THE ECONOMICS OF CONTROLLING INFECTIOUS DISEASES ON DAIRY FARMS

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Abstract

Cost effective disease control on the dairy farm can enhance productivity and subsequently profitability. Previous economic studies on animal disease have focused on production losses and evaluation of disease eradication programs and provided little guidance as to the optimal prevention action. This paper presents a theoretical model on the economics of livestock disease and develops an empirical model to determine the optimal set of control strategies for four production limiting cattle diseases: bovine viral diarrhea (BVD), enzootic bovine leukosis (EBL), Johne's Disease (JD) and neosporosis. Control functions indicating the prevalence of infection with each of the four diseases for each of the ten strategies are estimated. The optimal strategies that minimize total disease cost (direct production losses and control expenditures) are provided for each disease on the basis of farm survey results from the Maritime provinces. The results emphasize the importance of introduction checks before new animals enter the herd and adequate vaccination protection as cost-effective control strategies.

THE ECONOMICS OF CONTROLLING INFECTIOUS DISEASES ON DAIRY FARMS

Net returns to producers and processors in the dairy sector are negatively affected by disease. Disease can reduce the efficiency of inputs which are converted to outputs (i.e. lower feed efficiency or increasing cow mortality) thereby lowering profit margins through higher input costs and/or lower yields. Diseases can also reduce revenue through lower quality and lower production levels. Consumer reaction to the prevalence of disease could also cause a shift in the demand curve leading to a drop in output price. This aggregate effect may reduce the competitive position of a given sector relative to other sectors within the region or relative to the same sector across regions.

In the Canadian dairy sector, there is concern regarding the effects of four production limiting diseases: bovine viral diarrhea (BVD), enzootic bovine leukosis (EBL), Johne's Disease (JD) and neosporosis. The concern has been manifested in the formation of the Production Limiting Disease Committee (PLDC) in 1997. The four dairy diseases that are the focus of the PLDC are not treatable and presumed to impose large productivity losses on affected farms although the actual extent of the costs is unknown. The losses are mainly from reduced milk production due to mortality, weight loss, abortion, and growth retardation. These diseases may also become a focus of public health attention as is the case with JD and its possible connections with Crohn's disease in people (Fidler *et al.* 1994). At the present time, detection and removal of permanently infected cattle from herds are considered as the primary ways of preventing the diseases. Little is known about the actual costs and benefits of the possible methods for controlling any of the four dairy diseases.

The few studies examining the economics of animal disease have tended to focus exclusively on the losses to producers (Bennett 1992) or on the value of eradication programs (Dijkhuizen *et al.* 1995). Losses are estimated as the proportion of animals with the disease multiplied by the number of animals in the region and by the dollar value per animal of lost output as compared to a healthy animal. A major limitation in defining the optimality of resource use is that this approach fails to recognize prevention and treatment costs. Total losses from the disease should include not only direct production losses but also control expenditures. In addition, knowing the dollar value of yield losses only indicates the existence of a problem but no direction on how to deal with it. Assessing the relationship between control strategies and disease prevalence allows for the calculation of the total losses from the disease associated with alternative control practices. The optimal management strategy minimizes total disease costs.

The purpose of this paper is to determine the optimal set of control practices that minimize the total economic costs for each of the following four production limiting diseases: BVD, EBL, JD and neosporosis. The paper begins with the development of a conceptual model assessing the optimal level of control practices and it considers both direct losses and control expenditures. Within this first section, the fallacy of examining only direct disease losses when addressing how to manage a given disease is discussed. The second section of the paper develops an empirical model of the study conducted for the Maritime provinces. The prevalence of the disease infection for each of the ten control strategies is predicted and then fed into a spreadsheet model to measure the *ex post* costs at the herd level from direct production losses and treatment costs. The optimal strategies for each of the four diseases are determined by summing the *ex ante*

costs of alternative control strategies and the *ex post* losses, and comparing across practices. The paper concludes with implications of the results for herd health managers.

CONCEPTUAL MODEL

Modelling Direct Costs of Disease

The direct effects of infectious disease that have been the exclusive focus of many previous studies can be represented by the following production function:

$$Q = f(R / \overline{N}, \overline{K}) \qquad (1)$$

where Q is the flow of output (i.e. milk, weight gain), R is the level of variable inputs (i.e. feed, labour), $\overline{N}$ is the size of the herd, and K is the level of fixed factors. The disease can lower output by increasing the mortality rate (reducing $\overline{N}$) or by reducing the efficiency of the inputs R. The latter effect is captured by a variation of equation (1) that assumes the disease is present $f^D(R / \overline{N}, \overline{K})$. Examples of a 'healthy' and a 'diseased' production function are illustrated in Figure 1 adapted from McInerney (1996). In addition, an input price (P_R) to output price (P_Q) ratio line is included. The tangency of this line to the production function indicates the level of variable input use that will maximize profits (i.e. where marginal value product is equal to the marginal factor cost of the input).

Several points to be considered when estimating the direct costs of infectious disease of dairy cattle are shown in Figure 1. First, the impacts will vary by farm depending on characteristics such as size, type, or location. For example, assuming input use remains constant, the reduction in output for an intensive operation using an input level of R_H is $Q_H - Q_H^D$. This loss is greater than that suffered by a low input farm

($Q_L - Q_L^D$) using R_L inputs ($R_L < R_H$). Second, input use will be affected so economic costs should account for resource adjustments and not only the reduction in output. The original profit maximizing equilibrium without the disease is at *E* and the farmer uses R_H to produce Q_H. The disease alters the production function and the new equilibrium is E^D with the farmer using R_L inputs and generating an output of Q_L^D. The traditional approach of determining the cost of the the disease would estimate the loss as the reduction in output valued at output price $(Q_L - Q_L^D) \cdot P_Q$. However, this approach overstates the true loss because it does not account for the adjustment in input use. The actual loss is the difference in profit $(P_Q \cdot Q_H - P_R \cdot R_H) - (P_Q \cdot Q_L^D - P_R \cdot R_L)$ or $A - B$ in Figure 1. Note that the disease may also lead to a drop in the price of the output which would increase the price ratio (P_R / P_Q) and thus lower input use and increase the extent of the loss from the disease.

