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Evaluating the uncertainty in estimates of the economic impacts of Bovine-Leukosis virus in U.S. dairy cows

Willard C. Losinger*

Losinger Economic Consulting Services, 5212 Kingsbury Estates Drive, Plainfield, Illinois 60586, USA

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Abstract

An examination of the economic impacts of Bovine-Leukosis virus indicated that reduced milk production, attributed to the presence of Bovine-Leukosis virus in dairy cows, reduced consumer surplus by 2.7 ± 2.3 billion US$ (bUS$), and resulted in a total partial equilibrium loss of 720 ± 560 million US$ (mUS$) to the U.S. economy in 1996. Most of the economic surplus lost by consumers was transferred to producers, whose economic surplus increased by 2.0 ± 1.8 bUS$ as a result of reduced milk production attributed to the presence of Bovine-Leukosis virus in dairy cattle. Uncertainty analysis showed that an estimate of the milk-production decline per percent increase in the prevalence of Bovine-Leukosis virus in dairy cows accounted for most of the uncertainty in the economic-impact estimates. If Bovine-Leukosis virus had not been present in U.S. dairy cows, then milk production would have increased by 2.0 billion ± 1.5 billion kg, the price would have fallen by 3.8 ± 3.2 cents/kg, and the value of the milk produced would have decreased by 2.1 ± 1.9 bUS$. Guidelines delineated by the International Organization for Standardization, for evaluating and expressing uncertainty in measurement, are discussed and proposed for use in the context of broad national estimates, for which the economic impacts of Bovine-Leukosis virus serve as an example. The principal advantages of the methodology are the clarity and transparency of results, and the ability clearly to identify major uncertainty contributors.

JEL classification: CO2, C13, C81, Q11

Keywords: Cost of disease; Economic surplus; NAHMS; Uncertainty propagation

1. Introduction

Few scientific researchers would disagree with the National Institute of Standards and Technology NIST (1994) statement that "a measurement result is complete only when accompanied by a quantitative statement of its uncertainty. The uncertainty is required in order to decide if the result is adequate for its intended purpose and to ascertain if it is consistent with other similar results." However, many scientists continue to present measurement results or estimates, such as the national impacts of specific diseases, without addressing the uncertainty of their results. For example, using data from the U.S. Department of Agriculture (USDA) National Animal Health Monitoring System (NAHMS) Dairy 1996 Study, Ott et al. (2003) concluded that Bovine-Leukosis Virus (BLV) in dairy cows caused a 525 mUS$ loss to the U.S. economy because of reduced milk production, and provided no statement of the uncertainty in this estimate. The computation was based partially on an elasticity of demand (for milk) provided by Wohlgenant (1989), and on an elasticity of supply (for milk) provided by Adelaja (1991), neither of whom examined the uncertainty of their elasticities.

The NIST (1994) provides some practical guidelines for computing and expressing uncertainty in measurement. The NIST guidelines are similar to those described in the *Guide to the Expression of Uncertainty in Measurement* (GUM) (International Organization for Standardization, 1995). The GUM encompasses an eight-step process for expressing uncertainty in measurement, and for combining individual uncertainty components into a single total uncertainty:

1. Express mathematically the relationship between the measurand Y and the input quantities X_i upon which Y depends.
2. Determine x_i, the estimated value of X_i, either from the statistical analysis of a series of observations, or by other means. (Capital letters indicate "true" values, and small letters denote estimates of true values.)
3. Evaluate the standard uncertainty $u(x_i)$ of each x_i, either from the statistical analysis of the series of observations

*Corresponding author. Tel.: 1-815-254-1868; fax: 1-810-483-6821.
E-mail address: wlosinger@netzero.com (W. C. Losinger).

(called *Type A evaluation of standard uncertainty*), or by other means (called *Type B evaluation of standard uncertainty*).
4. Evaluate the covariances associated with any input quantities that are correlated.
5. Calculate the result of the measurement (i.e., the estimate y of the measurand Y) from the mathematical expression of the relationship between Y and the input quantities X_i, using the estimates x_i.
6. Determine the combined standard uncertainty $u_c(y)$ of the measurement result y from the standard uncertainties and covariances associated with the input estimates.
7. Determine an *expanded uncertainty* U, such that the interval $y - U$ to $y + U$ encompasses a large fraction of the distribution of values that could reasonably be attributed to Y. U is obtained by multiplying the standard uncertainty by a coverage factor reflective of the level of confidence required for the interval.
8. Report the result of the measurement y together with its combined standard uncertainty $u_c(y)$ or expanded uncertainty U, and describe how y and $u_c(y)$ or U were obtained.

A correlation analysis is appropriate when input quantities are measured at the same time (for example, when data come from the same questionnaire in a survey of farms, or when different measurements are taken at the same time during an experiment). However, correlation analysis is not always appropriate. Correlations need not be investigated for input quantities whose contribution to the variance of the measurand is less than 10% (Kessel et al., 2001). The GUM (International Organization for Standardization, 1995) recommends that the numerical values of estimates and their uncertainties not be given with an excessive number of digits (it is usually sufficient 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. First-order Taylor-series approximation (with higher-order terms included in the Taylor-series expansion in the case of nonlinear functions, and incorporating correlation coefficients in the case of correlated input quantities) is the standard method for combining standard uncertainties (International Organization for Standardization, 1995).

Using linear supply and demand curves, and assuming a parallel shift in the supply curve (due to the presence of BLV in dairy cattle), Ott et al. (2003) determined that reduced milk production in dairy cows that tested positive for BLV was associated with a 285 mUS$ economic-surplus loss for producers, a 240 mUS$ economic-surplus loss for consumers, and a consequent sum-total loss to the economy of 525 mUS$. The presence of BLV in dairy cows may reduce milk production, which is represented by a leftward-shift in the supply curve for milk. Reduced milk production causes the equilibrium market price for milk to rise as the quantity falls. While a loss in economic surplus accrues to consumers, a portion of this loss is transferred to producers as an economic gain (Nicholson, 1995). Therefore, the loss to the economy is not the sum-total of economic surplus losses experienced by producers and consumers.

