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DAIRY CATTLE HOOF DISEASE COSTS AND CONSIDERATIONS FOR PREVENTION

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DAIRY CATTLE HOOF DISEASE COSTS AND CONSIDERATIONS FOR PREVENTION

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Agriculture, Food and Environment at the University of Kentucky

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2018

ABSTRACT OF DISSERTATION

DAIRY CATTLE HOOF DISEASE COSTS AND CONSIDERATIONS FOR PREVENTION

Lameness is considered one of the most important health and welfare issues in the dairy industry. Understanding the total cost per case of disease-specific lameness can help producers select better treatment, prevention, and control strategies for their herds. The first objective of our research was to calculate the costs associated with 3 lameness causing hoof diseases: digital dermatitis, sole ulcer, and white line disease. To accomplish this, a survey of hoof health professionals (hoof trimmers and veterinarians) was conducted to identify treatment related expenditures per case. Data from the hoof trimmer responses to the survey and previously published research were incorporated into a farm-level stochastic simulation model to determine the expected costs per case of each disease and the most influential factors associated with disease costs. The cost per case was calculated by disease type, severity (mild or severe), incidence timing (0 to 60 days in milk, 61 to 120 days in milk, 121 to 240 days in milk, or >240 days in milk), and parity group (primiparous or multiparous). The second objective of our research was to determine the economic value of investing in different lameness prevention strategies. Two prevention strategies were considered: 1) prevention of infectious hoof diseases and 2) prevention of non-infectious hoof diseases. The total expenditures (therapeutics, outside labor, on-farm labor, and prevention costs) and losses (discarded milk, reduced milk production, extended days open, increased risk of culling, increased risk of death, and recurrence losses) associated with each prevention strategy before and after prevention implementation were calculated and compared to find the breakeven investment cost.

KEYWORDS: lameness, hoof health, animal health economics, decision support

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December 15, 2017

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CONSIDERATIONS FOR PREVENTION

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CHAPTER 1

Review of literature: Dairy cow lameness expenditures, losses, and total cost

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Abstract

Lameness is one of the most costly dairy cow diseases, yet adoption of lameness prevention strategies remains low. Low lameness prevention adoption might be attributable to a lack of understanding regarding total lameness costs. In this review, we evaluated the contribution of different expenditures and losses to total lameness costs. Evaluated expenditures included labor for treatment, therapeutic supplies, lameness detection, and lameness control and prevention. Evaluated losses included non-saleable milk, reduced milk production, reduced reproductive performance, increased animal death, increased animal culling, disease interrelationships, lameness recurrence, and reduced animal welfare. The previous literature on total lameness cost estimates was also summarized. The reviewed studies indicated that previous estimates of total lameness costs are variable and inconsistent in the expenditures and losses they include. Many of the identified expenditure and loss categories require further research to accurately include in total lameness cost estimates. Future research should focus on identifying costs associated with specific lameness conditions, differing lameness severity levels, and differing stages of lactation at onset of lameness to provide better total lameness cost estimates that can be useful for decision making at both the herd and individual cow level.

Keywords: disease economics, animal health economics, hoof health, hoof disease, dairy health

Introduction

Lameness is a prominent issue in the dairy industry. Adams et al. (2016) estimated 2014 lameness prevalence in United States herds as 10%, whereas other studies have found lameness prevalence to reach as high as 55% (Von Keyserlingk et al., 2012). Lameness is perceived by producers as one of the top three major health concerns in their herds, with the other two being mastitis and fertility (Leach et al., 2010a). However, understanding of the actual cost of lameness is lacking. Leach et al. (2010a) found that producers cited lack of knowledge about lameness costs as one reason less effort was made to prevent lameness compared to mastitis. If producers estimate lameness costs as less than the cost of implementing lameness prevention and control strategies, those management practices are not likely to be adopted (Leach et al., 2010a). This review aims to 1) identify and discuss the individual factors contributing to total dairy cow lameness costs and 2) summarize previous estimates of total dairy cow lameness costs.

Calculating disease costs

McInerney et al. (1992) defined the total cost of disease as including two components: expenditures and losses. Expenditures focus on disease treatment and investment in prevention whereas losses are the indirect result of disease occurrence, including reduced milk production, reduced reproductive performance, and other factors (McInerney et al., 1992). Figure 1.1 categorizes common expenditures and losses associated with dairy cow lameness, as summarized in this review.

Given that numeric values change over time with inflation, this review focuses more on the contribution of each expenditure and loss category to total lameness costs rather than exact price estimates. However, the relative importance of different factors within a study depends on which factors were included in the total cost estimate. For example, treatment expenditures may contribute a large percentage to total lameness costs in a study where treatment, reduced milk production, and reduced reproductive performance are the only factors included. In a different study where the increased risk of culling and control and prevention investments are also included, treatment will likely contribute a reduced percentage to the total cost. When dollar values are given, the originally reported value was converted to United States dollars and adjusted for inflation to represent 2017 values.

Lameness expenditures

Two main types of disease expenditures exist: treatment expenditures and prevention expenditures (McInerney et al., 1992). Treatment expenditures consist of labor and supplies necessary for treatment (i.e., therapeutics) which are generally reported as a price per case. These estimates for lameness would be most accurate via surveys of hoof trimmers, veterinarians, and producers because they are the individuals charging and paying for them. However, very few large surveys asking for hoof trimmer, veterinary, or producer perception of treatment expenditures associated with lameness, and especially specific lameness conditions, have been conducted. Prevention expenditures include inputs associated with any control or prevention strategy, including management strategies implemented for early detection. Prevention expenditures could also be thought of as investment expenditures because money is spent on prevention with the purpose of reducing total lameness costs (via reductions in lameness incidence). Detection and prevention expenditures are rarely included in calculations of the cost per case of lameness. Instead, these expenditures are typically, although incorrectly, classified as general management costs.

Labor for treatment

On-farm staff, hoof trimmers, or veterinarians most frequently treat lameness. In a survey of 184 farms across the United States, 77% of farms used a professional hoof trimmer for hoof trimming services whereas 16% used a veterinarian or on-farm staff and 7% used no hoof trimming services at all (Adams et al., 2016). Bruijnis et al. (2010) estimated the likelihood of treatment by a producer, hoof trimmer, or veterinarian for seven different lameness conditions, based on experiences in the Netherlands. According to their mathematical model, the probability of a lameness case resulting in labor by the dairy producer (i.e., pulling the cow out of the herd to examine or treat her) ranged from 20% of cases for interdigital dermatitis with heel erosion, sole hemorrhage, or corns (interdigital hyperplasia) to 100% of cases for foot rot. The probability of treatment by a hoof trimmer for each lameness type ranged from 0% of cases for foot rot to 40% of cases for sole ulcers. The probability of a veterinarian visit for each lameness type was either 1% of cases (interdigital dermatitis with heel erosion, digital dermatitis, sole hemorrhage, white line disease, or corns) or 5% of cases (foot rot or sole ulcer). The estimated involvement by a hoof trimmer or veterinarian may seem low, but might result from the difficulty of bringing a hoof trimmer or veterinarian to the farm for every detected lameness case. In other words, only the cases that exist when hoof trimmers or veterinarians are already physically present are likely to be treated by them. When the hoof trimmer or veterinarian is not there and able to treat a case of lameness, lameness conditions that are difficult to treat (e.g., sole ulcers and white line disease) may be left untreated. For example, Horseman et al. (2013) found that if lame cows were only treated by a foot trimmer or veterinarian (not on-farm staff) treatment could be delayed anywhere from 1 week to 1 month.

