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Economic impacts of reduced milk production associated with epidemiological risk factors for Johne's disease on dairy operations in the USA

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An examination of the economic effects of epidemiologic risk factors for Johne's disease identified regional and herd size differences as having the greatest impact. Having dairy cows that were not born on the operation was the most important factor over which individual producers had the most immediate control. Economic consequences associated with using multiple-cow-maternity housing and multiple-preweaned-calf housing were not statistically significant. Economic welfare analysis was applied, and the GUM Workbench was used to analyse uncertainties in the estimates of the economic impacts.

Keywords: Cost of disease, dairy cows, dairy production, economic surplus, NAHMS, welfare analysis, uncertainty propagation.

To identify factors associated with specific outcomes (such as the presence of disease), it is a fairly common practice for epidemiologists to develop logistic-regression models from survey or case-control data. For example, the National Animal Health Monitoring System (**NAHMS**), of the United States Department of Agriculture (**USDA**) Animal and Plant Health Inspection Service (**APHIS**), used data from a national survey of US dairy producers to develop a logistic-regression model to pinpoint categorical risk factors associated with the presence of Johne's disease on US dairy operations (USDA, APHIS, 1997). To assess disease-prevention strategies, it is becoming increasingly popular for epidemiologists to combine information from logistic-regression models with knowledge of the proportions of cases in the population, to compute the population-attributable fraction (**PAF**) (Rockhill et al. 1998). PAF is a measure of the fraction of disease that could be prevented by eliminating exposure to a specific categorical risk factor from a population, while the distribution of other risk factors in the population remains constant (Rockhill et al. 1998).

Benefit-cost analysis offers a valuable tool that can be applied to determine where to invest funds to control a disease such as Johne's disease. To initiate the benefit-cost analysis, one needs information on the benefits that are anticipated to accrue from the disease control programme, as well as data on the costs of the proposed measures. Recently, Losinger (2005) reported that reduced milk production (associated with Johne's disease) caused a total loss of \$200 million ± \$160 million to the US economy, including a drop of \$770 million ± \$690 million in consumer surplus and increase of \$570 million ± \$550 million in producer surplus, in 1996. The present study measures the economic impacts of eliminating – from the US population of dairy cattle – exposure to the Johne's-disease risk factors identified by the USDA, APHIS (1997). Decision-makers could use these results to determine where to focus efforts to control Johne's disease in US dairies.

Materials and Methods

Using data from the NAHMS Dairy '96 Study (which included 2542 dairy operations from the major dairy-producing states in the USA), the USDA, APHIS (1997) developed a logistic-regression model that identified categorical risk factors (i.e. categorical variables) associated with Johne's disease on US dairy operations (Table 1). A dairy operation where at least two dairy cows tested positive for Mycobacterium paratuberculosis antibodies, or where one cow tested positive for *M. paratuberculosis* antibodies and at least 5% of culled cows exhibited symptoms consistent with Johne's disease during the previous 12 months, was considered 'Johne's positive' (USDA : APHIS, 1997). Wells & Wagner (2000) again presented the model and repeated the procedures followed to create the model.

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Table 1. Proportion of Johne's-positive operations, logarithms of the odds ratios (i.e. coefficients from the logistic-regression model) and population-attributable fractions for risk factors identified as being associated with a dairy operation being Johne's-positive in the USA

	Johne's-positive operations†		Logistic-regression model†		Population-attributable fraction	
Risk factor	Proportion	SE	Coefficient	SE	PAF	SE
Number of dairy cows:						
<100	0·083	0·013	0·0	—	—	—
100–299	0·211	0·027	0·4	0·21	0·070	0·031
⩾300	0·706	0·031	1·4	0·30	0·532	0·058
Total	1				0·602	0·066
Region:						
West	0·037	0·008	0·0	—	—	—
Southeast	0·093	0·013	0·2	0·36	0·017	0·028
Northeast	0·201	0·030	0·3	0·31	0·052	0·048
Midwest	0·669	0·033	0·8	0·28	0·368	0·087
Total	1				0·437	0·013
Percent of dairy cows not born on the operation:						
0%	0·254	0·038	0·0	—	—	—
1–24%	0·415	0·044	0·5	0·26	0·163	0·068
25% or more	0·331	0·039	0·7	0·26	0·167	0·045
Total	1				0·330	0·083
Multiple-cow-maternity housing used in previous year:						
No	0·428	0·044	0·0	—	—	—
Yes	0·572	0·044	0·4	0·28	0·189	0·082
Multiple-preweaned-calf housing used in previous year:						
No	0·498	0·043	0·0	—	—	—
Yes	0·502	0·043	0·4	0·16	0·166	0·073

† Source: USDA, 1997

The basic formula for computing the population-attributable fraction is:

$$PAF_i = p_i\left(\frac{e^{\beta_i}-1}{e^{\beta_i}}\right) \quad (1)$$

where PAF_i is the population-attributable fraction, β_i is the coefficient from the logistic-regression model, and p_i is the proportion of cases for the *i*-th category of a categorical risk factor (Rockhill et al. 1998). The logistic-regression model coefficients, and the associated proportion of Johne's-positive operations, appear with the se in Table 1. For the base category ($i=1$), $\beta_1=0$, e^{β_1} equals one, and the PAF_1 is zero. For categories other than the base category, PAF_i indicates the fraction of disease that could be prevented by shifting everyone in a particular category to the base category of the risk factor (Rockhill et al. 1998). The combined PAF for a variable with multiple categories is computed by summing the PAF_i of the non-base categories:

$$PAF = \sum_{i=2}^{k} PAF_i = \sum_{i=2}^{k} p_i\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right) \quad (2)$$