BLV is a retrovirus that primarily affects lymphoid tissue of cattle, and causes malignant lymphoma and lymphosarcoma, for which no cure exists (Johnson, 1998). BLV is primarily transferred within blood lymphocytes, and results in enlarged lymph nodes, weight loss, decreased milk production, fever, and loss of appetite as tumors invade different parts of the body.

This report reestimates changes in consumer and producer surplus, and the total loss to the U.S. economy caused by reduced milk production associated with BLV in dairy cows. Uncertainties in these estimates are evaluated in accordance with the GUM (International Organization for Standardization, 1995), which culminated from a recognized need for consensus on an internationally-accepted procedure for expressing uncertainty in measurement, and for combining individual uncertainty components into a single total uncertainty. In addition, this report compares the total value of milk production in the United States, with and without BLV during 1996. The focus of the study is at the national U.S. level; given the partial-equilibrium nature of the model used, it refers to impacts on the U.S. dairy industry only.

2. Materials and methods

Changes in producer and consumer surplus were estimated based on the assumption of linear demand and supply curves and a parallel shift in supply, similar to the procedures outlined by Ott et al. (2003). This analysis uses Ott et al.'s (2003) estimate of a milk-production decline of 4.7 kg per cow ($u = 1.7$ kg/cow) for each percentage point increase in the prevalence of BLV at the U.S. national level. The uncertainty associated with the milk-production decline was reported by Ott et al. (2003) from a regression analysis that was created using SUDAAN, which is a specialized computer program for analyzing survey data (Shah et al., 1996). The NAHMS Dairy 1996 Study indicated that 46.3% ($u = 1.4\%$) of dairy cows were infected with BLV (USDA: Animal and Plant Health Inspection Service, 1997). The reduction in milk production per cow (as a result of BLV) was estimated by multiplying Ott et al.'s (2003) estimated milk-production decline by the share of dairy cows infected with BLV (similar to what Ott et al., 2003, did).

The National Agricultural Statistics Service (NASS) of the USDA indicated a 1996 U.S. population of 9,372,000 dairy cows that produced 70,003 million kg of milk at a mean price of 0.328 US$ per kg (USDA: NASS, 1999). The NASS provided an approximate uncertainty for milk production of 0.9% (relative to its reported figures), and for the number of dairy cows of 1.3%, in 1996 (USDA: NASS, 1996). No information is available on the uncertainty of the NASS' estimate of the average price of milk during 1996. For this analysis, a relative uncertainty in the price of milk of 1.3% was used as a conservative estimate, because this was the larger of the uncertainties

Table 1
Input quantities used in the computation of economic impacts of BLV, their sources and uncertainties

Input quantity	Distribution	Value	Standard uncertainty	Degrees of freedom	Source
Kg/cow milk-production decline per % increase in BLV prevalence	Normal	4.7	1.7	50*	Ott et al. (2003)
BLV prevalence in cows (%)	Normal	46.3	1.4	50	USDA, APHIS (1997)
Number of dairy cows	Normal	9,327,000	122,000†	50	USDA, NASS (1999)
Kg milk produced in 1996	Normal	70.003 billion	630 million†	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).

given for milk production and for the number of dairy cows. The GUM (International Organization for Standardization, 1995) permits an educated guess of an input quantity's uncertainty when no other information is available.

The reduction in total milk production due to BLV in 1996 was estimated by multiplying the reduction in milk produced per cow (as a result of BLV) by the number of dairy cows.

The price elasticity of demand (Nicholson, 1995) is a measure of the extent to which changes in the price (P) of a good interrelate with changes in the quantity (Q) purchased. For fluid milk, Meilke et al. (1996) listed 15 different researchers' estimates of the price elasticity of demand in the United States and Canada. The estimates ranged from −0.04 to −0.73, with a mean of −0.25, a standard deviation of 0.20, and a standard uncertainty of 0.05 (as calculated from the list of estimates provided by Meilke et al., 1996).

The price elasticity of supply is a measure of the extent to which relative changes in the price of a good interrelate with relative changes in the quantity supplied (Nicholson, 1995). Adelaja (1991) provided price elasticities of milk supply of 0.6785, 0.3815, and 0.7585 for small, medium, and large farm size categories respectively (no uncertainties were given). Adelaja (1991) found that elasticities varied with farm size due to differences (by size) in capital intensity, specialization, yield variability, herd-size variability, and rates of entry into and exit from dairy production. For this analysis, a rectangular distribution with 0.3815 and 0.7585 set as the lower and upper limits, was applied.

Table 1 lists the input quantities used in this analysis. For normally distributed Type B data, the GUM Workbench assigns a default value of 50 degrees of freedom (Metrodata GmbH, 1999). In many cases, the input quantities were based on hundreds or thousands of survey observations, and hundreds or thousands of degrees of freedom could have been assigned instead of 50. However, once the number of degrees of freedom gets beyond 10, then the coverage factor is essentially two (for a 95% confidence interval, assuming a Gaussian distribution). Therefore, a default of 50 degrees of freedom is more than adequate for normally distributed Type B data. Table 2 provides the model equations that formed the basis of the analysis. The GUM Workbench (Metrodata GmbH, 1999) was used to create the estimates and propagate the uncertainties for the change in consumer surplus, change in producer surplus, and total economic loss due to reduced milk production attributed to BLV in dairy cows. Losinger (2004) reviewed the GUM Workbench, and furnished information on how to use the software to generate estimates and associated uncertainties. The GUM Workbench is a specialized computer program that computes

Table 2
Model equations used in the analysis

Model equations:

$\mathrm{BLVeffect} = \mathrm{Milkdecline} * \mathrm{BLVprev}$

$\Delta Q = \mathrm{BLVeffect} * \mathrm{Cows}$

$Q' = Q + \Delta Q$

$\Delta P = (\Delta Q * P)/(e_D * Q)$

$P' = P + \Delta P$

$Q_c = Q' - e_s * \Delta P * Q/P$

$CS_{trans} = |\Delta P * Q_c| + |0.5 * \Delta P * (Q - Q_c)|$

$CS_{lost} = |0.5 * (\Delta Q)^2 * P * (e_D - e_S)/e_D{}^2 * Q|$

$\Delta CS = CS_{trans} + CS_{lost}$

$PS_{lost} = \Delta Q * P'$

$\Delta PS = CS_{trans} - PS_{lost}$

$\text{Total economic loss} = CS_{lost} + PS_{lost}$

$\mathrm{Value} = P * Q$

$\mathrm{Value}' = P' * Q'$

$\Delta\mathrm{Value} = \mathrm{Value}' - \mathrm{Value}$

BLVeffect = reduced milk production per cow due to BLV (kg/cow); Milkdecline = Milk-production decline per cow per percent increase in BLV prevalence (kg/cow/%); BLVprev = BLV prevalence in cows (%); ΔQ = Change in total milk production due to BLV (kg); Cows = Number of dairy cows (n); Q = Quantity of milk produced with BLV (kg); Q' = Quantity of milk produced without BLV (kg); ΔP = Change in price of milk ($/kg); P = Price of milk with BLV ($/kg); P' = Price of milk without BLV ($/kg); e_D = Price elasticity of demand for milk; e_S = Price elasticity of supply for milk; Q_c = Quantity of milk produced where P' intersects S (kg); CS_{trans} = Consumer surplus transferred to producers ($); CS_{lost} = Consumer surplus lost ($); ΔCS = Change in consumer surplus ($); PS_{lost} = Lost producer surplus ($); ΔPS = Change in producer surplus ($); Value = Value of milk produced with BLV ($); Value′ = Value of milk produced without BLV ($); ΔValue = Change in value of milk produced ($).

estimates, combined standard uncertainties, and coverage factors in accordance with the recommendations established by the International Organization for Standardization (1995). The GUM Workbench calculates sensitivity coefficients using numerical partial differentiation, applies Taylor-series approximation to compute combined standard uncertainties, and uses Satterthwaite's approximation to compute combined degrees of freedom (Metrodata GmbH, 1999).

3. Results

Tables 3–5 provide the uncertainty budgets, estimates, and expanded uncertainties for the change in consumer surplus, change in producer surplus, and total economic loss due to reduced milk production attributed to BLV in dairy cows. The indices, which show each input quantity's percent contribution to the square of the measurand's uncertainty, indicate that the uncertainty in the decline in milk production per cow per percent increase in BLV prevalence (from the model of Ott et al., 2003) contributed towards most of the uncertainty in the measurands of these tables. Price elasticity of demand for milk was a distant second, followed by price elasticity of supply for milk (for the change in producer surplus and for the total loss to the economy). All other input quantities contributed less than 1% to the square of the measurands' uncertainties.

Table 3
Uncertainty budget for the change in consumer surplus that resulted from reduced milk production attributed to the presence of BLV in dairy cows

Input quantity	Sensitivity coefficient*	Uncertainty contribution†	Index‡ (%)
Kg/cow milk-production decline per % increase in BLV prevalence	-5.9×10^8	-1.0×10^9	75.1
BLV prevalence in cows (%)	-5.9×10^7	-8.3×10^7	0.5
Number of dairy cows	-2.9×10^2	-3.6×10^7	0.0
Kg milk produced in 1996	5.6×10^{-4}	3.5×10^5	0.0
Mean price of milk in 1996 ($/kg)	-8.3×10^9	-1.8×10^7	0.0
Price elasticity of demand for milk	-3.0×10^8	-5.7×10^8	24.2

The final estimate for the change in consumer surplus is -2.7 US$ $\times 10^9$, with a standard uncertainty of 1.2 US$ $\times 10^9$ and 64 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

$$-2{,}700{,}000{,}000 \pm 2{,}300{,}000{,}000 \text{ US\$}$$

*$\partial y/\partial x_i$ 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).

†Product of the standard uncertainty (Table 1) and the sensitivity coefficient. The sum of the squares of the 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% (but may not exactly due to rounding), and provides information on the relative importance of the contribution of each input quantity to the uncertainty of the measurand.

Table 4
Uncertainty budget for the change in producer surplus as a result of reduced milk production attributed to the presence of BLV in dairy cows

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index (%)
Kg/cow milk-production decline per % increase in BLV prevalence	4.2×10^8	7.2×10^8	63.9
BLV prevalence in cows (%)	4.3×10^7	6.0×10^7	0.4
Number of dairy cows	2.1×10^2	2.6×10^7	0.0
Kg milk produced in 1996	1.6×10^{-4}	9.8×10^4	0.0
Mean price of milk in 1996 ($/kg)	6.1×10^9	1.3×10^7	0.0
Price elasticity of demand for milk	1.1×10^{10}	5.4×10^8	35.5
Price elasticity of supply for milk	-1.6×10^8	-1.7×10^7	0.0

The final estimate for the change in producer surplus is an increase of 2.0 US$ $\times 10^9$, with a standard uncertainty of 9.0 US$ $\times 10^8$ and 58 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

$$2{,}000{,}000{,}000 \pm 1{,}800{,}000{,}000 \text{ US\$}$$

See Table 3 for additional explanation.

