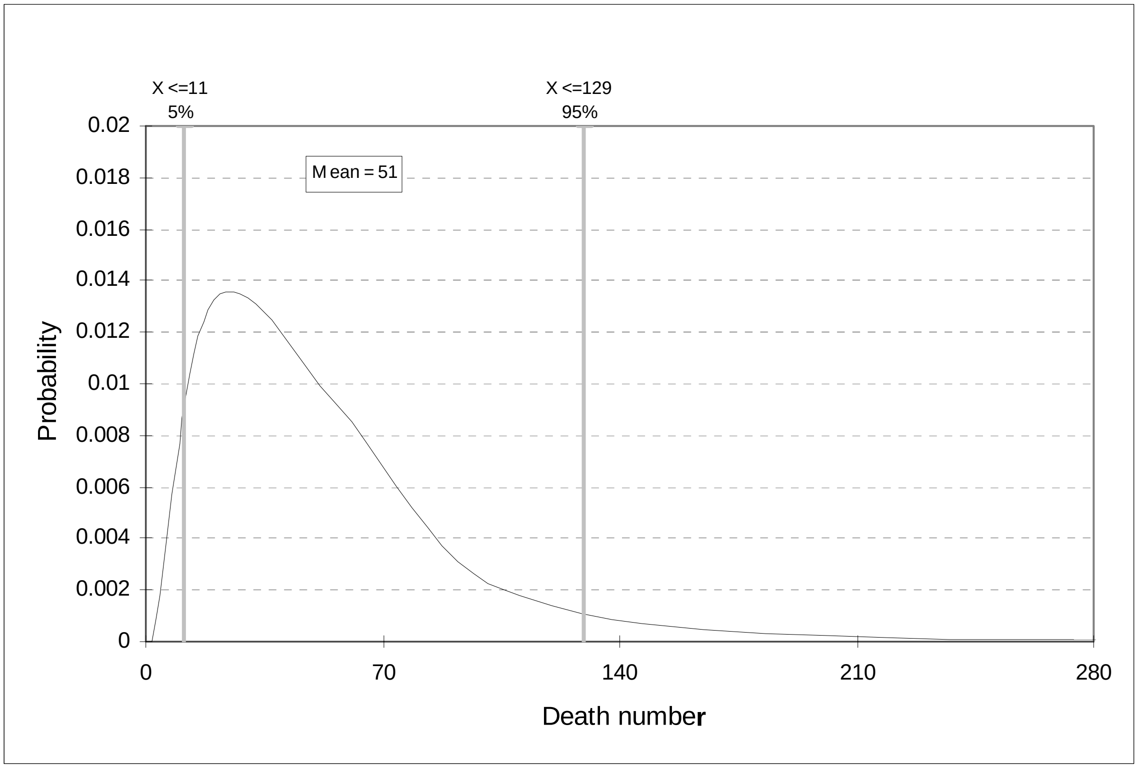


Figure 4 Estimate of Annual Total Cases of Human Salmonellosis Attributable to Pork

