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A Multifactorial Risk Prioritization Framework for Foodborne Pathogens

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We develop a prioritization framework for foodborne risks that considers public health impact as well as three other factors (market impact, consumer risk acceptance and perception, and social sensitivity). Canadian case studies are presented for six pathogen-food combinations: *Campylobacter* spp. in chicken; *Salmonella* spp. in chicken and spinach; *Escherichia coli* O157 in spinach and beef; and *Listeria monocytogenes* in ready-to-eat meats. Public health impact is measured by disability-adjusted life years and the cost of illness. Market impact is quantified by the economic importance of the domestic market. Likert-type scales are used to capture consumer perception and acceptance of risk and social sensitivity to impacts on vulnerable consumer groups and industries. Risk ranking is facilitated through the development of a knowledge database presented in the format of info cards and the use of multicriteria decision analysis (MCDA) to aggregate the four factors. Three scenarios representing different stakeholders illustrate the use of MCDA to arrive at rankings of pathogen-food combinations that reflect different criteria weights. The framework provides a flexible instrument to support policymakers in complex risk prioritization decision making when different stakeholder groups are involved and when multiple pathogen-food combinations are compared.

KEY WORDS: Consumer; DALY; food safety; pathogens; public policy; risk prioritization

1. INTRODUCTION

Experts and stakeholders have urged the development of science- and risk-based systems to prioritize and manage foodborne hazards by cost-effective means in order to lower the incidence and impacts of human foodborne disease. Internationally, governments and nongovernmental organizations are undertaking efforts to develop new and more efficient food safety controls directed at specific foodborne hazards in order to improve public health. In practice, managers face difficult challenges in marshalling the data and information needed to guide their decisions on priorities for controlling foodborne risks.

We present a framework for prioritizing these risks that addresses these challenges in two important ways. First the framework recognizes that multiple health, economic, and social factors may play a role in prioritization. While public health concerns are frequently first and foremost in risk managers' concerns, other characteristics of risks also influence

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decision making. A review shows that most approaches to risk prioritization developed to date are based on measures of health outcomes and do not systematically account for other factors that may be important to decision making.[1] Our framework systematically develops information on these factors in order to facilitate more consistent and transparent risk comparison and prioritization. Second, the framework develops two formats (info cards and multicriteria decision analysis) for presentation of data and analysis to risk mangers for their use in prioritization. These formats are flexible and allow risk managers, as well as different stakeholders, to choose appropriate ranking criteria and a weight for each criterion. We demonstrate the framework with six pathogen-food case studies based on Canadian data.

To our knowledge, this is the first framework to jointly consider public health and other factors relevant to the prioritization of microbial foodborne risks including estimates of market-level impact, consumer perception and acceptance of risk, and social sensitivity for consumers and firms in a rigorous manner. Furthermore, the multicriteria ranking process is transparent in terms of criteria and weights and allows for systematic evaluation of different scenarios based on stakeholders' goals and interests.

2. RATIONALE FOR MULTIFACTORIAL RISK PRIORITIZATION

Decision-making and risk-ranking processes for foodborne pathogens operate within a socioeconomic and political context and should aim at effective food risk mitigation strategies that are in the public interest. In recent years, improved surveillance methods have become available to provide data for the scientific and risk-based analysis of foodborne pathogens as well as the design of effective mitigation strategies. However, despite improvements in data availability, only a few attempts have been made to develop an integrated and harmonized system for risk management that allows decisionmakers to prioritize risks and interventions in an evidence-based yet multidisciplinary manner.[2,3] Review of current microbial risk management systems suggests a strong focus on mitigating the human health impacts of foodborne diseases.

Microbial food-safety incidents resulting in sizeable market disruptions and public media attention have accentuated the need to incorporate broader economic and public factors into food risk prioritization. For example, the National Research Council in the United States,[4] the United Kingdom,[5] and the U.S. Environmental Protection Agency[6] have emphasized the consideration of multiple science-based risk indicators in order to achieve greater consistency and public acceptance of governmental risk appraisal guidelines. In particular, the role of public concerns, consumer perceptions, and economic risks were acknowledged as important factors as part of the risk assessment process that previously has not been included. Havelaar *et al.*[7] also present a strong rationale for using an integrated approach based on epidemiology, risk assessment, and economics to support risk management decisions. Moreover, recent discussion at a joint FAO/WHO expert consultation on incorporating microbiological risk assessment in the development of food safety standards and guidelines[3] supports the adoption of an integrated and multifactorial risk assessment and presents a strong rationale for the consideration of market and trade impacts in risk management decisions. For example, a FAO/WHO expert meeting convened to address microbial concerns regarding fruits and vegetables defined six criteria to be used to rank commodities. Three criteria are associated with the market impact: size and scope of production, diversity and complexity of production chain/industry, and extent of international trade and economic impact.[8]

In the United States, the Food Safety Research Consortium has developed a risk-ranking tool that evaluates multiple aspects of public health including incidence, severity of outcomes, monetary (e.g., cost of illness), and nonmonetary factors (quality adjusted life years).[9] Beyond, the New Zealand Food Safety Authority's microbial risk management framework includes public health measures weighted by severity in the general public and subpopulations and acknowledges economic implications of foodborne pathogens on trade.[10,11] The European Commission [12] and International Risk Governance Council (IRGC)[2] have put forward integrated conceptual frameworks that highlight the importance of balancing scientific, economic, social, and cultural aspects of risks and benefits as well as risk-benefit distribution within society. The IRGC proposal is a general approach to risk governance, not specific to foodborne risks.[2] To our knowledge, it is still conceptual and has not been implemented.

After review of the above literature, we chose four major factors to be included in our multifactorial risk prioritization framework for foodborne pathogens: public health, market impact, consumer

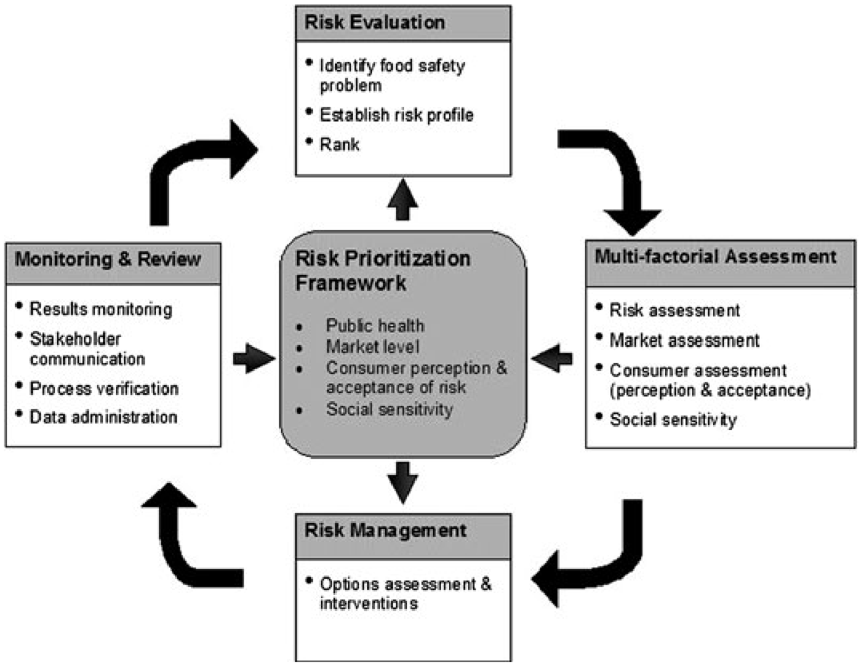


Fig. 1. Information flows between the multifactorial risk prioritization framework and a typical risk management cycle.

perception and acceptance of risk, and social sensitivity. These factors were chosen to give complete but distinct coverage of the factors that affect decision making by risk managers. As described in the next section, multiple measures are used to quantify each of the four factors.

The multifactorial risk prioritization framework is a new component to be added to the cycle of steps common to many risk management approaches in use around the world. For example, Fig. 1 shows Health Canada's cycle[13] as the outer loop of the figure, with the addition of the risk prioritization framework as a new hub of the system. The steps in the outer loop are generally followed in a sequential order, beginning with risk evaluation (Block A). The assessment step (Block B) includes formal scientific processes to generate detailed knowledge of the risks. Although the assessment step is an integral component of a risk management framework, it is generally undertaken by experts with required scientific and technical skills rather than risk managers. Risk management (Block C) includes reviews of options and implementation of interventions based on knowledge derived from risk assessments and is followed by routine surveillance and data gathering designed to track specific interventions (Block D).