Table 3 shows that reduced milk production attributed to BLV in dairy cows caused consumer surplus to fall by 2.7 bUS$ (standard uncertainty = 1.1 bUS$). Most (2.6 bUS$, standard uncertainty = 1.1 bUS$) of the reduction in consumer surplus (due to reduced milk production attributed to BLV in dairy cows) was transferred to producers as a gain. For producers, this transfer more than offset the 590 mUS$ (standard uncertainty = 190 mUS$) of lost producer surplus (that accounted for most of the 720 mUS$ loss to the total U.S. economy), so that the total impact on producers was an increased surplus of 2.0 bUS$ (Table 4). Lost consumer surplus that was not transferred to producers amounted to 130 mUS$ (standard uncertainty = 110 mUS$). The total loss was the sum of the lost producer surplus and the lost consumer surplus that was not transferred to producers (Table 5).

Only the prices and quantities reported by the NASS figured into the computation of the value of milk produced in 1996 (Table 6). If BLV had not been present in U.S. dairy cows, then milk production would have increased by 2.0 billion ± 1.5 billion kg, and the price would have fallen by 3.8 ± 3.2 cents/kg. The decline in milk production per cow per percent increase in BLV prevalence (from the model of Ott et al., 2003) contributed towards most of the uncertainty in the projected value of milk that would have been produced if no BLV had been present in U.S. dairy cows in 1996, followed by the price elasticity of demand for milk (Table 7). Although the confidence intervals for the value of milk produced with and without BLV overlap (Tables 6 and 7). Table 8 shows that the value of milk produced would have been significantly lower if BLV had been absent from the U.S. dairy cow population. The GUM Workbench

Table 5
Uncertainty budget for the total economic loss resulting from reduced milk production attributed to BLV in dairy cows

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index (%)
Kg/cow milk-production decline per % increase in BLV prevalence	1.6×10^8	2.8×10^8	97.6
BLV prevalence in cows (%)	1.7×10^7	2.3×10^7	0.7
Number of dairy cows	8.2×10^1	1.0×10^7	0.1
Kg milk produced in 1996	-7.1×10^{-4}	-4.5×10^5	0.0
Mean price of milk in 1996 (US$/kg)	2.2×10^9	4.7×10^6	0.0
Price elasticity of demand for milk	6.0×10^7	3.0×10^7	1.2
Price elasticity of supply for milk	1.6×10^8	1.7×10^7	0.4

The final estimate for the total economic loss resulting from reduced milk production attributed to BLV in dairy cows is 7.2 US$ $\times$ 10^8, with a standard uncertainty of 2.8 US$ $\times$ 10^8 and 52 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

720,000,000 ± 560,000,000 US$

See Table 3 for additional explanation.

Table 7
Uncertainty budget for the total value of milk that would have been produced in 1996, if there had been no BLV in dairy cows

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index (%)
Kg/cow milk-production decline per % increase in BLV prevalence	-4.6×10^8	-7.8×10^8	60.7
BLV prevalence in cows (%)	-4.7×10^7	-6.5×10^7	0.4
Number of dairy cows	-2.3×10^2	-2.8×10^7	0.0
Kg milk produced in 1996	3.3×10^{-1}	2.1×10^8	4.3
Mean price of milk in 1996 (US$/kg)	6.4×10^{10}	1.4×10^8	1.9
Price elasticity of demand for milk	-1.1×10^9	-5.7×10^8	32.7

The estimate for the total value of milk that would have been produced during 1996 (if BLV had been absent from dairy cows) is 2.1 US$ $\times$ 10^{10}, with a standard uncertainty of 1.00 US$ $\times$ 10^9 and 66 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

21,000,000,000 ± 2,000,000,000 US$

See Table 3 for additional explanation.

calculated a correlation of 0.25 between the value of milk produced in 1996 (with BLV present on U.S. dairy operations) versus the value of milk that would have been produced if there had been no BLV in 1996.

The overall economic impacts of reduced milk production associated with BLV in U.S. dairy cows are summarized in Table 9.

4. Discussion

Ott et al. (2003) described the creation of the sample weights for use in their analysis. The sample weight indicates the number of farms in the population that each farm in the sample represents. Because large farms (that accounted for a large portion of the animal population) were sampled at a much higher rate than the more numerous small farms (that accounted for a small proportion of the animals), large farms typically received much smaller sample weights than small farms in NAHMS national studies (Losinger, 1997). Thus, responses from small farms tend to have a greater impact on farm-level estimates than responses from large farms. For animal-level estimates from NAHMS surveys, it is customary to modify the sample weights to reflect the number of animals (rather than the number of farms represented) by multiplying the sample weight by

Table 6
Uncertainty budget for the total value of milk produced in 1996 (with BLV in dairy cows)

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index (%)
Kg milk produced in 1996	3.3×10^{-1}	2.1×10^8	65.3
Mean price of milk in 1996 (US$/kg)	7.0×10^{10}	1.5×10^8	34.7

The estimate for the total value of milk produced during 1996 (with BLV in dairy cows) is 2.3 US$ $\times$ 10^{10}, with a standard uncertainty of 2.6 US$ $\times$ 10^8 and 91 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

23,000,000,000 ± 510,000,000 US$

See Table 3 for additional explanation.

Table 8
Uncertainty budget for the difference between the total value of milk that would have been produced during 1996 if there had been no BLV in dairy cows, and the total value of milk produced in 1996

Input quantity	Sensitivity coefficient	Uncertainty contribution	Index (%)
Kg/cow milk-production decline per % increase in BLV prevalence	-4.6×10^8	-7.8×10^8	64.7
BLV prevalence in cows (%)	-4.7×10^7	-6.5×10^7	0.5
Number of dairy cows	-2.3×10^2	-2.8×10^7	0.0
Kg milk produced in 1996	1.1×10^{-3}	7.0×10^5	0.0
Mean price of milk in 1996 (US$/kg)	-6.4×10^9	-1.4×10^7	0.0
Price elasticity of demand for milk	-1.1×10^9	-5.7×10^8	34.8

The estimate of the difference between the total value of milk that would have been produced during 1996 if there had been no BLV in dairy cows, and the total value of milk produced in 1996, is −2.1 US$ $\times$ 10^9, with a standard uncertainty of 9.7 US$ $\times$ 10^8 and 58 degrees of freedom. The resulting value and expanded uncertainty, with a coverage factor of two, is then:

−2,100,000,000 ± 1,900,000,000,000 US$

See Table 3 for additional explanation.