(for a categorical variable with k categories). The combined PAF shows the fraction of disease that could be prevented by shifting everyone outside of the risk factor's base category to the base category (while the distribution of other factors in the population remained constant) (Rockhill et al. 1998). Using the above equations, the GUM Workbench (Metrodata GmbH, 1999) was applied to compute estimates and uncertainties of the PAF for each of the Johne's disease risk factors that had been identified in the model of the USDA, APHIS (1997). The GUM Workbench is specialized software that computes estimates, combined standard uncertainties, and coverage factors, following the recommendations of the International Organization for Standardization (1995). The GUM Workbench calculates sensitivity coefficients by applying numerical partial differentiation, uses Taylor-series approximation to compute combined standard uncertainties, and Satterthwaite's approximation to compute combined degrees of freedom (Metrodata GmbH, 1999). The last two columns of Table 1 present PAF and se for each of the risk factors for Johne's disease. PAF indicate, for example, that about one-third of Johne's-positive operations could have been prevented if no cows on the operation had been born outside of the operation. Tables 2–4 provide the uncertainty budgets of PAF for ⩾1% of dairy cows not born on the operation, the use of multiple-cow-maternity housing, and the use of multiple-preweaned-calf housing. These tables show that most of the uncertainty (>90%) in PAF proceeded from the

Table 2. Uncertainty budget for the population-attributable fraction for ⩾1% of dairy cows not born on the operation

Input quantity	Sensitivity coefficient†	Uncertainty contribution‡	Index§
Proportion of Johne's-positive operations where 1–24% of dairy cows were not born on the operation	0·39	0·017	4·3%
Logarithm of the odds ratio for a dairy operation where 1–24% of dairy cows were not born on the operation being Johne's-positive	0·25	0·066	63·2%
Proportion of Johne's-positive operations where ⩾25% of dairy cows were not born on the operation	0·50	0·020	5·6%
Logarithm of the odds ratio for a dairy operation where ⩾25% of dairy cows were not born on the operation being Johne's-positive	0·17	0·043	26·9%

† $\partial y/\partial x_i$: describes how the estimated value of the measurand, *y*, varies with changes in the estimated value of the input quantity x_1, x_2, … (International Organization for Standardization, 1995)
‡ Absolute value of the product of the SE (Table 1) and the sensitivity coefficient. The sum of the squared values in this column equals the square of the uncertainty in the estimated value of the measurand *y*
§ Percent contribution to the square of the measurand's uncertainty. This is 100 times the ratio of the square of the input quantity's uncertainty contribution to the square of the uncertainty in the estimated value of the measurand. This column sums to 100%

Table 3. Uncertainty budget for the population-attributable fraction for the use of multiple-cow-maternity housing

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index
Proportion of Johne's-positive operations that used multiple-cow-maternity housing	0·33	0·015	3·1%
Logarithm of the odds ratio for a dairy operation that used multiple-cow-maternity housing being Johne's- positive	0·39	0·081	96·9%

Table 4. Uncertainty budget for the population-attributable fraction for the use of multiple-preweaned-calf housing

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index
Proportion of Johne's-positive operations that used multiple-preweaned-calf housing	0·33	0·014	3·8%
Logarithm of the odds ratio for a dairy operation that used multiple-preweaned-calf housing being Johne's-positive	0·34	0·071	96·2%

logistic regression model coefficients. The proportions of cases contributed towards <10% of the uncertainties in PAF.

Losinger (2005) described the procedures that were involved in determining the quantity, price and total value of milk that would have been produced if Johne's disease had not been present on US dairy operations, and how consumer surplus, producer surplus, and the total economy were affected by Johne's disease in 1996. Consumer surplus is the difference between what consumers are willing to pay for a product, and the amount that consumers actually pay. Producer surplus is the difference between the amount of money that producers receive for a commodity, and the amount that they would be willing to accept to supply a given quantity. The input quantities are listed again in Table 5. The present analysis uses a modification of the same set of model equations (Table 6). Previously (Losinger, 2005), the decline (due to Johne's disease) in the quantity of milk produced was obtained by multiplying together the kg/cow milk-production decline on Johne's-positive dairy operations (USDA, APHIS, 1997), the proportion of operations that were Johne's-positive in 1996 (USDA, APHIS, 1997), and the number of dairy cows in the USA in 1996 (USDA, NASS, 1999). For the present analysis, the decline (due to specific risk factors for Johne's disease) in the quantity of milk produced was obtained by

Table 5. Input quantities used in the computation of economic impacts of Johne's-positivity on US dairy operations, their sources and uncertainties (This table previously appeared in Losinger, 2005)

