Interpretive Summary: Cost of different types of clinical mastitis in dairy cows. Cha. This study estimated the cost of 3 different types of clinical mastitis (gram-positive, gram-negative and other) in dairy cows, by modification of an existing economic model. We also determined the optimal management decision of whether to keep a cow, replace her with a heifer, or inseminate her, depending on her unique characteristics. This model allows for parameters such as production costs, economic values and disease frequencies to be altered, hence can provide farmers economically optimal guidelines specific to their individual cows.

COST AND MANAGEMENT OF MASTITIS TYPES IN COWS

Title: The cost and management of different types of clinical mastitis in dairy cows calculated by dynamic programming

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ABSTRACT

The objective of this study was to calculate the cost of 3 different types of clinical mastitis (CM) (due to gram-positive bacteria, gram-negative bacteria and other organisms) at the individual cow level and thereby identify the economically optimal management decision for each type of mastitis. We made modifications to an existing dynamic optimization and simulation model, studying the effects of various factors (incidence of CM, milk loss, pregnancy rate and treatment cost) on the cost of different types of CM. The average costs per case (USD) of gram-positive, gram-negative and other CM were 133.73, 211.03 and 95.31, respectively. This model provided a more informed decision making process in CM management for optimal economic profitability and determined that 93.1% of gram-positive CM cases, 93.1% of gram-negative CM cases and 94.6% of other CM cases should be treated. The main contributor to the total cost per case of gram-positive CM was treatment cost (51.5% of the total cost per case), milk loss for gram-negative CM (72.4%) and treatment cost for other CM (49.2%). The model affords versatility as it allows for parameters such as production costs, economic values and disease frequencies to be altered. Therefore, cost estimates are the direct outcome of the farm specific parameters entered into the model. Thus, this model can provide farmers economically optimal guidelines specific to their individual cows suffering from different types of CM.

Key Words. mastitis, gram-positive, gram-negative, dynamic programming

INTRODUCTION

Mastitis reduces dairy farm profitability with losses stemming from both milk production decreases and discarded milk, and treatment and culling costs (Gröhn et al., 2005). The specific inflammatory response from a mastitis incident is dependent on the bacterial species involved (Bannerman, 2008). Depending on the pathogen involved, the impact may vary, so studies determining which pathogens have the greatest impact on cow health, production and profitability are valuable (Gröhn et al., 2004).

Treatment for mastitis is the most common cause of antibacterial use on dairy farms. There are public concerns, however, of the possible health hazards posed by the presence of antibiotic residues and other drugs in milk (Erksine et al., 2003). This is despite all bulk tanks being tested for antibiotics. Antibiotic use also raises questions of reduced animal welfare and biosecurity (Sørensen et al., 2010).

A fundamental component of mastitis control programs is the identification of pathogens in mastitis samples. For example, the ability to determine whether a cow is suffering from gram-positive or gram-negative CM would help determine the choice of antimicrobial therapy (Waage et al., 1994) and potentially reduce unnecessary use of antibiotics.

Most pathogens which cause mastitis can be classified as gram-positive or gram-negative bacteria and determined by on-farm culturing, which is generally faster and more convenient than sending the milk sample to a commercial laboratory (Hertl et al., 2010). The on-farm culture has an approximate 24 h turn-around time. The development of cow-side tests identifying whether a case of mastitis is gram-positive or gram-negative is ongoing (Waage et al., 1994; Yazdankhah, 2001). The objective of this study was to calculate the cost of different types of clinical mastitis (**CM**) (due to gram-positive bacteria, gram-negative bacteria and other organisms) and to determine the optimal management decision of whether it may or may not be economically optimal for a cow to be (1) replaced with a heifer, (2) kept in the herd (and treated if she has a CM case), but not inseminated or (3) kept (and treated if she has a CM case) and inseminated, for each type of CM. We did this by modifying an existing dynamic programming model previously used to study CM and other diseases in dairy cows (Bar et al., 2008a; Cha et al., 2010).

MATERIALS AND METHODS

Clinical mastitis categorization

We classified CM into 3 categories: (1) CM due to gram-positive bacteria, (2) CM due to gram-negative bacteria and (3) CM due to other organisms (hereafter, referred to as gram-positive CM, gram-negative CM and other CM).