Table 9
Summary of economic impacts of reduced milk production associated with BLV in U.S. dairy cows in 1996. Figures are ± 2 sigma

Variable	Impact
Total quantity of milk produced (kg × 10^9)	−2.0 ± 1.5
Mean price of milk (cents/kg)	3.8 ± 3.2
Total value of milk produced (US$ × 10^9)	2.1 ± 1.9
Consumer surplus transferred to producers (US$ × 10^9)	2.6 ± 2.1
Lost consumer surplus not transferred to producers (US$ × 10^6)	130 ± 210
Net change in consumer surplus (US$ × 10^9)*	−2.7 ± 2.3
Lost producer surplus (US$ × 10^6)	590 ± 370
Net change in producer surplus (US$ × 10^9)†	2.0 ± 1.8
Net economic loss (US$ × 10^6)‡	720 ± 560

*The net drop in consumer surplus was the sum of the consumer surplus that was transferred to producers and the consumer surplus that was lost (i.e., not transferred to producers).

†The net change in producer surplus was the consumer surplus that was transferred to producers, minus the lost producer surplus.

‡The net economic loss was the sum of the lost consumer surplus not transferred to producers and the lost producer surplus.

the number of animals (Losinger, 2002). Thus, large farms tend to receive much higher animal-level weights (which reflect the number of animals that each participating operation represents) than small farms. Ott et al. (2003) used farm-level rather than animal-level weights in their annual value of production (AVP) and milk-production models. The model for milk production is in terms of kg per cow *per operation* (rather than kg per cow). Using farm weights for animal-level estimates can yield highly inaccurate results. Moreover, one might argue that the results of Ott et al. (2003) should not be applied to the entire U.S. dairy population because sample selection for the Dairy 1996 Study was limited to a rather narrowly defined target population: dairy operations with ≥30 dairy cows in 20 states (USDA, Animal and Plant Health Inspection Service, 1997). However, if one may regard the statistical model of Ott et al. (2003) as indicating the physical relationship that exists between BLV and milk production, that would apply to all dairy cows regardless of the operation's sample weight, and that would pertain to dairy cows outside of the target population, then using the milk-production decline per percentage increase in BLV prevalence to estimate BLV's national economic impact may be viewed as justified.

Ott et al.'s (2003) analysis of the association between BLV and herd-level productivity on U.S. dairy farms represented at least the fourth in a series of economic analyses which derived directly from the NAHMS Dairy 1996 data. The first examined herd-level economic losses associated with Johne's disease (Ott et al., 1999). Articles on the economic impacts of recombinant bovine somatotropin (rBST) (Ott and Rendleman, 2000) and bulk-tank somatic-cell counts (Ott and Novak, 2001) have appeared in the interim. In most of these reports, the principal variable for analysis was what Ott et al. (2003) termed the "Annual Value of Production" (AVP), which Ott et al. (1999) called "Annual Adjusted Value of Production," and which Ott and Novak (2001) called the "Value of Dairy Herd Productivity." AVP was derived on an annual per cow basis as the sum of the value of milk production (milk priced at 28.6 cents/kg) and the value of newborn calves (valued at 50 US$ each), minus the net replacement cost. The "net replacement cost" was the cost of replacements (priced at 1,100 US$ each), minus the value of cows sold to other producers (priced at 1,100 US$ each) and to slaughter (400 US$ for cows in good condition, 250 US$ for poor-condition cows). Ott and Rendleman (2000) analyzed "Non-Milk Productivity" (AVP minus the value of milk production). In addition, Ott and Rendleman (2000); Ott and Novak (2001); and Ott et al. (2003) used milk production per cow as a variable for analysis. The AVP variable included one input (dairy-cow replacements) and three outputs (milk, calves, and culled cows) (Ott et al., 2003). All three outputs are complementary: a cow obviously cannot produce milk without first producing a calf, and cows are generally slaughtered when they reach the end of their careers as milk-producers. However, a certain degree of substitutability is possible. If a new technology increases total milk production, and also increases the number of days of milk production, then fewer calves may be produced per cow over a given time period. If a profit function had been developed for this vector of outputs, then some straightforward procedures could have been applied to study the relationships between the inputs and the various outputs, and to determine optimum rates of input application. Creating a dependent variable by combining dollar-values attributed to various input- and output-quantities (as Ott et al., 2003, did for AVP) is a rather questionable technique for analyzing multi-output production. In theory, producers make production decisions based upon the prices (and other constraints) that they face (Debertin, 1986). Prices received and paid may vary considerably from one producer to the next. One producer may make production decisions that are very different from another's, but that are appropriate given that producer's conditions. Assigning the same dollar-value to outputs for all producers, and then summing the results to generate a dependent variable for analysis, may lead to erroneous conclusions that some producers are achieving higher profits than others based upon certain independent variables when, in fact, all may be maximizing profit given their particular constraints. Furthermore, the dependent variable (AVP) created by Ott et al. (2003) renders impossible the computation of profit-maximizing rates of input application. The present analysis was limited solely to the economic impact of reduced milk production associated with BLV in US dairy cows, and made use only of Ott et al.'s (2003) estimate of a milk-production decline of 4.7 kg per cow for each percentage point increase in the prevalence of BLV at the U.S. national level, and not the AVP variable.