The multifactorial risk prioritization framework presented here is positioned in the center of the overall decision-making cycle. In an iterative process, it provides information and tools to support risk evaluation and management and is updated by new information generated by the assessment and surveillance steps. The hub is a knowledge base and tools to support multifactorial risk prioritization. The knowledge base consolidates data from a wide range of sources, including scientific literature, government agencies, industry groups, and expert opinions. Several measures are combined to calculate indicators for all four factors. The knowledge base must be updated on a regular basis because risk management is an iterative process and managers reevaluate priorities at periodic intervals. To date, the multifactorial risk prioritization framework has two tools (formats) to support prioritization for foodborne risks: detailed info cards for each of the four factors and multicriteria decision analysis based on the factors. This framework is not intended to replace decisionmakers; instead, it facilitates decision making by experts and ensures that problem formulation and analysis are transparent and defensible.

3. MEASURING THE FACTORS AND DEVELOPING INFO CARDS

The basic building block of the framework's knowledge base is a pathogen-food combination. The knowledge base is implemented through Excel spreadsheets that hold information for each of the four factors (public health, market impact, consumer perception and acceptance, and social sensitivity) for each pathogen-food combination. Info cards including explanatory text in consistent formats are then used to summarize key data and calculated values. A set of four cards (one for each major factor) for each pathogen-food pair provides a base level of information for decisionmakers, including the most recent annual and three-year average values where appropriate. There is also a summary card for each pathogen-food pair that presents the multifactorial risk profile.

The measures used for each of the four factors are described in detail below. We present six Canadian case studies in this article to illustrate the collection and use of data for the multifactorial risk prioritization framework, as well as the application of the framework's decision tools. The six combinations were chosen based on the authors' expert knowledge to capture a diverse range of impacts across the four major factors in order to demonstrate fully the functionality of the framework. These six case studies are: *Campylobacter* spp. in chicken; *Salmonella* spp. in chicken and spinach; *Escherichia coli* O157 in spinach and beef; and *Listeria monocytogenes* in ready-to-eat meats. It was not possible to match time frames exactly for all of the data and calculations (e.g., incidence data were available up to 2004 but market data were available up to 2006). However, comparisons are made across case studies using data from identical time frames for each factor with one exception that is noted in the measures for public health. Info cards for the case study of *Campylobacter* spp. in chicken are used for illustration.

3.1. Public Health Factor

Public health impacts of foodborne risks are a primary factor of concern for risk managers in making prioritization decisions. In the multifactorial risk prioritization framework, the info card for the public health factor for each pathogen-food combination includes a short description of the type of foodborne illness (es) that can occur, sources of data, a health outcome tree, and a table of data for the latest year used and for a three-year average ending in the latest year used. The tree of health outcomes illustrates the distribution of illnesses by severity level and the potential for long-term sequelae for a particular pathogen. Fig. 2 shows the public health info card for *Campylobacter* spp. in chicken. The info card is the first tool the framework makes available to decisionmakers.

We selected the calculated disability-adjusted life years (DALY) and cost of illness (COI) associated with a particular pathogen-food combination as summary measures of public health impact to be compared across pathogen-food combinations. DALY is a summary measure of a population health gap and combines morbidity and mortality measurements in a single parameter. DALY values are not biased by regional or national health-care costs and were used to quantify burden of disease in the World Health Organization Global Burden of Disease Study.[14,15] A DALY variant was also used by the World Bank in its seminal review of health sector priorities.[15] We recognize that there is ongoing discussion about the appropriate values for disability weights that reflect the valuation of the time lived in a nonfatal health status.[16] For the case studies, we use the values proposed by Kemmeren *et al.*[17]

In addition to the DALY, we also use the monetary measure cost of illness (COI) as a summary health measure to better capture the economic dimension of the public health impact for foodborne microbial risks. Cost of illness measures the actual value of expenditures for medical care and foregone wages arising from the illness, as opposed to the hypothetical value from willingness to pay (WTP), another monetized measure available for assessing health impacts. Compared to WTP, the COI approach does not require assumptions on the structure of preferences when aggregating across the population and is the preferred approach for this framework.

Although the two summary measures of public health overlap to some degree, we believe that both are important for risk ranking and that they provide complementary information. Two recent studies[18,19] highlight that COI calculations fail to account for costs associated with pain and suffering, loss of quality life, and psychological factors. The DALY measure, on the other hand, captures factors that affect quality of life and weights pain and suffering according to the severity of the outcome. However, monetization of the DALY can be complicated because it represents the cumulative loss of years and does not necessarily reflect the actual cost of a disease to society. In the cases presented here, we consider both measures to quantify the public health impact. Ultimately, however, it is up to risk managers to decide whether to include both DALY and COI or a single public health criterion in the ranking step.

The DALY and COI measures are based on an estimate of the total illness attributed to a particular

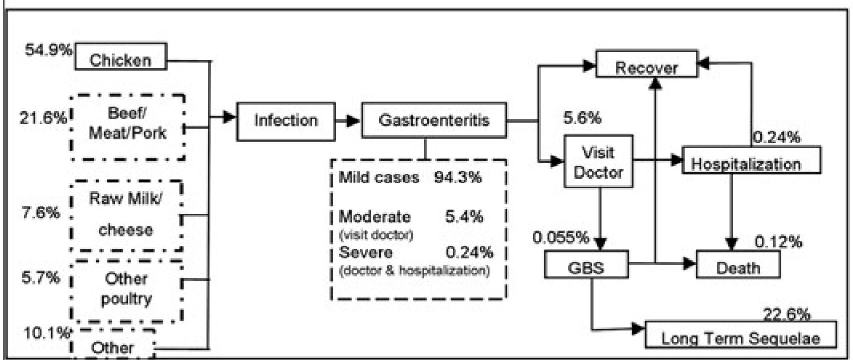
PUBLIC HEALTH IMPACT

CAMPYLOBACTERIOSIS

It is an acute bacterial disease which attacks the digestive system. A person can be infected by eating undercooked chicken or pork, or drinking contaminated water or raw milk. Infection may also be contracted from close contact with infected puppies and kittens, farm animals or infected infants. The illness is characterized by diarrhea, abdominal pain, malaise, fever, nausea and vomiting. Complications of Campylobacteriosis include Guillan-Barré syndrome (GBS) an illness which causes progressive weakness and paralysis; recovery is often slow and the condition may lead to death in some cases.

DATA

Data was collected for the period from 1994 to 2004. Disease incidence data was obtained from Notifiable Diseases On-line (Public Health Agency of Canada website) and population estimates were obtained from Statistics Canada. An underreporting factor of 36 was used to estimate total illness.



Cost-of-illness was calculated based on medical costs, loss of productivity and loss of life. OHIP costs were considered for doctor's visit, emergency services and hospitalization. The years of life loss and the years lived with disability were calculated to determine the Disability Adjusted Life Years (DALYs).

Public Health Information (associated with ***chicken*** *consumption)*	2004		*Annual average* (2002 –2004)	
		#cases		#cases
Incidence of Campylobacteriosis	453*	144,289	495*	155,973
Case-fatality of Campylobacteriosis	0.003%	5	0.003%	5
Cost-of-Illness (COI)	$73,830,000		$79,810,000	
Disability Adjusted Life Years (DALYs)	746		808	

*Per 100,000

Fig. 2. Information card for public health: *Campylobacter* spp.—Chicken.

pathogen-food combination. The total number of illnesses is estimated from reported incidence[20] and population data as follows:

Total number of illnesses attributed to a pathogen-food combination
= Reported incidence rate for the pathogen
× Canadian population
× Percentage of illness transmitted by food
× Proportion attributable to a particular food
× Underreporting factor. (1)

Estimates of the percentage of illness transmitted by food and the proportion attributable to a particular food are taken from Lee and Middleton[(22)] for salmonellosis and campylobacteriosis in chicken. For all other pathogen-food combinations, estimates are taken from a foodborne outbreak database maintained by the Health Risk Modeling section of the Laboratory for Foodborne Zoonoses, Public Health Agency of Canada (Personal communication: Judy Greig, Public Health Agency of Canada). Underreporting factors for all of the pathogens except *L. monocytogenes* are derived from a Canadian study

Table I. Data Sources for DALY and COI Calculations

Parameters	Pathogen-Food Combination[a] C-C	S-C	S-S	L-RTEM	E-S	E-B
Mild, moderate, & severe outcomes	Buzby *et al.*[60], Lee and Middleton[22]	USDA/ERS[28], Lee and Middleton[22]		Voetsch *et al.*[61], Doorduyn *et al.*[62]	Frenzen *et al.*,[18] Tarr *et al.*,[63] Griffin,[64] Boyce *et al.*[65]	
Long-term sequelae	Buzby *et al.*[60]	Not applicable		Voetsch *et al.*,[61] WHO Listeria Risk Assessment[66]	Tarr *et al.*,[63] Griffin,[64] Boyce *et al.*[65]	
Duration of illness and loss of work days	Majowicz *et al.*[19]			OCCI[29]	Frenzen *et al.*[18]	
Fatalities	Lee and Middleton[22]			Doorduyn *et al.*[62]	Rangel *et al.*[67]	
Medical care utilization rates	Majowicz *et al.*[19]			No data available for Listeria; assumed same as E. coli (Frenzen *et al.*[18])	Frenzen *et al.*[18]	
Loss of productivity	Majowicz *et al.*[19]			OCCI[29]	Frenzen *et al.*,[18] Tserenpuntsag *et al.*,[68] Garg *et al.*[69]	