Gram-positive CM included *Streptococcus* spp., *Staphylococcus aureus* and *Staphylococcus* spp. Gram-negative CM included *Escherichia coli*, *Klebsiella* spp., *Citrobacter* spp. and *Enterobacter* spp. Other CM included *Arcanobacterium pyogenes*, *Mycoplasma* spp., *Corynebacterium bovis*, *Pseudomonas* spp. and yeast.

Replacements and inseminations optimization and simulation model

Software. The model was built using the Multi Level Hierarchic Markov Process (MLHMP) software as the application program interface (Kristensen, 2003). We modified an existing optimization and simulation model which was first developed to study the cost of generic CM in dairy cows, then 3 different types of lameness in dairy cows (Bar et al., 2008a; Cha et al., 2010).

The model. The model was constructed as a 3-level hierarchic Markov process comprised of: the founder (parent) level containing state variables of permanent traits throughout the cow's life span, the child level divided into stages representing one whole lactation, and the grandchild level divided into stages of one month during lactation. The possible actions in a given month of lactation that could occur at the final level are: (1) replace the cow with a calving heifer, (2) keep the cow for another month without insemination and treat her if she has CM or (3) keep the cow for another month and inseminate her and treat her if she has CM (Bar et al., 2008a). Figure 1 is a schematic representation of the model used in the current study on CM. At the founder level, 5 milk yield categories (kg) were modeled as: -5, -2.5, 0, +2.5, and +5 from the mean level of milk production per day; these represented the cow's genetic potential. At the child level, 8 possible whole lactation stages were modeled. At the grandchild level, 20 lactation stages (mo) were modeled. In each stage the cow was described by one level within each of the following states: 5 temporary (i.e., daily) milk yield levels, 9 pregnancy states (0 = open, 1-7 = 1-7 mo pregnant and milking and 8 = last 2 mo of pregnancy and dry (not milking)), 1 involuntarily culled state and 13 CM states. The CM states were defined as: 0 = no CM, 1 = first occurrence of gram-positive CM (observed at the end of the stage enabling immediate culling with no loss to treatment or production), 2, 3 and 4 corresponding to 1, 2, 3 and more mo after the first case of gram-positive CM (this does not mean reoccurrence, but rather time horizon since the first case of gram-positive CM), respectively, 5 = first occurrence of gram-negative CM and 9 = other CM (with numbers from 6-8 and 10-12 corresponding to 1, 2, 3 and more mo after the first case of the CM type, respectively, and again, this does not mean reoccurrence, but rather time horizon since the first case of gram-negative or other CM, respectively).

In the case of a reoccurrence, if a cow has reoccurrence of e.g. gram-positive CM, she will return to state 1, when she has a reoccurrence of gram-negative CM, she will return to state 5, and in the case of other CM, she will return to state 9.

The objective function maximized by the model was the discounting criterion (Kristensen, 2003), which maximizes the net present value of the cow using a yearly interest rate of 8% (De Vries, 2006; Bar et al., 2008a; Federal Reserve Bank of Kansas City, 2011).

Optimization technique. By combining the advantages of the two types of iteration methods used to solve the Markov Process (namely value iteration and policy iteration), a new notion of a hierarchic Markov process was developed by Kristensen (1988; 1991), which forms the basis of our dynamic program. This solution approach allows us to obtain solutions to large state space problems as described below (Kristensen, 1996).

Value iteration is performed to identify the decision that maximizes the total expected discounted rewards when the process starts from state *i* and continues for *n* stages before ending. Policy iteration involves choosing an arbitrary set of decision rules for each state at each stage and solving a set of simultaneous linear equations describing the expected future rewards of a process starting from state *i* and running over an infinite number of stages until the same optimal decision is reached (Kristensen, 1996; Cha et al., 2010). Our model is structured in such a way that a cow can be replaced until time infinity, hence at the founder (parent) level, we have an infinite time horizon. At the subprocess (child and grandchild) levels, however, we have a finite time horizon (i.e., the lifespan of a specific cow).

Kristensen (1988; 1991) combined the benefits of both policy and value iteration, by applying value iteration to the subprocesses and using these results in the final step of the policy iteration method of the main process. Hence, in our model, at the founder level, we used policy iteration, and at the child and grandchild levels, value iteration (Figure 1). More details of the mathematics pertaining to this technique can be found in Cha et al., 2010.