Table 1.1 includes 7 different studies that calculated total lameness costs per case (both non-specific and condition-specific) and provided a breakdown of the costs contributed by at least 6 different expenditures or losses. Within these studies, the contribution of producer labor to total lameness cost estimates ranged from 2% to 16%, making it on average the seventh most important cost category of those evaluated. The contribution of outside labor (veterinarian or hoof trimmer fees) to total lameness cost estimates ranged from 1% to 43%, making it on average the fifth most important cost category of those evaluated. Some of the variation in these observations can be attributed to labor expenditures being dependent on the type of lameness with some treatments being more intensive than others. Kossaibati and Esslemont (1997) surveyed 10 veterinarians in the United Kingdom about the cost of veterinary labor and found that sole ulcers resulted in the greatest labor charge per affected cow ($66), followed by digital lameness ($49), and interdigital lameness ($39). However, the percentage of the total cost attributed to veterinary labor was actually greatest for interdigital lesions (12%) and least for sole ulcers (6%). Sole ulcers are expected to have greater losses (e.g., reduced milk yield, reduced reproductive performance, increased culling risk) than infectious diseases because of their longer duration (Charfeddine and Pérez-Cabal, 2017); therefore, the percent of costs associated with labor is smaller. Charfeddine and Pérez-Cabal (2017) surveyed Spanish hoof trimmers to estimate the total cost of three different lameness conditions while considering severity of lameness as a factor. In mild lameness cases, they found that the condition with the greatest contribution of labor (including labor from both hoof trimmers and producers) to the total cost per case was digital dermatitis (49%), followed by white line disease (29%), and sole ulcers (25%). The opposite order was true for severe lesions (23%, 19%, and 15% for sole ulcers, white line disease, and digital dermatitis, respectively). For all lameness conditions, the contribution of labor to total costs is less in severe cases compared to mild cases because of the increase in losses (e.g., increased chance of culling, greater milk production reduction). Beyond lameness condition type, location of the study could also influence the contribution of labor to total lameness costs. For example, involvement by veterinarians is more common, and even required for treatment, in some countries.

Liang et al. (2017) surveyed 19 veterinarians and industry professionals and used their estimates to simulate both veterinary and producer labor costs associated with 7 different diseases (mastitis, metritis, hyperketonemia, left displaced abomasum, retained placenta, lameness, and hypocalcemia). Among all disease, the veterinary and producer labor costs associated with non-specific lameness were second highest only behind left displaced abomasum. Therefore, regardless of the percentage of total lameness costs attributed to labor, labor expenditures due to lameness are substantial compared to other diseases.

Therapeutics

Therapeutic expenditures include any medications or supplies used to treat diagnosed cases of lameness. Therapeutic expenditures vary greatly depending on the cause of lameness. For example, standard treatment of noninfectious hoof lesions like sole ulcers and white line disease includes trimming and blocking the hoof to reduce weight bearing on the affected claw (Andrews et al., 2008). Alternatively, digital dermatitis treatment often involves cleaning and topical application of antibiotics using a foot wrap. In addition to the type of lameness, the severity of lameness when treated can also influence therapeutic expenditures (Charfeddine and Pérez-Cabal, 2017). The farm’s hoof trimmer or veterinarian, depending on who is conducting the diagnosis and treatment of lameness cases, sets the prices associated with therapeutics.

Therapeutic expenditure estimates ranged from 2% to 37% of the total cost per case of lameness, making it on average the fourth most important cost category of those evaluated in Table 1.1. Excluding Liang et al. (2017), all therapeutic expenditure estimates included in Table 1.1 were 20% or less, with most being 10% or less. Liang et al. (2017) conducted a survey of veterinarians and other industry professionals to identify expected therapeutic expenditures. The considerable variation among respondents ($42 ± 46), likely due to a small sample size (n = 19), may have contributed to their difference in findings compared to other studies. The fact that this is the most recent of the studies may also have contributed to this finding. Liang et al. (2017) additionally found that therapeutic expenditures associated with lameness were second highest among common dairy diseases, only behind left displaced abomasum.

As expected, lameness conditions that require more supplies to treat had an increased contribution of therapeutics to total costs. Kossaibati and Esslemont (1997) found that the cost of interdigital lesions was more dependent on therapeutics (8% of the total cost) than either the cost of digital lesions (5% of the total cost) or sole ulcers (4% of the total cost). Charfeddine and Pérez-Cabal (2017) found that white line disease had the greatest contribution of therapeutics to the total cost per case (16% and 12% for mild and severe lesions, respectively). Second and third were sole ulcers (15% and 12% for mild and severe lesions, respectively) and digital dermatitis (7% and 4% for mild and severe lesions, respectively). Increased lameness severity was again associated with greater losses (reduced milk production, reduced reproductive performance, etc.), decreasing the therapeutics-associated total cost percentage.

Lameness detection

When done correctly, monitoring for the presence of disease can lead to detection at an early stage and allow for earlier treatment, potentially reducing expenditures and losses associated with that case. Additionally, monitoring disease presence is important for recognizing a problem and identifying prevention practices that can reduce overall incidence of disease. Expenditures associated with lameness detection include labor for implementation and, in some cases, the cost of supplementary supplies or tools.

The simplest form of on-farm lameness detection is visual locomotion scoring. Van Nuffel et al. (2015a) identified at least 25 different visual scoring systems for dairy cow lameness characteristics. They noted that although these methods are relatively easy to use and inexpensive to implement (i.e., the only expenditure is labor), the amount of time it takes to conduct scoring on an entire herd means they are not often executed. Another method of lameness detection is identification of lesions during routine visits by a hoof trimmer. Although no added expenditures are associated with this method, relying on it alone can result in missed lameness cases between hoof trimmings, leading to increased severity. This is an especially unreliable lameness detection method in the United States where Adams et al. (2016) reported that 7% of dairy herds never trim their cows, 20% only trim cows when they are visibly lame, and 36% only trim once per lactation.

Recently, individual animal monitoring technologies have shown potential for lameness detection. Walk-over or stand-on load cells, pressure-sensitive position mats, vision techniques, accelerometers, and other already available sensor data (e.g., milk production, activity, rumination time) have all been evaluated for the possibility of automated lameness detection (Van Nuffel et al., 2015b). The economic value of investing in an automated lameness detection system remains unquantified. One difficulty of identifying the value of automated lameness detection is determining what will be done when a lameness alert is given (Van Nuffel et al., 2015b). If a reason for the lameness alert is identified, treatment can occur and reduced severity of the condition is beneficial to the farm. However, if a reason for lameness is not found, the value of the early detection is negative instead of positive (i.e., labor was used to check the cow and evaluation of the hooves for a problem could result in hoof damage). One possibility is that the technology alert occurs before the lameness condition is visibly apparent (i.e., not a false alert, just early), but without an actionable response to that alert, it has no value. Regardless, the economic potential of automated estrus detection systems has been quantified (Rutten et al., 2014, Dolecheck et al., 2016) and it stands to reason that some of these systems could additionally be used for lameness detection with minimal added expenditures (i.e., only labor for checking alerted cows).

Regardless of the available options, lameness diagnosis on dairy herds is generally not proactive. One reason for this may be that producers tend to underestimate the prevalence of lameness in their herds (Bell et al., 2006, Espejo et al., 2006, Leach et al., 2010a). Additionally, producers perceive lameness management to be more challenging to include in daily routines compared to other health issues, like mastitis, which can be managed in the parlor (Leach et al., 2010a). Instead, lame cows are often only identified after they become severely lame (Mill and Ward, 1994), completely ignoring mildly lame cows that would benefit most from early detection. Possibly for this reason, no identified studies included an estimate for expenditures on lameness diagnosis or detection in their calculated total lameness cost. However, if detection and diagnosis is proactive, an accurate estimate of a herd's total lameness cost should include the cost of proactive diagnostic measures.

Lameness control and prevention

Control and prevention strategies for reducing lameness incidence can be either repetitive actions, or one-time, long-term investments. Examples of repetitive investments include preventive hoof trimming (Fjeldaas et al., 2006), footbaths (Laven and Hunt, 2002), hoof health feed additives (Bergsten et al., 2003), or even genetic selection (Pritchard et al., 2013). An example of a long-term investment in lameness prevention would be the installation of rubber flooring (Vanegas et al., 2006) or the redesigning of poorly constructed freestalls (Ito et al., 2010). Expenditures associated with these different strategies might include labor, supplies, and depreciation.

Although many of these strategies are lameness specific, some lameness control and prevention expenditures could overlap with control and prevention of other diseases. For example, updating old freestalls could improve more than just lameness incidence (e.g., reduced mastitis incidence, improved cow longevity). Therefore, identifying the proportion of prevention costs associated with a specific management change that should be attributed to lameness is essential for accurate total lameness cost estimates. The effects of most of these prevention and control strategies are not well studied and are difficult to quantify. Therefore, how best to account for these expenditures when estimating the total cost of lameness is unclear.