The statistical models developed by Ott et al. (1999), Ott and Rendleman (2000), Ott and Novak (2001), and Ott et al. (2003) were quite similar. In proceeding from Ott et al.'s (1999) models to the models of Ott and Rendleman (2000), the "Johne's Disease" variables were removed, and the functional form for percent rBST use was changed from a square root to a quadratic expression. Ott et al. (1999) chose a square-root representation for percent rBST use because "initial analysis demonstrated a nonlinear relationship between milk production and percent BST use," and "in part because of the large number of herds that did not use any BST." Ott and Rendleman (2000) used a quadratic term for percent rBST use "to measure a potential declining marginal physical product of milk production as rBST increases." Ott and Novak (2001) used a simple linear term for percent rBST use. Because "Ott and Rendleman (2000) found that as the percentage of cows being administered rBST rose, the associated marginal increase in milk yield became smaller," Ott et al. (2003) reverted to a square-root representation for percent BST use. A new variable introduced by Ott et al. (2003) was the percent of cows in third or greater lactation (via "piecewise regression"). In addition, Ott et al. (2003) added two new "management index" variables that resulted from a "correspondence analysis" that combined 24 variables into 2. In previous analyses, the use of Dairy Herd Improvement Association (DHIA) records "served as a proxy measure for management capability" (Ott et al., 1999). Ott and Novak (2001) stated that they had attempted to combine 18 variables of management practice into four management indices, using factor analyses, to account for the influence of management ability on AVP, but decided to use DHIA records as a measure of management ability because 83% of the increase in the R^2 value could be obtained from the use of DHIA records, and because including additional management variables reduced the number of respondents with complete information by 6%. When the various models were applied to the same dependent variable, the R^2-squared values were not substantially different across analyses. The statistical models presented by Ott et al. (2003) were the only ones in the series that included BLV among the explanatory variables.

Elasticities of supply and demand are typically estimated from observed market conditions. Assumptions about the shape of the supply and demand curves can become increasingly unrealistic the further one extrapolates beyond observed conditions. The change in consumer surplus was measured based on a shift in supply along a small portion of a fixed demand curve. In contrast, the measurement of part of the change in producer surplus involved finding the area between two parallel supply curves projected to the horizontal axis (where the price of milk is zero). One might therefore feel more confident about the overall accuracy of the change in consumer surplus than about the change in producer surplus. The shape of the supply curves beyond observed market conditions are really not known, and one must make simplifying assumptions of one sort or another if one is going to offer any sort of estimate of changes in producer surplus that result from shifts in supply. Supply curves are usually depicted as having a positive Y intercept, because the marginal cost of providing the first unit of milk is positive; however, inelastic supply curves do not have a positive Y intercept, and economic surplus changes cannot be computed from negative prices. Zhao et al. (1997) show that only local rather than global linearity is required for the proper calculation of economic surplus under a parallel supply shift, and the restriction that supply has to be elastic in order to have a positive intercept is unnecessary. Lindner and Jarrett (1978) and Miller et al. (1988) described the impacts that various assumptions concerning the shifts in supply curves could have on the calculation of the change in producer surplus. Economists working in multidisciplinary settings frequently work with the assumption that a relatively small change in the unit cost of production can be modeled as a parallel shift of the supply curve. For example, Forsythe and Corso (1994) assumed a parallel shift in the supply curve when they measured the change in producer surplus resulting from the National Pseudorabies Eradication Program. Kennedy et al. (2000) assumed a parallel shift in the supply curve when they computed changes in producer and consumer surplus that resulted from Hazard Analysis and Critical Control Points. The rectangular distribution is recommended in error propagation when all values between two limits have the same likelihood from an observer's point of view, and where it is impossible to prefer specific values without having more knowledge (Kessel, 2003). Therefore, a rectangular distribution, with more ample limits than those used for the elasticity of demand, was chosen for the elasticity of supply. The goal of the present study was not to find exact values for the changes in economic surplus (which, at any rate, is impossible), but rather to apply the analytic principles delineated by the International Organization for Standardization (1995) to find confidence intervals for the changes in economic surplus, such that the confidence intervals included a large fraction of the distribution of values that could reasonably be attributed to the changes in economic surplus. The specific values obtained here should not be used outside the context of their associated uncertainties.

Researchers are under increasing pressure to demonstrate the quality of their results by providing a measure of the confidence that can be placed on their results, and the degree to which their results would be expected to agree with other results. A limitation of many prior economic-welfare analyses of animal diseases (for example, Forsythe and Corso, 1994; Ott et al., 2003) was that they completely ignored the uncertainty of their estimates. Piggott (2003) used a Monte Carlo method to compute confidence intervals for estimated welfare effects (for producers) from generic advertising of meat, and found that the impact was not significantly different from zero. If measured, one would not be surprised to find the uncertainties associated with measures of economic welfare to be rather large. A principal advantage of following the recommendations presented by the GUM (International Organization for Standardization, 1995) is the transparency of the methods. Presenting an uncertainty budget that, for each input quantity, lists its source, distribution, value, uncertainty, degrees of freedom, and that analyzes its contribution to the measurand's uncertainty, is an effective means of conveying the confidence that can be placed in a researcher's results. The indices of the uncertainty contributions (Tables 3–5) tell at-a-glance which input quantities had the greatest impact on the uncertainty of the measurand. In each case, the index for the decline in milk production per cow per percent increase in BLV (which derived from the regression model of Ott et al., 2003) was greater than the index for all other input quantities combined. This suggests that the greatest improvement in the estimate of the economic cost of BLV could be derived by concentrating on finding a better estimate of the decline in milk-production per cow per percent increase in BLV. Or, perhaps a national estimate of the decline in milk production per cow per percent increase in BLV, with a standard error that was 36% of the estimate (Table 1), is the best that one could reasonably expect to find. Thus, relatively large uncertainties would be appropriate for any measurand for which the decline in milk production per cow per percent increase in BLV is an input quantity. A more precise estimate of, for example, the number of dairy cows (whose contribution to the overall uncertainties of the economic impacts was less than 0.1%, Tables 3–8) would have had a trivial impact on the uncertainties of the measurands. Although the NASS did not provide an uncertainty for the price of milk in 1996, the conservative estimate used here proved adequate, because the uncertainties in the effect of BLV on milk production, and the price elasticity of demand, accounted for the lion's share of the uncertainties in the measurands. Readers who wish to propose a different value for an input quantity, or a different model equation, can easily do so based on this analysis. When an uncertainty for an input is unknown, the International Organization for Standardization (1995) permits analysts to use an educated guess. Given that prices fluctuate more often than production and that there is usually a lag between price change and production adjustment, one might suggest trying price uncertainties higher than 1.3%. However, the contribution of the uncertainty assigned to the price of milk to the uncertainty in the various measurand's was so small (Tables 3–8) compared to the major contributors as to be trivial. If one wanted a superior estimate of the economic impacts of reduced milk production associated with BLV, then one would be advised to concentrate one's efforts on finding a better estimate of the impact of BLV on milk production.