Model parameters

Description of data. Model parameters were obtained from analyses of data from 7 dairy herds in New York State. These 7 herds were followed for approximately 4 years, and contained a total of 23,902 lactations in 14,208 cows.

Parameters. Model parameters specific to the 3 different types of CM are given in Table 1.

A decision to treat a cow with gram-positive CM was associated with a cost (USD) of 73.50. This cost was an estimated average from antibiotics (8), the decreased value of 5d worth of discarded milk from an average production cow (20), 50% of cows receiving anti-inflammatory drugs and fluid IV or per os (15.50), labor (20) and culturing (10). A decision to treat a cow with gram-negative CM was associated with a cost of 35.50. This cost was an estimated average from 50% of cows receiving anti-inflammatory drugs and fluid IV or per os (15.50), labor (10) and culturing (10). The decision to treat a cow with other CM was associated with a cost of 49.50. This was an estimated average from antibiotics (4), 50% of cows receiving anti-inflammatory medication and fluid IV or per os (15.50), labor (20) and culturing (10); we assumed the discarded milk could be used in place of milk replacer for calves. Recognizing that the cost of treatment varies by farm (depending on drug administration, days of discarded milk due to drug use, etc.), a sensitivity analysis (described later below) of the cost of treatment was also performed.

Pregnancy risk was set to 0.21 per month. Odds ratios which would reduce the rate of conception for each type of CM were applicable only for the first month after the cow got CM (i.e. CM states 1, 5 and 9) and also if she got another case of the same type of CM (where she would return to state 1, 5 or 9 for a recurrent case of gram-positive, gram-negative or other CM, respectively). If a cow contracted CM, her probability of going into the pregnancy state the following month was multiplied by this formula: (pregnancy rate*conception odds ratio for type of CM/(1-pregnancy rate+pregnancy rate*conception odds ratio for type of CM)). The voluntary waiting period was 60 d. The maximum calving interval was 20 mo and the involuntary culling risk at calving was 2%.

The monthly risk estimates (first case and recurrent cases), by lactation and CM type, were obtained from generalized linear mixed models with a random herd effect. The monthly risks for repeated cases were an average of the monthly risks for the second and third CM occurrence. The monthly risk estimates for the second CM occurrence in multiparous cows meant the cow could have had any type of CM within the lactation (and no CM in the previous lactation). The monthly risk estimates for the third CM occurrence in multiparous cows referred to cows that had already experienced 2 cases of CM (of any type) within the lactation and without CM in the previous lactation.

The cost of a calving first lactation animal (all costs in USD) was 1,600, average monthly cow maintenance cost was 150 and insemination cost/month of insemination was 20. The average price for a calf born was 200. The milk price was $0.31/kg and the feed cost/kg of dry matter was $0.20. The cull price for voluntarily culled cows was $0.74/kg of body weight.

Other parameters and prices and costs were taken from Bar, (2007), De Vries (2006) and Bar et al. (2008a). The milk yields, transition probabilities (the probabilities describing the different states a cow can transition to from one month to another), exit from the herd and effects of CM are described in Bar et al. (2008a).

Estimating CM cost

The average net returns per cow per year for a herd without CM were compared with the average net returns per cow per year for a herd with CM (by type), while keeping other parameters constant. The profit or loss was divided by the CM incidence to generate the herd average cost per case of CM. As the cost of CM was minimized under optimal treatment decisions, it is possible that these values differ from actual farm figures.

The effects of milk loss, decreased fertility and treatment cost on the average cost of a CM case were also determined by obtaining the net present values of the model with and without the CM type and effect in question, then dividing by the incidence of CM.

The net present value (NPV) is the current value of actions where the benefits and costs of the actions are calculated until the end of the time horizon. This is achieved by discounting the various benefits and costs by an annual interest rate over that time period. An interest rate of 8% was used (De Vries, 2006; Bar et al., 2008a; Federal Reserve Bank of Kansas City, 2011). The discounting factor (β) is equal to exp(-r) where $r = 0.08$, i.e. $\beta = 0.92$. The retention payoff (RPO) value is the NPV of retaining a cow compared with the NPV of her replacement (Bar et al., 2008b), i.e. $NPV_{retaining} - NPV_{replacing}$.

