Annual Review of Resource Economics

# Production Diseases Reduce the Efficiency of Dairy Production: A Review of the Results, Methods, and Approaches Regarding the Economics of Mastitis

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Annu. Rev. Resour. Econ. 2019. 11:289–312

First published as a Review in Advance on July 12, 2019

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

https://doi.org/10.1146/annurev-resource-100518-093954



## Keywords

agricultural economics, natural resource economics, mastitis, production disease, dairy farm

## Abstract

Mastitis is the most important production disease in dairy farming, leading to considerable inefficiency in production. In 1992, an important paper describing a simple but very useful economic framework for production diseases in animal farming was published. In a systemic literature search, 77 articles were found on the economics of mastitis. Throughout the years, little progress has been made to improve the economic framework regarding production diseases in animal farming, but methodological progress was made in the biological aspect of bioeconomic models. Research focused on the failure costs of mastitis and cost-benefit analyses of cow-level decisions (treatments). The average failure costs of mastitis were $US131 per cow per year. Future economic research should focus more on the utilization of currently

available large databases. The economic framework should be extended toward mastitis as an externality of dairy production (welfare), the externalities of optimal use of chemical and pharmaceutical compounds (antimicrobials), and explaining farmers' decisions regarding mastitis.

## INTRODUCTION

Worldwide, dairy production is an important economic activity. Dairy farms utilize a large part of the world's agricultural land resources, either by direct use (e.g., grazing or as the farm's own fodder crops) or indirectly by purchasing feed. The total production of milk from dairy cattle in 2017 was estimated to be 696 billion kg (IDF 2018). Inefficiencies in milk production, therefore, may have large economic consequences. Inefficiencies in dairy production can originate from many managerial areas; one example is the occurrence of animal disease.

One specific type of farm animal disease is so-called production disease, of which there are many definitions. In this article, we define production diseases as animal diseases that persist in food animal production systems (Kyriazakis 2015). Production diseases originate from an interaction of management, climate, facilities, nutrition, and genetics with pathogens. Although epidemic contagious diseases may result in large economic effects during outbreaks and generate much more publicity because of the public policy response, production diseases are more economically important for the overall efficiency of animal production.

Production diseases reduce yield (morbidity) and cause mortality resulting in large year-to-year losses at the farm level, leading to increased food costs for consumers. An externality of these diseases is the decreased animal welfare and use of antimicrobials and other pharmaceutical and chemical compounds that are used to reduce the losses of the diseases. The most important production disease in dairy cattle is mastitis (inflammation of the udder; see the sidebar titled Mastitis). Because of the nature of production diseases, their eradication is not feasible. Thus, the management question becomes one of optimal disease level determined by control costs and disease losses and consideration of marginal costs and benefits. Determining the optimal level of control efforts is a difficult proposition for the farm manager and their veterinary advisors.

In 1992, a pioneer in the field of economics of animal health, John McInerney, published a paper in which a framework was provided on the economics of animal production diseases (McInerney et al. 1992). He later extended this framework (McInerney 1996). Those two papers can be seen as key publications in the economic thinking about production diseases. It is unclear how much

### MASTITIS

Annually, approximately 20–40% of all lactating cows experience one or more cases of clinical mastitis (defined as visible where the cow displays definitive symptoms). Moreover, at any given time, 10–30% of all lactating cows on a farm have subclinical (invisible to the human eye) mastitis during lactation. Clinical mastitis must be detected and diagnosed by the farmer and sometimes assisted by a veterinarian. Subclinical mastitis can be detected by measuring the somatic cell count in the milk, which is a measure of the number of leukocytes in the milk. An increased somatic cell count is an indication of an inflammatory reaction. In many milk payment systems, the somatic cell count measured in the bulk milk is used as a milk quality aspect. On the basis of the bulk milk somatic cell count milk quality, dairy farmers often receive a penalty or bonus payments. The somatic cell count is often measured at the cow level as part of a milk production recording program, the results of which can help the farmer manage decisions.

progress has been made in our economic thinking about production diseases. Therefore, the primary objective of this review is to describe and discuss the progress in economic research regarding production diseases in livestock farming, using mastitis as proxy. The secondary objective of this review is to summarize the costs of mastitis as an example of the inefficiency in animal production caused by animal diseases.

The review is organized as follows. First, the McInerney framework for farm-level management of production diseases is reviewed. Then the peer-reviewed literature on the economic aspects of mastitis are described and categorized. An overview of the costs of mastitis is provided, and highlights in economic thinking and modeling are specifically described. Finally, future directions for the economic analysis of production diseases are discussed.

## FARM ANIMAL DISEASE IN AN ECONOMIC FRAMEWORK

In a time when the economics of animal health evolved, a number of conceptual studies were published. Some of these were relatively pragmatic (e.g., Dijkhuizen et al. 1991, Carpenter 1993), but one did provide a very interesting theoretical framework. McInerney et al. (1992) framed animal production diseases in a simple but useful economic framework. Prior to that article, most research examining the economics of disease focused on the costs related to disease and implied that diseases with higher costs were more important and should be a higher priority for management attention. Focusing only on costs of disease, however, is not useful to determine appropriate management or policy decisions for several reasons. First, it is difficult to calculate the costs of a disease that is complicated by many aspects of morbidity and mortality. The default is that the direct cost of disease is generally the result of a simple accounting of physical quantities lost or forgone along with expenditures for disease control, such as pharmaceuticals. Second, the disease costs focus exclusively on the farm or livestock sector and ignore market and welfare effects. Third, the analysis ignores what a decision maker might actually do with the cost estimates. The previous disease control literature rarely considered the economic costs of disease reduction or eradication. Combined, this could provide for a basic cost-benefit analysis. However, cost-benefit analysis is often not rigorous and may be of limited use in decision making. What was lacking in this earlier literature, then, was a unifying economic model of livestock disease.

McInerney et al. (1992) recognized that production diseases lower the productivity of animal farming systems by increasing the inputs required to produce a given level of output or, equivalently, decreasing the amount of output for a given amount of output relative to a healthy animal. Following their work, consider output as a function of variable and fixed resources. The production function can be expressed as

$$Q = F(R, K),$$

where $Q$ is output, $R$ is variable inputs, and $K$ includes fixed inputs. Output is sold at $P_{\mathrm{D}}$, and variable inputs are purchased for $P_{\mathrm{R}}$. Healthy animals produce more output for the same amount of input than do diseased animals. **Figure 1** illustrates this relationship and shows that disease loss can be considered a relationship rather than a single value. Recognizing that the production function of diseased animals differs from that of healthy animals, disease changes both optimal output level and input use. With diminishing marginal effects, the loss from disease is smaller at lower levels of productivity. Thus, more investment in control is justified at higher productivity levels. The loss due to the disease is the output reduction, $Q_0 - Q_{\mathrm{D}}$, the resources used to control the disease, $R_0 - R_{\mathrm{D}}$, or any combination in between. Disease lowers the output for a given amount of input and the effectiveness of the inputs. Note that such a production function can be defined at the individual animal level as well as at the farm level.