Figure 1

Modelling Disease Control

The next step to addressing optimal resource use in dealing with infectious disease in dairy cattle is to include control expenditures in addition to the direct losses examined in the previous section. Disease control efforts, denoted by *V*, could include both prevention and treatment costs at the farm level and institutional efforts at the aggregate regional level. The optimal level of disease control (and subsequently disease level) cannot be determined using the same framework as most resources in which additional inputs generally lead to higher output levels. Instead, disease control is considered a damage control input because it acts to prevent output from falling rather

than to enhance production further. The following framework for modelling disease control is adapted from Lichtenberg and Zilberman (1986) who were the first to correctly specify the indirect effects damage control inputs have on output. Their work into pesticides has been extended and applied by several studies including Pannell (1990) and Fox and Weersink (1995) but this is the first attempt to extend the approach to disease control of dairy cattle.

We begin by assuming there are two types of disease control expenditures: a) prevention which is an *ex ante* response denoted by V_P; and b) treatment which is an *ex post* response to disease denoted by V_T. The level of the disease is given by D with D_O indicating the present level after *ex ante* control (V_P). The disease level encompasses both the severity of a given disease and the prevalence of infection, although both elements could be decomposed. The present level of disease is assumed to depend on the level of preventive care (V_P) and other farm inputs (R) according to;

$$D = D_O(V_P, R) \qquad (2)$$

with D inversely related to V_P $(\partial D / \partial V_P < 0)$. The function is assumed to be convex with increasing levels of preventive care required to reduce disease levels a given amount $(\partial^2 D / \partial V_P^2 > 0)$. It is also assumed that R and V_P are substitutes as suggested by McInerney (1996).

The resulting level of disease (D) after *ex ante* (V_P) control is assumed to affect production (Q) through the following damage function;

$$Q = Q_O(R)[1 - F(D)] \qquad (3)$$

where Q_O is the disease–free output level that depends on the level of conventional inputs *R* and *F(D)* is the proportion of output lost with disease level *D*. For simplicity, the *K* and *N* used in the production relationship given by equation (1) are dropped from this production function. The decline in production can result from increased mortality or abortion (among others) as discussed earlier. *F(D)* is bounded between 0 and 1 with production equal to Q_O if D=0 $(F(0) = 0)$ and equal to 0 for high levels of the disease $(F(\infty) = 1)$. While the slope of the damage function is negative, its shape is uncertain.

As production (*Q*) is affected by *ex ante* efforts (V_P), treatment expenditure (V_T) can be influenced by present disease level, D, derived from V_P. It can be shown as the following control function:

$$V_T = \alpha\, Q(D) \qquad (4)$$

where D is the level of current disease after prevention control and α represents the magnitude of treatment response to reduce disease symptoms of infected animals. α is greater than or equal to zero ($\alpha \geq 0$), but not likely to be greater than 1 because treatment cost greater than direct production loss is not rational. If α is high, farmers use more treatment control than when α is low. The α approaches 0 when there is no effort for treating infected cows $(V_T = 0)$ that are showing negligible signs of disease.

The profit maximization problem for the producer can be summarized as

$$\pi = P_Q Q - P_R R - P_{V_P} V_P - P_{V_T} V_T \text{ - } F \qquad (5)$$

$$\text{s.t } D = D_O(V_P,\ R) \qquad (2)$$

$$Q = Q_O(R)[\ 1 - F(D)] \qquad (3)$$

$$V_T = \alpha\, Q(D) \qquad (4)$$

where π is annual profit and F is the cost of all other inputs. Substituting the control function for preventive care *(2)* into the production function *(3)* results in the following response function:

$$Q = Q_O(R)[\,1 - F(D_O(V_P, R))] \qquad (3^1)$$

Substitution of the production function given by (3^1) into *(5)* results in an unconstrained profit maximization problem.

The first order conditions for preventive control are

$$\frac{\partial \pi}{\partial V_P} = P_Q \cdot \frac{\partial Q}{\partial D} \cdot \frac{\partial D}{\partial D_O} \cdot \frac{\partial D_O}{\partial V_P} - P_{V_P} = 0$$

$$= P_Q(-Q_O) \cdot \frac{\partial F}{\partial D} \cdot \frac{\partial D_O}{\partial V_P} - P_{V_P} \qquad (6)$$

Thus, for a given price ratio, the marginal product of preventive care and its level of use depend on the disease-free output (Q_O), the severity of the output reduction from the disease $(\frac{\partial F}{\partial D})$, its effectiveness in reducing the initial incidence of the disease $(\frac{\partial D_O}{\partial V_P})$, and the effect of the disease on output $(\frac{\partial Q}{\partial D})$.

Similarly, the first order condition for treatment control is

$$\frac{\partial \pi}{\partial V_T} = - P_{V_T} \cdot \alpha \cdot Q(D) = 0 \qquad (7)$$

The marginal product of treatment is directly related to the extent of treatment response to reduce disease symptoms of infected animals (α) and the decrease in production with the present level of the disease $(Q(D))$.

The final choice variable is other input use *(R)* and its optimal level is where,

$$\frac{\partial \pi}{\partial R} = P_Q \cdot \frac{\partial Q}{\partial R} - P_R = 0$$

$$= P_Q \left\{ [\frac{\partial Q_O}{\partial R}(1 - F(D))] + (Q_O \cdot \frac{\partial F}{\partial D} \cdot \frac{\partial D_O}{\partial R}) \right\} - P_R = 0 \qquad (8)$$

The profit maximizing choice of other inputs thus depends on how it affects the disease free output $(\frac{\partial Q_O}{\partial R})$ and how it affects the initial level of the disease $(\frac{\partial D_O}{\partial R})$.

Solving the three first order conditions simultaneously would allow the optimal input choices to be determined $(R^*, V_P^* \text{ and } V_T^*)$ which upon substitution into the control function *(2)* would enable one to calculate the optimal disease rate that accounts for both the benefits of preventing output loss and the costs of treatment. This optimal disease level (D^*) can be expressed as $D^* = D^*(V_P^*, V_T^*, R^*)$.