Exit from the herd

Exit from the herd can be due to two reasons: (1) voluntary culling based on what the model recommends or (2) due to what is commonly referred to as involuntary culling. Involuntary culling can be due to euthanasia or cows sold for slaughter because of reasons other than milk yield, pregnancy or CM (i.e. reasons not determined directly from the model). The values used for the probability of involuntary culling are discussed in Bar et al. (2008a). As the probability of involuntary culling of gram-negative mastitic cows was approximately 4 times that of healthy cows, this was reflected in the monthly involuntary culling values used in our model for gram-negative CM (unpublished data). The mortality of gram-negative CM was simplified to be 2% and 4% for primipara and multipara, respectively (Gröhn et al., 2005).

Sensitivity analyses

Given that economic values such as milk price, replacement cost and treatment cost can vary from time to time and farm to farm, a sensitivity analysis was performed to evaluate how an increase and decrease of 20% in each of these values individually affected the percentage of CM cases in the herd and the average cost per case. Further, we also measured the effect of halving the incidence of all 3 different types of CM, and also the effect of increasing the pregnancy rate by 20% (from 0.21 to 0.25) to determine which of these two management measures have the most beneficial effect on the average cost/case of CM.

RESULTS

The cost of different types of CM

The effects of each different type of CM on net return, incidence of CM, percent of CM cases treated, average cost of CM and average cost per case, are shown in Table 2. The monetary values correspond to averaging over cow characteristics (parity, month of lactation, etc.). The average cost per case (USD) was greatest for gram-negative CM at 211.03 (32.71/0.155) (where 32.71 is the average cost (=390.06-357.35) and 0.155 is the incidence of gram-negative CM), followed by gram-positive CM at 133.73 (16.85/0.126), and other CM at 95.31 (15.44/0.162). The percentage of mastitic cows recommended to be treated, following an optimal replacement policy, was 93.1, 93.1 and 94.6 for gram-positive, gram-negative and other CM, respectively. For the remainder of cows, the recommended policy was to cull immediately.

The effects of exogenous factors on the cost of different types of CM

We quantified how penalties associated with each type of CM, i.e., the milk loss, decreased fertility and treatment cost, contribute to the average cost per case of each type of CM. For gram-positive CM, the total cost (133.73) was comprised mostly of the treatment cost (68.89; 51.5% of the total cost), followed by milk loss (49.64; 37.1%) and decreased fertility (15.20; 11.4%). For gram-negative CM, the total cost (211.04) was primarily from the milk loss (152.76; 72.4%), followed by treatment cost (32.74; 15.5%) and decreased fertility (25.54; 12.1%). For other CM, the same trend was seen as for gram-positive CM, i.e. the treatment cost (46.86; 49.2%) contributed most to the total cost (95.30), followed by milk loss (38.64; 40.5%) and decreased fertility (9.80; 10.3%).

We increased and decreased the milk price by 20%, to observe how sensitive the average cost/case was to milk prices for each type of CM (Table 3). When we increased the milk price by 20%, the average cost/case of all CM increased by 11.7% (from 155.08 to 173.23), and decreased by 11.1% (from 155.08 to 137.91) when we decreased milk price by 20%. Gram-negative CM was most sensitive to these changes; the average cost per case increased by 14% (from 211.03 to 240.63) and decreased 13.1% (from 211.03 to 183.37) when milk price was increased and decreased by 20%, respectively.

When we increased and decreased the replacement cost by 20%, the average cost/case of CM increased by 5.3% (from 155.08 to 163.23) and decreased by 4.1% (from 155.08 to 148.67), respectively (Table 3). Gram-negative CM was most sensitive to these changes; the average cost/case increased by 6.7% (from 211.03 to 225.15) and decreased by 5.2% (from 211.03 to 200.06) when replacement cost was increased and decreased by 20%, respectively.

When we increased and decreased the treatment cost by 20%, the greatest change in cost/case was seen for gram-positive CM (increase of 10.4%, from 133.73 to 147.60, and decrease of 10.2%, from 133.73 to 120.13, respectively), followed by other CM (increase of 9.2%, from 95.31 to 104.10, and decrease of 8.9% from 95.31 to 86.84), and gram-negative CM (increase of 3.6%, from 211.03 to 218.57, and decrease of 3.4% from 211.03 to 203.96) (Table 3).