[a]*Campylobacter* spp. in chicken (C-C), *Salmonella* spp. in chicken (S-C), *Salmonella* spp. in spinach (S-S), *E.coli* O157 in spinach (E-S), *E.coli* O157 in beef (E-B), *L. monocytogenes* in ready-to-eat meats (L-RTEM).

conducted by Thomas *et al.*[23] The underreporting factor for *L. monocytogenes* is based on data from the Ontario Ministry of Agriculture and Food.[24]

Mild, moderate, and severe levels of illness are defined using guidelines proposed by the Economic Research Service, U.S. Department of Agriculture (ERS/USDA).[18] The mild category includes cases that did not visit a physician and recover fully; moderate cases are those that visit a physician, use the emergency room or walk-in-clinic, and recover fully; and severe cases are those that are hospitalized, some recover and others die. The probabilities of developing long-term sequelae, such as Guillain-Barré syndrome (GBS) in campylobacteriosis cases, are obtained from the literature for each pathogen as summarized in Table I. For *E. coli* O157, there are three categories for severe outcomes: hospitalized cases with and without haemolytic uremic syndrome (HUS) and hospitalized HUS cases that developed end-of-stage renal disease (ESRD). For *L. monocytogenes,* there are two main categories of outcomes: noninvasive (febrile gastroenteritis form) and invasive (perinatal and nonperinatal) with the long-term sequelae being neurological disorders. The number of cases for each health outcome in the tree is estimated by multiplying the total number of illnesses (Equation (1)) by the frequency for the outcome. The number of deaths associated with a pathogen-food combination is calculated according to the method suggested by Mead *et al.*[25] as the number of reported illnesses[20] attributed to that combination multiplied by twice the case fatality rate for the pathogen to account for underreporting.

The DALY is computed for each pathogen-food combination by summing the years of life loss (YLL) and the years lived with disability (YLD), as follows:[14,17]

$$\text{DALY} = \text{YLL}^{*} + \text{YLD}^{**}, \qquad (2)$$

*YLL (Years of Life Loss) $= \sum_{j=1}^{9} d_j e_j$ (j = age group, d = # deaths, e = expected life span for age group); **YLD (Years Lived with Disability) = $\sum_l n_l t_l w_l$ (l = health outcome, n = # of cases, t = duration of the illness, w = disability/severity weight).

Nine age categories (0–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–39, 40–59, and ≥60 years) are used in the calculation of YLL. The reported incidence rate by age group,[20] demographic data,[21] and the adjusted case fatality rates described previously are used to estimate the number of deaths for each age category. Life expectancy data for the Canadian population are obtained from Statistics Canada.[26] Estimates of illness duration are from the sources defined in Table I and varied with illness severity and pathogen. For each pathogen, disability weights for all health outcomes are obtained from previously published studies.[17,27]

The COI is calculated based on the methodology used by ERS[18,28] and includes direct medical costs, loss of productivity, and loss of life. Medical care utilization includes the number of physician office, walk-in-clinic, home, emergency room, and outpatient clinic visits and hospitalizations for each severity outcome. The rates of use of these services are based on estimates derived from a population-based survey of the incidence and costs of gastroenteritis infections in Hamilton, Ontario.[19] Medical care costs on a per case basis are based on the standard fees payable under the Ontario Health Insurance Plan. In Canada healthcare is a provincial responsibility and medical costs vary across the country. Ontario costs for physician fees and hospitalizations are used in this analysis to maintain consistency with the Ontario case costing initiative (OCCI) data used for hospitalization costs (see below). Furthermore, Ontario is the province with the largest share (38%) of the Canadian population. Further development of costs by province will provide a more precise national COI estimate.

Hospitalization costs are derived from the OCCI[29] for nonchronic *Campylobacter* and *Salmonella* infections, HUS, and ESRD. Average costs for the period 2002–2006 are extracted from the OCCI database. Since hospitalization costs for *E. coli* O157 infections, Guillain-Barré syndrome (GBS), and listeriosis cases are not available through OCCI, the following assumptions are made. Hospitalization costs for *E. coli* O157 infections are assumed to be the same as for nonchronic *Campylobacter* infections. It is assumed that all GBS cases required an extended period of hospitalization, so the cost per case is taken as the maximum estimated cost of hospitalization for degenerative nervous disorders provided by OCCI. The latter is also used for the neurological disorders associated with listeriosis. For severe cases of listeriosis, the average cost for "other meningitis" and "other septicaemia" from OCCI are used. Hospitalization costs for fatal and nonfatal cases are assumed to be equal. Direct medical costs are calculated based on the estimated number of cases and costs for each outcome and then summed to a total cost across all outcomes.

Productivity costs are calculated based on a valuation of time lost from work because of illness and do not include productive activities outside the paid workforce such as stay-at-home mothers or the elderly. The calculations are based on an assumption that 54.7% of the Canadian population is in paid employment, an estimate derived from the 2006 Census undertaken by Statistics Canada.[30] The number of days spent away from work is obtained from a variety of sources (Table I) and is a function of both the pathogen and severity level. The estimated value of a single day's loss of productivity is based on the average rate for a day of paid employment in Ontario. The average rate of pay for a working week is estimated as the product of the mean hourly wage rate and the mean number of days worked per week among the population engaged in paid employment. Both are derived from the Labor Forces Survey undertaken by Statistics Canada.[31] Life loss is calculated by multiplying the number of deaths by the value for a statistical life. The value of a statistical life is CAN$6.11 million, taken from the *Canadian Cost-Benefit Analysis Guide*,[32] because federal departments and agencies use this resource for cost-benefit analysis to support regulatory decisions in Canada.

Both DALY and COI are calculated using the reported incidence rates and population data on an annual basis. Average values based on the most recent three years of available data are used to represent the two summary public health dimensions in the risk profile. For all pathogens except *L. monocytogenes*, the average values reported here are based on reported cases for 2002, 2003, and 2004. Since there is no Canadian data reported beyond 2003 for *L. monocytogenes*, the averages for DALY and COI are based on 2001, 2002, and 2003.

3.2. Market Impact Factor

In addition to public health impacts, foodborne pathogen incidence and outbreaks can have economic effects in markets for food and agricultural products.[33,34] Quantification of such effects is important not only in cases where an entire industry is affected (e.g., BSE in Europe, Canada, and the United States), but also when a single firm or group of firms is affected by an outbreak (such as *E. coli* 0157:H7 outbreaks at individual foodservice or food manufacturing establishments with concomitant spill-over effects). The info card for the market impact factor for each pathogen-food combination includes a short description of the industry, a description of the economic measures included on the card, and a table of data for the latest year used and for a three-year average ending in the latest year used. As discussed in detail below, all of these measures reflect the size and characteristics of a market that may be affected by foodborne pathogen incidence or outbreaks rather than the actual impacts of such occurrences. Fig. 3 shows the market impact info card for *Campylobacter* spp. in chicken.

MARKET IMPACT

Chicken consumption in Canada has been steadily increasing over the last 3 decades. The demand for chicken rose by 136% from 1975 to 2005. Since 1979, the Canadian production of chicken has been regulated under a supply management system. The intention of the supply management system is to match demand with domestic supply and to guarantee a predetermined price to producers. For the most part Canadian producers meet domestic demand and world-wide Canada is ranked 15th as a chicken exporter. Chicken production is mainly concentrated in ON, QC and BC.
Data was obtained from Agriculture Economic Statistics (May 2007), CANSIM II (Statistics Canada) and Agriculture and Agri-Food Canada. Averages were calculated based on the most recent 3 years including 2006. The following market characteristics provide an overview of the commodity market and points of comparison to the other commodities.

✓ Industry size is depicted by farm cash receipts, which is the total revenue to farms in an agricultural sub-sector. It is comprised of agricultural commodity sales and program payments.

✓ The importance of the commodity at the consumer level is represented by the total value at retail, which is the amount of the final consumer good purchased, multiplied by the average price per unit weight.

✓ The value of exports and imports is the quantity of the exported and imported commodity multiplied by the repspective values.

✓ To depict the economic significance of the commodity market in the domestic market, the following formula applies: Total value at retail + value of exports – value of imports.

✓ The proportion of the domestic consumption of the commodity that is domestically produced is calculated by the domestic consumption divided by the domestic production.

✓ The key import/export market values depict the importance of imports and exports of the commodity. For the import market, the key import market number is calculated by the value of all imports of a specific commodity divided by the value of the total agri-food imports.

Market Information ($1,000)	2006	Annual average (2004-2006)
Size of Industry (farm gate) farm cash receipts	$1,545,000	$1,580,000
Total Value at retail	$5,791,000	$5,664,000
Value of exports	$223,000	$223,000
Value of imports	$396,000	$415,000
Economic importance of the domestic market	$5,619,000	$5,472,000
% domestic consumption/domestic production	108.9%	107.6%
Key export market	0.80%	0.83%
Key import market	1.72%	1.94%

Fig. 3. Information card for market impact: *Campylobacter* spp.—Chicken.