Determining the optimal input choices requires knowledge of the production function, the damage function and the control function. Although knowledge in these areas is improving accurate estimates of the effects of disease on output, the effectiveness of treatment strategies on disease levels is somewhat limited. However, the model can still be used as a basis for assessing management choices. Rather than solving for the single optimum strategy, the profit levels of alternative strategies can be compared. Assuming R^O is the input use in the absence of disease, the profit level (π^O) would be

$$\pi^o = P_Q Q_O(R^O) - P_R R^O \qquad (9)$$

while profit for the use of management strategy i (π^i) involving the use of input R^i and control inputs of V_P^i and V_T^i would be

$$\pi^i = P_Q Q^i(V_P^i, R^i) - P_R R^i - P_{V_T} V_T^i - P_{V_P} V_P^i \qquad (10)$$

The choice of inputs from the observable set that maximizes profits will also be the one that minimizes the losses from the effects of the disease. These losses will be the difference between disease-free profit (π^O) and the profits of the given strategy i (π^i) or

$$\begin{aligned}\pi^O - \pi^i &= [P_Q Q_O(R^O) - P_R(R^O)] - [P_Q Q^i(V_P^i, R^i) - P_R R^i - P_{V_T} V_T^i - P_{V_P} V_P^i] \\ &= P_Q[Q_O(R^O) - Q^i(V_P^i, R^i)] - P_R(R^O - R^i) + P_{V_T} V_T^i + P_{V_P} V_P^i \qquad (11)\end{aligned}$$

The above expression can be related to the isoquant concept proposed by McInerney (1996). The first cost is the *ex post* costs, direct loss $[P_Q(Q_o - Q^i)]$ plus treatment cost $(P_{V_T} V_T)$ and the second is the *ex ante* cost, prevention cost $(P_{V_P} V_P)$. Assuming for the present time that other input use is not affected by the disease $(R^O = R^i)$, then the two cost components can be plotted on a single diagram. The corresponding level of direct loss, given the amount of control expenditure for alternative control strategies, is shown in Figure 2. A frontier of the technically efficient strategies is given by the isoquant PP'. For example, strategy M is better than strategy D because each strategy results in the same level of *ex post* costs (P_m) but *ex ante* cost is less with M than with $D(A_m < A_d)$.

Figure 2

However, there is a technical limit to reducing the losses that can be avoided. Point A on the curve is considered the 'technical optimum' in disease control (McInerney 1996) and the *ex post* losses cannot be lowered past point P_a. Any additional expenditure beyond A_a would be irrational. At point A, total losses would be C_a $(P_a + A_a = C_a)$.

The point where total losses $\{P+A = [P_Q(Q_O - Q^i) + P_{V_T}V_T] + (P_{V_P}V_P)\}$ is at a minimum can be represented diagrammatically where a line of 45° slope is tangential to *PP'*. In Figure 2, total costs of the disease are minimized with strategy *M*, with *ex post* losses of P_m and *ex ante* costs of A_m. Strategy *M* minimizes the avoidable costs of disease and the remaining total losses of $C_m(P_m + A_m = C_m)$ are unavoidable. It is the avoidable costs that should be the focus of management decisions. For example, both strategies *A* and *D* have the same total losses of $C_a\,(P_a + A_a = P_d + A_d)$. Most would dismiss strategy *D* as technically inefficient and assume strategy *A* is optimal because it reduces the *ex post* losses of the disease to the lowest possible level at P_a. However, the reduction in production loss and treatment cost come at the expense of higher prevention expenditure. It is undoubtedly true that a reduction in disease costs would be desirable, but the reductions may have no obvious relation to the total cost. Total costs also depend on such technical factors as the nature of the disease, the technology of control methods, the production systems employed, and management skills available (McInerney 1996). Total losses are minimized with strategy *M* and the difference between losses at this point (C_m) and those with either strategy *A* or *D* (C_a) represent the costs that can be avoided through management choices $(C_a - C_m)$. Technical research may allow further reductions in the unavoidable costs of C_m but not decisions by the individual producer.

EMPIRICAL MODEL

Definition of Control Strategies

The data on management practices and prevalence of infection with the four diseases was obtained from a survey of 90 dairy herds in the Maritime provinces of Canada (VanLeeuwen *et al.* 2001). Using a stratified 2-stage random sampling, 90 herds were chosen from all herds enrolled in a monthly milk recording program provided by the Atlantic Dairy Dairy Improvement Corporation (ADLIC), with 30 herds being from each of the provinces of New Brunswick, Nova Scotia, and Prince Edward Island. Blood samples were collected on each surveyed farm from 30 randomly selected cows. While on the farm, information on basic farm disease control practices was also gathered through the completion of a questionnaire. Investigated disease control practices fell into two general categories: animal movement and control, and vaccination history.

On the basis of a statistical analysis to determine the extent of use and collinearity among these practices (see authors), 10 potential control strategies were identified and are listed in Figure 3. Four general groups of practices were used to define the 18 control strategies: 1) opportunity for direct contact, 2) source of purchased animals, 3) introduction checks, and 4) vaccination.

The first set of practices delineating farms is whether a farm is closed or open. A farm is considered open if it purchases animals and/or allows for direct contact with cattle from other herds. Such direct contact likely increases the risk of disease infection through nose-to-nose or fecal-oral contact. If a farm was open, it could buy directly from other producers or it could purchase from other sources such as dealers or public auctions. It is assumed that buying direct from other farmers would lower the risk of

disease infection compared to other sources, because dealers and auctions handle cattle from many farms, leading to greater contact with cattle from multiple sources, and therefore more exposure to various infectious diseases. According to the survey in the 90 Maritime dairy herds, 10 herds were found to raise a heifer for internal replacement without purchasing from outside while 29 and 43 herds purchased animals from other producers and dealers/auctions, respectively.

Farmers purchasing animals can undertake several introduction check procedures, including isolating purchased animals for a period before allowing them in contact with the rest of the herd. For this study, it was assumed that farmers in an open farm either conduct no introduction checks or check records for either leukosis or vaccination history depending on the disease of concern.

Finally, both open and closed farms can vaccinate. An adequate vaccination program is defined as one in which cows were vaccinated for respiratory diseases including BVD in 1997, the animals received a booster in the first year of vaccinating (for killed BVD vaccines, this was not required if a live-virus vaccine was used), and the vaccination and booster were given after 6 months of age to prevent interference of maternal antibodies with the vaccine. Vaccination is performed on all cows in the herd.