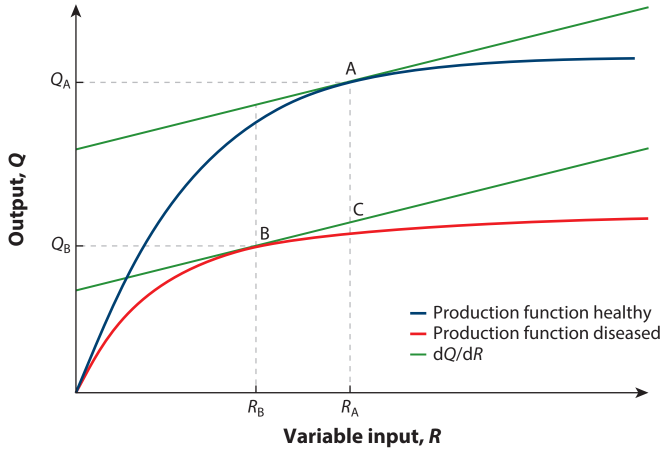


**Figure 1**

Livestock production functions between output $Q$ and variable input $R$ with and without disease. A and B denote the optimal level of production for the health and diseased situation given the relation $\mathrm{d}Q/\mathrm{d}R$. C can be used to calculate the true economic loss from disease. Adapted with permission from McInerney (1996).

In order to maximize profit, input and output prices can be included, and the input is chosen to satisfy the relation $\mathrm{d}Q/\mathrm{d}R = P_{\mathrm{R}}/P_{\mathrm{Q}}$. The result is that the common marginal revenue equals the marginal cost condition (A in the healthy production function). Because the economically optimal response is to lower inputs in response to the disease (i.e., the relative cost of the input increases as its effectiveness is diminished by disease), the optimal level of production in the diseased production function would be B. Consequentially, the cost of the disease is lower than would be estimated by a simple disease cost. The true estimate of the economic loss resulting from the disease is AC. Note that this loss estimate assumes that the disease does not lower market price of the output because of quality or safety issues.

The other economic aspect is the disease control that includes additional inputs, $V$, such as labor, medicine, and veterinary services. The production function can now be expressed as

$$Q = F(R, V, K),$$

where $V$ is disease control that is chosen as well as the variable input $R$. The resulting economic optimization reveals that there is an optimal level of disease control effort depending on the output and input prices. Control inputs should be used until marginal value of the last input equals its marginal cost. With costly disease control inputs and diminishing effectiveness of those inputs, this result implies an optimal level of disease that is likely to be greater than zero. This contrasts with the goal of veterinarians and health professionals, which is generally the eradication or minimization of a disease. Another important result of the model is that variable inputs, $R$, and disease control inputs, $V$, may be substitutes. For many diseases, the effects may be counteracted by veterinary expenditures or an increase in variable inputs such as feed and labor.

McInerney et al. (1992) and McInerney (1996) proposed considering the trade-off between disease losses, defined as direct disease effects (e.g., lost output, death, infertility, reduced growth) and expenditures defined as resources used as a consequence of disease. McInerney et al. (1992) defined loss $L$ as the direct effect of the disease, such as depressed output, mortality, and infertility. The resources that are used to control or eliminate disease are called expenditures, $E$, and include,

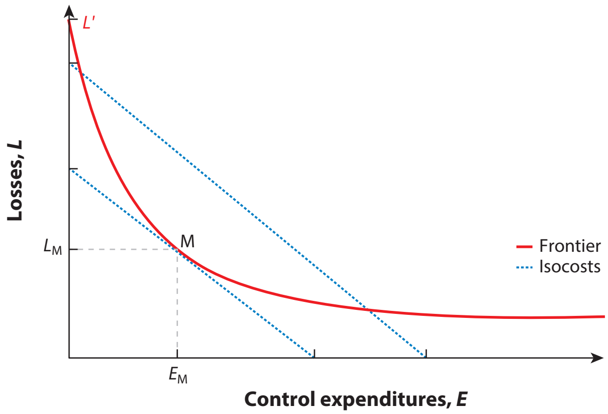


**Figure 2**

Disease loss-expenditure relationship. The frontier gives the relationship between the lowest losses achievable for any level of control expenditures. The other lines give two possible isocost lines of combinations of disease loss and control expenditures. $L'$ denotes the maximum losses as they will occur when zero control is carried out. Point M denotes the optimal level of control, with expenditures $E_M$ and losses $L_M$. Adapted with permission from McInerney (1996).

for example, veterinary services, drugs, and hygiene. The cost of the disease can be expressed as the sum of those two components:

$$C = L + E,$$

where $C$ is the total costs incurred by the disease rather than merely the disease losses. Specifying the cost in this way, along with the recognition that $L$ and $E$ are substitutes, results in a goal to minimize total disease costs, $C$.

The relationship between the $L$ and $E$ can be represented as a frontier as in **Figure 2**. In the absence of control expenditures, the losses are $L$. When control expenditures increase, losses decrease but at a decreasing rate. The line $L'$ is a frontier defining the lowest losses achievable for any level of control or the least possible control expenditures to restrict losses to a given level. If disease can be eradicated, the frontier will intersect the $E$ axis. **Figure 2** illustrates a condition that recurs. Production diseases, of which mastitis is seen as the most important, do meet that condition.

Optimal disease management involves achieving the lowest total disease cost. The dashed lines in **Figure 2** represent isocost lines of combinations of disease loss and control expenditures. The lowest cost combination is ($E_M$, $L_M$), which satisfies the standard equimarginal condition. Note also that the minimum losses achievable in the illustrated case are $C_M$. In this case, disease eradication is not possible, and decisions should consider avoidable rather than total costs.

## OVERVIEW OF PUBLICATIONS ON THE ECONOMICS OF MASTITIS

A systematic search was undertaken to find publications on the economics of mastitis. Web of Science was searched using the following terms:

- TITLE: (udder health OR mastitis OR udder disease OR intramammary infection OR somatic cell count OR dry cow) and

- TITLE: (*economic* OR profit* OR financial OR cost* OR control OR losses OR value OR performance)

In total, 564 publications were found from 1992 to 2018. Subsequently, only those that focused on the economics of mastitis in dairy cattle were selected, and others were excluded for various reasons: they excluded economics of mastitis (*n* = 358), were in other language than English (*n* = 18), focused on mastitis in humans (*n* = 95), focused on economics of mastitis in animals other than cattle (*n* = 7), and were not peer reviewed (*n* = 12). In addition, five publications were selected based on the expertise of the authors (Oliver et al. 2003, Berry et al. 2004, Halasa et al. 2010, Petzer et al. 2017, Aghamohammadi et al. 2018) and were added to the remaining 74. Two articles were not electronically available (Degraves & Fetrow 1993, Miller et al. 1993). Thus, we reviewed 77 papers aimed at the economics of mastitis (**Supplemental Table 1**).

Supplemental Material >

Five publications (Seegers et al. 2003, Petrovski et al. 2006, Halasa et al. 2007, Hogeveen et al. 2011, Hogeveen & Van der Voort 2017) were overviews or reviews. The other 70 studies carried out novel economic evaluations of one or more aspects of mastitis and/or mastitis control. When looking at the publication dates of these publications, it is interesting that the early 1990s saw a consistent number of publications (2–3 per year). In the early 2000s, the number of publications regarding mastitis control was low, whereas in the last 10 years, the number of publications increased to 2–8 per year. Obviously, there has been a renewal of interest in the economics of mastitis in the last decade. In the early 1990s, most research work was done in the United States and United Kingdom, but in later years other (mostly European) research groups published on mastitis as well. The largest number was published in the Netherlands (*n* = 21), followed by the United States (*n* = 18) and the United Kingdom (*n* = 9). Two articles were published on the economics of mastitis in South America (both in Brazil), five focused on Africa (3 in Ethiopia, 1 in Egypt, and 1 in South Africa), and two covered India. In the past 20 years, two groups have been especially active in the field of the economics of mastitis: the research group on the economics of animal health in Wageningen/Utrecht, Netherlands and a joint research group consisting of epidemiologists and agricultural economists at Cornell University, New York.