There is a broad range of economic measures that may be used to quantify potential domestic and international market impacts related to different pathogen-food combinations in total and as distributed across the supply chain. The info card presents several measures to risk managers to help inform and contextualize the potential distributional consequences of incidence or outbreaks. These include farm cash receipts, total value at retail, value of exports, value of imports, proportion of domestic consumption of the food product produced domestically, and key export market and key import market (respectively, export (import) volume of a food product relative to overall agri-food exports (imports)). Farm cash receipts (farm gate sales) reflect the potential economic impact of the incidence of a foodborne pathogen on primary agricultural production. Including separate measures for value of retail sales (the amount of the final consumer goods purchased multiplied by the price consumers paid), exports, and imports provides information useful in terms of gauging where a sector/market might be particularly vulnerable (e.g., from domestic market effects or largely from trade actions). The ratio of domestic consumption that was domestically produced and the ratio of the product's volume of imports (exports) to the total volume of agri-food imports (exports) reflect the relative importance of the product domestically and in terms of trade.

We selected a calculated measure, the economic importance of the domestic market, as the summary measure of market impact to be compared across pathogen-food combinations. This measure is calculated as total value at retail plus the value of exports and less the value of imports. This summary measure does not explicitly incorporate the distribution of economic activities through the marketing channel, although this distribution is represented in other data presented on the info card. The aim of this admittedly crude measure is to account for the size of the economic activity at risk from foodborne pathogen incidence or outbreaks. The size of the domestic market is a surprisingly difficult concept to capture. A measure of farm-level economic activity alone ignores the sizeable processing sector in contemporary food supply chains. Moreover, there are clear negative consequences for the food processing, distribution, and retail sectors when foodborne pathogen incidence and outbreaks result in reduced consumption. Thus we use total value at retail as a starting point for the summary measure in order to reflect the entire value added along the marketing channel. Many agri-food commodities are traded internationally and such markets can be important for the domestic agri-food sector, hence the rationale for adding the value of exports. For example, incidence of foodborne pathogens can result in closure of borders or significant reductions in trade as a means of providing sanitary and phytosanitary protection. At the same time, deleting the value of imports from retail sales ignores the value created domestically due to value added to imported commodities, and in this sense the measure of economic impact is an underestimate.

All of the measures presented on the info card, including the summary measure, are not ideal in that they reflect the size and characteristics of a market that may be affected rather than the actual impacts of foodborne pathogen incidence or outbreaks. However, our choice of market impact factors was guided by several considerations. In particular, it is desirable to have measures of economic activity that are objectively measurable, as well as transparent and clear to decisionmakers, and that capture the size of the market and the distribution of economic activity along the marketing channel. Furthermore, it is our experience that in the context of overall risk prioritization for a large number of pathogen-food combinations, it is challenging for several reasons to obtain the data and conduct the in-depth analyses necessary to pinpoint the potential market impacts of a particular incidence or outbreak related to a pathogen.

First, it is challenging to obtain the appropriate data for markets and market-level impacts for specific food products, particularly when these occur over several related levels of the food supply chain. For example, farm-cash receipts are not available for processed foods such as ready-to-eat meats and specific information on exports and imports is also lacking for this market. As a further example, effects on wages and number of employees in a particular sector should be taken into consideration; however, these data were not available on a food-product level in Canada. Further challenges arise across the board for data on processed foods.

Second, while the economic effects arising from foodborne pathogen incidence or outbreaks can be large, they can also be difficult to predict. Even when analysis is available based on incidents related to specific pathogen-food combinations, it is difficult to quantify how consumers and producers will react to an incident related to different pathogen-food combinations. Economic theory does provide some insight into the expected direction of the effect; it is nevertheless true that predictions of the magnitude of any demand or supply curve shifts, and subsequent changes in the price and quantity of supply and demand, will reflect a high degree of uncertainty without in-depth quantitative analysis. Such uncertainty translates into imprecise measurement of the impact of foodborne pathogen incidence or outbreaks on producer surplus and money metric measures of consumer utility (e.g., compensating variation, equivalent variation, or even consumer surplus).

Further, even if the impact of a foodborne pathogen incident on consumers and producers could be measured with precision, these only reflect the direct impact of that incident and tend to ignore the distribution of costs along the supply chain. Other indirect effects (e.g., multimarket spillover effects, impacts on industries providing inputs to the directly affected sector, etc.) are equally important but very difficult to measure without resorting to applied/computable general equilibrium models. Similarly, we may be able to estimate the costs to industry of the mitigating actions taken, but this does not imply that these costs are not passed on to consumers, at least in part, through prices. The degree to which costs are passed on in this way will reflect market structure, modes of competition, etc., and so are likely to be quite case specific. Arguably, the models we employ provide sufficient detail to capture the directly affected industry and at the same time are sufficiently broad to enable measurement of intersectoral effects arising from a food safety incident.

Ideally, in measuring impacts one would strive to undertake a full welfare analysis related to a foodborne pathogen incidence or outbreak. However, such analysis often takes considerable time and effort. It would also likely be largely idiosyncratic in that results from a welfare analysis for one pathogen-food combination may not lend themselves to extrapolation to other combinations. Conducting in-depth economic impact analyses in the context of overall risk prioritization for a large number of pathogen-food combinations would be akin to also requiring full-blown risk assessments for all the combinations. In such circumstances, we argue that an alternative means of capturing potential market-level effects in an aggregate manner as proposed here is warranted.

Data for the potential market-level effects included on the info card are obtained from Agriculture Economic Statistics (May 2007),[35] Statistics Canada (CANSIM II),[36,37] and Agriculture and Agri-Food Canada.[38] Averages for the respective measures are calculated based on 2004, 2005, and 2006 data. The measures reported on the card assume the impact is for a year in duration. The framework can accommodate event durations longer or shorter than a year by applying a discount adjustment so that the value of market-level effects for different pathogen-food combinations are measured on the same time scale.

3.3. Consumer Perception and Acceptance of Risk Factor

Currently available frameworks for risk prioritization generally give little consideration to consumer perception and acceptance of risk. However, it may be a relevant factor to risk managers in choosing priorities as consumer risk perception and acceptance can affect how they view the net benefits of consuming a food. The info card for consumer perception and acceptance of risk for each pathogen-food combination in the multifactorial risk prioritization framework includes a short description of the criteria used to capture this factor, the method used to rank criteria, and a table of scores for the criteria and for a summary measure of the criteria. Fig. 4 shows the consumer perception and acceptance info card for *Campylobacter* spp. in chicken.

A concern with including consumer risk perception and acceptance in risk prioritization is that consumer perceptions of the risks associated with a particular pathogen-food combination may bear little relationship to scientific determinations of risks as measured by the probability of an adverse health outcome.[39–41] Risk perceptions among the lay public reflect many factors, including the way in which risk contexts are framed, bias related to the ability to mentally visualize an adverse health outcome occurring, overconfidence in their own ability to assess risk, and a tendency to discount very small risks. Further, the acceptability of a particular risk takes account of a wide range of qualitative factors that do not enter into a scientific risk assessment, including: the degree to which the risk is perceived to be controllable, whether exposure is voluntary or involuntary, the nature of the associated health outcomes over time (in particular whether they are acute or chronic), and perceptions of the individual's and experts' knowledge of the risk.[39,41,42]

Risk managers are aware of and may be influenced by consumer risk perceptions and acceptance. Consumers may be willing to accept a foodborne pathogen risk if their perception of the risk is low or if the perceived benefits arising from the consumption of that particular food offset the perceived ill consequences. Consumer perceptions of the risks associated with food can also be an important determinant of the confidence the general public has in the food system and in prevailing systems of public regulation and oversight. Relatively small but highly visible outbreaks of disease can have a profound impact on the trust that consumers have in food producers, manufacturers, and/or distributors or in government regulators. Thus, consumer risk perception and acceptance can be an important factor in decision making and as such is formally incorporated into this framework to allow a transparent and systematic evaluation of this factor. Of course, the perceptions of risk managers with respect to consumer concerns may exhibit biases, in the same way that consumer perceptions themselves are biased. Incorporating a measure of consumer perceptions into the framework aims to offset this bias.

CONSUMER PERCEPTION AND ACCEPTANCE OF RISK

INTRODUCTION

Five criteria were selected to characterize consumer perceptions and acceptance of risks associated with Campylobacteriosis attributed to chicken consumption.

Four experts ranked each criterion as low, medium or high, according to consumers' perspectives. Numerical values were assigned to the nominal scales (low=1, medium=2, and high=3) and an average ranking was calculated for each criterion. The average for each criterion was added to obtain a total score (out of 15) and the total score was normalized to a value between 0 and 1.