Combining these alternative practices formed 10 potential control strategies for evaluation, as indicated in Figure 3. The proportion of surveyed farms using each strategy is also listed in Figure 3. The most common control strategy involved purchasing from other producers with vaccination and without introduction checks (strategy 5) and raising replacements with vaccination (strategy 1). Approximately 17% of the surveyed farms used these strategies.

Figure 3

Costs of Control Strategies

The first step in the analysis was to determine the costs associated with each of the 10 control strategies (*A* in Figure 2). As discussed above, the control strategies consisted of various combinations of three general sets of practices: animal movement, introduction checks, and vaccination.

According to the original survey (VanLeeuwen *et al.* 2001), the vaccines commonly used in Maritimes were Cattlemaster 4 ($3.08 per dose), Cattlemaster 4+L5 ($4.05), Sentry 4/Somnugen ($3.69), Sentry 9/Somnugen ($4.22), Triangle 4 ($3.32), and Triangle 9 ($3.75). An adequate vaccination program was assumed to include: 1) using vaccine for respiratory disease including BVD in 1997; 2) the animals received a booster in the first year of vaccination; and 3) the vaccination and booster were given after 6 months of age. A cost for these practices of $14.04 per cow and per year was calculated by multiplying the average price of the above vaccines ($3.68) plus the extra labor fee for vaccination ($1.00), by the number of doses per year [1.5 = young stock (2) + mature animal (1)], and then doubling this to take into account that any given farm has approximately twice as many cattle on the farm (including young stock) as the number of cows in the ADLIC records.

Three practices related to animal movement were defined: 1) raising all replacements internally and no outside purchase, 2) purchasing directly from other producers, and 3) purchasing from any sources. Each farm is assumed to be categorized into one of these independent and mutually exclusive classifications. Raising all replacements internally is assumed to be the most expensive of the 3 practices as more

labor and capital is required. The cost of raising heifers over a 2-year period is estimated to be $1,922 based on data from the Ontario Dairy Accounting Project (ODAP) 2000 survey (Lang, 2001). The cost is similar to recent estimates in studies from Pennsylvania, Virginia and Iowa (Lang, 2001). It is assumed that open farms sell all their new-born calves at $400 and purchase their bred replacements at $2,000. Thus, the cost of purchasing is the difference or $1,600 per animal. In addition, the two-year costs for raising or purchasing heifers are divided in half to put the costs on an annual basis.

It is assumed that purchasing from non-producer sources such as public auctions is the cheapest means to acquire a replacement. Purchasing directly from other producers is assumed to be more expensive due to the costs for searching and bargaining. While the purchase price of the animal is not likely to be different between the two sources, the time involved in finding suitable replacements from other producers is assumed to increase the cost by $100 per animal. The current study assumes that 25% of the 50 cow herd is replaced in any year so that the above per cow opportunity cost of replacement is multiplied by 12.5.

If an animal is purchased, it may go through two possible introduction checks. First, the animal may be placed directly into the herd at no cost but it may increase the likelihood of increased prevalence of infection with disease. Second, the farmer may check the records of the cow before it enters the herd. It is assumed that the farmer checks for EBL at a cost of $6.50 per head and checks the vaccination history at a cost of $5 per head in the case of the other three diseases. These prices were from the Nebraska Veterinary Diagnostic Laboratory System. The annual cost for an average herd associated with the 10 control strategies is listed in Table 1

Table 1

Relationship between Control and Disease Level

A necessary element in determining the optimal strategy is the relationship between the management strategies and the prevalence of disease infection (also known as the control function in the conceptual model). The control function for each disease was estimated using the dependent variable as infection prevalence level within a herd and the explanatory variables as the set of management practices making up the potential control strategies. Because the dependent variable is bounded between 0 and 1, a Tobit model was estimated.

***Ex Post* Costs of Disease**

The control function described in the previous section determined the disease level associated with each control strategy. The next step is to assess the costs associated with that prevalence of infection (or the damage function from the conceptual model). Direct production loss and treatment cost of infectious diseases were assessed using a partial budget model developed by (authors) from a framework suggested by Bennett *et al.* (1999). The structure for this model consisted of three main sections. The first contained information on dairy farm characteristics such as the size of the population at risk, the prevalence of disease infection, and prices for milk and cattle. The second calculated the direct losses of the diseases, which are associated with milk loss, premature voluntary culling and reduced slaughter value, mortality loss, and abortion and

reproductive loss. The third section estimated the costs of undertaken treatment measures. The components of each section are described in more detail in (authors).

Each infectious disease under study can have two states: subclinical infection (where an animal is infected but shows no obvious physical signs of disease, although production or other functions may be inhibited) and clinical infection (where an animal is infected and shows physical signs of disease, such as production losses, coughing, diarrhea, etc.). The ex post effects of each disease include both states of infection.

RESULTS

Control Function

The results of the Tobit regression for each of the four diseases are listed in Table 2. The signs on the explanatory variables were generally biologically plausible but relatively few are significant at $p<0.1$ due to only 90 herds being in the study. Purchasing animals, as opposed to raising them internally, was generally associated with higher prevalence levels for all four diseases but the impacts were statistically insignificant except in the case of JD. In addition, purchasing animals through a dealer or an auction was associated with higher prevalence levels of infection for BVD, EBL, and neosporosis than directly buying from other producers. Checking for leukosis in the case of EBL and the animal's vaccination history for the other three diseases were related to lower prevalence of infection with all of the four diseases, albeit statistically insignificant. These introduction checks are meant to prevent the introduction of clinically infected animals that show symptoms of the diseases although they do not help to detect subclinically infected animals for any of the diseases. Checking for leukosis status is

very important for controlling the prevalence of leukosis because prevalence can easily rise if purchases are made without checking.

Vaccination was associated with reduced prevalence of infection for BVD, EBL, and JD but the effect was significant only for BVD. Because killed virus vaccines commonly used in the surveyed area can effectively reduce the occurrence of BVD, using vaccination was expected to show a strong negative relationship with the prevalence of BVD. For EBL, because BLV is primarily horizontally transmitted by blood (virus-infected lymphocytes), vaccination is likely a surrogate measure of good management where needles are not reused, thereby reducing other sources of blood transfer. Details of these results can be found in (authors).