Very few estimates of total lameness costs include any allocation to prevention strategies. Kaneene and Hurd (1990) surveyed 60 Michigan (USA) herds to find that, on average, $4/cow per year was spent on prevention of lameness as estimated by the producers. Among 7 other diseases, lameness prevention costs ranked as the third greatest, only behind mastitis ($9/cow per year) and fertility problems ($7/cow per year). Miller and Dorn (1990) estimated lameness prevention expenditures (including preventive trimming, veterinary services, and labor) using data from 16 Ohio dairy farms (1 304 total cows) to be $2/cow per year. Prevention expenditures for lameness were greater than for hypocalcemia, displaced abomasum, or dystocia, but less than mastitis, infertility, pneumonia, or “other” diseases. For both of these studies, prevention cost estimates focused on disease-specific costs rather than general management practices like nutrition and housing, likely resulting in under-estimation of prevention costs for all diseases. Additionally, these estimates of prevention expenditures were all reported as $/cow per year rather than $/case. Although prevention is generally paid in $/cow per year, producers should also consider how much they are spending on prevention per case to help determine if prevention expenditures are beneficial. For example, Bennett et al. (1999) estimated expenditures on lameness prevention via hoof trimming in the United Kingdom to range from $6 to $12 per case of non-specific lameness (4% to 7% of total case costs, depending on the assumptions used in their model).

Ettema and Østergaard (2006) estimated the value of five lameness prevention strategies (footbathing, rubber flooring, pasture access, trimming, and biotin supplementation) using a stochastic Monte Carlo model. The model included reduced milk yield, reduced feed intake, weight loss, reduced conception rate, and increased mortality as lameness outcomes. Assuming an average Danish dairy herd, all strategies increased the total profit margin per cow-year with rubber flooring providing the greatest increase ($9/cow-year) and footbathing providing the least increase ($2/cow-year). However, the cost associated with each prevention strategy was not included. Therefore, the increase in profit margin would only be realized if expenditures on the prevention strategy were less than the potential profit. The expenditures associated with implementation (including labor, supplies, etc.), the current herd prevalence of lameness, and the effectiveness of the prevention strategy would influence the overall value of each control and prevention strategy.

Lameness losses

Whereas expenditures involve increased costs, losses revolve around reduced returns. The three categories that most losses will fall under are reduced outputs, reduced output quality, and animal welfare effects. In previous estimates, losses represent 37% to 93% of total lameness costs, outweighing the expenditures in most cases (Table 1.1).

Estimates of disease losses typically come from epidemiological or survey studies. Commonly, animals are observed over a defined period of time and comparisons (e.g., milk production, reproductive performance) are made between those cows that became lame and those cows that did not. Results between studies conducted this way can be difficult to compare for many reasons. First, the definition and identification of lameness are not always consistent. Whereas some studies use periodic visual lameness scoring to define lameness, others use lesion presence, and still others rely on farmer or veterinarian identified lameness cases. Second, the losses associated with a disease are specific to both the severity of disease and the timing of disease occurrence within the lactation, which depends on the disease definition and identification strategy. Studies using periodic visual lameness scoring will likely identify and treat cows before the time a producer generally would, resulting in an underestimation of lameness losses because of reduced lameness severity. On the contrary, cases defined by farmer or veterinarian diagnosis will likely be more severe but may mean that mild lameness is entirely overlooked. Third, the potential confounding factors that studies account for can differ. Some of the losses associated with lameness, including reduced milk production and reduced reproductive performance, are related to many other factors (e.g., nutrition, other diseases) that need to be considered to accurately estimate losses associated with just lameness. This is different from expenditures, which are linked to a specific disease or condition.

Undoubtedly, other losses beyond those mentioned exist but are hard to define or difficult to quantify. Losses are discussed with emphasis on the general influence of lameness on the amount or quality of the product (e.g., milk production, days open) rather than the exact value of that amount because market values fluctuate greatly with farm location and time.

Non-saleable milk

Milk discarding is required after antibiotic treatment. Although antibiotic use is common for mastitis cases (Rollin et al., 2015), most lameness cases do not require antibiotics, resulting in no discarded milk. Stricter antibiotic use guidelines worldwide could further reduce discarded milk associated with lameness and other diseases. Non-saleable milk loss estimates were consistent between the studies identified, ranging from 1% to 11% of the total cost per case of non-severe lameness, making it on average the least important cost category of those evaluated in Table 1.1.

Lameness treatments including antibiotic use are more common when lesions are severe. Charfeddine and Pérez-Cabal (2017) found in their survey that no antibiotics, and therefore no resulting discarded milk, were needed for mild lesions. However, survey respondents did use antibiotics for severe lesions, resulting in some discarded milk (258 kg/treatment, 331 kg/treatment, and 312 kg/treatment for severe digital dermatitis, sole ulcer, and white line disease, respectively). They estimated that milk withholding represented the second most important cost for severe lesions (24%, 20%, and 20% of the total costs associated with a cow affected by severe digital dermatitis, severe sole ulcers, and severe white line disease, respectively). The specific dollar value of discarded milk is dependent on the milk market where a herd is located and the potential alternative uses of that milk (i.e., feeding discarded milk to calves).

Reduced milk production

Lameness influences milk production via many different and interrelated factors. Huxley (2013) summarized previous studies that estimated a milk yield loss of 270 to 574 kg per lactation when lameness occurred. Evidence exists that this milk loss occurs during not only clinical lameness, but also pre-diagnosis and post-recovery depending on lameness type (Green et al., 2002, Amory et al., 2008, Charfeddine and Pérez-Cabal, 2017). Because of this, the point in lactation that a lameness case occurs will influence the total milk loss associated with incidence of the disease (i.e., milk loss may continue until the end of the lactation). The relationship between lameness and milk production is two-fold. Although lameness incidence decreases milk production, increased milk production is also a risk factor for lameness (Barkema et al., 1994, Green et al., 2002, Amory et al., 2008). Barkema et al. (1994) estimated that for every 100 kg increase in milk production during the first 100 DIM of the previous lactation, cows experienced a 1.1 times greater chance of lameness in the current lactation. Therefore, the effect of lameness incidence on milk production may lead to some high producing cows becoming average producing cows rather than average producing cows becoming low producing cows.

The exact dollar value of reduced milk production is dependent on the estimated yield reduction, the value of milk (milk price plus bonuses), and the change in feed costs (Charfeddine and Pérez-Cabal, 2017). Because this milk is never produced, as compared to discarded milk, the feed costs savings are especially important to account for. Reduced milk production expenditure estimates have ranged from 9% to 39% of the total cost per case of lameness, making it on average the third most important cost category of those evaluated in Table 1.1. Variation in the percentage of total lameness costs contributed to reduced milk production may result from some studies considering higher yielding cows to be more susceptible to lameness whereas others did not.

Lameness condition type also influences observed reduced milk production. Charfeddine and Pérez-Cabal (2017) estimated reduced milk production to contribute between 13% and 18% to total costs per case for mild and severe digital dermatitis, sole ulcers, and white line disease. The only exception was an increased percentage (34%) for mild digital dermatitis cases because their shorter duration resulted in reduced expenditures and other losses. Cha et al. (2010) estimated reduced milk production to represent 27% of total costs per case for both digital dermatitis and foot rot and an even greater amount (38% of the total case cost) for sole ulcers. The increased percentages of total cost attributed to reduced milk production reported by Cha et al. (2010) were likely the result of only 3 factors being included in their estimates: treatment, reduced milk production, and reduced reproductive performance.

Reduced reproductive performance

Traditionally, lameness has been thought to reduce reproductive performance via decreased estrus detection (Lucey et al., 1986). However, Collick et al. (1989) noted that overall days open was affected by lameness more than the time to first service, suggesting that reduced estrus detection may not be the only factor contributing to poor reproductive performance in lame cows. Recently, hormone profiles of lame cows have been studied to further define the relationship between lameness and reproductive performance (Walker et al., 2008, Sood et al., 2009, Morris et al., 2011). The exact physiological mechanism by which lameness affects reproductive performance remains undefined, but is likely a combination of multiple factors.

Huxley (2013) provided a summary of studies that considered the effect of lameness on reproductive performance. In the reported papers, lameness resulted in a mean 7 d longer time to first service, 30 d increase in days open, 20% lesser conception rate, and 1.2 more services per conception. The exact value of these adverse effects depends on the cost of a day open or the value of a pregnancy. Both of these are herd specific, making an estimate of the economic influence of lameness on reproduction difficult. A critical contributor to the extent of reduced reproductive performance resulting from lameness is the timing of the disease (Lucey et al., 1986). If lameness occurs in later lactation, after pregnancy establishment, its effect on reproduction will likely be lesser than if the occurrence is before first breeding. However, the effect of late lactation lameness on the next lactation has not been thoroughly explored.