Input quantity	Distribution	Value	Standard Uncertainty	Degrees of Freedom	Source
Kg/cow milk-production decline on Johne's-positive dairy operations	Normal	288	111	50†	USDA, APHIS, 1997
Percent of dairy operations that were Johne's-positive in 1996	Normal	21·6	1·7	50	USDA, APHIS, 1997
Number of dairy cows	Normal	9 327 000	122 000[2]	50	USDA, NASS 1999
Kg milk produced in 1996	Normal	70·003 billion	630 million[2]	50	USDA, NASS, 1999
Mean price of milk in 1996 ($/kg)	Normal	0·328	0·004‡	50	USDA, NASS, 1999
Price elasticity of demand for milk	t	−0·25	−0·05	14	Meilke et al.1996
Price elasticity of supply for milk	Rectangular§	0·56995	0·18855	∞	Adelaja, 1991

† For normally distributed Type B data, the GUM Workbench assigns a default value of 50 to the degrees of freedom (Metrodata GmBH, 1999)
‡ Uncertainties are based on USDA, NASS, 1996
§ For the rectangular distribution, the value is the midpoint between the upper and lower limits, and the half-width of this limit is listed in the uncertainty column. Degrees of freedom are infinite by definition (Metrodata GmBH, 1999)

multiplying the same series of terms by the PAF for the risk factor. Then, the same model equations developed by Losinger (2005) were used to compute the price and total value of milk that would have been produced if everyone in the risk category had been transferred to the base category of the risk factor. In addition, changes in consumer surplus, producer surplus, and total economic surplus were computed using welfare analysis, and the GUM Workbench, as described by Losinger (2005).

Table 6. Model equations used in the analysis

Model Equations:

$\Delta Q = \text{Johneseffect} * (\text{pcposherds}/100) * \text{cows} * \text{PAF}$
$Q' = Q + \Delta Q$
$\Delta P = (\Delta Q * P)/(e_D * Q)$
$P' = P + \Delta P$
$Q_c = Q' - e_s * \Delta P * Q/P$
$CS_{trans} = |\Delta P * Q_c| + |0{\cdot}5 * \Delta P * (Q - Q_c)|$
$CS_{lost} = 0{\cdot}5 * \Delta P * (Q' - Q_c)$
$\Delta CS = CS_{trans} + CS_{lost}$
$PS_{lost} = \Delta Q * P'$
$\Delta PS = CS_{trans} - PS_{lost}$
$\text{TOTAL ECONOMIC LOSS} = CS_{lost} + PS_{lost}$

ΔQ = Change in total milk production due to a Johne's-disease risk factor (kg)
Johneseffect = Reduced milk production on Johne's-positive dairy operations (kg/cow)
pcposherds = Percent of dairy operations that were Johne's-positive
cows = Number of dairy cows (n)
PAF = Population-attributable fraction for a Johne's-disease risk factor
Q = Quantity of milk produced with Johne's disease (kg)
Q' = Quantity of milk produced without Johne's disease (kg)
ΔP = Change in price of milk ($/kg)
P = Price of milk with Johne's disease ($/kg)
P' = Price of milk without Johne's disease ($/kg)
e_D = Price elasticity of demand for milk
e_S = Price elasticity of supply for milk
Q_c = Quantity of milk produced at Point C (kg) of Figure 1 in Losinger (2005)
CS_{trans} = Consumer surplus transferred to producers ($)
CS_{lost} = Consumer surplus lost ($)
ΔCS = Change in consumer surplus ($)
PS_{lost} = Lost producer surplus ($)
ΔPS = Change in producer surplus ($)

Results

Table 7 shows the economic impacts of increased milk production associated with removing specific risk factors for Johne's disease from the US population of dairy cows in 1996. Herd size accounted for the greatest impacts associated with Johne's disease. Table 1 suggests that about one-half of Johne's-positive operations could have been averted if operations with >300 dairy cows had reduced their size to <100 cows. Regional differences in Johne's disease were also important. PAF of Table 1 suggest that, if all dairies had been in the Western region, then about 40% of Johne's disease would have been prevented. The total economic impact would have been 82 ± 75 *dollars* (Table 7). The total economic impact of having ⩾1% of dairy cows that were not born on the operation was 64 ± 60 million dollars, although the individual changes in consumer and producer surplus were not statistically significant (Table 7). Economic impacts for the use of multiple-cow-maternity housing and multiple-preweaned-calf housing were not statistically significant.

Tables 8–10 present uncertainty budgets for the total economic loss resulting from reduced milk production attributed to Johne's disease associated with having ⩾1% of dairy cows not born on the operation, the total economic loss resulting from reduced milk production attributed to Johne's disease associated with dairy operations having used multiple-cow-maternity housing during the previous year, and the total economic loss resulting from reduced milk production attributed to Johne's disease associated with dairy operations having used multiple-preweaned-calf

Table 7. Economic impacts of increased milk production associated with removing specific risk factors for Johne's disease from the US population of dairy cows in 1996. The coverage factor is two (i.e. plus or minus twice the standard uncertainty)