Table 2

The full models of the regression results were used to predict the prevalence of the four diseases associated with the 10 control strategies. For example, for a farm that does not purchase replacements and does not have direct contact with other cattle and vaccinates, the prevalence level of EBL was 0.046 (=0.154+0.037*0–0.015*0+0.092*0–0.041*0–0.108*1). The predictions were forced to be bounded between 0 and 1. For example, the same control strategy for BVD resulted in a predicted prevalence of –0.265 (=0.188–0.453) but this value was truncated at 0.

Strategies using vaccination practices (1, 3, 5, 7, and 9) minimized prevalence of infection with BVD to zero. Because vaccination for BVD significantly protected for the disease, herds using vaccination had lower prevalence than similar herds without vaccination. Average BVD prevalence of vaccinated herds was 0 while average BVD prevalence of unvaccinated herds was 0.20. Introduction checks were associated with

lower prevalence of infection with BVD, compared with the same farms without introduction checks.

For EBL, herds purchasing from other producers who check for leukosis and who vaccinate (strategy 3) had the lowest prevalence (0.03) of infection with EBL. Similar to BVD, vaccination was associated with reduced prevalence of infection with the disease. Average prevalence of EBL for vaccinated herds was 0.09 while average prevalence of unvaccinated herds was 0.20.

All control strategies had zero prevalence of infection with JD. For neosporosis, farmers who purchased from other farmers and who have introduction checks of purchased animals (strategy 4) had the lowest prevalence (0.03).

Overall, herds that conduct introduction checks on purchased animals and that vaccinate (strategy 3) had the minimum predicted prevalence with the four diseases (BVD and JD: 0; EBL: 0.03; neosporosis: 0.04). The predicted prevalence associated with the 10 strategies showed that closed farms had generally higher EBL and neosporosis infection than farms that purchase directly from other producers. Because farms that were closed at the time of the study may not have been closed for long, the farms could have already acquired substantial infection levels that were being sustained within the herd through horizontal and vertical transmission. This is quite possible, given that the diseases have a subclinical state that requires laboratory testing for detection.

Table 3

Costs of Control Strategies

Given the results of the control functions of the 10 control strategies (Table 3), economic costs derived from the strategies were measured in a spreadsheet model. The spreadsheet model allowed us to identify *ex ante* ($P_{V_P}V_P$) and *ex post* [$P_Q(Q_O - Q^i) + P_{V_T}V_T$] costs of the strategies. The total costs for each of the strategies for BVD, EBL, JD and neosporosis are discussed below.

Table 4

Costs of BVD

The spreadsheet model provided the optimal control strategy minimizing total costs of BVD among the proposed strategies. Five strategies (strategy 1, 3, 5, 7, and 9) minimized the prevalence of infection with BVD at zero and consequently had no direct loss and treatment cost. Farms purchasing replacements from a dealer or an auction and who vaccinated (strategy 9) were found to be the optimal control strategy because they had the minimum total cost [\$702 = $P_{V_P}V_P$ (\$702) + $P_Q(Q_O - Q^i)$(\$0) + $P_{V_T}V_T$(\$0)]. If the same open farms did not vaccinate (strategy 10), direct loss [$P_Q(Q_O - Q^i)$] and treatment cost ($P_{V_T}V_T$) increased by \$1,480 and \$38, respectively. The increase in *ex post* costs of \$1,518 is greater than the cost of vaccination (\$702), showing the cost-effectiveness of vaccinating. For closed farms, average total disease cost was \$1,283 higher than with open farms due largely to high internal replacement costs. Similar to open farms, vaccination on the closed farms was efficient because total costs were, on average, \$19 lower (\$2,715 vs. \$2,734).

Costs of EBL

Open farms that purchased replacements through a dealer or auction without an introduction check but who vaccinated (strategy 10) had the minimum total cost ($729), derived mainly from no *ex ante* cost ($P_{V_P} V_P$ = $0). Although herds purchasing from other producers and who checked records before introduction and who vaccinated (strategy 3), had the lowest prevalence (0.03) of disease infection and consequently the minimum *ex post* cost ($78), it did not minimize the total cost because of the high costs of prevention control ($2,174).

Although vaccination is effective in reducing the prevalence of EBL, the total costs of EBL are higher with strategies that vaccinate than those who do not. Average total cost of open farms that vaccinate was $1,666 while it was $1,244 for those open farms that do not vaccinate. For closed farms, use of vaccination increased total costs from $2,403 to $2,845. The result is attributable to the relatively small production losses associated with EBL (see authors).

Costs of JD

Since the predicted prevalence of infection with JD was zero for the 10 control strategies, the optimal practice is the one that minimizes *ex ante* prevention costs. Thus, the optimal practice was to purchase replacements from dealers or auctions and introduce them into the herd without any introduction checks. Neither is vaccination used.

Costs of neosporosis

Open farms that conduct an introduction check on replacements purchased through a dealer or an auction but not vaccinate (strategy 8) had the minimum total cost ($1,008) among strategies to control for neosporosis. This strategy had an *ex ante* cost of

$144 and *ex post* costs of $864. Farms with the same set of practices except for purchasing directly from other producers (strategy 4) had a lower prevalence of neosporosis (0.03 vs. 0.09) but had higher *ex ante* costs and consequently higher total costs ($1,682 vs. $1,008). Neosporosis was the only one of the four diseases for which there was not a negative relationship between vaccination and prevalence of disease infection. As a result, total costs for neosporosis were higher on farms that vaccinated than those that did not.

Aggregate costs of the control strategies

The *ex ante* prevention costs are only incurred once for four diseases. The ten control strategies are used to control a number of diseases jointly. The cost effectiveness of a strategy in controlling all the four diseases cannot be found by simply assuming the disease costs for each of the four diseases in Table 4. Thus, the aggregate prevention costs for each strategy are found by summing the *ex post* costs of direct production losses and treatment expenses for each disease and adding this to the *ex ante* prevention cost of the control strategy given in Table 1.