A total of 34 papers were published on failure costs, of which 11 were at the cow/case level, 22 at the herd level, and 1 at the regional level. Six articles estimated the total costs of mastitis (failure costs plus preventive costs). A total of 30 papers described a cost-benefit analysis, of which 15 were aimed at the cow level (especially regarding treatments), and 15 focused on the herd level (especially improved prevention).

## Reviews and Extensions of the McInerney Framework

Since 1992, five reviews have been published on the economics of mastitis. The review by Seegers et al. (2003) primarily analyzed the effects of mastitis on milk production (including changes in milk composition) as well as on culling and lethality and linked these effects with price levels to estimate costs of mastitis. Petrovski et al. (2006) provided an extensive review of the costs of mastitis and summarized these in relation to the various factors discussed in articles they reviewed. As a result, they developed a framework that could be used to account for all cost factors. The authors did not use common definitions or categorizations for cost factors, making cost calculations difficult to compare. Therefore, Halasa et al. (2007) introduced a framework of cost factors to be accounted for when calculating failure costs of mastitis and linking that framework to failure costs estimations at the herd level published since 1992. A further update of failure cost estimations at the herd level was published later by the same group (Hogeveen

## OPTIMIZING THE TOTAL COSTS OF PRODUCTION DISEASES

The total costs of production diseases at the farm level consist of failure costs plus preventive costs. Failure costs are defined as losses due to disease, combined with the costs (expenditures) of reducing the negative effects of disease occurrence (e.g., treatment and diagnostics to support treatment decisions). Failure costs are composed of production losses, such as milk, a reduced life expectancy of cows, and treatment costs or costs for other resources. Preventive costs are defined as those preventing occurrence of disease and comprise investments, labor, and consumables to prevent animals becoming diseased. There is a substitution relation between failure and prevention costs. The economic optimal level of prevention is at the point where the total costs is minimized.

et al. 2011), which clearly distinguished between failure costs and preventive costs. Recently, the McInerney framework on losses and control was updated. Hogeveen & Van der Voort (2017) proposed the use of failure costs versus preventive costs to better mimic the decision framework for farmers, who decide on further prevention given the failure costs of disease (see the sidebar titled Optimizing the Total Costs of Production Diseases).

## Failure Costs at the Cow Level or Case Level

Case-level publications evaluated the effects of a single case of clinical mastitis (Sasidhar et al. 2002, Perez-Cabal et al. 2008, Rollin et al. 2015) or subclinical mastitis (Mungube et al. 2005, Atasever & Erdem 2009, El-Tahawy & El-Far 2010, Tesfaye et al. 2010, Sinha et al. 2014, Dahl et al. 2018, Goncalves et al. 2018, Hadrich et al. 2018). Some of the failure costs at the cow or case level were completely normative, meaning that no empirical data were used in the calculations, except results from other (peer-reviewed) papers or from experts (Atasever & Erdem 2009, Rollin et al. 2015). Most of the studies were based on empirical data on milk production losses due to subclinical mastitis or treatments needed for clinical mastitis and combined these observations with normative (representative) price levels. In a study specifically addressing the association between mastitis and loss of pregnancy, data were collected on the loss of pregnancy in relation to mastitis (Dahl et al. 2018). A normative economic calculation was made to evaluate the economic consequences of mastitis, with special reference to pregnancy loss. Hadrich et al. (2018) utilized a large database (approximately 5.5 million lactations), from which they combined somatic cell count patterns with milk production losses, therewith distinguishing between cases of subclinical mastitis. In contrast to that study, Goncalves et al. (2018) carried out a more precise study collecting quarter milk samples from 146 cows with chronic subclinical mastitis.

## Failure Costs at the Herd Level

Great diversity was evident in the 20 publications we reviewed on failure costs at the herd level. Several studies utilized dynamic programming models (Bar et al. 2008, 2009; Cha et al. 2011, 2014; Heikkila et al. 2012), which are at the individual cow level. Net profits were also calculated for cows without mastitis. Therefore, the costs of mastitis could and were expressed as average costs per cow on the farm.

Hillerton et al. (1992) estimated the cost of a specific type of clinical mastitis (summer mastitis). Similarly, Huijps et al. (2009a) studied another specific type of mastitis, namely heifer mastitis (mastitis that occurs at the very early start of a cow's first lactation and is associated with heifer rearing). Some studies focused on clinical mastitis (Beck et al. 1992; Wolfová et al. 2006; Bar et al. 2008, 2009; Hultgren & Svensson 2009; Cha et al. 2011, 2014), whereas others only considered herd-level bulk milk somatic cell counts (Dekkers et al. 1996, Dillon et al. 2015, Gulzari et al. 2018). The most complete estimates accounted for clinical and subclinical mastitis (Østergaard et al. 2005, Huijps et al. 2008, Halasa et al. 2009a, Hagnestam-Nielsen & Østergaard 2009, Nielsen et al. 2010, Getaneh et al. 2017, Guimarães et al. 2017). To distinguish between different pathogens, some studies modeled pathogen-specific effects of clinical mastitis (Østergaard et al. 2005; Halasa et al. 2009a; Cha et al. 2011, 2014; Gussmann et al. 2018).

Almost all studies were normative rather than empirical in nature. They utilized knowledge from other peer-reviewed papers and expertise of the authors. Three studies on the herd-level failure costs were (partly) based on empirical data. Wolfová et al. (2006) based their results on data collected on five farms where they measured the incidence and some associated information (e.g., duration of the cases, treatment) and combined those data with standard price levels to calculate the failure costs of clinical mastitis. Huijps et al. (2008) collected data from 68 farmers, calculating the costs of mastitis using a straightforward calculation tool based on farm-specific input. All aspects of mastitis occurrence (level of bulk milk somatic cell count and incidence of clinical mastitis), consequences of mastitis (milk production losses and culling), and price levels were estimated by the farmers instead of being based on representative norms or price levels. The only full empirical study by Dillon et al. (2015) used panel data containing accountancy data in combination with bulk milk somatic cell count data to evaluate the effects of mastitis on farm income.

Some studies that only provided failure costs did link to the prevention of mastitis. Beck et al. (1992), Dekkers et al. (1996), and Nielsen et al. (2010) looked at the potential for investment by evaluating the reduction in mastitis costs with decreasing occurrence. Beck et al. (1992) reflected on this investment potential by comparing it to the costs of preventive measures [based on the mastitis five-point plan (Neave et al. 1969)] without estimating the effectiveness of those preventive measures, so it was not a complete cost-benefit analysis. Hultgren & Svensson (2009) combined cost estimations with risk factors for mastitis occurrence.

Finally, in a microeconomics-oriented study, Losinger (2005) did a partial analysis of the regional economic effects of mastitis, only considering normative milk production losses related to increased somatic cell counts.