The reported percentage of total lameness costs attributed to reduced reproductive efficiency ranged from 0% to 48%, making it on average the second most important cost category of those evaluated in Table 1.1. Parity contributed to some of the variation observed. Liang et al. (2017) found that reproductive losses represented 3% and 25% of the total costs per case for primiparous and multiparous cows, respectively, noting that unique market conditions assumed in their study resulted in deviations from previous cost of days open estimates. On the other extreme, both Kossaibati and Esslemont (1997) and Esslemont (2005) estimated the greatest percentage of total lameness costs attributed to reduced reproductive performance (42% and 48%, respectively) when considering interdigital lameness. The actual effect (in days open) of interdigital lameness on reproductive performance was assumed less than a sole ulcer in the same studies, but because interdigital lameness was assumed to have no effect on culling, the percentage of the total cost per case attributed to reduced reproductive performance was greater.

As with expenditures and other losses, the type of lameness also influences the value of reduced reproductive performance. Cha et al. (2010) found that although the percentage of costs attributable to reduced reproductive performance was similar between sole ulcers (33%) and digital dermatitis (31%), that percentage was greater (45%) in foot rot cases partially because of relatively lesser treatment costs for foot rot. However, Charfeddine and Pérez-Cabal (2017) found a lesser percentage of costs attributable to reduced reproductive performance with only around 3% for severe digital dermatitis and white line disease ($12 and $19, respectively), but 6% for severe sole ulcers ($38). Their lesser contribution of costs to reduced reproductive performance can be attributed to the reduced effects of lameness on days open in their study compared to those summarized by Huxley (2013).

Increased death and culling

Relatively few animals die as a direct result of lameness. However, welfare standards requiring cows to be ambulatory to enter a slaughter facility result in euthanasia of some lame cows on-farm rather than them being sold as cull cows. Thomsen et al. (2004) found in interviews with Danish producers that although only 2% of unassisted deaths were attributed to lameness, 40% of euthanized cases were. The USDA (2007) National Animal Health Monitoring System Dairy Survey reported that 20% of United States dairy cow deaths resulted from euthanasia after either lameness or injury. McConnel et al. (2015), utilizing the same data, noted a relationship between lameness and mortality where mortality was predicted to increase by 0.8% for every 1% increase in the proportion of lame cows. However, this could be a result of lameness causing other diseases to occur which are ultimately the cause of euthanasia rather than lameness itself.

The exact percent of lameness cases that result in death remains mostly undefined in the literature. Based on previous veterinary experience in the United States, Guard (2008) estimated that 2% of lame cows become disabled to the point that they are not accepted for slaughter. However, this anecdotal estimate may be more accurate for herds before the strict non-ambulatory guidelines put into place in the United States in 2004. Regardless, for any lameness cases that do result in euthanasia, the cost to the producer is the same as a dead cow plus the cost of euthanasia (captive bolt, gunshot, veterinarian, etc.) and the emotional toll that does not have a well-defined value.

Alternatively, the effect of lameness on culling has been extensively explored with the general conclusion being that lameness incidence decreases the productive life of a dairy cow (Huxley, 2013). Charfeddine and Pérez-Cabal (2017) found that incidence of either sole ulcer or white line disease decreased the length of productive life between 35 and 71 d compared to unaffected animals. No significant effect of digital dermatitis on the length of productive life was found. Similarly, Cramer et al. (2009) identified no effect of infectious lameness (foot rot, digital dermatitis, and heel horn erosion) on culling. In studies where culling has not been found to be affected by non-infectious lameness this is rationalized because the cows that are more susceptible to culling are also the superior producing cows and, therefore, they are not viewed by producers as uneconomical (Barkema et al., 1994, Archer et al., 2010). Additionally, cows might be recorded as leaving the herd for low production or reproductive failure when lameness was the root cause of removal (Guard, 2008). This emphasizes the importance of disease incidence recording and the proper identification of culling reason to be able to accurately estimate the effects of different diseases on culling.

Estimates for losses associated with an increased risk of culling or death ranged from 0% to 50% of the total cost per case of lameness, making it on average the most important cost category of those evaluated in Table 1.1. The extremely low values (0%) were only found in estimates for interdigital lameness, with most estimates falling between 20% and 40%. Charfeddine and Pérez-Cabal (2017) found that premature culling was the greatest contributor to the cost of a case of mild or severe sole ulcers or white line disease and severe digital dermatitis (23% to 40%). The contribution of culling costs to the cost of mild digital dermatitis was less (10%). Liang et al. (2017) found parity to have little effect on the portion of total lameness costs attributable to culling which accounted for 14% and 16% in primiparous and multiparous cows, respectively.

The cost of culling depends greatly on how culling is calculated. Basic culling costs can be calculated as the cost of a replacement minus the slaughter value of the cull cow. However, this method only accounts for the financial cost of culling, ignoring the economic costs (Bewley et al., 2010). More complex and thorough methods, like retention pay-off, are better for capturing the difference between the potential future value of a cow and the potential future value of her replacement (Groenendaal et al., 2004) and should be used for disease culling cost estimates.

Disease relationships and recurrence

Relationships between diseases are complex and not well defined. When lame and non-lame cows have been compared, similar percentages of common diseases (retained placenta, metritis, hypocalcemia, left displaced abomasum, and dystocia) have been found (Melendez et al., 2003, Booth et al., 2004, Hernandez et al., 2005). Contradicting results exist for hyperketonemia, potentially because of the method of comparison and definitions of hyperketonemia used. Peeler et al. (1994) noted that both dystocia and mastitis increased the risk of lameness pre-breeding (odds ratios = 1.5 and 1.5, respectively), whereas lameness incidence itself increased the risk of mastitis (odds ratio = 1.4). However, other studies have found no link between lameness and mastitis (Melendez et al., 2003, Booth et al., 2004, Hernandez et al., 2005). Another investigated relationship that could be related to the reduced reproductive performance of lame cows is the connection between ovarian cysts and lameness. Melendez et al. (2003) found that the odds of a lame cow having an ovarian cyst were 2.63 times greater than the odds of a non-lame cow. However, given that this was an observational study only, it cannot be concluded that a cause-effect relationship exists.

In situations where lameness is directly responsible for changing the incidence of other diseases, the expenditures and losses associated with those diseases should be included in total lameness costs. Alternatively, if a lameness case is the result of another disease, costs associated with that case should not be considered as contributing to total lameness costs. Very few total lameness cost estimates have even attempted to account for this source of loss. When estimating total lameness costs, Enting et al. (1997) did account for relationships between lameness and other diseases, finding that the contribution of other diseases to total lameness costs (i.e., costs associated with other diseases resulting from lameness) was minimal (1% of total lameness costs).

Not only is the relationship between lameness and other diseases important, but also the potential for lameness recurrence. Costs associated with recurring cases should be considered as part of the total cost of the original case, rather than separately. In previous lameness cost estimates, some studies assume lame cows undergo costs associated with 1.4 cases because of recurrence rates (Kossaibati and Esslemont, 1997, Esslemont, 2005, Ettema and Østergaard, 2006). Using this assumption, Esslemont (2005) found that repeat case costs were 3%, 7%, and 3% of total lameness costs per cow affected by digital, interdigital, and sole ulcer conditions, respectively. However, the recurrence rate of 1.4 appears to be an assumption made by these authors rather than supported by published literature. More recently, Charfeddine and Pérez-Cabal (2017) recorded relapse rates on 804 Spanish farms, finding a range of 2.0 to 3.1 relapses per case depending on lameness condition and parity. However, accurate recurrence rate estimates alone do not answer the question of how much extra cost is attributed to repeat cases. Although recurrence does incur additional costs, those costs are likely not as great as the original case (i.e., total lameness costs do not double with recurrence). Because data is lacking to know how to handle this, some disease models have assumed that recurring disease cases only increase direct costs (labor, therapeutics, and non-saleable milk) and have no influence on indirect costs (milk loss, reproductive performance, culling, etc.; Kossaibati and Esslemont, 1997, Rollin et al., 2015) . Estimates for losses associated with lameness case recurrence ranged from 3% to 14% of the total cost per case of lameness, making it on average the sixth most important cost category of those evaluated in Table 1.1.

Until we have a better understanding of relationships between other diseases and lameness, lameness recurrence rates, and lameness recurrence costs, estimating the economic losses associated with these factors is difficult. Regardless, acknowledging these factors highlights that current estimates may not be accounting for every economic loss associated with lameness.

Reduced animal welfare

Often, diagnosis of lameness does not occur until the cow is obviously limping (Mill and Ward, 1994), indicating a high level of pain (Whay et al., 1998). In surveys, producers have acknowledged the link between lameness and cow pain and suffering (Mill and Ward, 1994, Leach et al., 2010b), but they do not always acknowledge a cost associated with pain and suffering. As previously mentioned, the fact that lame cows might also be the highest yielding cows may influence a producer's view on the welfare effects of the disease. In reality, the pain and suffering associated with lameness has at least two economic consequences.