The strategy with the lowest aggregate cost did not minimize the disease costs for any of the four diseases separately. Open farms purchasing directly from other producers, that check records before introduction, and that do not vaccinate (strategy 4) had the minimum aggregate total cost for the four diseases. The herd-level total cost of this optimal control strategy was $2,122, derived from an *ex ante* cost of $1,394 and *ex post* costs of $728 (BVD:$76, EBL:$364, JD:$0, and neosporosis:$288). This strategy has one of the lowest control costs but is also effective in preventing disease infection,

particularly for neosporosis for which the predicted prevalence level was the minimum (0.03).

Farms purchasing replacements from a dealer or an auction, conducting checks before introducing these animals, and using vaccination (strategies 7) had the next lowest aggregate cost. Thus, careful purchasing of new animals is an effective means of preventing production limiting diseases in general.

Closed farms (strategies 1 and 2) had aggregate costs more than double the cost of the optimal strategy. While predicted prevalence levels are generally low across the four diseases, the reduction in direct losses does not offset the substantially higher prevention costs associated with maintaining a closed farm.

DISCUSSION

This paper has presented a theoretical model on the economics of infectious disease control in dairy herds and developed an empirical model to determine the optimal set of control strategies for four production limiting diseases: BVD, EBL, JD, and neosporosis. The *ex ante* costs of implementing 10 prevention strategies were estimated for a representative Maritime dairy farm. The *ex post* costs associated with each of the 10 strategies were assessed for each disease on the basis of predicted prevalence levels (control function) and estimated direct production losses (damage function). The optimal control strategy minimizing the total disease costs which are the sum of *ex ante* and *ex post* costs.

The results in the optimal control strategies emphasize the importance of considering prevention cost when determining cost-effective control strategy.

Minimizing direct production losses will not generally minimize the total costs of a given disease. For example, the lowest predicted prevalence of infection levels was associated with closed farms. However, the cost of raising all replacements internally and preventing contact with other animals is costly. In contrast, conducting checks on new animals before introducing them into the herd, and vaccinating are cost-effective strategies, particularly when considering a management strategy to minimize total costs across all the four diseases. The optimal strategy for dealing with an individual disease does vary between diseases depending on its characteristics. For example, the direct losses with EBL were estimated to be relatively small for a given prevalence level so minimizing prevention costs is a guiding criterion. The same result holds for JD as there is little difference in predicted infection rates across the investigated control strategies because hygienic calf rearing appears to be a crucial component of disease control.

For aggregate costs of the four diseases, closed farms had the highest costs due to assumption that open farms do not raise any heifers and that it is cheaper to buy than to raise heifers. This simplification pertains to only a minor portion of the dairy industry and not the majority of farms that raise most and buy a few numbers of heifers.

Previous studies on the economics of animal disease have been limited due in part to the large economic and epidemiological requirements (Dijkhuizen *et al.* 1995). The farm survey data on Maritime dairy farms along with disease parameters collected from previous studies allowed the empirical model to be estimated. However, it is important to note that a strong assumption has been made about the direction of causation between the practices and prevalence of disease infection. The cross-sectional data from the Maritime study limit the inferences only to those related to associations, not causation. This study

assumes that practices determine disease prevalence but time series-cross sectional data is necessary to understand the dynamic effects of the practices. However, the existing data were the best available and results in reasonable predicted prevalence levels, which are listed by control strategy in Table 3. Future work should consider the dynamic effects of strategies on prevalence of infection and alternative strategies such as calf-raising practices that may be effective in controlling JD.

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Table 1. Control costs (E) for each control strategy ($/herd/year)

Control Strategies					Predicted cost
#	**Farm**	**Vaccination**	**Source**	**Checks**	**Calculation of Control Costs**
1	Closed	Yes	N/A	N/A	($1,922-$1,600)*0.5*0.25*50 cows + $14.04*50cows = $2,715
2	Closed	No	N/A	N/A	($1,922-$1,600)*0.5*0.25*50 cows = $2,013
3	Open	Yes	Other producer	Yes	($100 + $6.5 + $5)*0.25*50 cows + $14.04*50cows = $2,096
4	Open	No	Other producer	Yes	($100 + $6.5 + $5)*0.25*50 cows = $1,394
5	Open	Yes	Other producer	No	$100*0.25*50 cows + $14.04*50cows = $1,952
6	Open	No	Other producer	No	$100*0.25*50 cows = $1,250
7	Open	Yes	Dealer/ Auction	Yes	($6.5 + $5)*0.25*50 cows + $14.04*50cows = $846
8	Open	No	Dealer/ Auction	Yes	($6.5 + $5)*0.25*50 cows = $144
9	Open	Yes	Dealer/ Auction	No	$14.04*50cows = $702
10	Open	No	Dealer/ Auction	No	= $0

Table 2. Tobit results on relationship between management practices and prevalence of disease infection within herd.

Explanatory Variable	Diseases			
	BVD	**EBL**	**JD**	**Neosporosis**
Intercept	0.188 (0.966)	0.154 (1.734)	-0.028 (-1.424)	0.184 (3.150)
Direct contact	-0.065 (-0.394)	0.037 (0.488)	-0.001 (-0.001)	-0.015 (-0.317)
Animal movement				
Purchase direct	0.008 (0.051)	-0.015 (-0.196)	**0.031*** **(1.908)**	-0.052 (-0.994)
Other sources	0.276 (1.635)	0.092 (1.187)	0.009 (0.599)	0.014 (0.271)
Introduction checks	-0.116 (-0.633)	-0.041 (-0.486)	-0.002 (-0.168)	-0.092 (-1.610)
Vaccination	**-0.453*** **(-2.629)**	-0.108 (1.396)	-0.009 (-0.605)	0.018 (0.362)
Log likelihood	-69.867	-41.200	18.070	-15.308
Psuedo R^2	0.077	0.054	-0.137	0.133

The values of the management practices represent coefficients.
( ): t-values given in parentheses.
*: Statistically significant values ($p \leq 0.1$).