## Total Costs at the Herd Level

Yalcin et al. (1999) and Yalcin (2000) used routinely collected bulk milk somatic cell counts to estimate production losses due to subclinical mastitis and calculated the associated costs for milk quality penalties. The study combined these failure costs with survey results on preventive measures [based on the mastitis five-point plan (Neave et al. 1969)] and used normative price levels for the reduced milk production and preventive measures. Geary et al. (2012) used a farm profitability calculation model to evaluate the costs of mastitis for various levels of bulk milk somatic cell counts, milk production effects, treatments, and some preventive measures at the herd level. In a follow-up study, these calculations were extrapolated to the national level for Ireland (Geary et al. 2013). Van Soest et al. (2016) collected data on the occurrence of clinical mastitis and somatic cell count from 120 Dutch dairy farms. They linked those values to calculate the failure costs per farm. These failure costs were combined with estimated costs of preventive measures, as they were collected using a questionnaire. The study calculated the total costs of mastitis, utilized the failure cost-preventive cost frontier described by Hogeveen & Van der Voort (2017), and discussed trade-offs between failure costs and preventive costs. The same approach was also used by Aghamohammadi et al. (2018); using a questionnaire, data were collected at 374 Canadian dairy farms that were used to determine the farm-specific total failure costs and preventive costs.

## Cost-Benefit Analysis of Measures at the Cow Level

Most studies evaluating the costs and benefits at the cow level considered different types of treatment of mastitis. Van Eenennaam et al. (1995) used a cost-benefit analysis at the cow level on the results of a large clinical trial focusing on one specific type of mastitis: that caused by toxin-producing pathogens. Shim et al. (2004) described an experiment with two possible treatments for clinical mastitis. Considering the costs for treatment and discarded milk due to treatment, a cost-benefit analysis was calculated for the alternative treatment compared to the basic treatment. Using a stochastic simulation model, Steeneveld et al. (2011) compared numerous antimicrobial treatment approaches for clinical mastitis. The researchers considered transmission of mastitis so that a cure results in a lower amount of pathogen shedding and therefore a decreased transmission rate. The benefits of cure will thus extend beyond the individual cow. Moreover, various cow factors and their association with the cure of mastitis were evaluated, including whether treatment should be based on factors beyond the pathogen, including cow characteristics. Down et al. (2013) did similar work on the optimal treatment of clinical mastitis. Using the earlier published dynamic programming model (Cha et al. 2011), Kessels et al. (2016) evaluated the economic effect of different treatment and vaccination strategies at the cow level. Optimal culling and insemination decisions were assumed. Van Soest et al. (2018) created a stochastic Monte Carlo simulation model to estimate the cost-effectiveness of an additional pain reduction treatment combined with antimicrobial treatment of mild clinical mastitis. Oliver et al. (2003) evaluated the effect of the antibiotic treatment of heifers (before the first calving) to reduce the level of heifer mastitis. Effects on milk production and occurrence of clinical mastitis were measured, and economic consequences were evaluated using normative (representative) calculations.

One option in cases when a cow has clinical mastitis is to cull rather than treat the cow. Because culling decisions are complex, models must compare future profits of culling versus replacement of the animal. If the expected future net returns of the cow with mastitis (that are expected to be lower than those of the same cow without mastitis) are lower than the expected net returns of replacing that cow, the decision to cull the cow is economically beneficial. Stott & Kennedy (1993) used a dynamic programming model to specifically study the culling of cows in cases of clinical mastitis.

Four studies focused on the treatment of cases of subclinical mastitis. Swinkels et al. (2005a,b) described the treatment of two types of subclinical mastitis using a partial budgeting approach. An important effect taken into account was the reduction of transmission of mastitis when a case is cured. This means that a better cure will result in fewer cows with mastitis because the rate of transmission will be reduced. Using a more robust modeling method (including stochasticity), Steeneveld et al. (2007) worked on the treatment of chronic subclinical mastitis. Petzer et al. (2017) also took transmission of pathogens into account when evaluating the costs and benefits of treating subclinical *Staphylococcus aureus* mastitis. Their model was at the herd level to enable improved modeling of the transmission of pathogens.

Diagnostic tools are becoming more available because of progress in microbiological research. Murai et al. (2014) created a stochastic simulation model to study the diagnostics of mastitis, given the many novel diagnostic tools that were becoming available at that time. The test characteristics were based on empirical data. Cha et al. (2016) used the aforementioned dynamic programming model (Cha et al. 2011) to evaluate the cost-effectiveness of diagnostics for selecting a proper treatment for clinical mastitis cases.

Finally, Berry et al. (2004) studied the use of dry cow therapy for individual cows, looking at the type of pathogen present (or absent) at the time of drying off as well as the effectivity of antimicrobials to cure existing infections and to prevent infections during the dry period.

## Cost-Benefit of Measures at the Herd Level

Although the cost-benefit calculations at the cow level were focused on complementary treatment decisions, the range of measures was evaluated at the herd level. Some of these studies evaluated individual cow measures at the herd level. Zepeda et al. (1998), for instance, built a herd-level optimization model to evaluate additional diagnostics to support treatment decisions. Although the decisions were cow specific in the model, the costs and benefits of additional diagnostics were evaluated at the herd level. Halasa (2012) evaluated cow-level decisions (treatment of clinical mastitis) at the herd level using the previously described stochastic simulation model (Halasa et al. 2009a). Because the model enabled the simulation of mastitis transmission, the treatment of individual cows affected the herd level. Similar work on topics such as the transmission of mastitis (Steeneveld et al. 2011, Down et al. 2013) attributed the economic effects of transmission to the individual cow.

The simulation model of Halasa et al. (2009a) was also used in two other studies. One focused on the treatment of chronic contagious clinical mastitis (Van den Borne et al. 2010) and another on dry cow therapy (Halasa et al. 2010). The latter work was based on two extensive meta-analyses of the effects of dry cow therapy on the cure of existing mastitis infections and prevention of mastitis in the dry period (Halasa et al. 2009b,c). In recent years, the use of antimicrobials to prevent mastitis during the dry period has been discussed. Consequently, several studies have focused on the economics of dry cow therapy and the currently often preferred selective dry cow therapy. Despite Berry et al.'s (2004) study of dry cow therapy as a cost-benefit analysis at the individual cow level, the application of dry cow therapy is seen as a herd strategy. Huijps & Hogeveen (2007) used a Monte Carlo simulation model to evaluate selective dry cow therapy compared to blanket dry cow therapy or no dry cow therapy. Scherpenzeel et al. (2016) worked out a number of scenarios for selective dry cow therapy and evaluated the use of antimicrobials, the occurrence of (clinical) mastitis, and the economic effect of each scenario based on recommendations for the Dutch situation. In a follow-up study, Scherpenzeel et al. (2018) created a linear programming model to optimize application of dry cow therapy with antimicrobials. Somatic cell count thresholds used to select cows for dry cow therapy were optimized with the objective of minimizing the total costs of mastitis and treatment. By adding a constraint on the percentage of cows allowed to be treated with antimicrobials at drying off, the economic effect of a larger reduction in the use of antimicrobials than what was optimal could be estimated for different farm situations. Down et al. (2017) described their herd-level cost-benefit analysis of cow-level decisions. The authors developed a Monte Carlo simulation model and used it to evaluate the use of diagnostics (on-farm bacteriological culturing) in combination with diagnostics-based treatments.