The average cost per case increased when the incidence of all different types of CM was halved. The greatest increase was in the other CM category (from 95.31 to 98.47, a 3.3% increase) (Table 3).

When pregnancy rate was increased by 20%, the average cost per case decreased. Of the 3 categories of CM, the largest decrease was seen in the other category (from 95.31 to 92.70, a 2.7% decrease) (Table 3).

Retention payoff of open healthy and mastitic cows

Our economic model calculates the retention payoff for cows, dependent on their individual characteristics. Figures 2 and 3 are hypothetical examples of retention payoffs under an optimal policy for cows free of CM and with different types of CM, specific to an open (non-pregnant), second lactation cow with average milk yield per 305 day lactation, and with permanent milk yield of 1,500 kg per 305 day lactation less than the average in the herd, respectively. The optimal policy recommended by the model (keep but not inseminate, keep and inseminate or replace) is also illustrated by the symbols on the graph.

In Figure 2, the RPO (USD) of cows at calving was 1,227, 1,091, 1,053 and 933 for no CM, other CM, gram-positive CM and gram-negative CM, respectively. The average cost at calving was calculated by subtracting the RPO for the different types of CM from the RPO for no CM. The average cost at calving was 136 (1,227-1,091), 174 (1,227-1,053) and 294 (1,227-933) for other CM, gram-positive CM and gram-negative CM, respectively. When the RPO is negative, it is more profitable to cull the cow than keep her. This was observed at month 12 for no CM, month 11 for other CM, and month 10 for gram-positive and gram-negative CM. Our figure illustrates the recommended policy until month 14; cows in month 14 and onwards were all recommended to be replaced.

In Figure 3, it can be seen that the culling recommendation has shifted forward, i.e., culling was recommended at month 9 for a cow without CM, and at month 7 for cows with gram-positive, gram-negative and other CM. The RPO of these cows at calving was 626, 518, 481 and 422, for no CM, other CM, gram-positive and gram-negative CM, respectively. Therefore, the average cost at calving was 108 (626-518), 145 (626-481) and 204 (626-422) for other CM, gram-positive and gram-negative CM, respectively. Our figure illustrates the recommended policy until month 12; cows in month 12 and onwards were all recommended to be replaced.

Endogenous factors affecting the cost of CM

Tables 4 and 5 are a cross-sectional view of Figures 2 and 3 at 4 and 8 months after calving, respectively (but with more information than the figures, i.e., Tables 4 and 5 also include cows of high permanent milk yield potential and pregnant cows).

The cost of CM is dependent on endogenous factors, i.e., permanent (genetic) milk yield potential, pregnancy status and lactation (Tables 4 and 5). The general trends are discussed below.

For a cow 4 months after calving (Table 4), we found that the average cost of CM was greater in open cows compared with pregnant cows. Also, the average cost of CM was greater in younger cows compared with older cows.

The average cost was greatest for gram-negative CM, followed by gram-positive CM, and other CM, for each permanent milk yield potential and pregnancy status combination. Also, the cost was greatest for cows that were high milk producing, followed by average and low producing.

At 8 months after calving (Table 5), the average cost was generally greater for cows suffering from gram-negative CM, and this was followed by gram-positive CM and other CM. Also, in the low permanent milk yield potential category, pregnant cows had a higher average cost of CM compared with open cows, but this was reversed in the average and high permanent milk yield potential categories. Similar to the trend at 4 months after calving, younger cows had a higher average cost of CM than older cows and the higher the permanent milk yield potential of the cow, the greater the average cost of CM (Table 5).

Exit from the herd (voluntary culling and involuntary culling)

When all the different types of CM were included in the model, the percentage exit from the herd was 35.5 (comprised of 17% from voluntary culling and 18.5% from involuntary culling). This increased to 38.7 (20.8, 17.9) when milk price was increased by 20%, and decreased to 33.1 (13.8, 19.3) when milk price was reduced by 20%. When replacement cost was increased by 20%, herd exit decreased to 33.6 (14.4, 19.2) and increased to 39.3 (17.5, 21.8) when replacement cost was reduced by 20%. When the incidences of CM were halved, herd exit decreased to 34.4 (15.7, 18.7), and when pregnancy rate was increased by 20%, it decreased to 33.4 (13.8, 19.6).