Consumer Perception and Acceptance Criteria	Score
Degree to which risk is perceived as uncontrollable by consumer	1.25
Degree to which risk is perceived as unknown to the individual	1.5
Degree to which risk is perceived as unknown to the scientists	2.0
Degree to which exposure to the risk is perceived to be involuntary	1.75
Degree to which consumer perceive outcome as severe	1.5
TOTAL SCORE - Consumer perception and acceptance of risk	0.3

Fig. 4. Information card for consumer perception and acceptance of risk: *Campylobacter* spp.—Chicken.

In this framework, consumer perceptions and acceptance of risk are defined by the degree to which a particular food-pathogen risk is perceived as uncontrollable by consumers, unknown to the individual, unknown to scientists, involuntary, and known to have a severe outcome. These have been shown in the literature to be key qualitative dimensions of risk perceptions. Our initial approach to quantifying these five criteria for each case study was to use expert opinion. Four members of the research team with experience in consumer behavior regarding food individually ranked the criterion into low, medium, or high. Numerical values are assigned to the nominal scales (low = 1, medium = 2, and high = 3) and the average score is calculated for each criterion. The summary measure for this factor is an average calculated on the basis of the five criteria. The average values for all five criteria are added and each sum is normalized on the basis of a maximum value of 15 to obtain an aggregated score between 0 and 1 that estimates consumer perception and acceptance of risk for a particular pathogen-food combination. It is important to note that this approach is used to generate data so that the framework could be illustrated. We are currently conducting additional research to better quantify this factor.

3.4. Social Sensitivity Factor

Risk prioritization may be influenced by the impact of pathogen-food combinations on vulnerable groups, with a greater weight put on these impacts than on the "average" for society as a whole.[4] Further, society may be interested in the wider social consequences associated with foodborne illness, perhaps representing external factors that spread beyond food consumers and food markets. Finally, there may be firms or other economic entities that are particularly vulnerable to the impacts of pathogen incidence or proposed interventions, for example, because of size or precarious economic circumstances. The info card for the social sensitivity factor for each pathogen-food combination includes a short description of the measure used to capture social sensitivity, a brief explanation of information used to gauge social sensitivity for the pathogen-food combination, and a table of data for the two social sensitivity

Fig. 5. Information card for social sensitivity: *Campylobacter* spp.—Chicken.

SOCIAL SENSITIVITY

Binary values (0 = no concern; 1=concern) are used to reflect the vulnerability of consumer groups and /or firm or market groups.

No human sub-populations are particularly susceptible to Campylobacter infections or are likely to suffer lingering health effects, beyond what is captured in the DALY and cost of illness metrics. The chicken industry is not one that is considered to be unique or niche in Canada.

Social Sensitivity Information	Score
Consumer perspective	0
Industry/firm perspective	0

criteria used. Fig. 5 shows the social sensitivity info card for *Campylobacter* spp. in chicken.

Social sensitivity may be a controversial factor to include in risk prioritization because it is dependent upon individual views and ethical positions. Internationally, there is no consensus on the relevance of such issues in a risk-prioritization context. Nonetheless, FAO/WHO guidelines[(3)] for risk analysis and the EU microbial risk framework[(12)] consider social and ethical concerns in societies that develop and use regulatory interventions to try to lower the burden of microbial food- and waterborne hazards. The EU in particular recognizes the need to consider the social impacts of its food safety controls and regulations beyond Europe and in particular on developing countries.

It is important to note that social sensitivity to impacts on a consumer group does not relate to the potentially greater personal risk that some consumers may face from a particular pathogen-food combination. This is incorporated into the public health factor. Rather, the issue is the disproportionate or excess impact on particular groups in terms of anticipated welfare consequences and the fact that society as a whole tends to react to and be sensitive to adverse impacts that these groups may experience. Such concerns may relate to, for example, the groups' more limited ability to take averting actions to self-protect or to altruism. Similarly, on the food supply side, social sensitivity does not reflect the economic impact on particular groups *per se*, which is included in the market impact factor. Instead, it reflects sensitivity to, for example, particular groups' economic vulnerability to the adverse effects of risks from particular pathogen-food combinations, the role such groups play in rural areas or as businesses in economically vulnerable areas, and their contribution to the historical and/or social fabric of society.

Two vulnerable groups (consumers and firms in the food supply chain) are chosen to represent the social sensitivity dimension in this framework. The consumer groups considered are the elderly, infants and young children, low income consumers, aboriginal populations, and individuals with compromised immune-systems. On the food supply side, the vulnerable groups considered include small producers, small and medium-sized enterprises, enterprises in marginal economic and/or aboriginal areas, and enterprises representing disproportionately important sources of employment or livelihood.

The framework incorporates social sensitivity to adverse effects from a particular pathogen-food combination through use of binary values of 0 (no concern) or 1 (concern) to reflect the existence of vulnerable consumer groups and firms/economic groups. The study authors assigned the score of 0 or 1 for each pathogen-food combination by consensus of the study authors in order to operationalize and illustrate the framework. These two binary variables are first approximations for capturing social sensitivity associated with different groups of consumers as well as firms. We recognize that additional research is

SUMMARY

CAMPYLOBACTERIOSIS AND CHICKEN CONSUMPTION

Criterion		3 yr avr	Score
Public Health Impact (2002– 2004)	Incidence (per 100,000)	495	n/a
	Case-fatality rate (%)	0.003%	n/a
	COI ($)	79,810,00	n/a
	DALY	808	n/a
Market Impact (2003-2006)	Size of the in-dustry: Farm gate ($1,000)	1,580,000	n/a
	Size of the in-dustry: Total value at retail ($1,000)	5,664,000	n/a
	Economic importance of the domestic market ($1,000)	5,472,000	n/a
	Key export market	0.83%	n/a
	Key import market	1.94%	n/a
Consumer Percep-tion and Accep-tance (1 to 3 scale)	Degree to which risk is perceived as uncontrollable by con-sumer		1.25
	Degree to which risk is perceived as unknown to the individ-ual		1.5
	Degree to which risk is perceived as un known to the scien-tists		2
	Degree to which exposure to the risk is perceived to be in-voluntary		1.75
	Degree to which consumer perceive outcome as sever		1.5
	Total (normalized, 0 to 1 scale)		0.3
Social Sensitivity (0 to 1)	Consumer		0
	Firm		0

Fig. 6. Summary card: *Campylobacter* spp.—Chicken.

needed to make the quantification of this factor more rigorous.

4. TOOLS FOR PRIORITIZING RISKS: INFO CARDS AND MULTICRITERIA DECISION ANALYSIS

4.1. Info Cards

The summary measures for each of the four factors are gathered into a summary info card. Fig. 6 shows the summary card for *Campylobacter* spp. in chicken. The five info cards (four factors and one summary) for each pathogen-food combination are the first tool provided to decisionmakers for risk prioritization. Other groups have shown the value of providing decisionmakers with risk summaries that present information in consistent categories. For example, summary sheets developed by Carnegie Mellon[43] were found to be the most useful feature of a risk ranking model for food safety.[44] The Canadian Food and Inspection Agency[45] and the New Zealand Food Safety Authority[10] have also developed risk summaries as a basis for decision making. Systematic and consistent presentation of information, in the format of information cards, can directly inform risk management decisions and the complete set provides context that is important for comparisons across pathogen-food combinations.

4.2. Multicriteria Decision Analysis

The second tool developed for use by risk managers in this framework is based on multicriteria decision analysis (MCDA) methodologies. These methodologies are powerful tools for ranking microbial risks based on multiple factors including public health, market impacts, consumer perception and acceptance, and social sensitivity. MCDA methods have been utilized to address a range of decision problems, including: the selection of solid and nuclear waste management and treatment facilities,[46–48] evaluation of irrigations systems,[49] and, more recently, in evaluating interventions to improve food safety[50] and human health.[51]

MCDA methodology is a powerful tool for clarifying and documenting the importance assigned to different factors in ranking risks. At the same time, the application of such a formal analysis requires that decisionmakers articulate their value structure, including the prioritization factors they consider and the value placed on each prioritization factor. Some MCDA methods are well suited to developing consensus among decisionmakers particularly when there are numerous stakeholders with different values.[52,53]

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), an outranking method developed by Brans *et al.*[54,55] and implemented in Decision Lab software (Visual Decision Inc., Montreal, QC, Canada), is used to demonstrate the ranking of foodborne microbial risks in a multifactorial framework. The PROMETHEE methodology is based on pair-wise comparisons of alternatives (i.e., pathogen-food combinations) on each criterion (i.e., factor) separately so differences in criteria scales do not influence the ranking. For this analysis, simple ranking relationships are used. Any positive difference in scores for two alternatives results in a higher ranking for the alternative with the higher score on that criterion. Complete rankings are based on the aggregation of all criteria with a weight assigned to each criterion and the calculation of a net outranking flow for each alternative under consideration. This calculation includes two components: the degree to which an alternative outranks other alternatives and the degree to which an alternative is outranked by other alternatives in the set. In this application, a higher net outranking flow corresponds to higher risk. The complete ranking approach may be compared with a utility function.[52]

The PROMETHEE methodology permits a "stability interval" analysis for a particular set of criteria weights. The complete rankings for a set of alternatives remain unchanged for any weight within the stability interval defined for each criterion and subject to the constraint that the sum of weights (expressed as decimal fractions) across all criteria is 1. This gives decisionmakers a starting point for considering weight adjustments in order to reach consensus in a group with different values. It may save considerable discussion time, if it can be shown that different value structures produce the same or similar rankings.