In a highly speculative paper, Miles et al. (1992) calculated the potential economic effects of novel developments in bioengineering at the state level in New York. The basis for the calculations was on-farm milk production losses related to the somatic cell count and treatment costs related to clinical mastitis, all of which were normative. A reduction of these costs was envisaged based on trial results and speculation of the effectiveness of novel treatments such as the use of vaccines and bacteriocins. Final results were provided at the state level, not correcting for changes in market equilibrium due to changes in supply. Treatments of clinical mastitis and the application of dry cow therapy were also studied by Allore & Erb (1998) using a bioeconomic, stochastic simulation model. Results of the simulation model were used to calculate economic effects of lactational therapy, dry cow therapy, vaccination, and generic prevention. Dynamic programming was applied by Yalcin & Stott (2000) to optimize similar herd-level decisions (dry cow therapy, treatment of clinical cases, and postmilking teat disinfection under optimal culling decisions).

In an economic calculation based on the results from the efficacy study of Huijps et al. (2010b), Hogeveen et al. (2011) evaluated the cost and benefits of 18 commonly prescribed preventive measures. A problem with cost-benefit studies is the lack of knowledge on the effectivity of preventive measures. In order to carry out a study on the efficacy of the preventive measures, Huijps et al. (2010b) did an extensive literature review of more than 400 papers on mastitis prevention. Only 43 contained useful quantitative information, which was based on intervention studies. Those studies all involved chemical or pharmaceutical compounds and were financed by companies. Therefore, expert opinions were systematically collected to evaluate the effectiveness of the proposed preventive measures. A cost-efficacy study was then carried out using data envelopment analysis.

Ruegg & Dohoo (1997) described the results of an experiment on two groups of cows with different measures of premilking teat hygiene. The results were combined with normative economics to conduct a straightforward economic analysis comparing both groups.

An economic study based on extensive data collection [150 variables regarding mastitis and fertility management, technical results, and economic results collected on 38 dairy farms (Rougoor et al. 1999)] as well as the association between management and technical and economic results (gross margin) was evaluated. Only awareness of diseases could be related to the gross margin of farms. Archer et al. (2014) introduced a novel method—Bayesian microsimulation—to determine budgets and their associated uncertainty available for preventive measures, given the expected effectivity and returns. The framework was tested for heifer mastitis with three different preventive measures. Using the same methodology, Down et al. (2016) used data collected on 77 UK dairy farms on the occurrence of clinical and subclinical mastitis in combination with changes in preventive measures. Posterior probabilities of the mastitis situation were calculated based on the preventive measures used and included the levels of uncertainty. These results were used in a stochastic Monte Carlo simulation of a theoretical UK dairy herd to estimate the cost-effectiveness of the methods.

### Other Approaches

Since 1992, only one series of studies went beyond the classical failure cost or cost-benefit studies utilizing behavioral economic concepts to examine farm manager decisions related to mastitis. The first study in this series used adaptive conjoint analysis to explore the role of economics (the reduction of failure costs or the role of milk quality payment schemes) in motivating farmers to improve mastitis on their farms (Valeeva et al. 2007). Interestingly, the relative importance of the milk quality payment systems was larger when it was a penalty system rather than a bonus demonstrating loss aversion. Huijps et al. (2009b, 2010a) followed up on this study using behavioral economics experiments with dairy farmers. They found evidence of an endowment effect as well as a gain-loss disparity in dairy farmers when they made decisions on prevention of mastitis (Huijps et al. 2010a). In another experiment dairy farmers were not indifferent to the types of preventive measures. Under equal cost-benefit circumstances, farmers had preferences for certain preventive measures over others (Huijps et al. 2009b).

## SUMMARIZING THE COSTS OF MASTITIS

### Cost Factors

The failure costs of mastitis, similar to those of other production diseases, typically consist of production losses and expenditures. In a framework presented by Halasa et al. (2007), the following cost factors were distinguished:

- Milk production losses. As a result of mastitis, a cow will produce less milk during the disease episode and afterwards due to changes in the milk glandular tissue. This will lead to revenues forgone and often results in lower costs for feed. In a quota situation (where a farmer is only allowed to deliver a maximum amount of milk per year), milk production losses will not result in lost revenues but in additional costs to have other animals produce the milk that was forgone.

- Expenditures for drugs. The most obvious cost factor associated with the treatment of mastitis is the expenditure for drugs.
- Losses because of withheld milk. With many (antimicrobial) treatments, milk may not be delivered during and after the treatment because of drug residues. This will result in lost revenues. Because the milk is produced, there are no savings in feed costs.
- Expenditures for the veterinarian. During severe cases of clinical mastitis, a veterinarian may assist the farmer with additional diagnostics to establish a proper treatment. In some (Scandinavian) countries, each antimicrobial treatment should be accompanied by a diagnosis carried out by a veterinarian.
- Labor costs. Treatments and additional care of mastitis cases require additional farm labor. Depending on the labor situation, the costs for this additional labor are either expenditures (in the case of hired labor) or opportunity costs (in the case of own labor).
- Milk quality payments. Most milk payment systems include incentives to produce high-quality milk. Regarding mastitis, these are either penalties when the somatic cell count (a measure in milk associated with mastitis) in the milk exceeds a certain limit or a bonus when a certain level of somatic cell count is met. More mastitis may lead to penalties or loss of bonus. Moreover, improper handling of milk after antimicrobial treatment may lead to penalties when milk is contaminated with antimicrobials.
- Expenditures for consumables (diagnostics). The occurrence of mastitis may lead to additional costs for diagnostics and other consumables.
- Reduced life expectancy of cows. Mastitis is associated with mortality (quite seldom) and reduced life expectancy of cows. As cows that are replaced will be slaughtered, mortality leads not only to additional costs for replacement animals but also forgone slaughter value. The early replacement connected with mastitis only leads to higher costs for replacement animals. Estimating the costs associated with the reduced life expectancy of cows is difficult because of three main factors. First, the production levels of cows are not stable over time (cows reach a maximum production approximately five years after starting to lactate). Second, the production costs and risk for diseases are not stable over time. Third, farms that rear their own replacement animals have a more or less fixed stock of replacement animals, as it takes two years to rear a replacement cow.

## Failure Costs of Mastitis

Although the publications on failure costs are often not comparable, a number of papers could be used to provide an overview of the failure costs of mastitis at the farm level (**Table 1**). For some Western countries (northwestern Europe and Canada), the average total failure costs of mastitis were $US177 per cow per year (see the sidebar titled Failure Costs of Mastitis). (All costs are in US dollars hereafter.) In Ethiopia, the estimated total failure costs were much lower ($29 per cow per year), but relative to the average farm income, the failure costs in Ethiopia were larger than in Western countries. The largest cost factor was milk production losses. On average, 58% of the total failure costs of mastitis were caused by the decreased milk production of cows. The second important cost factor was the cost of culling. On average, 26% of the total failure costs of mastitis was due to culling. However, estimates differed widely between studies. In the Swedish study (Nielsen et al. 2010), the costs for culling were estimated to be 0, whereas in one Dutch study (Halasa et al. 2009a), the costs for culling were estimated to be 60%. In Ethiopia, the costs of