First, some of the previously mentioned losses associated with lameness (i.e., reduced milk production, reduced reproductive performance) are likely a result of responses to pain and suffering. For example, lame cows tend to spend less time feeding (González et al., 2008) potentially because they spend more time lying down to relieve pressure from their feet (Ito et al., 2010). The result is reduced milk production and economic losses. The association between lameness and reduced reproductive performance might also be related to increased cortisol levels (caused by pain and stress that the animal is experiencing from lameness) affecting hormone function (Dobson and Smith, 2000). In these cases, the economic losses associated with pain and suffering during lameness are already accounted for within other loss categories.

The second economic consequence of poor animal welfare (i.e., pain and suffering) is the potential to influence consumer perception. McInerney (1996) pointed out that one mistake farmers make is assuming lameness costs occur only at the farm level. Recently, Leach et al. (2010b) found that this view may be changing. Seventy-two percent of surveyed United Kingdom dairy farms ranked the desire for a good public image as a "very" or "extremely" important factor contributing to lameness control. However, 35% of those farmers still felt the risk of lame cows influencing farm accreditation was of "very little" or "no" importance.

In reality, consumer perception of the quality of life of our livestock animals could someday result in economic consequences. If consumers lose faith in the production process of a product and reduce their consumption, the market for that product could be affected. This may result in indirect economic consequences to the farmer (i.e., a smaller milk market) or direct consequences in the form of new rules and regulations that dictate the amount of lameness that can be present on a farm or protocols for handling lameness cases. For example, Version 3 of the United States FARM (Farmers Assuring Responsible

Management) program sets the expectation that 95% of the cows on each evaluated dairy will score a 2 or less for lameness (on a 1 to 3 scale; NMPF, 2016). Lameness is a critical component in farm welfare audits around the world and producers will be (or already are) required to follow set guidelines to sell their milk. To date, no economic estimates of the total cost of lameness have included animal welfare.

Total lameness costs

Total lameness cost estimates

Previously reported total lameness cost estimates (expenditures + losses), adjusted to 2017 US dollar values, are listed in Table 1.2 along with which factors each cost estimate included. None of the identified studies considered expenditures associated with lameness detection or losses associated with animal welfare when calculating total lameness costs, pinpointing these two cost factors as requiring further research to estimate. Very rarely were costs associated with lameness control or prevention, interactions with other diseases, or lameness recurrence included. The few studies that did consider these factors were studies mostly conducted in 2006 or earlier. Although this seems counterintuitive, one possibility is that authors of more recent estimates purposely avoided including these factors because they understand the difficulty in accurately accounting for them. Additionally, some of these factors may be difficult to calculate at the case level rather than the herd level (e.g., lameness detection and control or prevention strategies). Factors considered in all or nearly all of the identified studies included labor for treatment (both producer and veterinary), therapeutics, non-saleable milk, reduced milk production, reduced reproductive performance, and an increased risk of culling.

For each study in Table 1.2, cost estimates were calculated as either the cost per cow per year or the cost per case. In studies where the cost per cow per year was calculated, lameness costs were spread across all animals in the herd, regardless of which cows experienced the disease. The resulting cost is highly dependent on the individual farm size and the prevalence of lameness in the herd. For this reason, the cost per case is preferred. Estimates of the cost per case of non-specific lameness ranged from $76 to $533, depending on the location of the study, the calculation method used, and the expenditures and losses that were selected for inclusion (Table 1.2). Liang et al. (2017) estimated that this total cost per case of non-specific lameness was less than a case of mastitis or displaced abomasum, but more than a case of metritis, retained placenta, ketosis, or hypocalcemia. Although more useful than costs per cow per year, these non-specific lameness total cost estimates assume all lameness to be identical.

Often, different lameness disease conditions have been classified into categories and costs are evaluated based on those lameness categories. The most commonly used categories include interdigital disease, digital disease, and sole ulcers (Esslemont and Peeler, 1993, Kossaibati and Esslemont, 1997, Esslemont, 2005, Willshire and Bell, 2009). Among these, sole ulcers are estimated as having the greatest total costs ranging from $232 to $1 073 per case or affected cow (thereby accounting for recurrence), depending on the location of the study, the calculation method used, and the expenditures and losses that were selected for inclusion (Table 1.2). Recently, the total costs of specific lameness conditions have been further explored. Willshire and Bell (2009) added estimates for digital dermatitis and white line disease in addition to the aforementioned general categories. Cha et al. (2010) and Charfeddine and Pérez-Cabal (2017) both looked at the total costs associated with digital dermatitis and sole ulcers whereas Charfeddine and Pérez-Cabal (2017) alone looked at white line disease and Cha et al. (2010) alone looked at foot rot. Based on these limited studies, digital dermatitis appears to have the least total costs of the evaluated conditions whereas sole ulcers have the greatest total costs (Table 1.2). Charfeddine and Pérez-Cabal (2017) noted that digital dermatitis generated overall lesser costs than noninfectious disorders mainly because of the reduced length of time the disease affected the animal, resulting in reduced treatment, labor, discarded milk, and milk loss; however, none of the studies considered the possibility of digital dermatitis or other infectious diseases transmitting to other animals. The importance of looking at total lameness costs specific to disease type was emphasized by Cha et al. (2010) who noted that the top cost contributors differed by disease. Milk loss contributed the most to the total cost of sole ulcers (38%), treatment was the greatest contributor to the total cost of digital dermatitis (42%), and decreased fertility was the greatest contributor to the total cost of foot rot (50%).

Accuracy of total lameness costs

Although condition-specific lameness costs are an improvement over non-specific cost estimates, these estimates are still highly dependent on the assumptions used in the model. In reality, the cost of lameness conditions varies by herd, cow, and lameness case characteristics. At the herd level, variation in market prices and management styles will affect lameness incidence, treatment, and recovery. At the cow level, the cost of a case of lameness depends on an individual cow's milk production potential, pregnancy status, and age (Cha et al., 2010). Finally, characteristics of the lameness case beyond disease type, including the point in lactation when a cow becomes lame and the severity of the lameness condition, will affect total lameness costs (Cha et al., 2010, Charfeddine and Pérez-Cabal, 2017). Of all these influential factors, only the severity of the lameness condition has been considered in any lameness cost estimates and only once by Charfeddine and Pérez-Cabal (2017). They found that although severe lesions were less common, their cost was almost 3 times greater than the cost of mild lesions because of their effect on the cow's longevity. The ideal scenario would be to provide decision support tools that could use herd, cow, and case-specific information to help a producer determine the best individual treatment and culling strategies whenever a cow became lame.

Beyond the definition of lameness used in an economic analysis (i.e., overall, disease type, or cow-specific) the accuracy of these estimates depends on many factors. First, the correct expenditures and losses for a disease need to be included in the model. Our understanding of lameness and all of the factors associated with it continues to develop, as emphasized by the variation in factors included in the 14 studies in Table 1.2. Likely, past estimates excluded some critical factors and current estimates are still missing factors we have yet to consider.

Even if researchers agreed on which expenditures and losses to include, this does not completely solve the problem. The reliability of cost estimates depends on the accuracy, availability, and reliability of the empirical data used to create them (Dijkhuizen et al., 1995). Estimates for some of the factors are lacking (e.g., the expenditures associated with detection and the losses associated with animal welfare issues). Additionally, most existing estimates for losses associated with lameness were generated from datasets where lameness was defined by a lameness or gait score rather than by the presence or absence of specific conditions. Therefore, the ability to generate further condition-specific lameness cost estimates is limited until this data exists. Recently, Charfeddine and Pérez-Cabal (2017) used a dataset containing over 108,000 records to estimate the effect of three specific claw disorders (digital dermatitis, sole ulcer, and white line disease) on milk production, fertility performance, and longevity. More studies of this nature and studies including additional lameness disease types, severity, and timing of occurrence would be valuable for improving total lameness cost estimates.

Conclusions

Accurate calculations of total lameness costs should include numerous expenditures and losses. Most of these require further empirical research to precisely define, especially with regard to specific lameness disease types, severity level, and the stage of lactation at occurrence. Total lameness costs are also influenced by many herd- and cow- specific factors. Regardless of the limitations of current lameness cost estimates, having an understanding of the components of total lameness costs can help to guide future research and to identify the potential effect of control and prevention strategies, leading to more proactive decision making and management.