	Milk production			Change in economic surplus		
	Quantity (kg × 10^9)	Price (cents/kg)	Total value ($ × 10^6)	Consumers ($ × 10^9)	Producers ($ × 10^6)	Total economy ($ × 10^6)
1996 Totals†	70·0 ± 1·2	32·8 ± 0·8	23·0 ± 0·5			
Total impact of Johne's disease‡	70·6 ± 1·4*	31·7 ± 1·0*	22·4 ± 0·8*	770 ± 690	−570 ± 550	200 ± 160
Number of dairy cows						
100–299	70·0 ± 1·3	32·7 ± 0·4	22·9 ± 0·5	53 ± 670	−40 ± 53	13 ± 16
>300	70·3 ± 1·3*	32·2 ± 0·7*	22·7 ± 0·6*	410 ± 380	−300 ± 300	103 ± 85
Total	70·4 ± 1·3*	32·1 ± 0·7*	22·6 ± 0·6*	463 ± 420	−340 ± 340	116 ± 97
Region						
Southeast	70·0 ± 1·3	32·8 ± 0·4	23·0 ± 0·5	60 ± 210	−40 ± 160	15 ± 51
Northeast	70·0 ± 1·3	32·7 ± 0·4	22·9 ± 0·5	40 ± 81	−30 ± 62	10 ± 20
Midwest	70·2 ± 1·3*	32·4 ± 0·6	22·8 ± 0·6	280 ± 290	−70 ± 60	71 ± 66
Total	70·3 ± 1·3*	32·3 ± 0·6	22·7 ± 0·6	330 ± 330	−250 ± 270	82 ± 75
Percent of dairy cows not born on the operation						
1–24%	70·1 ± 1·3	32·6 ± 0·5	22·9 ± 0·5	120 ± 150	−90 ± 120	31 ± 36
25% or more	70·1 ± 1·3*	32·6 ± 0·5	22·9 ± 0·5	130 ± 140	−100 ± 110	32 ± 31
Total	70·2 ± 1·3*	32·4 ± 0·6	22·8 ± 0·6	250 ± 260	−190 ± 210	64 ± 60
Multiple-cow-maternity housing used in previous year						
Yes	70·1 ± 1·3	32·6 ± 0·5	22·9 ± 0·5	140 ± 180	−110 ± 140	36 ± 43
Multiple-preweaned-calf housing used in previous year						
Yes	70·1 ± 1·3	32·6 ± 0·5	22·9 ± 0·5	130 ± 160	−90 ± 120	32 ± 38

† From Table 2
‡ From Losinger (2005)
* Significant difference ($P < 0.05$) from 1996 total

Table 8. Uncertainty budget for the total economic loss resulting from reduced milk production attributed to Johne's disease associated with having ⩾1% of dairy cows not born on the operation

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index
Reduced milk production on Johne's-positive dairy operations (kg/cow)	$2·2 \times 10^5$	$2·5 \times 10^7$	68·0%
Percent of dairy operations that were Johne's-positive in 1996	$3·0 \times 10^6$	$5·0 \times 10^6$	2·8%
Number of dairy cows	$6·8 \times 10^1$	$8·3 \times 10^5$	0·0%
Kg milk produced in 1996	$-6·3 \times 10^{-6}$	$-4·0 \times 10^3$	0·0%
Mean price of milk in 1996 ($/kg)	$1·9 \times 10^8$	$4·2 \times 10^5$	0·0%
Price elasticity of demand for milk	$5·4 \times 10^6$	$2·7 \times 10^5$	0·0%
Price elasticity of supply for milk	$1·4 \times 10^6$	$1·5 \times 10^5$	0·0 %
Proportion of Johne's-positive dairy operations where 1–24% of dairy cows were not born on the operation	$7·6 \times 10^7$	$3·4 \times 10^6$	1·3%
Log-odds ratio for operations where 1–24% of dairy cows were not born on the operation	$5·0 \times 10^7$	$1·3 \times 10^7$	18·4%
Proportion of Johne's-positive dairy operations where>25% of dairy cows were not born on the operation	$9·8 \times 10^7$	$3·8 \times 10^6$	1·6%
Log-odds ratio for operations where ≥25% of dairy cows were not born on the operation	$3·2 \times 10^7$	$8·4 \times 10^6$	7·8%

The final estimate for the total economic loss resulting from reduced milk production attributed to Johne's-positivity associated with having ⩾1% of dairy cows not born on the operation is $\$6·4 \times 10^7$, with a standard uncertainty of $\$3·0 \times 10^7$ and 99 degrees of freedom

Table 9. Uncertainty budget for the total economic loss resulting from reduced milk production attributed to Johne's disease associated with dairy operations having used multiple-cow-maternity housing during the previous year

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index
Reduced milk production on Johne's-positive dairy operations (kg/cow)	$1{\cdot}3\times10^{5}$	$1{\cdot}4\times10^{7}$	43·0%
Percent of dairy operations that were Johne's-positive in 1996	$1{\cdot}7\times10^{6}$	$2{\cdot}9\times10^{6}$	1·8%
Number of dairy cows	$3{\cdot}9\times10^{1}$	$4{\cdot}7\times10^{5}$	0·0%
Milk produced in 1996 (kg)	$-2{\cdot}1\times10^{-6}$	$-1{\cdot}3\times10^{4}$	0·0%
Mean price of milk in 1996 ($/kg)	$1{\cdot}1\times10^{8}$	$2{\cdot}4\times10^{5}$	0·0%
Price elasticity of demand for milk	$1{\cdot}8\times10^{6}$	$8{\cdot}8\times10^{4}$	0·0%
Price elasticity of supply for milk	$4{\cdot}5\times10^{5}$	$4{\cdot}9\times10^{4}$	0·0 %
Proportion of Johne's-positive dairy operations where multiple-cow-maternity housing was used	$6{\cdot}4\times10^{7}$	$2{\cdot}8\times10^{6}$	1·7%
Log-odds ratio for operations that used multiple-cow-maternity housing	$7{\cdot}6\times10^{7}$	$1{\cdot}6\times10^{7}$	53·4%