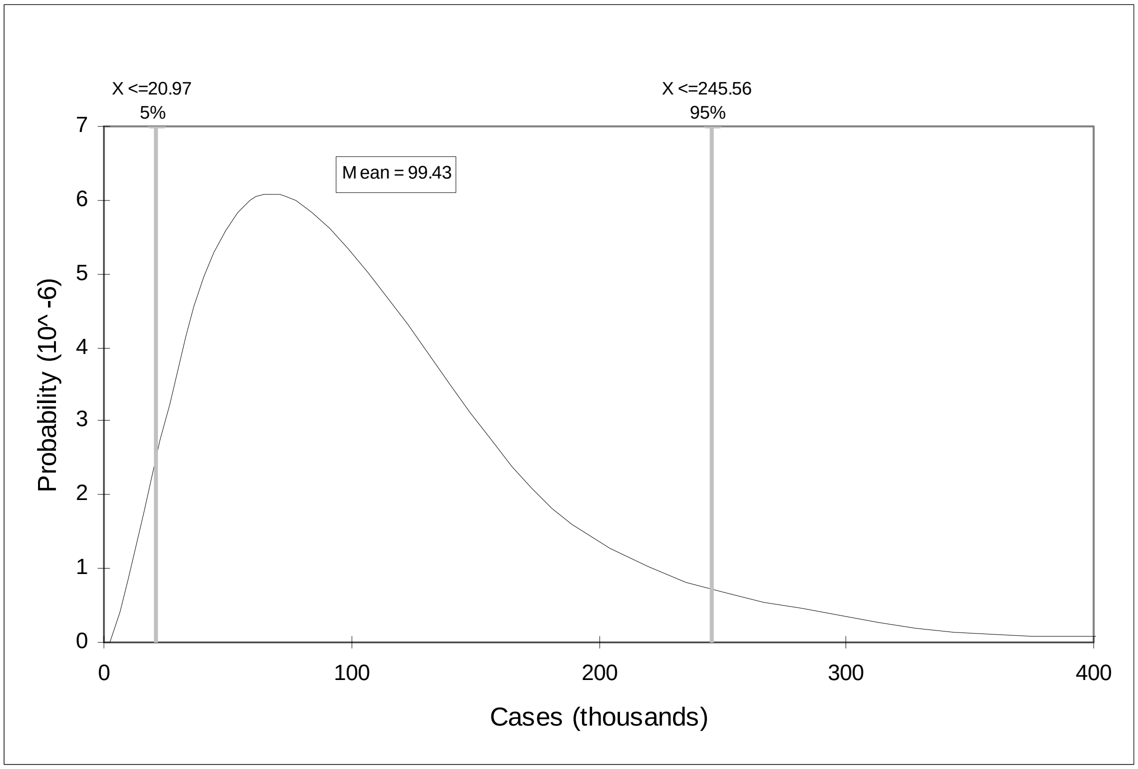


Table 1 Constants and Parameters Employed in the Farm-to-Fork Model

Table 1. Description of constant inputs

Name	Value of Constant	Sources
Number of sows	3005400	USDA, NASS (2001)
Number of gilts/barrows	93114900	USDA, NASS (2001)
Apparent salmonella positive on farm (sows)	0.02	McKean et al. (2001)
Apparent salmonella positive on farm (G/B)	0.06	USDA (1997)
Low bound of sensitivity of fecal sample	0.326	Funk et al. (2000)
High bound of sensitivity of fecal sample	0.688	Funk et al. (2000)
Specificity of fecal sammples	0.998	Baggesen et al. (1996)
Carcass weight of sows	309	USDA, NASS (2001)
Carcass weight of gilts and barrows	191	USDA, NASS (2001)
Ratio of pork to carcass	0.76	Hog carcass breakdown http://www.tysonfoodsinc.com
Ratio of trimmings to pork	0.13	Hog carcass breakdown http://www.tysonfoodsinc.com
Portion of sow pork going to ground pork	1	Assumed
Survival rate of Salmonella organisms for low risk population	0.00000010	USDA , FSIS (1998)
Survival rate of Salmonella organism for high risk population	0.00000100	USDA , FSIS (1998)
Total population in the U.S.A	287151740	US census bureau (2000)
High risk population in the U.S.A	57430348	Gerba, C.P. et al. (1996)
Low risk population in the U.S.A	229721392	Gerba, C.P. et al. (1996)
Treatment costs of salmonellosis with no physican visits	374	Buzby et al. (1996)
Costs of salmonellosis with physican visit	794	Buzby et al. (1996)
Costs of hospitalized patients	9087	Buzby et al. (1996)
Costs of death	385355	Buzby et al. (1996)
Costs adjusted by price index of 2000	260.8/201.4	http://www.bls.gov/cpi/home.htm