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Table 1.1 Contribution of expenditure and loss categories to the total cost of dairy cow lameness across identified studies that included at least 6 contribution categories

	Category contribution to total cost (%)									
	Expenditures				Losses					
Study	Producer labor	Outside labor[1]	Therapeutics	Total	Non-saleable milk	Reduced milk production	Reduced reproductive performance	Increased risk of culling and death	Repeat cases	Total
Kossaibati and Esslemont (1997)										
Digital lameness	6.2	8.1	5.4	20	9.0	10.0	14.5	35.3	11.5	80
Interdigital lameness	3.8	11.9	8.2	24	11.0	9.2	41.9	0.0	14.0	76
Sole ulcer	5.9	6.1	3.5	16	4.0	8.5	31.6	32.6	7.8	84
Esslemont (2005)										
Non-specific lameness	3.2	1.7	3.7	9	0.7	30.9	25.9	30.1	3.7	91
Digital lameness	2.5	1.7	3.0	7	0.4	38.8	13.7	36.9	3.0	93
Interdigital lameness	5.8	2.7	6.8	15	2.1	27.6	48.1	0.0	7.0	85
Sole ulcer	2.9	1.4	3.2	8	0.3	23.1	30.0	36.0	3.1	92
Guard (2008)										
Non-specific lameness	1.7	0.6	4.3	7	0.6	36.0	6.4	50.3	NA	93
Willshire and Bell (2009)										
Non-specific lameness	2.0	1.0	10.0	13	NA	24.0	39.0	24.0	NA	87
Bruijnis et al. (2010)										
Non-specific lameness	17.3	6.7	2.0	26	5.7	28.4	7.4	32.5	NA	74
Charfeddine and Pérez-Cabal (2017)										
Digital dermatitis, mild	7.0	42.5	7.0	57	0.0	33.8	0.0	9.6	NA	43
Digital dermatitis, severe	8.4	6.3	4.2	19	24.4	16.4	2.9	37.4	NA	81
Sole ulcer, mild	14.6	10.9	14.6	40	0.0	18.3	1.5	40.2	NA	60
Sole ulcer, severe	10.5	12.4	11.7	35	20.2	15.8	6.1	23.3	NA	65
White line disease, mild	16.4	12.3	16.4	45	0.0	13.4	3.0	38.5	NA	55
White line disease, severe	10.4	8.7	11.6	31	20.1	16.6	3.2	29.5	NA	69
Liang et al. (2017)										
Non-specific lameness, parity 1	7.1	19.2	37.1	63	1.1	12.9	3.1	19.5	NA[2]	37
Non-specific lameness, parity 2+	4.3	11.6	22.4	38	0.7	12.3	27.2	21.5	NA	62
Mean	7.2	9.2	9.7		5.9	20.9	23.6	27.6	7.6	

[1]Veterinarian or hoof trimmer fees, [2]NA = not provided

Table 1.2 Detailed summary of published research estimates of total dairy cow lameness costs, including lameness definition used, estimation method, and expenditure and loss categories accounted for within the estimates.

Study	Lameness definition	Estimation method	Expenditures included[1]					Losses included[2]								Cost estimate[3,4]
			L	V	T	D	P	N	M	F	C	X	O	R	W	
Harris et al. (1988)	Feet problems	One-time farm survey	X		X		X	X	X		X	X				$76/case
Kaneene and Hurd (1990)	Lameness, foot rot, corns	Longitudinal farm survey	X	X	X		X		X		X	X				$13/cow/y
Miller and Dorn (1990)	Lameness (nonspecific)	Longitudinal farm survey	X	X	X		X	X	X		X	X		X		$15/cow-y
Esslemont and Peeler (1993)	Lameness categories	Farm surveys and industry means	X		X			X	X	X	X			X		$201/case of interdigital disease $404/case of digital disease $982/case of sole ulcer
Enting et al. (1997)	Clinical digital disease	Partial budget model	X	X	X				X	X	X		X			$174/case
Kossaibati and Esslemont (1997)	Lameness categories	Farm and expert opinion surveys	X	X	X			X	X	X	X		X	X		$607/cow affected with digital disease $331/cow affected with interdigital disease $1 073/cow affected with sole ulcer
Esslemont (2005)	Lameness categories	Expert surveys and published means	X	X	X			X	X	X	X	X	X	X		$417/cow affected with digital disease $176/cow affected with interdigital disease $699/cow affected with sole ulcer
Ettema and Østergaard (2006)	Observable lameness without inspection of the claw or trimming	Simulation model	X	X	X				X	X		X		X		$307/affected cow
Guard (2008)	Limping or reluctance to move because of painful conditions of the digit(s)	Partial budget	X	X	X			X	X	X	X	X				$533/case
Willshire and Bell (2009)	Lameness categories and specific lesion types	Partial budget	X	X	X			X	X	X	X					$140/digital dermatitis case $344/digital lameness case $286/interdigital lameness case $960/sole ulcer case $555/white line disease case
Bruijnis et al. (2010)	Specific lesion types	Simulation model	X	X	X			X	X	X	X					$8/cow/y for interdigital phlegmon $7/cow/y for interdigital dermatitis and heel erosion $22/cow/y for digital dermatitis $6/cow/y for sole hemorrhage $3/cow/y for white line disease $11/cow/y for sole ulcer $2/cow/y for interdigital hyperplasia
Cha et al. (2010)	Specific lesion types	Simulation model		X	X				X	X	X					$243/sole ulcer case $149/digital dermatitis case $136/foot rot case
Charfeddine and Pérez-Cabal (2017)	Specific lesion types	Deterministic model	X	X	X			X	X	X	X			X		$53 to $402/cow affected with digital dermatitis $232 to $622/cow affected with sole ulcer $221 to $590/cow affected with white line disease
Liang et al. (2017)	Undefined	Simulation model	X	X	X			X	X	X	X	X				$185 to $333/case

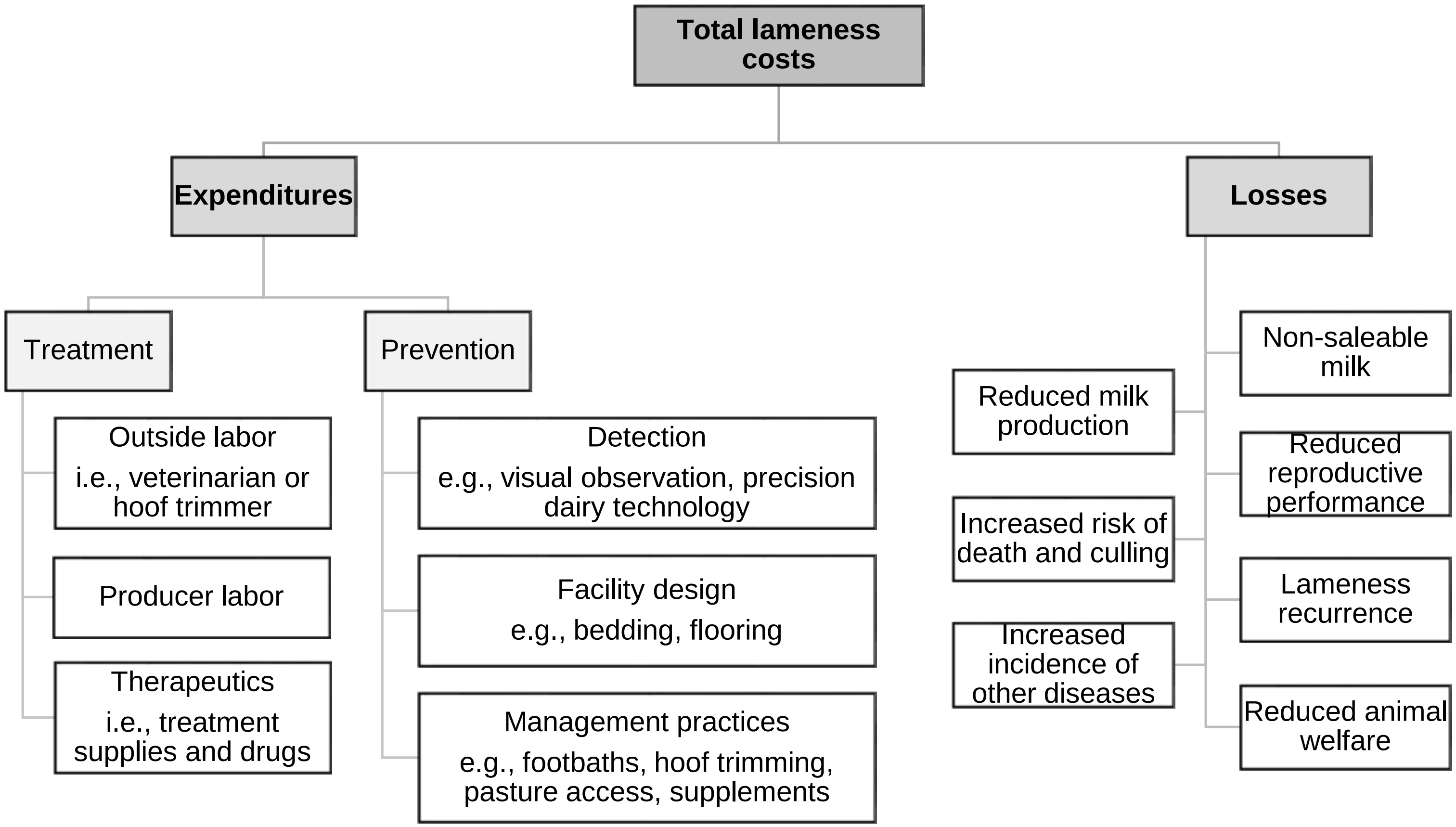
[1] L = producer labor; V = veterinary or hoof trimmer labor; T = therapeutics; D = lameness detection; P = lameness control and prevention