A number of other computer programs are available for computing uncertainty estimates. One example is @Risk (Palisade Corporation, 2002). Disney and Peters (2003) used @Risk to simulate models to derive the value of information for risky animal-disease import decisions. Disney et al. (2001) used @Risk to analyze benefits and costs of animal identification for disease prevention and control. Schoenbaum and Disney (2003) developed their own software, based on Monte Carlo simulation methods, to model the economic consequences of alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States. Many of these computer programs allow analysts to specify uncertainties with a variety of probability density functions. Currently, the GUM Workbench is limited to the normal, *t*, rectangular, triangular, and trapezoidal distributions, which are all symmetric distributions (Metrodata GmbH, 1999). In most cases, particularly if one has faith in the Central Limit Theorem, these distributions will be adequate for uncertainty propagations. A limitation of many of the alternative methods of computing measurement uncertainties (such as the jack-knife, the bootstrap, Monte Carlo simulations, or using @Risk) is that one does not end up with an uncertainty budget that allows one to view each input quantity's relative contribution to the overall uncertainty of the measurand. A principal advantage of conforming to the International Organization for Standardization's (1995) recommendations is the full transparency of the presentation. The GUM Workbench automatically provides uncertainty budgets that, for each input quantity, list its source, distribution, value, uncertainty, degrees of freedom, and that analyzes its contribution to the uncertainty of the measurands (Losinger, 2004). To date, the GUM Workbench has been used mostly in the physical sciences (especially by metrology laboratories): for example, Jalukse et al. (2004) used the GUM Workbench to analyze the uncertainty in electrochemical amperometric measurement of dissolved oxygen concentration, and Papadakis et al. (2004) used this program to calculate the measurement uncertainties of various elements in water samples. However, the principles of the GUM are quite applicable to economics and other social sciences.

In addition to uncertainty analysis, sensitivity analysis is a very popular method for examining the impact of changing the values of one or more input quantities. A significant disadvantage of sensitivity analysis is that it does not incorporate any explicit probability-based measure for the various proposed changes to the values of the input quantities (Marshall, 1999). Although any number of sensitivity analyses could be performed (by changing the values of input quantities), the International Organization for Standardization (1995) does not present any recommendations concerning sensitivity analysis.

The result that the dairy industry may be gaining economic surplus as a result of reduced milk production attributed to BLV in dairy cows (or, conversely, may lose economic surplus as a result of increasing milk production through eliminating BLV) may seem paradoxical to many people who are unfamiliar with economics. Consumers may stand to benefit more than producers from eliminating BLV in dairy cows, given the transfer in economic surplus from producers to consumers that would result from increased milk production. The gain in producer surplus attributed to BLV in dairy cows does not imply that dairy producers should be indifferent towards BLV on their operations. The statistical analyses for the Dairy 1996 Study indicate that dairy operations that have lower prevalences of BLV have higher milk production per cow, and may thus be more profitable than operations with higher prevalences of BLV (Ott et al., 2003). Beyond reduced milk production, BLV may lead to diminished reproductive efficiency, higher veterinary costs, and higher replacement costs (Ott et al., 2003). Dairy producers need to weigh the costs of measures aimed at reducing BLV in cows against the anticipated benefits of the expected reduction in BLV. Further research is warranted to identify management and other factors associated with BLV on dairy operations.

5. Conclusions

This article offers an example of how an uncertainty analysis may be presented, consistent with procedures outlined in the GUM (International Organization for Standardization, 1995), for an analysis of economic impacts of a disease that affects production in dairy cattle. The uncertainty budget makes it easy to perceive the relative contributions of various input quantities to the overall uncertainty of the measurand. Other researchers can see exactly what I have done, and, if they wish, make changes to the model equations or introduce different estimates for input quantities to derive different estimates for the economic impacts of BLV in dairy cattle.

The dairy industry may stand to benefit less from increased milk production (associated with eliminating BLV from dairy cows) than consumers, given the reduced price that would result from the increased production, and the fact that most of the economic surplus lost by consumers (as a result of reduced milk production attributed to BLV in dairy cows) was transferred to producers as economic gain. Individual dairy producers need to compare the costs of measures intended to reduce BLV with the anticipated benefits of decreased BLV, which is outside the scope of an economic-welfare analysis.

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References

Adelaja, A. O., 1991. Price changes, supply elasticities, industry organization, and dairy output distribution. Am. J. Agric. Econ. 73, 89–102.

Debertin, D. L., 1986. Agricultural Production Economics. Macmillan Publishing Company, New York.

Disney, W. T., Green, J. W., Forsythe, K. W., Wiemers, J. F., Weber, S., 2001. Benefit-cost analysis of animal identification for disease prevention and control. Rev. Sci. Tech. Off. Int. Epiz. 20, 385–405.

Disney, W. T., Peters, M. A., 2003. Simulation modeling to derive the value-of-information for risky animal disease-import decisions. Prev. Vet. Med. 61, 171–184.