The final estimate for the total economic loss resulting from reduced milk production attributed to Johne's-positivity associated with having used multiple-cow-maternity housing is $\$3{\cdot}6\times10^{7}$, with a standard uncertainty of $\$2{\cdot}1\times10^{7}$ and 110 degrees of freedom

Table 10. Uncertainty budget for the total economic loss resulting from reduced milk production attributed to Johne's disease associated with dairy operations having used multiple-preweaned-calf housing during the previous year

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index
Reduced milk production on Johne's-positive dairy operations (kg/cow)	$1{\cdot}1\times10^{5}$	$1{\cdot}2\times10^{7}$	42·9%
Percent of dairy operations that were Johne's-positive in 1996	$1{\cdot}5\times10^{6}$	$2{\cdot}5\times10^{6}$	1·8%
Number of dairy cows	$3{\cdot}4\times10^{1}$	$4{\cdot}1\times10^{5}$	0·0%
Milk produced in 1996 (kg)	$-1{\cdot}6\times10^{-6}$	$-1{\cdot}0\times10^{3}$	0·0%
Mean price of milk in 1996 ($/kg)	$9{\cdot}7\times10^{7}$	$2{\cdot}1\times10^{5}$	0·0%
Price elasticity of demand for milk	$1{\cdot}4\times10^{6}$	$6{\cdot}8\times10^{4}$	0·0%
Price elasticity of supply for milk	$3{\cdot}5\times10^{5}$	$3{\cdot}8\times10^{4}$	0·0%
Proportion of Johne's-positive dairy operations where multiple-preweaned-calf housing was used	$6{\cdot}3\times10^{7}$	$2{\cdot}7\times10^{6}$	2·1%
Log-odds ratio for operations that used multiple-preweaned-calf housing	$6{\cdot}6\times10^{7}$	$1{\cdot}4\times10^{7}$	53·2%

The final estimate for the total economic loss resulting from reduced milk production attributed to Johne's-positivity associated with having used multiple-preweaned-calf housing is $\$3{\cdot}2\times10^{7}$, with a standard uncertainty of $\$1{\cdot}9\times10^{7}$ and 110 degrees of freedom

housing during the previous year. The principal sources of uncertainty were the estimate of reduced milk production on Johne's-positive dairy operations, and the coefficients from the logistic-regression models.

Discussion

Wagner et al. (2001) calculated combined PAF (using a formula established by Bruzzi et al. 1985) for the risk factors presented here, and introduced the delete-a-group jack-knife method to estimate the uncertainty of the combined PAF. As mentioned above, the combined PAF shows the fraction of disease that could be prevented by shifting everyone outside of the risk factor's base category to the base category (while the distribution of other factors in the population remained constant). Because PAF for the base category is zero,

$$PAF=\sum_{i=2}^{k}p_i\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right)=\sum_{i=1}^{k}p_i\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right) \tag{3}$$

(where $i=1$ for the base category). Through some algebra,

$$PAF=\sum_{i=1}^{k}p_i\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right)=\sum_{i=1}^{k}p_i-\sum_{i=1}^{k}\frac{p_i}{e^{\beta_i}} \tag{4}$$

which simplifies to

$$PAF=1-\sum_{i=1}^{k}\frac{p_i}{e^{\beta_i}} \tag{5}$$

which is the expression established by Bruzzi et al. (1985), and used by Wagner et al. (2001).

Although equations (2) and (5) generate the same results for a variable's combined PAF, these two equations are associated with very different implications for the variance structure of the combined PAF. In equation (3) above, PAF_1 (which is for the base category) is added to the combined PAF for the variable. At this point, PAF_1 still adds zero to the combined PAF for the variable, in addition to adding zero to the variance – because $(e^{\beta_1}-1)$ equals zero. However, in equations (4) and (5), p_1 now combines with the rest of the p_i to add to a constant, one, which has no variance. However, in equation (5), one must now subtract p_1, which has a variance that must be included in the calculation of the variance of the combined PAF for the full variable.

Furthermore, the sensitive coefficients (i.e. the partial derivatives) of the input quantities suggest different properties for the estimators. For the logistic-regression model coefficients, the sensitivity coefficient is simply p_i/e^{β_i}, whether one accepts either the simple additive model (2) or the formula of Bruzzi et al. (1985) (5) for the combined PAF. However, for the proportion of cases, the sensitivity coefficient is $(e^{\beta_i}-1)/e^{\beta_i}$ for the simple additive model (2), and $-1/e^{\beta_i}$ for the model of Bruzzi et al. (1985) (5). For the simple additive model, the sensitivity coefficient for the proportion of cases is positive if β_i is positive, which means that the combined PAF increases as the proportion of cases increases. For the model of Bruzzi et al. (1985), however, the sensitivity coefficient is negative, which means that the combined PAF decreases as the proportion of cases increases. The implications of the sensitivity coefficients for the simple additive model (2) are more reasonable.