[2] N = non-saleable milk; M = reduced milk production; F = reduced reproductive performance; C = increased risk of culling; X = increased risk of death; O = relationships with other diseases; R = recurrence of lameness; W = animal welfare

[3] All foreign cost estimates were adjusted from the value reported to United States dollars using the mean exchange rate for the year of publication

[4] All costs were adjusted for inflation from the year of publication to 2017

Figure 1.1 Categorization of expenditures and losses that contribute to the total cost of dairy cow lameness



CHAPTER 2

A survey of United States dairy hoof care professionals on costs associated with treatment of hoof diseases

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Abstract

The objective of this study was to collect and summarize information on hoof disease specific treatment costs charged by hoof trimmers and veterinarians to dairy producers. Additional insight was provided into hoof trimmers' general billing practices and views on the amount and importance of different hoof diseases and the value of reducing lameness incidence. Responses were gathered from veterinarians (n = 18) and hoof trimmers (n = 116) through both online and paper survey platforms. Because of the limited number of respondents, veterinarian responses were not further analyzed. Of the 6 hoof diseases included in the survey, the treatment cost per case was greatest for toe ulcers ($20.2 ± 8.5), sole ulcers ($19.7 ± 8.6), white line disease ($19.5 ± 8.1), and thin soles ($18.1 ± 8.1), and least for infectious diseases (foot rot and digital dermatitis; $8.0 ± 7.6 and $7.5 ± 9.6, respectively). Of these diseases, digital dermatitis represented most of the lameness cases treated by respondents over the past year (43.9 ± 20.4%) whereas toe ulcers and thin soles represented the least (5.3 ± 4.1% and 5.3 ± 5.7%, respectively). Respondents that served mostly large herds (> 500 lactating cows) reported a lower prevalence of digital dermatitis and a higher prevalence of sole ulcers. Respondents from the Northeast reported a higher prevalence of sole ulcers than other regions outside the Midwest; both were similar to the prevalence of sole ulcers reported in the Midwest.

When respondents were asked which disease was associated with the greatest total cost per case to the producer (treatment and labor costs plus the reduction in milk yield, reduced reproductive performance, etc.), hoof trimmers ranked digital dermatitis as having the greatest total cost per case and thin soles as having the least total cost per case. This result may have been biased by respondents thinking about the cost of each hoof disease at

the herd level rather than at the individual case level. Finally, respondents indicated that the most important benefits of reducing lameness were enhanced animal welfare and increased milk production whereas the least important benefit was reduced veterinary and hoof trimmer fees. This survey provided insight into the amount charged by hoof trimmers for hoof disease treatment, which can be used to improve the accuracy of hoof disease cost estimates and lead to better decision-making regarding both lameness treatment and prevention.

Keywords: lameness, hoof health, disease treatment costs, animal health economics

Introduction

The main cause of lameness in dairy cattle is hoof diseases (Van Nuffel et al., 2015a). Accurate estimates of the total cost of hoof diseases are essential for identification of the best lameness prevention and control strategies to incorporate into herd management (Dijkhuizen et al., 1995, Hogeveen et al., 2011). The total cost of any disease is comprised of the expenditures applied to treat and prevent the disease and the losses associated with disease occurrence (e.g., reduced milk yield, reduced reproductive performance, increased culling; McInerney et al., 1992). Losses associated with hoof diseases are defined using empirical studies that compare cows with and without lameness over time, often throughout a lactation. Many studies have been conducted with the objective of defining these losses associated with hoof diseases as summarized by Huxley (2013). Less emphasis has been placed on defining the expenditures associated with a hoof disease case.

Expenditures are divided between disease prevention and treatment costs (McInerney et al., 1992). Prevention expenditures are commonly ignored in hoof disease cost estimates because of their difficulty to calculate (Chapter 1). Treatment expenditures within hoof disease cost estimates are often based on the author's opinion or outdated and non-specific values. For example, treatment costs are assumed to be the same regardless of the hoof disease causing lameness and are not broken down into labor vs. supplies. In reality, these costs depend on the type of hoof disease, the severity of the condition, the treatment used, and the person treating the case (i.e., producer, hoof trimmer, or veterinarian). The best estimate of these costs would come from those that charge the producer for them (i.e., hoof trimmers and veterinarians), but limited published data from these sources exist.

This study aimed to collect and summarize information on hoof disease treatment costs charged by hoof trimmers and veterinarians to dairy producers. Additional insight was provided into hoof trimmers' general billing practices and views on the amount and importance of different hoof diseases and the value of reducing lameness incidence.

Materials and Methods

Survey development

A survey was drafted with the goal of defining treatment costs for a variety of hoof diseases as charged to producers by hoof trimmers and veterinarians. The drafted survey was reviewed by industry veterinarians (n = 2), academic veterinarians (n = 5), academic professionals (n = 7), and animal science graduate students (n = 10) to collect feedback on content and organization. Based on collected feedback, revisions were made before the survey was sent to survey participants. The final survey questions are included in Appendix Table A1. The revised survey was also reviewed by the University of Kentucky Institutional Review Board and found exempt from human subject protection regulations as described in 45 CFR 46.101(b).

Demographic information elicited by the survey included profession (veterinarian, hoof trimmer, or other), the location of practice (country or states served, if within the United States), herd sizes served, and the mean number of dairy cows trimmed per week (broken out into preventive and treatment trimmings). Respondents selecting "other" for their profession were removed from the survey results because they were outside of the target audience. General lameness questions were formulated to evaluate the rate charged by hoof trimmers and veterinarians to come to a farm and conduct either preventive or treatment trimmings. These questions included 1) asking respondents if they charged a visit, daily, or set-up fee and, if so, how much, 2) the on-farm rate ($/h or $/cow) charged for preventive trimming, and 3) the mean number of cows trimmed per hour.

Condition-specific lameness questions focused on 6 diseases: digital dermatitis, foot rot, sole ulcer, thin sole, toe ulcer, and white line disease. These diseases were chosen based on their expected prevalence and feedback from those who reviewed the first version of the survey. All diseases were defined within the survey according to industry standards (Zinpro, 2014; Appendix Figure A1). Condition-specific questions included the total amount charged to the producer for treatment of each disease along with the percent of the total cost attributed to labor and the percent of the total cost attributed to supplies. Additionally, respondents were asked to estimate the amount of time spent to treat a case of each disease, the percent of lameness cases treated in the past year attributed to each disease, and milk withhold recommendations following treatment. Retrospectively, the question about milk withhold recommendations was removed from the study results because of United States regulations restricting hoof trimmers from prescribing antibiotics.

Finally, respondents were asked to answer two rank order questions. First, they were asked to rank the 6 hoof diseases based on their opinion of the total cost per case to the producer (treatment and labor costs plus the reduction in milk yield, reduced reproductive performance, etc.) from most expensive (1) to least expensive (6). Second, they were asked to rank the importance to producers of 8 potential benefits (identified by the authors) of reducing dairy cow lameness from most important (1) to least important (8). The potential benefits included decreased incidence of other diseases (not lameness), enhanced animal welfare, increased milk production, increased reproductive performance, increased cow longevity, reduced drug and supply costs, reduced producer labor costs, and reduced veterinary and hoof trimmer fees.