Forsythe, K. W., Corso, B., 1994. Welfare effects of the National Pseudorabies Eradication Program: comment. Amer. J. Ag. Econ. 76, 968–971.

International Organization for Standardization, 1995. Guide to the Expression of Uncertainty in Measurement Corrected and Reprinted, 1995. International Organization for Standardization, Geneva.

Jalukse, L., Leito, I., Mashirin, A., Tenno, T., 2004. Estimation of uncertainty in electrochemical amperometric measurement of dissolved oxygen concentration. Accreditation Qual. Assur. 9, 340–348.

Johnson, R., 1998. Bovine-Leukosis. In: Aiello, S. (Ed.), The Merck Veterinary Manual. Merck & Co., Princeton, NJ, pp. 521–522.

Kennedy, T. K., Losinger, W. C., Hoag, D. L., 2000. Who pays for hazard analysis and critical control points? J. Appl. Animal Res. 17, 197–200.

Kessel, R., 2003. A novel approach to uncertainty evaluation of complex measurements in isotope chemistry. Dissertation for the Degree of Doctor in Science at the University of Antwerp.

Kessel, R., Berglund, M., Taylor, P., Wellum, R., 2001. How to treat correlation in the uncertainty budget, when combining results from different measurements. In: Ciarlini, P., Filipe, E. (Eds.), Advanced Mathematical and Computational Tools in Metrology V. World Scientific Publishing Co Pte Ltd, Singapore, pp. 231–241.

Lindner, R. K., Jarrett, F. G., 1978. Supply shifts and the size of research benefits. Am. J. Agric. Econ. 60, 48–58.

Losinger, W. C., 1997. Lorenz curves applied to livestock populations. Chance, 10(2):19–22.

Losinger, W. C., 2002. A look at raking for weight adjustment. Stats: Magazine Students Stat, 33(1): 8–12.

Losinger, W. C., 2004. A review of the GUM Workbench. Am. Stat. 58, 165–167.

Marshall, H. E., 1999. Sensitivity analysis. In: Dorf, R. C. (Ed.), Technology Management Handbook. CRC Press, Boca Raton, FL, pp. 59–63.

Meilke, K., Sarker, R., Le Roy, D., 1996. Analyzing the potential for increase trade in dairy products: a Canadian perspective. In: Loyns, R., Meilke, K., Knutson, R. (Eds.), Proceedings of the Second Agricultural and Food Policy Systems Information Workshop, Canada/U.S., pp. 241–272.

Metrodata GmbH, 1999. GUM Workbench: the tool for expression of uncertainty in measurement. Manual for version 1.2 English Edition. Teknologisk Institut, Taastrup, Denmark.

Miller, G. Y., Rosenblatt, J. M., Hushak, L. J., 1988. The effect of supply shifts on producers' surplus. Am. J. Agric. Econ. 70, 886–891.

National Institute of Standards and Technology, 1994. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technology Note 1297. National Institute of Standards and Technology, Gaithersburg, Maryland, USA. 20 pp.

Nicholson, W., 1995. Microeconomic Theory Basic Principles and Extensions, 6th edn. Dryden Press, Fort Worth. 901 pp.

Ott, S. L., Johnson, R., Wells, S. J., 2003. Association between Bovine-Leukosis virus seroprevalence and herd-level productivity on US dairy farms. Prev. Vet. Med., 61, 249–262.

Ott, S. L., Novak, P. R., 2001. Association of herd productivity and bulk-tank somatic cell counts in US dairy herds in 1996. J. Am. Vet. Med. Assoc. 218, 1325–1330.

Ott, S. L., Rendleman, C. M., 2000. Economic impacts associated with bovine somatotropin (BST) use based on a survey of US dairy herds. AgBioForum 3, 173–180.

Ott, S. L., Wells, S. J., Wagner, B.A., 1999. Herd-level economic losses associated with Johne's disease on US dairy operations. Prev. Vet. Med. 40, 179–192.

Palisade Corporation, 2002. Guide to Using @RISK Risk Analysis and Simulation Add-In Software for Microsoft Excel, Version 4.5. Palisade Corporation, Newfield, New York. 503 pp.

Papadakis, I., Kessel, R., Nevel, L., Norgaard, J., Aregbe, Y., Smet, M., Smeyers, P., Taylor, P. D. P., 2004. SI-traceable certification of the IMEP-12 water sample combining contributions from different reference laboratories. Accreditation Qual. Assur. 9, 704–710.

Piggott, N. E., 2003. Measures of precision for estimated welfare effects for producers from generic advertising. Agribusiness 19, 379–391.

Schoenbaum, M. A., Disney, W. T., 2003. Modeling alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States. Prev. Vet. Med. 58, 25–52.

Shah, B. V., Barnwell, B. G., Bieler, G. S., 1996. SUDAAN User's Manual, Version 6.40, 2nd edn. Research Triangle Institute, Research Triangle Park, North Carolina, 492 pp.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service, 1997. High Prevalence of Bovine Leukosis Virus (BLV) in U.S. Dairy Herds. USDA:APHIS:VS, Centers for Epidemiology and Animal Health, Fort Collins, Colorado.

U.S. Department of Agriculture, National Agricultural Statistics Service, 1996. Milk Production 12-13-96. NASS Report DA 1-1 (12-96). USDA:NASS, Washington, DC.

U.S. Department of Agriculture, National Agricultural Statistics Service, 1999. Milk Production, Disposition and Income 1998 Summary. NASS Report DA 1-2 (99). USDA:NASS, Washington, DC.

Wohlengant, M. K., 1989. Demand for farm output in a complete system of demand functions. Am. J. Agric. Econ. 71, 241–252.

Zhao, X., Mullen, J.D., Griffith, G. R., 1997. Functional forms, exogenous shifts and economic surplus changes. Am. J. Agric. Econ. 79, 1241–1251.