**Table 1 Overview of the failure costs of mastitis estimates since 1992[a]**

| Publication | Country | Currency | Total | Milk production losses | | Drugs | Discarded milk | Veterinarian | Labor | Quality | Culling |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total costs of mastitis** | | | | SCM | CM | | | | | | |
| Yalcin et al. (1999) | United Kingdom | £ | 150 | 112[b] | NA | 16[c] | NA | NA | NA | 1 | 21 |
| Østergaard et al. (2005) | Denmark | € | 165 | 122 | NA | 43 | NA | NA | NA | NA | NA |
| Huijps et al. (2008) | Netherlands | € | 158[d] | 87 | 26 | 6.8 | 10 | 0.4 | 3.7 | 0 | 25 |
| Halasa et al. (2009a) | Netherlands | € | 55[e] | 1.3 | 6.4 | 10[f] | NA | 1.9 | 9.2 | 0 | 33 |
| Nielsen et al. (2010) | Sweden | € | 121 | 19[g] | 55 | 45[h] | NA | NA | NA | NA | 0 |
| Van Soest et al. (2016) | Netherlands | € | 136 | 42 | 36 | 6.8 | 23 | 0.3 | 4.5 | NA | 23 |
| Getaneh et al. (2017) | Ethiopia | ETB | 29 | 1.9 | 2 | 0.5 | 3.7 | 0.5 | 0.1 | NA | 21 |
| Aghamohammadi et al. (2018) | Canada | $CDN | 428 | 161 | 56 | 3 | 17 | 6 | 8 | 10 | 170 |
| **Costs of clinical mastitis** | | | | | | | | | | | |
| Wolfová et al. (2006) | Czech Republic | € | 74[i] | NA | NA | NA | 44 | 17 | 5 | NA | NA |
| Bar et al. (2008) | United States | $US | 71 | NA | NA | NA | NA | NA | NA | NA | NA |
| Hagnestam-Nielsen & Østergaard (2009) | Sweden | € | 112 | NA | NA | NA | NA | NA | NA | NA | NA |
| Hultgren & Svensson (2009) | Sweden | € | 95 | NA | NA | NA | NA | NA | NA | NA | NA |
| Cha et al. (2011) | United States | $US | 69 | NA | NA | NA | NA | NA | NA | NA | NA |
| Heikkila et al. (2012) | Finland | € | 220 | NA | NA | NA | NA | NA | NA | NA | NA |
| Cha et al. (2014) | United States | $US | 77 | NA | NA | NA | NA | NA | NA | NA | NA |
| **Costs of subclinical mastitis** | | | | | | | | | | | |
| Mungube et al. (2005) | Ethiopia | $US | 38 | 38 | NA | NA | NA | NA | NA | NA | NA |
| Atasever & Erdem (2009) | Turkey | $US | 217 | 217 | NA | NA | NA | NA | NA | NA | NA |
| Tesfaye et al. (2010) | Ethiopia | $US | 79 | 79 | NA | NA | NA | NA | NA | NA | NA |
| Sinha et al. (2014) | India | INR | 22 | 22 | NA | NA | NA | NA | NA | NA | NA |

[a]Costs factors are based on Halasa et al. (2007). All estimates are expressed in $US per cow per year. If another currency was used in the original publication, these were converted using the conversion ratio on February 22, 2019.

[b]Milk production losses for CM and SCM. Net costs (reduced milk sales minus reduce costs for feed) are provided.

[c]Including costs for veterinarian, discarded milk, and labor.

[d]In Hogeveen et al. (2011), this estimate was updated toward a total cost of $93 per cow per year, because for milk production losses due to SCM, a reference was used that overestimated the reduction in milk yield.

[e]The paper described saved costs of $7 per cow per year.

[f]Including discarded milk.

[g]Including effects of an overly high bulk milk somatic cell count on milk price (quality payments).

[h]Including costs for a veterinarian.

[i]There were $8 per cow per year of other costs that could not be categorized.

Abbreviations: CM, clinical mastitis; NA, not applicable; SCM, subclinical mastitis.

## FAILURE COSTS OF MASTITIS

Relative to the gross margin per cow per year, the estimated failure costs of mastitis of $147 per cow per year are considerable. In the European Union (where almost all of the failure cost estimates were made), the average gross margin on dairy production varied in the past 10 years from $94 to $157 per 1,000 kg of milk. Assuming an average milk production of 8,500 kg per cow per year, the failure costs due to mastitis represent 11–18% of the gross margin of dairy farms.

culling comprised a large proportion of the total failure costs of mastitis. In contrast, expenditures for drugs and/or veterinarians were a relatively low cost factor. On average, 17% of the total failure costs of mastitis were caused by expenditures. These costs were especially high in Scandinavian countries (Denmark and Sweden), where the costs of treatment are much higher than elsewhere.

In the United States, only a few failure cost estimates exist for clinical mastitis (**Table 1**). Compared to those in other countries, these estimates were relatively low, on average $72 per cow per year. Nonetheless, given the total of 8.734 million lactating dairy cows in the United States, the aggregated failure costs of mastitis there are estimated to be $629 million per year. Because these are the failure costs of only clinical mastitis, the aggregated total failure costs for mastitis in the United States may be up to $1 billion per year. For the Netherlands, with a total of 1.63 million lactating dairy cows and average total failure costs of mastitis of $116.3 per cow per year, the estimated aggregated total failure costs of mastitis are $190 million per year.

The estimates for failure costs of subclinical mastitis showed much heterogeneity (**Table 1**). This may be because these estimates were mostly based on measurements of milk production losses on a small number of farms that could have been problem farms.

# THE PROGRESS IN ECONOMIC THINKING: HIGHLIGHTS AND NOVEL DEVELOPMENTS

## Conceptual Developments

In the years since the publication of McInerney et al. (1992), some studies further developed a conceptual approach. Halasa et al. (2007) wrote a review that introduced a framework of the cost factors to be taken into account when calculating failure costs of mastitis. Hogeveen & Van der Voort (2017) refreshed the framework of cost factors and updated the McInerney et al. (1992) framework, resulting in a failure costs–preventive costs frontier. For farmers and their advisors, two types of decisions are conceptually quite different from each other. The first type is on the optimization of treatment and associated diagnostics of (clinical) mastitis cases, whereas the second type is the optimization of prevention of mastitis. Therefore, the failure costs–preventive costs framework was introduced.

Several concepts from the field of behavioral economics were introduced by Huijps et al. (2009b, 2010a). Using economic experiments, these authors studied phenomena such as the endowment effect and gain-loss disparity as well as the farmers' preferences for certain types of preventive measures.

## Methodological Developments

Stott & Kennedy (1993) were the first to create a dynamic programming model to evaluate the economic effects of mastitis. Modeling mastitis management as a dynamic programming model focuses on maximizing the discounted expected value of net cash flows from the cows. The decision for each cow with mastitis is whether to treat or replace in each decision period. The decision is a classic asset replacement problem where the expected net present value of a particular cow's cash flow is compared to a challenger alternative. Results depend on the relative prices of milk and feed, cull and replacement cattle, and treatment costs and technologies. Initially, dynamic programming had been applied to dairy cattle replacement decisions (e.g., Van Arendonk 1985, Kristensen 1987). Because animal diseases are an important reason for culling, it is only logical to implement them in culling optimization calculations, as was first done in 1993. Dynamic programming has been one of the two modeling approaches that became most prominent in research on the economics of mastitis.