Table 3. Predicted prevalence of infection with the diseases for control strategy

	Control Strategies				Disease			
#	**Farm**	**Vaccination**	**Source**	**Checks**	**BVD**	**EBL**	**JD**	**neosporosis**
1	Closed	Yes	N/A	N/A	0	0.05	0	0.20
2	Closed	No	N/A	N/A	0.19	0.15	0	0.18
3	Open	Yes	Other producer	Yes	0	0.03	0	0.04
4	Open	No	Other producer	Yes	0.02	0.14	0	0.03
5	Open	Yes	Other producer	No	0	0.07	0	0.14
6	Open	No	Other producer	No	0.13	0.18	0	0.12
7	Open	Yes	Dealer/ Auction	Yes	0	0.13	0	0.11
8	Open	No	Dealer/ Auction	Yes	0.28	0.24	0	0.09
9	Open	Yes	Dealer/ Auction	No	0	0.18	0	0.20
10	Open	No	Dealer/ Auction	No	0.40	0.28	0	0.18

Table 4. Costs of production limiting disease by control strategy ($/herd)

	Control Strategies				Disease				
#	**Farm**	**Vaccination**	**Source**	**Checks**	**BVD**	**EBL**	**JD**	**neosporosis**	**Aggregate cost****
1	Closed	Yes	N/A	N/A	2,715	2,845	2,715	4,636	4,766
2	Closed	No	N/A	N/A	2,734	2,403	2,013	3,742	4,853
3	Open	Yes	Other producer	Yes	2,096	2,174	2,096	2,480	2,558
4	Open	No	Other producer	Yes	1,470	1,758	1,394	1,682	**2,122***
5	Open	Yes	Other producer	No	1,952	2,134	1,952	3,297	3,479
6	Open	No	Other producer	No	1,744	1,719	1,250	2,402	3,365
7	Open	Yes	Dealer/ Auction	Yes	846	1,184	846	1,902	2,241
8	Open	No	Dealer/ Auction	Yes	1,207	769	144	**1,008***	2,696
9	Open	Yes	Dealer/ Auction	No	**702***	1,171	702	2,623	3,091
10	Open	No	Dealer/ Auction	No	1,518	**729***	**0***	1,729	3,976

*: The optimal control strategies having the minimum costs.

**: Aggregate costs of a strategy are the *ex ante* prevention costs (see Table 1) plus the sum of the direct losses and treatment costs for each of the four diseases.

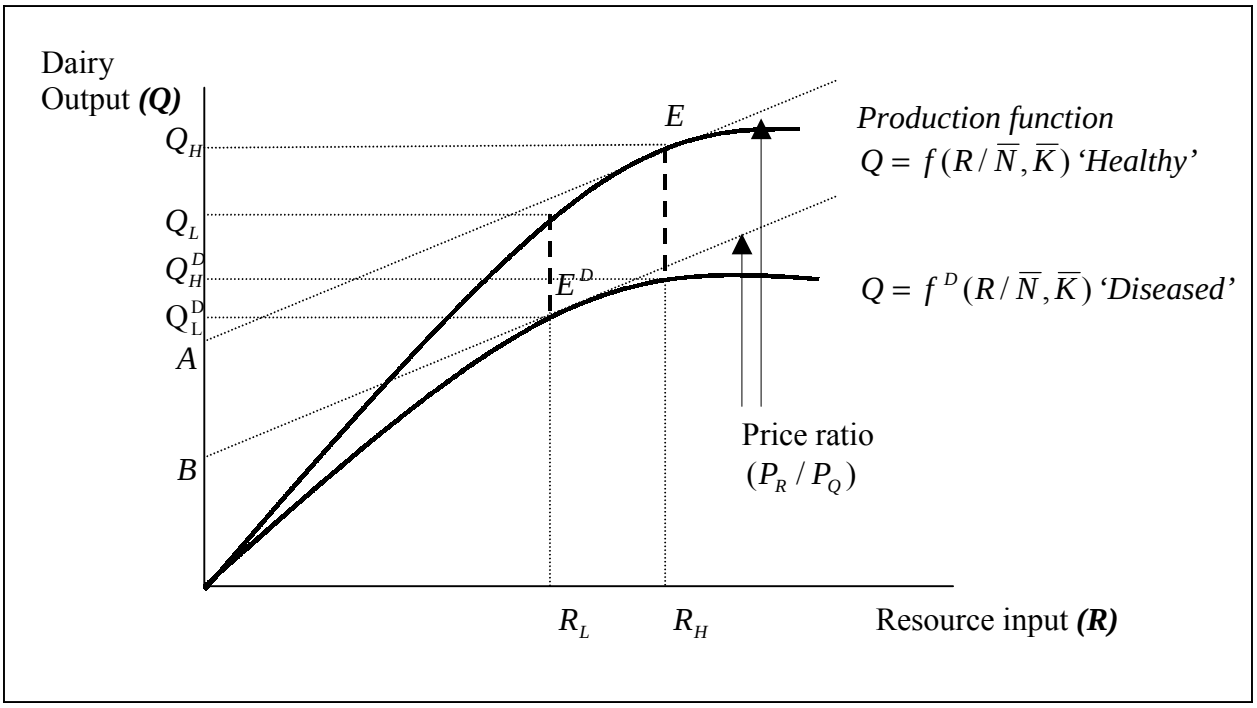


Figure 1. Resource adjustments and costs of dairy disease.

(Source: adapted from McInerney, 1996)