Table 2 Distributional Assumptions Employed in the Farm-to-Fork Model

Name	Distribution	Parameter / value	Sources
Apparent prevalence on the farm (sows)	Pert	Pert(0.039, 0.078, 0.078)	USDA (1997), Davies et al. (1998)
Apparent prevalence on the farm gilts and barrows (G/B)	Pert	Pert (0.03, 0.06, 0.06)	USDA (1997); Proesholdt (1999)
Prevalence on the farm (sows)	Triangular	Triang (0.05, 0.24, 0.24)	Funk et al. (2001); Smith(1995)
Prevalence on the farm gilts and barrows (G/B)	Triangular	Triang (0.04, 0.18, 0.18)	Funk et al. (2001); Smith(1995)
Prevalence increase in transport and lairrage (sows)	Triangular	Triang(2.17, 5.7, 8.3)	Larsen et al. (2003)
Prevalence increase in transport and lairrage (G/B)	Triangular	Triang(1.96, 3.9, 5.84)	Hurd et al. (2001); McKean (2001): Proesholdt (1999)
Prevalence reduction in slaughtering (sows)	Triangular	Triang(0.87, 0.911, 0.96)	USDA (2003) Progress Report
Prevalence reduction in slaughtering (G/B)	Triangular	Triang(0.87, 0.911, 0.96)	USDA (2003) Progress Report
Impacts of fabrication and retail on ground pork	Triangular	Triang(0.073, 0.099, 0.125)	Duffy et al. (2001)
Impacts of fabrication and retail on pork cuts	Triangular	Triang(0.083, 0.093, 0.103)	Duffy et al. (2001)
CFU/ounce in ground pork	Triangular	Triang(15, 716, 1418)	FSIS (1998) http://www.fsis.usda.gov/haccp/lethality.pdf
Amount of ground pork per serving for low risk population	Normal	Normal(3, 0.9 trunc(0.1, 6))	USDA (1998)
Amount of ground pork per serving for high risk population	Normal	Normal(1.5, 0.6 trunc(0.1, 6))	USDA (1998)
CFU/ounce in pork cuts	Triangular	Triang(15, 2828, 5642)	FSIS (1998), Duff et al. (2001)
Amount of pork cuts per serving for low risk population	Normal	Normal(3, 0.9 trunc(0.1, 6))	USDA 1994-1996 1998
Amount of pork cuts per serving for high risk population	Normal	Normal(1.5, 0.6 trunc(0.1, 6))	USDA 1994-1996 1998
Dose-response relationship	Beta-Poisson	Beta-Poisson(51.45, 0.1324)	WHO (2000) http://www.WHO.INT/FSF/Micro/Ra_Salmonella_report.pdf
Exposure adjustment for non-pork-eating group	Normal	Normal(0.924, 0.03, trunc(0, 1))	Miller et al. (2001)
Cooking effect for low risk population	Normal	Normal(0.15, 0.03, trunc(0, 1))	Gerba et al. (1996)
Cooking effect for high risk population	Normal	Normal(0.2, 0.03, trunc(0, 1))	Gerba et al. (1996)
No physican visit patients of low risk population	Triangular	Triangular(0.934, 0.95, 0.96)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Physican visit patients of low risk population	Triangular	Triangular(0.0364, 0.048, 0.0629)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Hospitalized patients of low risk population	Triangular	Triangular(0.00204, 0.00349, 0.00596)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Death of low risk population	Triangular	Triangular(0.000127, 0.000254, 0.000553)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
No physican visit patients of high risk population	Triangular	Triangular(0.9, 0.93, 0.95)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Physican visit patients of high risk population	Triangular	Triangular(0.0437, 0.0699, 0.0911)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Hospitalized patients of high risk population	Triangular	Triangular(0.00324, 0.00643, 0.0166)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/
Death of high risk population	Triangular	Triangular(0.000248, 0.000783, 0.00387)	USDA 1998 http://www.fsis.usda.gov/ophs/risk/