For the additive model for the combined PAF (2), the Taylor-series formula for the variance is:

$$u^2(PAF)=\sum_{i=2}^{k}\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right)^2 u^2(p_i)+\sum_{i=2}^{k}\left(\frac{p_i}{e^{\beta_i}}\right)^2 u^2(\beta_i) +2\sum_{i=2}^{k}\left(\frac{(e^{\beta_i}-1)}{e^{\beta_i}}\right)\left(\frac{p_i}{e^{\beta_i}}\right)u(p_i,\beta_i) \tag{6}$$

where u^2 is the variance and $u(p_i, \beta_i)$ is the covariance between p_i and β_i. For the model of Bruzzi et al. (1985), the variance formula is:

$$u^2(PAF)=\sum_{i=1}^{k}\left(-1/e^{\beta_i}\right)^2 u^2(p_i)+\sum_{i=1}^{k}\left(\frac{p_i}{e^{\beta_i}}\right)^2 u^2(\beta_i) +2\sum_{i=1}^{k}(-1/e^{\beta_i})\left(\frac{p_i}{e^{\beta_i}}\right)u(p_i,\beta_i) \tag{7}$$

As mentioned above, $\beta_1=0$ (for the base category), and $u^2(\beta_1)=0$. However, equation (7), the variance formula for the model of Bruzzi et al. (1985) (5), incorporates the variance associated with p_1 (the proportions of cases in the base category), whereas equation (6), the variance formula for the additive model (2), does not. Another important difference is that equation (6) implies that the variance of the combined PAF increases as the covariance between p_i and β_i increases (because both sensitivity coefficients are positive). Equation (7), on the other hand, yields the result that the variance of the combined PAF decreases as the covariance between p_i and β_i increases (because one sensitivity coefficient is negative). Benichou & Gail (1989) provided the basic method for applying Taylor-series approximation to compute the variance of the PAF (based on the formula of Bruzzi et al. 1985). Additionally, Benichou & Gail (1990) showed how to apply Taylor-series approximation to compute the variance of the PAF, when the formula of Bruzzi et al. (1985) was used to compute PAF from stratified samples.

Wagner et al. (2001) characterized the delete-a-group jack-knife method as easy to implement, and sufficiently flexible to approximate the uncertainty associated with *any* estimate (including the combined PAF) that derived from survey data. The delete-a-group jack-knife is quite similar to the random-groups standard-error estimator developed by Losinger (1997) for survey data from a systematic sample. For both estimators, the first step is to assign respondents systematically to a number of groups. For the random-groups method, the sample weights for each group are simply rescaled, such that the sum of the total sample weights (for each group) equals the sum of the original sample weights (Losinger, 1997). For the delete-a-group jack-knife method, the data for each group are removed from the sample, and the sample weights of the remaining respondents are rescaled such that the sum of the rescaled sample weights equals the sum of the original sample weights (i.e. prior to removing the group's data) (Wagner et al. 2001). In both cases, for each group, an estimate of the parameter of interest (in this case, the combined PAF) is obtained. One then has one estimate of the combined PAF from each group. The uncertainty associated with the combined PAF (for the population) is then derived by computing the SE among the group estimates of the combined PAF.

Compared with the GUM Workbench approach, procedures involved in creating jack-knife or random-groups estimators (including assigning the data to groups, re-weighting, computing new estimates, and finding the variability among the estimates) are more computer-intensive, and potentially more prone to snags. For example, because the delete-a-group jack-knife estimator could have an 'unreasonably large bias' when the stratum sample size was less than five, Wagner et al. (2001) were forced to collapse strata with fewer than five participants.

Ott et al. (1999) described the weight-creation methods that were followed for the NAHMS Dairy '96 Study: the sample weight was initially the inverse of the initial sampling fraction (which varied with sampling stratum), and was subsequently adjusted for non-response by study phase, and adjusted again to force NAHMS estimates to match NASS inventory estimates by poststrata based on state and operation-size categories. The procedures were similar to those described (in greater detail) for the NAHMS 1994–95 Cattle-on-Feed Evaluation (Losinger et al. 1997). Losinger et al. (1998) noted that the NAHMS weight-adjustment procedures, when applied to the NAHMS 1995 National Swine Study, resulted in a small number of farms receiving extremely large weights (due largely to low participation rates in certain poststrata). Losinger et al. (1998) understood that when a small number of participants had extremely large weights compared with the majority of survey participants, then the population estimates (and subsequent data analyses) would be heavily dependent on the responses given by the participants with the extreme weights. The solution of Losinger et al. (1998) was to truncate weights above a certain arbitrary maximum-permitted value, and to redistribute the excess weights to other participants. Losinger et al. (2000) described quality-control procedures, introduced during the NAHMS Beef '97 Study, for selecting auxiliary variables (to adjust weights for nonresponse) that were not only related to the propensity to respond, but also indicative of an operator's overall management strategy. For the NAHMS Swine 2000 Survey, adjusting survey weights through the process of raking to marginal totals was introduced (Losinger, 2002). A comparison between the raking procedure, and the methods that had traditionally been used for adjusting NAHMS-survey weights, demonstrated that the raking procedure gave superior results in terms of matching NASS estimates for both inventory and the numbers of farms, *without* ending up with a few extremely large weights that had to be truncated (Losinger, 2002). Confidence with the results of truncating excessively large weights was often not high, because of possible errors of judgment that might have occurred in deciding exactly where to truncate. Given the considerable problems that may have existed with the sample weights calculated for the Dairy '96 Study (because of lack of quality control, and the potential existence of some excessively large weights), application of the delete-a-group jack-knife by Wagner et al. (2001), which involved removing observations from the sample and rescaling the sample weights multiple times (to compute PAF according to the formula of Bruzzi et al. 1985), may cause some concern. In addition, with jack-knife and random-groups estimators, there is not the uncertainty budget to help evaluate the relative importance of contributors to the uncertainty.