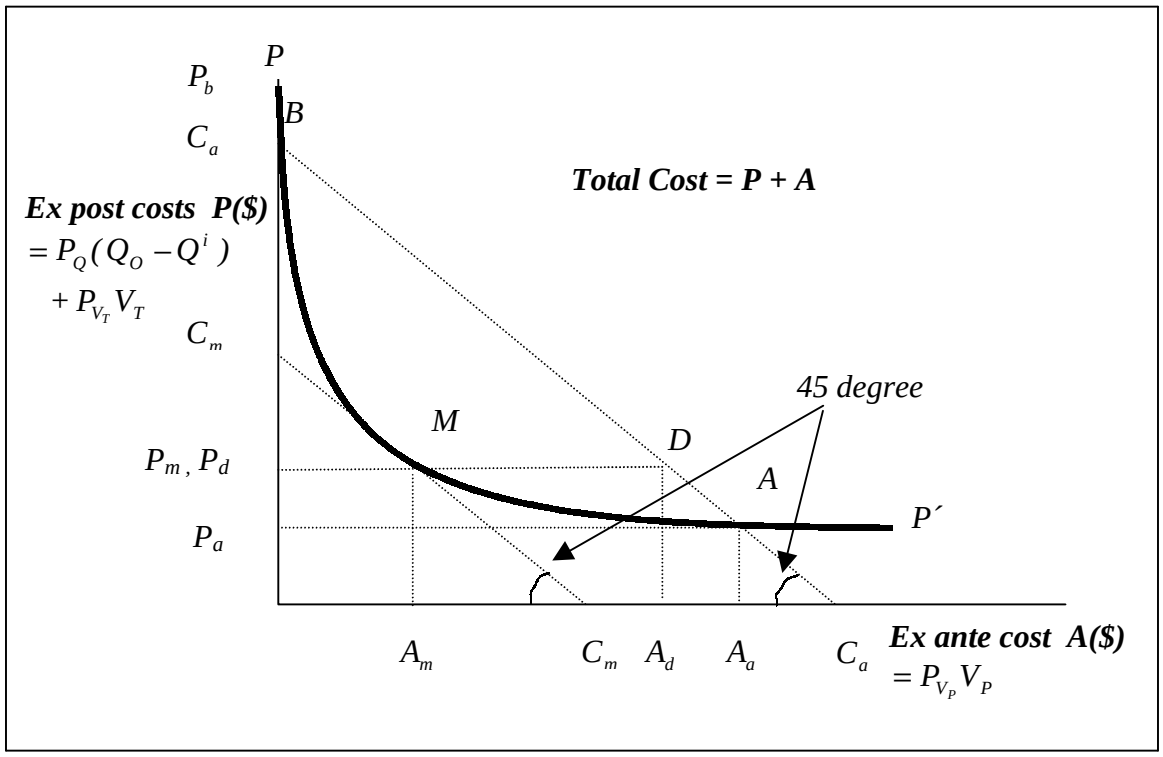
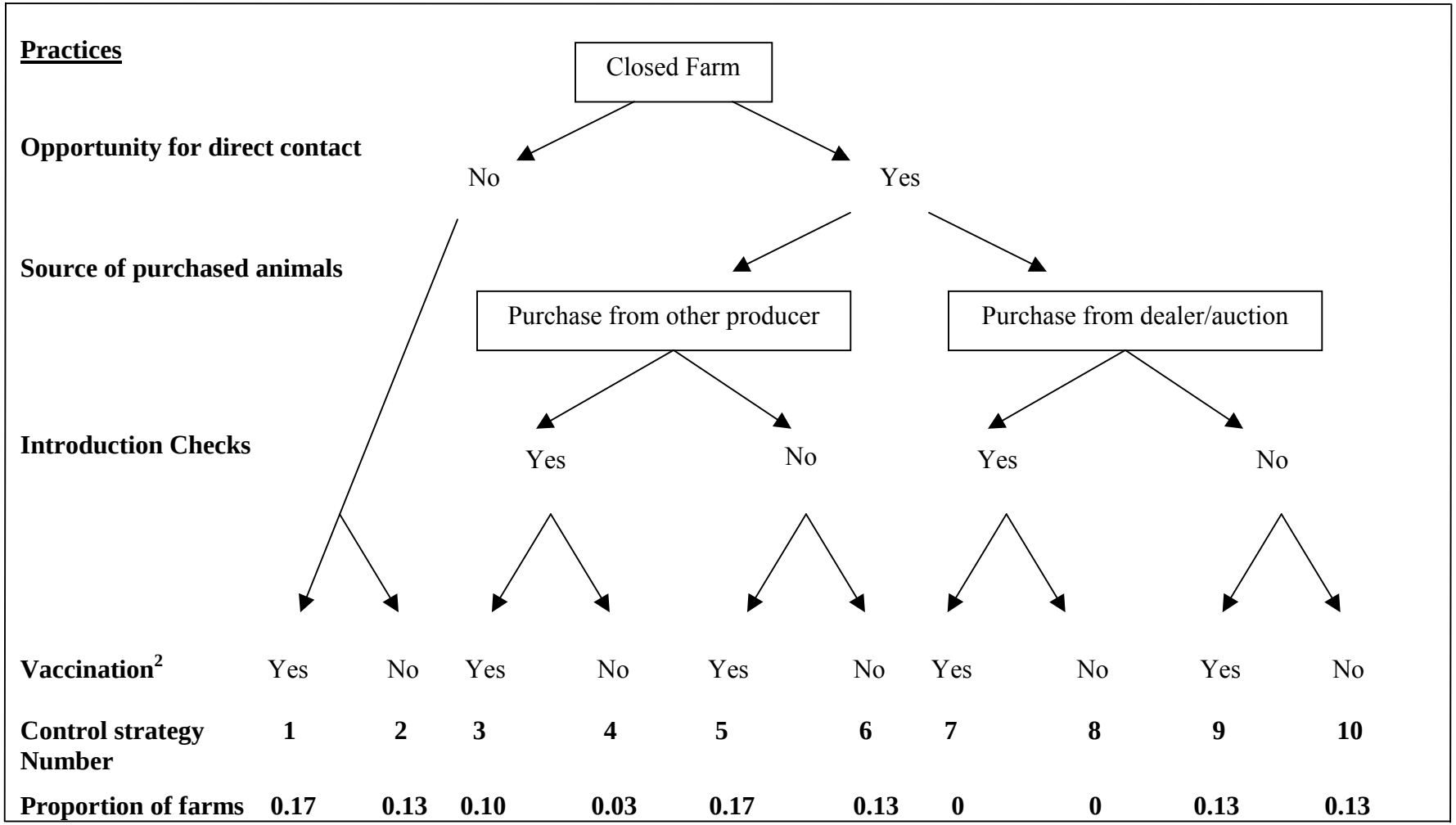


Figure 2. Disease *ex ante* cost counteract *ex post* losses.

(Source: adopted from McInerney, 1996)

Figure 3. Definition of management control practices



1: Introduction checks include checking for leukosis (Qleuksis) and/or vaccination history (Qvachist)
2: Vaccination includes adequate vaccination program (AVP)