5. RISK PRIORITIZATION RESULTS FOR SIX CANADIAN CASE STUDIES

Six Canadian case studies are developed to illustrate use of the multifactorial risk prioritization framework: *Campylobacter* spp. in chicken; *Salmonella* spp. in chicken and in spinach; *Escherichia coli* O157 in spinach and in beef; and *L. monocytogenes* in ready-to-eat meats. The top panel of Table II shows the data included on the summary info cards for the four factors for the case studies. Two of the factors have two summary measures so in total there are six summary measures: public health (DALY and COI), market impact (economic importance of domestic market), consumer perception and acceptance of risk (total normalized score), and social sensitivity (consumer and firm scores).

The risk profiles shown in the top panel of Table II illustrate one of the challenges in comparing and ranking microbial risks: each pathogen-food combination performs differently across the four major factors. *Campylobacter* spp. in chicken (C-C) and *Salmonella* spp. in chicken (S-C) are the highest risks based on the public health and market impact factors. In contrast, *E. coli* O157 in spinach (E-S) and *L. monocytogenes* in ready-to-eat meats (L-RTEM) have high values on the consumer perception and acceptance and social sensitivity scales. None of the case studies dominates on all of the criteria (i.e., factors).

Three scenarios are compared in order to illustrate the flexibility of a MCDA tool to accommodate different stakeholder values. The first scenario assumes the stakeholder values all four major factors, placing equal weight on each. In the second scenario, the stakeholder does not consider social sensitivity and assigns equal weights for the remaining three

Table II. Risk Profiles for the Six Pathogen-Food Combinations and Weights Assigned by Each Stakeholder

	Public Health		Market Impact	Consumer Perception and Acceptance	Social Sensitivity	
	DALY (years)	COI (CAN$ million)	Econ. Imp. of the Domestic Market (CAN$ Million)	Normalized Scores on 0–1 Scale	Consumer 0–1 Binary Score	Firm 0–1 Binary Score
Pathogen-food combinations[a]						
C-C	808	64.8	5,472	0.3	0	0
S-C	449	54.2	5,472	0.25	0	0
S-S	1	0.14	118	0.5	0	0
E-S	3	0.35	118	0.8	1	0
E-B	260	28.1	5,264	0.6	1	0
L-RTEM	58	8.8	974	0.6	1	1
Weights[b]						
Stakeholder 1	0.125	0.125	0.25	0.25	0.125	0.125
Stakeholder 2	0.165	0.165	0.33	0.33	0	0
Stakeholder 3	0.50	0.50	0	0	0	0

[a] *Campylobacter* spp. in chicken (C-C), *Salmonella* spp. in chicken (S-C), *Salmonella* spp. in spinach (S-S), *E.coli* O157 in spinach (E-S), *E. coli* O157 in beef (E-B), *L. monocytogenes* in ready-to-eat meats (L-RTEM).
[b] Stakeholder 1: 4 factors, equal weights; Stakeholder 2: 3 factors, equal weights, and Stakeholder 3: public health only.

Table III. Complete Ranking PROMETHEE I for Three Different Stakeholders

	Scenarios[a]		
RANKING	Stakeholder 1	Stakeholder 2	Stakeholder 3
1	E-B[b]	C-C	C-C
2	L-RTEM	E-B	S-C
3	C-C	S-C	E-B
4	S-C	L-RTEM	L-RTEM
5	E-S	E-S	E-S
6	S-S	S-S	S-S

[a] Stakeholder 1: All four factors weighted equally. Stakeholder 2: Social sensitivity not included, other three factors equally weighted. Stakeholder 3: Only public health factor weighted.
[b] *Campylobacter* spp. in chicken (C-C), *Salmonella* spp. in chicken (S-C), *Salmonella* spp. in spinach (S-S), *E.coli* O157 in spinach (E-S), *E. coli* O157 in beef (E-B), *L. monocytogenes* in ready-to-eat meats (L-RTEM).

factors. In the third scenario, the stakeholder places all weight on the public health factor. The bottom panel of Table II shows the criteria and weightings used by the three stakeholders.

The rankings under each scenario are shown in Table III. Under the first scenario with Stakeholder 1, *E. coli* O157 in beef (E-B) ranked as the highest priority, followed by *L. monocytogenes* in RTE meats (L-RTEM). When social sensitivity is removed as a criterion by Stakeholder 2, *Campylobacter* spp. in chicken (C-C) ranked first, *E. coli* O157 in beef (E-B) moved to second place, and *L. monocytogenes* in RTE meats (L-RTEM) is in the lower half of the rankings. When only public health is taken into consideration by Stakeholder 3, *Campylobacter* spp. in chicken (C-C) and *Salmonella* spp. in chicken (S-C) are the two highest risked priorities. All three stakeholders rank *E. coli* O157 in spinach (E-S) and *Salmonella* spp. (S-S) as the lowest risks for the six case studies.

Table IV shows stability intervals for each criterion in the first and second scenarios. The stability intervals for Stakeholder 1 allow some modification of weights but all of the intervals are more constrained than those for Stakeholder 2. Although the social sensitivity factor is not considered by Stakeholder 2, the stability analysis shows that consumer and firm sensitivities could be included with weights up to 0.105 without changing the complete rankings. However, this would require adjustments in weights for the other criteria so that the adjusted weights remain within the stability intervals and the sum of all weights is 1.

It is important to recognize that while MCDA methodologies provide tools to improve the decision-making process, they do not replace decisionmakers. Risk managers must identify the alternatives that are under consideration as well as the criteria and weights for the ranking algorithm. Furthermore, they must evaluate the rankings and may need to return to the framework's knowledge base and the info cards for additional information about particular microbial risks in order to understand and refine the rankings.

Table IV. Stability Intervals for Complete Rankings: Stakeholder 1 and Stakeholder 2

	Scenarios			
	Stakeholder 1		Stakeholder 2	
Criterion	Weight	Stability Interval	Weight	Stability Interval
DALY	0.125	0.087 to 0.125	0.165	0.0 to 0.371
COI	0.125	0.087 to 0.125	0.165	0.0 to 0.371
Market level	0.25	0.226 to 0.250	0.33	0.221 to 0.448
Consumer perceptions	0.25	0.250 to 0.268	0.33	0.263 to 0.391
Social sensitivity—consumer	0.125	0.125 to 0.160	0.0	0.0 to 0.105
Social sensitivity—firm	0.125	0.125 to 0.160	0.0	0.0 to 0.105

6. CONCLUSION AND FURTHER WORK

The multifactorial risk prioritization framework has been presented for feedback and recommendations to select groups of policymakers and risk analysts in public health regulatory agencies in Canada and the United States. Based on initial comments, there is agreement that the four major factors are relevant to risk prioritization decisions although there is need for further discussion about the specific measures. The framework clearly allows dimensions to be added or removed. However, it is important to understand that each dimension requires intensive data gathering and analysis.

The framework would benefit significantly from the availability of better data on all factors used in the analysis. For example, a key issue for comparing risks at the level of pathogen-food pairs is the attribution of illness to different foods. Several groups are working to improve food attribution methods[56–59] and members of our research group are collaborating with the Public Health Agency of Canada on a project to develop better estimates of food attribution for the Canadian population. The info cards for the case studies are implemented in spreadsheet formats but work is underway to develop an integrated database. The proposed measures for the four major risk factors can be modified in particular contexts if risk managers are not satisfied with them. In any case, the underlying knowledge base must be updated on a regular basis.

Two additional aspects of risk prioritization are the subject of further work on the framework. The first is to analyze uncertainty in the risk profile measures and the impact of this uncertainty on final rankings. An initial approach is to reflect aspects of uncertainty that can be addressed through the use of discrimination thresholds in the ranking or preference relationships defined for each criterion in PROMETHEE. For example, an indifference threshold can be defined for each criterion. Obviously there would be a tradeoff between the magnitude of the indifference threshold and the ability to differentiate risk rankings. We recognize there may be considerable uncertainty in some circumstances (e.g., the case of a new hazard) and risk managers must be aware of how this affects rank positions. Uncertainty in ranking for a pathogen-food pair would be a clear indicator that one or more aspects of the multifactorial risk assessment stage (Block B in Fig. 1) need to be addressed. A second further step is to begin assessment of interventions to control risks. Intervention analysis is expressly excluded from the framework presented here in order to prevent its conflation with risk prioritization.