DISCUSSION

When a cow contracts mastitis, the dairy farmer needs to decide whether treatment is warranted, and if so, what treatment is most appropriate. These decisions are ideally made based on the organism causing mastitis. In determining how to treat a cow, one common way of grouping these organisms is to separate them into gram-positive and gram-negative mastitis. These two groups of organisms cause mastitis of different symptoms and severity. This classification can form the basis of on-farm treatment protocols (Hertl et al., 2010).

The importance and reliance on classifications of mastitis has become prevalent in the literature. For example, a study conducted by Neeser et al. (2006) found that there were significant reductions in the amount of antimicrobial use when on-farm culture systems were employed. Most producers treated gram-positive mastitis with antibiotics, whereas gram-negative mastitis treatment varied. They concluded that the reduction in antimicrobial use could lead to several advantages, such as decreases in discarded milk and antimicrobial residues in milk, and improved treatment outcome due to targeted treatment. From our study, we found the average cost per case (USD) of gram-negative CM (211.03) was due mostly to milk loss, which is logical given that the milk loss was greatest for gram-negative CM out of the 3 types of CM (see also Schukken et al. (2009)). For gram-positive CM, this cost was primarily due to the treatment cost, which is also intuitive, given that the treatment cost was greatest for gram-positive CM, of all 3 types of CM. Similarly, treatment cost contributed most to the average cost per case of other CM.

The average cost per case with all 3 different types of CM in the model was 155.08, which is lower than that found in the study by Bar et al. (2008a) for generic CM, where the average cost per case was 179. This difference is due to a number of reasons: our model was more detailed in that generic mastitis was differentiated into types and data in our study were updated from Bar et al. (2008a), In Bar et al. (2008a) the parameter values used in the model (risk, treatment cost, involuntary culling, etc.) were for generic CM and not groups of CM, and we did not include a carryover state from the previous lactation. Unlike the generic CM case, if we were to include a carryover state, we would need to model all the different combinations of carryover effects possible (e.g. gram-positive CM in previous lactation, gram-negative CM in current lactation, or gram-positive CM in previous lactation, gram-positive CM in current lactation, etc.). This would cause the state-space of the model to grow considerably, increasing the time and computer capacity necessary to calculate an optimal solution. The inclusion of carryover effect is an area of future research.

Although a few studies have examined the cost of CM in dairy cows, none have quantified this cost at the individual cow level for 3 different types of CM. The study that comes closest to examining such costs was conducted by Sørensen et al. (2010). In that study, the authors estimated the costs related to 5 different pathogen-specific mastitis traits and unspecific mastitis using a stochastic simulation model (SimHerd IV). Costs ranged from 189.42USD to 724.64USD per case (converted on 20Aug2010 from €149 and €570, respectively), and were greater for contagious pathogens, compared with environmental pathogens.

In our study, not only did we calculate the cost of different types of CM, but also the sensitivity of these costs from parameter changes. When we increased the milk price, the average cost per case of CM increased, as the milk losses associated with each type of CM were higher valued. The reverse was seen when milk price was reduced. Again, as expected, the average cost of gram-negative CM was most sensitive to this change. The same pattern was observed when replacement cost was increased.

We increased and decreased treatment cost by 20% to account for differences across farms in e.g. the use of antibiotics and associated discarded milk. What we found was, despite these changes, the order of the cost of CM from most costly to least costly did not change (i.e. gram negative was always most expensive, followed by gram positive then other CM).

Between the two scenarios of increasing pregnancy rate or halving the incidence of CM, it was apparent that the former case led to a reduction in the average cost/case of CM, indicating the benefits to farmers of focusing on improving their breeding programs. The reason for the average cost per case of CM increasing when the herd CM incidence is halved is because when the chance of a cow having another CM case in the future is lower, there is a tendency to treat instead of cull, and overall this increases the average cost per case of CM.