A limitation of the present study is that it was performed without access to the raw data. Therefore, implementing a Taylor-series on a stratum-by-stratum basis, and taking into account elements of the sample design (as described by Benichou & Gail, 1990) was not possible. The International Organization for Standardization (1995) discusses the evaluation and use of information that did not derive from raw data or observations to which the researcher has access. A researcher with access only to means and SE may apply the GUM Method to estimate uncertainties in measurements that derive from such data. An advantage of having the raw data (for computing the PAF) is that one would be able to compute covariances between input quantities. One would expect the proportion of cases and the logistic-regression coefficients for the same category of a risk factor to be correlated when they came from the same data. If the logistic-regression model parameters and the estimates of the proportion of cases had come from completely different sources, then covariance would not be an issue. The International Organization for Standardization (1995) states that 'correlations between input quantities cannot be ignored if present and significant. The associated covariances should be evaluated if feasible by varying the correlated input quantities … or by using the pool of available information on the correlated variability of the quantities in question (Type B evaluation of covariance).' In a statistical analysis of the herd-level economic losses associated with Johne's disease on US dairy operations, Ott et al. (1999) felt that the impact of correlations that were less than 0·5 between variables in the same model was negligible. According to Kessel et al. (2001), correlations only really need to be investigated for input quantities whose contribution to the variance of the measurand is at least 10%. This is because the International Organization for Standardization (1995) specifically recommends that the numerical values of estimates and their uncertainties not be given with an excessive number of digits: it usually suffices to quote standard uncertainties or expanded uncertainties to at most two significant digits. Incorporating covariance estimates for input quantities whose contribution to the variance of the measurand is less than 10% would thus have a trivial impact on the results. The uncertainty budgets for PAF (Tables 2–4) show that the contributions that arose from the proportion of cases to the uncertainty of the PAF were small enough that the covariances between the proportion of cases and the logistic-regression coefficients for the same category of a risk factor could reasonably be ignored because, in each situation, the proportion of cases contributed <10% to the total uncertainty of the PAF.

Economic welfare analysis has many variants. Losinger (2005) listed a number of welfare analyses previously used for estimating the economic impacts of livestock disease problems. A deficiency of many previous welfare analyses was that the investigators often presented point estimates without addressing the uncertainty in their measurements. Researchers are facing mounting demands to demonstrate the quality of their results by providing a measure of the confidence that can be placed in their outcomes, and the extent to which their results would be expected to be in agreement with other results. Piggott (2003) used Monte Carlo integration (imposing theoretical inequality restrictions) to compute confidence intervals for estimated welfare effects (for producers) from generic advertising of meat. Although the methods developed by Piggott (2003) were quite elaborate, the 95% confidence intervals demonstrated that the estimated welfare effects were 'measured quite imprecisely.' It thus seems plausible that many previous estimates of welfare effects, which were not accompanied by an uncertainty analysis, were misleading, in that they may have been considerably less precise than their often sophisticated methodologies would have suggested and, in several cases, may not verily have been significantly different from zero.

A principal advantage of conforming to the International Organization for Standardization (1995) recommendations is the transparency of the methods. Presenting uncertainty budgets that, for each input quantity, list its source, distribution, value, uncertainty, degrees of freedom, and that analyse its contribution to the uncertainty of the measurands, is an effective means of conveying the confidence that can be placed in one's measurement results. The GUM Workbench accomplishes all of this automatically (Losinger, 2004). Thus far, the GUM Workbench has been used primarily in the physical sciences. For example, Jalukse et al. (2004) used the GUM Workbench to analyse the uncertainty in electrochemical amperometric measurement of dissolved oxygen concentration. Papadakis et al. (2004) employed the GUM Workbench to calculate the measurement uncertainties of various elements in water samples. The present study may in sooth represent the first application of the GUM Workbench to analyse the uncertainty of the economic welfare effects of risk factors for a specific animal disease.

The present study was limited to analysing economic changes (in consumer and producer surplus, and the net effect on the US economy) that would have resulted from increased milk production associated with eliminating exposure to specific risk factors for Johne's disease on US dairy operations. As mentioned by Losinger (2005), and detailed by Ott et al. (1999), a poorly designed questionnaire caused the bulk of the economics data that were collected during the NAHMS Dairy '96 Study – for the purpose of studying the economics of Johne's disease – not to be useful for analysis. Therefore the economic consequences of Johne's disease beyond reduced milk production (such as increased veterinary expenses, premature culling, diminished slaughter value, and reduced value of calves, dairy-bull semen and breeding stock) are beyond the scope of the present analysis. The uncertainty analyses (Tables 7–10) indicated that most of the uncertainty in the economic estimates derived from the estimated reduction in milk production on Johne's-positive dairy operations, and from the coefficients of the risk-factors model (both of which originated from analyses of NAHMS Dairy '96 data). Thus, the greatest improvement in the precision of the estimates of the economic impacts of risk factors for Johne's disease would proceed from better estimates of these parameters. A more precise estimate of, for example, the number of dairy cows or the amount of milk produced in 1996 in the USA, would have had a trivial impact on the calculations of the economic impacts, as these variables consistently accounted for $<0{\cdot}1\%$ of the uncertainties in the measurands. A total of 2542 dairy operations participated in the NAHMS Dairy '96 study, and superior estimates of Johne's disease risk factors are not presently available for the USA.