The multifactorial risk prioritization framework aims to improve the decision-making process by providing tools necessary to allow multiple cross-disciplinary factors to be handled in a scientific and rigorous manner. In addition, it promotes a balanced and transparent decision-making process. This framework provides important decision-support tools for risk managers, ones that will enable them to make scientifically sound and defensible risk management decisions in an effective and expedient manner.

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REFERENCES

1. Henson S, Caswell J, Cranfield J, Fazil A, Davidson VJ, Anders S, Schmidt C. A multi-factorial risk prioritization framework for food-borne pathogens, 2007. Available at http://ssrn.com/abstract=989768. Accessed on January 30, 2009.
2. International Risk Governance Council. Risk governance towards an integrative approach, 2005. Available at http://www.irgc.org/IMG/pdf/IRGC_WP_No_1_Risk_Governance__reprinted_version_.pdf. Accessed on January 30, 2009.
3. Food and Agriculture Organization of the United Nations and World Health Organization. Principles and guidelines for incorporating microbiological risk assessment in the development of food safety standards and related texts. Kiel, Germany. Report of a Joint FAO/WHO consultation, March 18–22, 2002. Available at http://www.fao.org/docrep/006/y4302e/y4302e00.HTM. Accessed on January 31, 2009.
4. Stern PC, Fineberg HV (eds.). Understanding risk. Washington, DC: National Academies Press, 1996.
5. HM Treasury. Managing risks to the public: Appraisal guidance, 2005. Available at: http://www.hm-treasury.gov.uk/d/Managing_risks_to_the_public.pdf. Accessed on January 30, 2009.
6. U.S. Environmental Protection Agency. Risk characterization handbook, 2000. Available at http://www.epa.gov/OSA/spc/pdfs/rchandbk.pdf. Accessed on January 30, 2009.
7. Havelaar AH, Bräunig J, Christiansen K, Cornu M, Hald T, Mangen MJJ, Mølbak K, Pielaat A, Snary E, Van Pelt W, Velthuis A, Wahlström H. Towards an integrated approach in supporting microbiological food safety decisions. Zoonoses and Public Health, 2007; 54:103–117.
8. Food and Agriculture Organization of the United Nations and World Health Organization. Microbial hazards in fresh fruits and vegetables (pre-publication version), 2008. Available at http://www.fao.org/ag/agn/agns/files/ffv_2007_Final.pdf. Accessed on January 30, 2009.
9. Batz MB, Hoffmann S, Krupnick AJ, Morris JG, Sherman DM, Taylor MR, Tick JS. Identifying the most significant microbiological foodborne hazards to public health: A new risk ranking model, 2004. Available at http://www.thefsrc.org/Discussion%20Papers/FRSC-DP-01.pdf. Accessed on January 30, 2009.
10. New Zealand Food Safety Authority. Food safety in New Zealand: Application of a risk management framework, 2008. Available at http://www.nzfsa.govt.nz/about-us/risk-management-framework/page-03.htm. Accessed on January 30, 2009.
11. New Zealand Food Safety Authority. Food administration in New Zealand—A risk management framework for food safety. joint ministry of health and ministry of agriculture and forestry food harmonization project, 2000. Available at http://www.nzfsa.govt.nz/policy-law/codex/publications/introduction-to-codex/rmgmtpr.pdf. Accessed on January 30, 2009.
12. European Commission. Risk assessment of foodborne bacterial pathogens: Quantitative methodology relevant for human exposure assessment. Health and Consumer Protection Directorate-General Directorate C - Scientific Opinions, C1 - Follow-Up and Dissemination of Scientific Opinions, Preliminary Report, 2002. Available at http://europa.eu.int/comm/food/fs/sc/ssc/out252_en.pdf. Accessed on January 30, 2009.
13. Health Canada. Health Canada decision-making framework for identifying, assessing, and managing health risks, 2000. Available at http://www.hc-sc.gc.ca/ahc-asc/alt_formats/hpfb-dgpsa/pdf/pubs/risk-risques-eng.pdf. Accessed on January 30, 2009.
14. Murray CJL. Quantifying the burden of disease: The technical basis for disability-adjusted life years. Bulletin of World Health Organization, 1994; 72: 429–445.
15. Mathers CD, Lopez AD, Murray CJL. The burden of disease and mortality by condition: Data methods, and results for 2001. Chapter 3 in Lopez AD, Mathers CD, Ezzati M, Jamison DT, Murray CJL (eds). Global Burden of Disease and Risk Factors. Washington, DC: World Bank, 2006.
16. Arnesen T, Kapiriri L. Can the value choices in DALYs influence global priority-setting? Health Policy, 2004; 70:137–149.
17. Kemmeren JM, Mangen MJJ, van Duynhoven YTHP, Havelaar AH. Priority setting of foodborne pathogens: Disease burden and costs of selected enteric pathogens, 2006. RIVM report 330080001. Available at http://www.rivm.nl/bibliotheek/rapporten/330080001.pdf. Accessed on January 30, 2009.
18. Frenzen PD, Drake A, Angulo FJ. Emerging Infectious Program FoodNet Working Group. Economic cost-of-illness due to *Escherichia coli* O157:H7 infectious in the United States. Journal of Food Protection, 2005; 68:2623–2630.
19. Majowicz SE, McNab WB, Sockett P, Henson S, Dore K, Edge VL, Buffett MC, Read S, McEwen S, Stacey D, Wilson JB. The burden and cost of gastrointestinal illness in a Canadian community. Journal of Food Protection, 2004; 69:651–659.
20. Public Health Agency of Canada. Notifiable disease online. Available at http://dsol-smed.phac-aspc.gc.ca/dsol-smed/ndis/index_e.html. Accessed on January 30, 2009.
21. Statistics Canada. Estimates of population, by age group and sex for July 1, Canada, provinces and territories, annual (persons), 1971 to 2008 (table 051-0001), Available at http://cansim2.statcan.ca/cgi-win/cnsmcgi.pgm?regtkt=&C2Sub=&LANG=E&C2DB=PRD&C2USER=&C2PASS=&C2APASS=&C2USEWRK=&SDDSLOC=//www.statcan.gc.ca/imdb-bmdi/*.htm&ROOTDIR=CII/&VEC=&RESULTTEMPLATE=CII/CII_ASUM&ARRAY_SUMM=1&SDDSID=&DRILLFILE=&ARRAYID=510001. Accessed on January 30, 2009.
22. Lee MB, Middleton D. Enteric illness in Ontario, Canada from 1997 to 2001. Journal of Food Protection, 2003; 66:953–961.
23. Thomas MK, Majowicz SE, Sockett PN, Fazil A, Pollari F, Dore K, Flint JA, Edge VL. Estimated numbers of community cases of illness due to *Salmonella*, *Campylobacter* and verotoxigenic Escherichia coli: Pathogen-specific community rates. Canadian Journal of Infectious Diseases and Medical Microbiology, 2006; 30:229–234.
24. Ontario Ministry of Agriculture and Food. Food Safety Science Unit. Impact of Foodborne Disease from Microbial Pathogens, Food Types and Pathogen-Food Combinations in Ontario. Guelph, ON: Canada, 2005.
25. Mead PS, Slutsker L, Dietz V, McCaig LF, Bresee JS, Shapiro C, Griffin OM, Tauxe RV. Food-related illness and disease in the United States. Emerging Infectious Diseases, 1999; 5:1–31.
26. Statistics Canada. Life Expectancy, 2006. Available at http://www.statcan.ca/english/studies/82-003/archive/2005/17-1-e.pdf. Accessed on January 30, 2009.
27. Havelaar AH, Van Duynhoven YT, Nauta MJ, Bouwknegt M, Heuvelink AE, De Wit GA, Nieuwenhuizen MG, van de Kar NC. Disease burden in the Netherlands due to infections with Shiga toxin-producing *Escherichia coli* O157. Epidemiology and Infection, 2004; 132:467–484.
28. U.S. Department of Agriculture, Economic Research Service. Foodborne illness cost calculator: Assumption details and citations for *Salmonella*. Available at http://www.ers.usda.gov/data/FoodBorneIllness/salmAssumptionDescrip