The other prominent modeling method is Monte Carlo simulation, which can be seen as a class of computational algorithms based on repeated random sampling. Elements of the simulation process that are probabilistic are represented using an appropriate probability distribution and, with each iteration, one number will be drawn from each of the probability distributions in the simulation model. After a number of iterations, a distribution of the output variables is provided. In bioeconomic models, this process offers insight into the naturally occurring variation in biological systems and the consequential economic effects thereof. The first study using Monte Carlo simulation was published in 1996 (Dekkers et al. 1996). Monte Carlo models had been applied earlier in animal disease modeling (e.g., Hogeveen et al. 1993, Carpenter 1998) but not in the economics of mastitis. Dekkers et al. (1996) created a straightforward simulation model for bulk milk somatic cell count and added one stochastic element. Later, a more complex bioeconomic stochastic simulation model was developed and published (Allore & Erb 1998), in which pathogens causing clinical and subclinical mastitis were modeled, including the effects on milk production, treatments, and culling. Results of the simulation model were used to calculate economic effects. Although the economic calculations were quite straightforward, the complexity of the modeling could be seen in the biological part. Mastitis is an immensely complex disease with many interactions between the cow, environment, and management. In bioeconomic models, this complexity is captured by simulating the mastitis and its interactions. The simulated technical results are then translated into monetary terms by multiplying effects with prices. Numerous bioeconomic Monte Carlo models have been published in the years after these first articles. Two lines of models were extended throughout a number of studies. The first line of work is based on a model simulating a full herd (Sørensen et al. 1992), and the second one is based on a mastitis transmission simulation model (Halasa et al. 2009a). Most Monte Carlo simulation models included variation and therefore gave a range of outcomes showing the risk of mastitis. For uncertain input variables, the most likely value was used, ensuring that the variation of outcome was a result of naturally occurring variation and not of uncertainty in values or price levels.

The published work on the economics of mastitis was either at the cow level, e.g., the costs of a case of clinical mastitis or the cost-efficiency of different treatment of clinical mastitis, or at the herd level, e.g., the total failure costs of mastitis. However, because of potential transmission of mastitis from one cow to another, a better cure at the cow level does have an effect on the herd level. This requires an extension of the scope of cow-level decision support models, a phenomenon first modeled by Swinkels et al. (2005a). The model was a partial-budget economic calculation where an average time period for cure was estimated, and this average time was used to derive the number of cows infected by a certain non-cured cow with mastitis. Thus, the herd effect of curing a single cow could be attributed to the treated cow, making cow-level modeling possible. Because the phenomenon of transmission of pathogens is often used to advocate more extensive treatment and the culling of chronically infected cows, Halasa et al. (2009a) created a bioeconomic stochastic simulation model at the herd level, enabling the simulation of mastitis transmission in the full herd in an epidemiologically sound way.

## Empirical Research

Until 1999 most publications on the economics of mastitis were model based. Rougoor et al. (1999) were the first to use extensive data (150 variables regarding mastitis and fertility management, technical results, and economic results) that were collected from 38 farms. However, given the heterogeneity of the data, a much larger sample than 38 farms is needed to draw any proper conclusions on the association between mastitis and mastitis management and farm economic performance. The next attempt to evaluate the economics of mastitis using farm data was carried out in Ireland, where Dillon et al. (2015) used panel data containing accountancy data in combination with bulk milk somatic cell counts to evaluate the effect of changes in bulk milk somatic cell count on farm income.

Another approach to work with empirical data was directed at the collection of input data for a normative failure cost calculation model on farms (Huijps et al. 2008). All factors comprising the failure costs of mastitis, such as an incidence of clinical mastitis, level of somatic cell count, as well as production losses and price levels, were estimated at the farm level in a participatory approach. As a result, farm-specific estimates were made, and the variation in costs of mastitis between farms could be evaluated.

## From Failure Costs to Total Costs

Yalcin et al. (1999) were the first to make an estimate of the total mastitis costs. Based on a survey, observations, and routinely available data, the authors estimated the total costs of mastitis for dairy farms in Scotland. The number of preventive measures studied was quite small and based on a very basic protocol to control mastitis, the five-point plan (Neave et al. 1969). Although other estimations for the total costs of mastitis have also been made, they are difficult to compare because no proper definition of preventive measures is available. Van Soest et al. (2016) collected data from 120 Dutch dairy farms on the occurrence of clinical mastitis and cow somatic cell count to calculate the failure costs per farm. These failure costs were combined with estimated costs of ten preventive measures collected using a questionnaire. The study calculated the total costs of mastitis and utilized the failure cost-preventive cost frontier described by Hogeveen & Van der Voort (2017). Finally, given the increased interest in environmental sustainability, the failure costs of increased somatic cell counts were recently combined with greenhouse gas emissions (Gulzari et al. 2018).

# DISCUSSION

In this review, we have examined the progress in economic thinking regarding animal production diseases. We focus on mastitis, as it is the most important production disease in dairy farming, and most research papers that we reviewed addressed mastitis (Niemi et al. 2014). Moreover, most work on the economics of production diseases in general has been carried out on dairy cattle. For instance, in poultry production, only a few publications could be found on the economics of production diseases (Jones et al. 2018). Therefore, the progress that has been made in economic thinking on production diseases in animal production systems is evident in the scientific literature on the economics of mastitis.

In total, we evaluated 77 peer-reviewed papers published since 1992. These were scientific publications solely aimed at the economic aspects of mastitis. Publications that were more general in nature (e.g., Bennett 2003, Bennett & IJpelaar 2005) were not reviewed. Interestingly, almost all were published in veterinary and animal science journals, whereas only a few were published in agricultural economics journals. This partly explains the lack of description of economic theories used by the authors in their studies. A clear identification of the theory is a typical aspect of articles in (agricultural) economics and other social science journals. This result can also be attributed to the authors. In approximately 10% of the papers we reviewed, the authors consisted solely of economists, and approximately 30% had authors defined as animal scientists (veterinarians, mastitis researchers, and/or epidemiologists). Most articles (~60%) had a mixed authorship composed of mastitis researchers and animal health or agricultural economists. First authors were often scholars in the animal sciences who were assisted by economists. Consequently, many of the studies sought an economic answer to a practical question—for instance, the calculation of the failure costs of a specific mastitis situation or a management measure of interest—rather than attempting to further the field of animal health economics. As a consequence of this pragmatic approach to research on the economics of mastitis, the framework described in McInerney et al. (1992) and McInerney (1996) is usually not utilized. This framework was difficult to follow in a time when the data were lacking to properly work out animal health problems according to theory, whereas the operations research–based approach of Dijkhuizen et al. (1991) requires less basic knowledge about input-output relations regarding animal health, which resulted in numerous publications on several animal health problems.

Methodological progress has been made over the past 25 years. Two main methodological approaches can be distinguished: the use of dynamic programming to optimize a number of decisions (insemination and culling) in relation to mastitis and the use of Monte Carlo simulation modeling. Both modeling approaches are bioeconomic in nature, and progress has clearly been made in the biological modeling of mastitis. More complex situations (e.g., the interaction between animals regarding transmission of disease) can be modeled. The interest of the research groups (often within veterinary or animal science departments) might have stimulated this line of development toward improved biological modeling rather than economic modeling.

An interesting question is why so few agricultural economists have worked on animal production diseases. One reason could be the amount of heterogeneity present in animal diseases that might have hampered the estimation of cow- and/or farm-level production functions. Without proper production functions, useful estimations of economic input-output relations are difficult. In order to capture heterogeneity, large amounts of high-quality data are necessary. The availability of more data offers opportunities to conduct more in-depth economic studies, bringing economic theory further into the domain of animal production diseases. A good start would be to revisit the McInerney framework to fit currently available data. Such an improved framework should look at the individual animal (cow) as well as at the herd and the interaction between those two levels.