Losinger (2005) presented uncertainty budgets for the change in consumer surplus, change in producer surplus, and net economic impact of Johne's disease. The principal finding of Losinger (2005) was that, because demand for milk was relatively inelastic, increased milk production (that would have resulted from eliminating Johne's disease) would have caused the price and total value of production to fall. This would have benefitted consumers and the economy as a whole, but resulted in an economic loss to dairy producers. The solution for dairy producers is not obvious. Government price supports in the early 1980s were very costly to US taxpayers, and led to overproduction (DeMause, 1984). The US government was confronted with stockpiling, and eventually giving away, huge quantities of powdered milk, cheese and butter (DeMause, 1984). Decision-makers will need to be ready to plan for the consequences of increased milk production as efforts are launched to bring Johne's disease under control.

Herd size accounted for the greatest impacts associated with Johne's disease. Table 1 suggests that about one-half of Johne's-positive operations could have been averted if operations with >300 dairy cows had reduced their size to <100 cows. The average number of cows per dairy operation has been increasing steadily over time (USDA : APHIS, 1996). When large numbers of animals are raised in confined settings, animal disease risks tend to increase, and the losses associated with disease outbreaks may tend to magnify themselves. The present study suggests that operators of large dairies with >300 cows may wish to exercise special vigilance with regard to Johne's disease.

Regional differences in Johne's disease were also important. PAF of Table 1 suggest that, if all dairies had been in the Western region, then about 40% of Johne's disease would have been prevented. The total economic impact would have been 82 ± 75 million dollars (Table 7). Moving all dairies to the West would certainly be an absurd solution. However, the regional results would be relevant in determining where to focus attention for controlling Johne's disease (the Midwest region obviously has the greatest need). In addition, knowledge of where Johne's disease is most and least prevalent would be useful in making business decisions concerning where to establish new dairies. Some might consider it more prudent to establish a new dairy in a part of the country where Johne's disease presents less of a risk. On the other hand, an operator who is able (in a cost-effective manner) to keep his dairy herd free of Johne's disease may have a competitive advantage in an area where the disease is depressing milk production on many of the other farms. Surely region is a proxy for a diverse set of risk factors such as climate, other environmental factors, farming systems, regional cattle density, wildlife, local cattle trading activity, etc. The inclusion of region in the original statistical model served to prevent variables from entering the model purely because of regional differences in management. USDA, APHIS (1997), and Wells & Wagner (2000), provided details on the selection of risk factors for the statistical model.

In terms of factors over which dairy producers had the most immediate control, having dairy cows that were not born on the operation presented the greatest risk and generated the greatest cost associated with Johne's disease. Whether the percent of cows not born on the operation was between 1% and 25%, or >25%, seemed not to make a difference. Moving either category to 0% would have reduced the prevalence of Johne's disease by 16% (Table 1). Moving both categories to 0% would have saved the economy 64±60 million dollars (Table 4). Gould (2004) stated that the principal means by which Johne's disease entered a herd was through acquisition of infected cattle. Results of the NAHMS Dairy '96 study indicated that almost half of producers either had not heard of Johne's disease, or had heard of Johne's disease but knew very little else about the disease (USDA, APHIS, 1997). At times, dairy producers may need to introduce new cows from outside the operation. Dairy operators should make an effort to verify that the source of new dairy cattle is free of Johne's disease. Perhaps some sort of a certification programme would be the most cost-effective means of reducing the economic impacts of Johne's disease. Only about 1% of dairy operations participated in a Johne's disease certification programme in 1996 (USDA, APHIS, 1997).

Once Johne's disease has been introduced to a dairy herd, the operator is confronted with the challenge of containing the disease. Recommendations provided by Rossiter & Burhans (1996) centre on preventing animals from ingesting *M paratuberculosis* (in manure, milk, colostrum, etc.), and decreasing the contamination of the environment. The UK Department for Environment, Food and Rural Affairs (2004) furnished some useful suggestions – concentrating chiefly on biosecurity and improved cleanliness – for dairy producers to control Johne's disease. Not using multiple-cow-maternity housing and multiple-preweaned-calf housing might be included among the effective means of reducing the spread of Johne's disease between cattle on an operation. However, these practices would not stop Johne's disease from entering the herd through new acquisitions, and would not be important for operations where Johne's disease was absent. Thus, the economic impacts of these practices (Table 7) were non-significant.

The present study indicates the magnitude of the economic impacts of reduced milk production associated with some of the major risk factors for Johne's disease. Information on the costs associated with removing risk factors would be required in order to determine where to invest funds to control this disease. Thus, further research on the costs associated with control efforts is warranted.

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