tions.asp?Pathogen=Salmonella&p=1&s=4683&y=2006&n = 1397187. Accessed on January 30, 2009.
29. Ontario case costing initiative. Available at http://www.occp.com/. Accessed on January 30, 2009.
30. Statistics Canada. Incoming and earnings highlighted tables, 2006 census. Available at http://www12.statcan.ca/english/census06/data/highlights/income/index.cfm?Lang=E. Accessed on January 30, 2009.
31. Statistics Canada. Labour force survey estimates (LFS), by provinces, territories and economic regions, 3-month moving average, unadjusted for seasonality, monthly (person unless otherwise noted). Available at http://cansim2.statcan.ca/cgi-win/cnsmcgi.exe?Lang=E&RootDir=CII/&ResultTemplate=CII/CII___&Array_Pick=1&ArrayId=2820054. Accessed on January 30, 2009.
32. Treasure Board of Canada Secretariat. Canadian cost-benefit analysis guide: Regulatory proposals, 2007. Available at http://www.regulation.gc.ca/documents/gl-ld/analys/analys-eng.pdf. Accessed on January 30, 2009.
33. Henson SJ, Mazzocchi, M. Impact of the BSE crisis on UK agribusiness: Results of an event study of equity prices. American Journal of Agricultural Economics, 2000; 84:370–386.
34. Sparling D, Caswell JA. Risk management in the integrated NAFTA market: Lessons from the case of BSE. Review of Agricultural Economics, 2006; 28:212–228.
35. Industry Canada. Trade by product. Available at http://strategis.ic.gc.ca/sc_mrkti/tdst/tdo/tdo.php#tag. Accessed on January 30, 2009.
36. Statistics Canada. Farm cash receipts. Available at http://www.statcan.ca/bsolc/english/bsolc?catno=21-011-XWE. Accessed on January 30, 2009.
37. Statistics Canada. Average retail prices for food and other selected items, monthly (dollars), Jan 1995 to Dec 2008 (table 326-0012). Available at http://cansim2.statcan.ca/cgi-win/cnsmcgi.pgm?regtkt=&C2Sub=&LANG=E&C2DB=PRD&C2USER=&C2PASS=&C2APASS=&C2USEWRK=&SDDSLOC=//www.statcan.gc.ca/imdb-bmdi/*.htm&ROOTDIR=CII/&VEC=&RESULTTEMPLATE=CII/CII_ASUM&ARRAY_SUMM=1&SDDSID=&DRILLFILE=&ARRAYID=3260012. Accessed on January 30, 2009.
38. Agriculture and Agri-Food Canada. Canada's poultry and egg international trade. Available at http://www.agr.gc.ca/poultry/trin_e.htm. Accessed on January 30, 2009.
39. Frewer LJ, Howard C, Hedderley D, Shepherd R. Methodological approaches to assessing risk perceptions associated with food-related hazards. Risk Analysis, 1998; 18:95–102.
40. Fife-Schaw CR, Rowe G. Public perceptions of everyday food hazards: A psychometric study. Risk Analysis, 1996; 16:487–500.
41. Fischoff B, Slovic P, Lichtenstein S, Read S, Combs, B. How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. Policy Sciences, 1978; 9:127–152.
42. Slovic P, Fischoff B, Lichtenstein S. Facts and fears: Understanding perceived risk. Session III in Schwing RC, Albers WA (eds). Societal Risk Assessment: How Safe is Safe Enough? New York: Plenum Press, 1980.
43. Florig HK, Morgan MG, Morgan KM, Jenni KE, Fischhoff B, Fishbeck PS, DeKay ML. A deliberative method for ranking risks (I): Overview and test bed development. Risk Analysis, 2001; 21:913–921.
44. Webster KD, Jardine CG, McMullen L, Cash SB. Risk ranking: Investigating expert and public differences in evaluating food safety risks, 2008. Available at http://ageconsearch.umn.edu/bitstream/6378/2/pr080002.pdf. Accessed on January 30, 2009.
45. Canadian Food Inspection Agency. Animal health risk analysis framework for biotechnology-derived animals, 2004. Available at http://www.inspection.gc.ca/english/sci/ahra/bioanima/bioanimae.html. Accessed on January 30, 2009.
46. Linkov L, Satterstrom FK, Kiker G, Seager TP, Bridges T, Gardner KH, Rogers SH, Belluck DA, Meyer A. multicriteria decision analysis: A comprehensive decision approach for management of contaminated sediments. Risk Analysis, 2006; 26:61–78.
47. Hokkanen J, Salminen P. Locating a waste treatment facility by multicriteria analysis. Journal of Multi-Criteria Decision Analysis, 1997: 6:175–184.
48. Briggs T, Kunsch PL, Mareschal B. Nuclear waste management: An application of the multicriteria PROMETHEE method. European Journal of Operational Research, 1990; 44:1–10.
49. Raju K, Pillai CRS. Multicriterion decision making in performance evaluation of an irrigation system. European Journal of Operational Research, 1999; 112:479–488.
50. Fazil A, Rajic A, Sanchez J, McEwen S. Choices, choices: The application of multi-criteria decision analysis to a food safety decision making problem. Journal of Food Protection, 2008; 71:2323–2333.
51. Baltussen R, Niessen L. Priority setting of health interventions: The need for multi-criteria decision analysis. Cost Effectiveness and Resource Allocation, 2006; 4:4–14.
52. Figueira J, Greco S, Ehrgott M. Multiple Criteria Decision Analysis: State of the Art Surveys. New York: Springer, 2005.
53. Belton V, Stewart T. Multiple Criteria Decision Analysis: An Integrated Approach. Boston, MA: Kluwer Academic Publishers, 2002.
54. Brans JP, Vincke P, Mareschal B. How to select and how to rank projects: The PROMETHEE method. European Journal of Operational Research, 1986; 204:228–238.
55. Brans JP, Vincke P. A preference ranking organization method: The PROMETHEE method for MCDM. Management Science, 1985; 31:647–656.
56. Hoffmann S, Fischbeck P, Krupnick A, McWilliams M. Using expert elicitation to link foodborne illnesses in the United States to foods. Journal of Food Protection, 2007; 70:1220–1229.
57. Batz MB, Doyle MP, Morris JG, Painter J, Singh R, Tauxe RV, Taylor MR, Lo Fo Wong DMA. Attributing illness to food. Emerging Infectious Diseases, 2005; 11:993–999.
58. Public Health Agency of Canada. Source attribution: Focus on source and pathogens. Available at http://www.phac-aspc.gc.ca/c-enternet/source-eng.php. Accessed on January 30, 2009.
59. Havelaar AH, Galindo AV, Kurowicka D, Cooke RM. Attribution of foodborne pathogens using structured expert elicitation. Foodborne Pathogens and Disease, 2008; 5:649–659.
60. Buzby JC, Roberts T, Allos BM. Estimated annual costs of *Campylobacter*-associated Guillain-Barré syndrome. Economic Research Service, U.S. Department of Agriculture Economics, 1997. Available at http://www.ers.usda.gov/publications/aer756/AER756.PDf. Accessed on January 30, 2009.
61. Voetsch AC, Angulo FJ, Jones TF, Moore MR, Nadon C, McCarthy P, Shiferaw B, Megginson MB, Hurd S, Anderson BJ, Cronquist A, Vugia DJ, Medus C, Segler S, Graves LM, Hoekstra RM, Griffin PM. Centers for Disease Control and Prevention Emerging Infections Program Foodborne Diseases Active Surveillance Network Working Group. Reduction in the incidence of invasive listeriosis in foodborne diseases active surveillance network sites, 1996–2003. Clinical Infectious Diseases, 2007; 44:513–520.
62. Doorduyn Y, de Jager CM, Van Der Zwaluw WK, Wannet WJ, Van Der Ende A, Spanjaard L, van Duynhoven YT. Invasive *Listeria monocytogenes* infections in the Netherlands, 1995–2003. European Journal of Clinical Microbiology and Infectious Diseases, 2006; 25;433–442.

63. Tarr PI, Gordon CA, Chandler WI. Shiga-toxin producing *Escherichia coli* and haemolytic uraemic syndrome. Lancet, 2005; 365:1073–1086.
64. Griffin PM. *Escherichia coli* O157:H7 and other enterohemorrhagic *Escherichia coli*. In Blaser MJ, Smith PD, Ravdin JI, Greenberg HB, Guerrant RL. (eds). Infections of the Gastrointestinal Tract. New York: Raven, 1995.
65. Boyce TG, Swedlow DL, Griffin PM. *Escherichia coli* O157: H7 and the haemolytic-uremic syndrome. New England Journal of Medicine, 1995; 333:364–368.
66. World Health Organization. Risk assessment of *Listeria monocytogenes* in ready-to-eat foods, 2004. Available at http://www.who.int/foodsafety/publications/micro/mra_listeria/en/index.html. Accessed on January 30, 2009.
67. Rangel JM, Sparling PH, Crowe C, Griffin PM, Swerdlow DL. Epidemiology of *Escherichia coli* O157: H7 outbreaks, United States, 1982–2002. Emerging Infectious Diseases, 2005; 11;603–609.
68. Tserenpuntsag B, Chang HG, Smith PF, Morse DL. Hemolytic uremic syndrome risk and *Escherichia coli* O157: H7. Emerging Infectious Diseases, 2005; 11:1955–1957.
69. Garg AX, Suri RS, Barrowman N, Rehman F, Matsell D, Rosas-Arellano MP, Salvadori M, Haynes RB, Clark WF. Long-term renal prognosis of diarrhoea haemolytic uremic syndrome: A systematic review, meta-analysis, and meta-regression. JAMA, 2003; 290:1360–137.