Much of the work on the economics of mastitis has been focused on the failure costs of the disease. Summarizing the estimates of these studies shows that the failure costs of mastitis are considerable: $147 per cow per year. Given a gross margin on dairy production ranging from $94 to $157 per 1,000 kg milk in the past 10 years (EU 2018) and assuming an average milk production of 8,500 kg per cow per year, these losses represent 11–18% of the gross margin of dairy farms. Only a relatively small part of these failure costs consists of visible expenditures. Most failure costs are due to milk production losses and reduced life expectancy of cows (61–90%). Farmers, therefore, likely underestimate these costs, as has been shown by Huijps et al. (2008). Thus, estimates of the failure costs of mastitis do not directly support decisions, but they can be used to create awareness of the problem of mastitis.

Although two studies addressed a wider economic level than that of the individual farm (Miles et al. 1992, Losinger 2005), these were poorly undertaken. Economists understand that industry-, sector-, or economy-wide effects of disease are not accurately estimated by multiplying the cost per animal (or herd) by the number of animals (or herds). Eliminating or diminishing disease effects will result in a higher quantity of milk supplied to the market, having effects on the price equilibrium, ceteris paribus. Additionally, consumer valuation of livestock products may be affected by the presence or absence of disease. Within the field of the economics of mastitis, efforts should be made to publish these types of studies and move the research further beyond the farm level.

Evidently, a cost-benefit analysis of a proposed preventive measure will be of a higher value to support decisions than an estimation of the failure costs. For cow-level decisions, especially involving veterinary drugs, there is ample knowledge that enables proper cost-benefit analyses, as has been shown by several studies aimed at specific cow-level treatment decisions. However, at the herd level, the number of studies that are useful for farmers and their advisors to support decisions are limited. Only a few studies evaluated a larger number of preventive measures, using expertise to estimate the effectiveness of preventive measures.

Although not explicitly stated, almost all studies focused on supporting farmers' decisions assumed profit maximizing behavior of the farmers. Mastitis can be seen as a reduction of production efficiency. However, because of the animal welfare consequences, mastitis can also be seen as an externality of dairy farming. An optimal level of mastitis from a profit maximization perspective may therefore not provide an optimal level of mastitis from a societal perspective. Another externality is the potential for disease treatment to have effects beyond the farm. The obvious example in dairy cattle is the potential for antimicrobial resistance from antibiotics used to treat or prevent mastitis. Antibiotics are used to treat clinical mastitis in lactating cattle or used in some cases for dry cattle treatment (mastitis prevention). The cost and regulation of antibiotics vary across countries. If antibiotic use leads to antimicrobial resistance that affects other animal or even human populations, it would have a great cost to society. From a public policy perspective, the trade-off is between the decreased production losses from using antibiotics (e.g., less milk loss and involuntary culling) and the costs from inability to treat animal and human infections due to antimicrobial resistance. Because farm managers can be expected to focus on the private, farm-level aspects of the decision, if there are public costs, antibiotics will be overused. A reduction in the use of antibiotics to meet public interests will be associated with cost at the farm level (Lhermie et al. 2018). Although these externalities are acknowledged and known, no publications were found that monetarized the animal welfare and antimicrobial externalities of mastitis. As a first step, the McInerney framework could be modified so that the treatment costs were increased to reflect the social costs associated with production diseases. To this end, taxes on antibiotics have been suggested (Hollis & Ahmed 2013).

Because of the externalities associated with mastitis, governments and dairy processors are also interested in reducing the level of mastitis and want to create incentives for farmers to do so. Economic calculations are often used to motivate farmers to change their behavior. However, it is known that economic arguments used by advisors are often ignored by farmers (Valeeva et al. 2007). In the last decade, numerous studies have tried to understand farmers' decision making regarding mastitis by using theories other than utility theory. However, only a few studies trying to understand farmers' decision making have used other economic theories, such as prospect theory (Huijps et al. 2010a). More studies have focused on theories from communication sciences and social psychology to explain the behavior of dairy farmers regarding production diseases (Rehman et al. 2007, Gilbert & Rushton 2018) and more specifically mastitis (e.g., Van den Borne et al. 2014, Mekonnen et al. 2017). However, there are no proper attempts to apply utility maximizing theory to explain farmers' behavior. For this reason, it is important to understand the objectives of farmers and the relative utility associated with those objectives. Future economic research to better understand incentives of farmers is therefore warranted (Hennessy & Wolf 2018).

Another direction for future research might involve incorporating models from pest management. Economic threshold models are standard in assisting decision making about pest management but they have not generally been applied to livestock health issues (Davis & Tisdell 2002). Similar to pest management decisions, farmers' decisions on mastitis treatment involve balancing the benefits of control and prevention against the costs, but they are also influenced by risk attitudes and information constraints (Waterfield & Zilberman 2012). As milk quality standards increase with related premiums and discounts along with treatment options and technologies, the economic intervention threshold for mastitis changes. Existing management heuristics and applications to unique farm and market situations might be improved by applying the principles of economic threshold models.

## CONCLUSIONS

Mastitis is the most important production disease in dairy farming, leading to considerable inefficiency in production. In 1992, an important paper was published (McInerney et al. 1992), describing a simple but very useful economic framework for production diseases in animal farming. Because of the importance of mastitis, most publications on the economics of production diseases in dairy farming focused on mastitis. Since 1992, 79 peer-reviewed articles were published on the economics of mastitis, two of which were excluded from our evaluation here. Only one of the 72 papers describing economic analyses of mastitis was published in an agricultural economics journal, whereas the others were published in veterinary or animal science journals. Therefore, they paid scant attention to a theoretical economic framework, and as a consequence, only little progress has been made in improving the economic framework to study production diseases in animal farming.

Most publications estimated the failure costs of mastitis in a specific regional or farming situation. The average total failure costs of mastitis were $147 per cow per year, which is estimated to be 11–18% of the gross margin per cow per year. The two most important cost factors behind these failure costs were milk production losses and culling. At the cow level, a number of usable cost-benefit studies were carried out, primarily to support treatment decisions in the case of specific types of (clinical) mastitis. Most studies had a limited scope of preventative measures, and only a few of the published cost-benefit studies can be used to support farmers in their decisions regarding preventive costs. The lack of good cost-benefit studies on preventive measures is most likely due to a lack of data on the effectivity of preventive measures.

Besides a number of straightforward economic calculation studies that were almost all normative in nature and sometimes linked farm-level observations with prices and other economic input, bioeconomic models were often used in the studies we evaluated. There were two main methodological approaches. The first used dynamic programming, wherein the economic effects of mastitis were modeled under the assumption of optimal culling and insemination decisions. In the second approach, the stochasticity of the biological system was modeled using Monte Carlo simulation. The methodological progress in modeling focused on the biological part of the bioeconomic models. The current bioeconomic models, however, do not handle economic optimization regarding input-output relations. Future research might employ several approaches, including improved production function estimation (at the farm level and cow level) in analysis, the effective use of available data, and improved bioeconomic models. Future research should also focus more on generating knowledge about input-output relations regarding mastitis management. The increasing availability of big databases can support this research.

In addition to leading to farm-economic inefficiencies, mastitis can also be seen as an externality because of the effect on cow welfare and the use of antimicrobials to treat mastitis. Economic research on mastitis, therefore, is increasingly used to explain farmers' behavior about mastitis decisions. Improved economic frameworks are needed to integrate these aspects of externality and farm behavior in the current utility-based framework.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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