Both Figures 2 and 3 illustrate that cows with CM should be replaced earlier than cows without CM, and that cows with lower milk yield should be replaced earlier than cows with higher milk yield. From Figure 3, it can be seen that cows with gram-negative CM are recommended to be inseminated only once compared with cows having gram-positive and other CM; this can be attributed to the greater milk loss from gram-negative CM (Schukken et al., 2009), making it less economically optimal to spend the money on inseminating them from that one point onwards. The cross sectional views of the figures (Tables 4 and 5) quantified what one would expect in the average cost/case of CM, as permanent milk yield, age, type of CM and pregnancy status vary. For example, as permanent milk yield potential increased from low to high, the average cost/case of CM increased. As expected, the older the cow is, the lower the average cost/case of CM, as an older cow has less lifespan remaining, than a younger cow, for the cow to succumb to the detrimental effects of disease (and for these to be translated into monetary losses). Gram-negative CM generated the highest cost, as has been the case so far. Generally, CM cases were more costly in open cows, as they have the added effect of reduced fertility (unlike pregnant cows, as they are already with calf). Among cows 8 mo after calving (Table 5), in the low permanent milk yield potential category, however, pregnant cows had a higher average cost of CM compared with open cows, which is due to these cows being further into pregnancy, and a greater probability of going to term (unlike cows at 4 mo, where the opposite trend was seen in average cost/case of CM).

As anticipated, when milk price increased, culling (voluntary) increased as well, due to the increased cost from milk loss and the greater expected profit of a replacement heifer. When the incidence of CM was halved, and pregnancy rate increased, culling (voluntary) percentages decreased. When replacement cost increased, culling (voluntary) was reduced, as it was more expensive to replace than to keep a cow.

In our model, we use a monthly time step, where we assume that e.g. all CM cases occurring 152 – 183 days after calving occur at day 183, enabling the decision to cull (and not treat) before incurring the costs of disease. The only exception to this is the first stage after calving which has a length of only 3 days, i.e. we assume that all cows that have mastitis shortly after calving have it by the third day after calving (Bar et al., 2008a). This is also because we estimate a greater risk for CM in these days.

Our study focuses on decisions for individual animals, and as such is an individual based model. All modeling techniques have their advantages which need to be weighed with their disadvantages in selecting the technique most appropriate for the study. The limitations of our individual cow model are that we cannot include herd dynamics, e.g. infectivity of CM, and see the effects of this at the individual cow level. If the latter were the focus of our study, then another modeling techniquewould be appropriate.

Our research was specific to cow characteristics which allows us to undertake a comprehensive analysis of the costs of CM by type. Further, the cost of disease depends on the fate of the cow. If the cow is to be culled, milk loss effects and fertility effects are not applicable. If the cow is pregnant, disease effects on fertility are not applicable. Pregnant cows were almost always recommended to be kept in the herd until the next lactation. Because the CM losses in these cows are only the treatment cost and milk loss and these were assumed to be the same for both high yielding cows and low yielding cows, the cost of CM is the same for all these pregnant cows. Intuitively, one would assume that a high producing cow loses more milk to CM (compared with an average or low producer); however, we have assumed this to be the same. While we know that high milk production is a risk factor for mastitis (Gröhn et al., 1990; Gröhn et al., 1995), we have not investigated whether these losses are different for low or high milk producing cows, though this would not be unexpected. Because we do not included this risk factor in our model, and assume that milk loss is consistent across all milk production levels, it is possible that there may be more variability in the results than currently shown in our model.

Further, we did not model seasonality and milk component variations, or the exact shape of the lactation curves beyond 10 mo, as these issues were beyond the scope of our study objectives. A further limitation includes the assumption that the farmer has complete knowledge of cow traits, and that a replacement heifer immediately enters the milking herd following a cow replacement, which is not always the case (Bar et al., 2008a).

The ‘treat’ decision which our economic model can recommend does not take into account how effective the treatment may be. And given that in our current model, CM is divided into 3 categories of gram-positive, gram-negative and other CM, the treatment policies for each type of bacteria in each category are assumed to be the same. Admittedly, the success and type of treatment for bacteria within each group, or even the same bacterial species between different strains, can differ; however, the focus of our economic model was not to assess the success of different types of treatment options.

This model, therefore, serves as a decision tool to aid farmers when deciding what to do with their diseased cows. The economic values, production costs and disease frequencies can be altered, hence, the results can be made applicable to individual farms, although our used values are representative.

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