Survey distribution

The target audience for the survey was veterinarians and hoof trimmers. Therefore, the American Association of Bovine Practitioners (AABP) and the Hoof Trimmers Association (HTA) were identified as potential respondent sources. Based on the response rates from AABP and HTA members to a previous lameness survey (Kleinhenz et al., 2014), the decision was made to create an online version of the survey for AABP members and a paper version of the survey for HTA members.

The online survey was created using Qualtrics (Qualtrics Research Suite, Provo, UT). We identified that the best way to distribute the online survey to AABP members would be through their member e-mail listserv ($n \approx 2{,}000$ recipients). A link to the survey was first sent to the AABP listserv on June 12, 2017. Follow-up e-mails were sent to the AABP listserv 1 week and again 4 weeks after the original e-mail solicitation to remind potential respondents to complete the survey. The final e-mail to the AABP listserv, sent on August 1st, 2017, indicated that the survey would be closing on August 15th, 2017. All e-mails sent to AABP members and the online survey itself included instructions for accessing and returning (via mail at their own expense) a downloadable paper version of the survey in case that was the respondent's preference. All online surveys submitted by and paper surveys received by August 31st, 2017 were included in the analysis.

Hoof trimmers identified by the HTA (n = 548) were mailed a paper survey with identical questions as the online survey on June 12, 2017, using a third-party mailing company selected by the HTA. The paper survey included pre-paid envelopes to return the survey to the University of Kentucky. The paper survey also included instructions to access the online version of the survey in case that was the respondent's preference. One week after the first paper survey mailing, a follow-up postcard was sent to all original recipients to remind them to return the survey. A difference in postage class resulted in the reminder postcards arriving before the originally mailed paper survey. Because of this, the second and final mailing of the paper survey (only sent to non-respondents) was delayed until 5 weeks after the original mailing (July 17, 2017). Non-respondents were identified by labeling the originally mailed surveys with a number that corresponded to a recipient. The list of recipients was not referenced after the final mailing. All paper surveys received by August 31st, 2017 were included in the analysis.

At survey closure, 83 people had started the online survey and 16 completed the entire online survey (completion rate = 19%). One hundred and twenty-three paper surveys were returned, and only 1 was from a veterinarian. Therefore, we obtained a 22% response rate from the targeted mailing list. Nine paper survey respondents indicated that they were retired, 1 respondent indicated that they only trimmed beef cattle, and 1 other indicated that they only trimmed for their own herd; these 11 surveys were removed from the dataset.

Statistical analysis

Responses from paper surveys were manually entered into the online survey to standardize data from both sources. When respondents reported a range for any answer (e.g. indicated that they trimmed 10 to 15 cows per hour), the mean of the range was calculated for further analysis (e.g. 12.5 cows per hour). For questions where answers were supposed to add up to 100%, (i.e., the percent of each type of hoof disease treated and the percent of the total cost attributed to labor and supplies), if the total was not 100% the answers were standardized to total 100%. For rank order questions, if two or more options were ranked the same, the tied rankings were removed from the dataset (n = 4 for the rank order question about the total cost per case of disease and n = 5 for the rank order question about the importance of potential benefits of reducing lameness). Finally, any unanswered questions were removed from the dataset.

Respondents were categorized by profession (veterinarian or hoof trimmer), region of practice, herd sizes served, and trimming frequency. The region of practice was defined based on a respondent's answer to which states they served in the United States. The region classifications included Midwest (states represented included IA, IL, IN, KS, MI, MN, ND, NE, OH, SD, and WI), Northeast (states represented included CT, MA, MD, ME, NH, NY, PA, RI, and VT), Southeast (states represented included AL, AR, FL, GA, KY, MO, MS, TN, and VA), Southwest (states represented included NM and TX), and West (states represented included CO, ID, MT, OR, and WA). If the respondent indicated they served herds in more than one region, their region was defined based on the category representing most of the listed states. Eighty-two percent of respondents were from either the Midwest or the Northeast; therefore, the remaining regions were grouped into an "other" region category. Only 3 usable responses were from outside the United States; these responses were removed from the dataset because of the inability to distinguish which currency answers were given in.

Herd size served was based on each respondent's answer to the question, "Estimate the number of farms you perform preventive or corrective trimming for each year that would fall under each category: small herds (fewer than 100 lactating cows), medium herds (between 100 and 500 lactating cows), and large herds (over 500 lactating cows)." Respondents were placed into 1 of 3 categories based on which size herds represented most of their clientele. A respondent with most of their clientele classified as small herds was categorized as "small" herd size served, a respondent with most of their clientele classified as medium herds was categorized as "medium" herd size served, and a respondent with most of their clientele classified as large herds was categorized as "large" herd size served. In cases where the respondent served the same number of herds in two categories, preference was given to the extreme value (i.e. if the same number of small and medium-sized herds were served, the respondent was classified as "small" herd size served, and if the same number of medium and large herds were served, the respondent was classified as "large" herd size served; in no cases were the same number of small and large sized herds served).

Trimming frequency was based on the response to the question, "On average, how many dairy cows do you conduct preventive trimming for weekly (i.e., routine trimming)?" Tertiles were calculated from the responses used in linear regression analysis and were used to classify trimming frequency as either low (≤ 150 trims per week), medium (between 150 and 250 trims per week), or high (≥ 250 trims per week).

Statistical analyses were conducted using SAS Version 9.4 (SAS Institute Inc., Cary, NC). For both online and paper surveys, provided answers were included in the descriptive statistics even if a respondent did not finish the survey (22% and 78% completion rate for online and paper surveys, respectively). The MEANS procedure was used to summarize how many cows were trimmed per hour when conducting preventive trims, the rate charged for preventive trimming, the percent of lameness treatments attributed to each hoof disease, the time spent treating each hoof disease, the total cost per case of each hoof disease, the percent of the total costs of each hoof disease attributed to labor, and the percent of the total costs of each hoof disease attributed to supplies. The FREQ procedure was used to summarize if an extra fee was charged (yes or no) and the frequency of ranking for both rank-order questions.

Because very few responses were received from veterinarians (n = 18), only hoof trimmer responses were analyzed for statistical difference by demographics. The GLM procedure of SAS was used to analyze the effects of region, herd size served, and trimming frequency on the preventive trimming rate, the number of cows trimmed per hour, the percent of treated lameness cases attributed to each hoof disease, the amount of time spent treating each hoof disease, the total cost charged to producers for treatment of each hoof disease, the percent of the total cost of each hoof disease attributed to labor, and the percent of the total cost of each hoof disease attributed to supplies:

$$y_{ijkl} = \mu + Region_i + HerdSize_j + TrimmingFrequency_k + e_{ijkl}$$

where y is the outcome variable of interest for the *l*th respondent classified in the *k*th trimming frequency category, the *j*th herd size served category, and the *i*th region; μ is the intercept; *i* is Midwest, Northeast, or Other; *j* is small, medium, or large; *k* is low, medium, or high; and e_{ijkl} is residual error. For all models, differences were considered significant when $P < 0.05$ and all effects were retained regardless of significance.

Results and Discussion

The objective of this study was to gain insight into hoof disease treatment costs charged to dairy producers by hoof trimmers and veterinarians. Table 1 summarizes the distribution of respondents used in at least one descriptive statistic calculation by profession, survey type returned, region of practice, herd size served, and trimming frequency. The survey distribution methods used in our study (i.e., online surveys for veterinarians and mailed surveys for hoof trimmers) were based on results from Kleinhenz et al. (2014) who surveyed the same population. Different from Kleinhenz et al. (2014), we received very few completed AABP responses to our online survey. The low completion rate of online surveys could indicate that veterinarians who started the survey deemed the topic inapplicable to them. To support the idea that the veterinarian respondents were less involved in lameness treatment than the hoof trimmer respondents, all veterinary respondents to the survey were categorized in the low trimming frequency group (Table 1). Additionally, one veterinary respondent stated, “I rarely get asked to work on lame cows.” In agreement, Adams et al. (2016) reported that 77% of United States dairy farms used a professional hoof trimmer for hoof health services compared to only 16% using a veterinarian or on-farm staff. Still, one limitation of the current study is that the received responses, especially from veterinarians, may not be entirely representative of the target population because of nonresponse bias. Because of this, veterinarian response summary statistics are only included in the Appendix (Tables A2 to A4). Interpretation of veterinarian responses should be conducted carefully, keeping in mind the limited response rate.

General lameness

On average, hoof trimmers reported trimming 10.0 ± 5.0 cows per hour (n = 116). The number of cows trimmed per hour differed by trimming frequency with low and medium frequency trimmers trimming fewer cows per hour than high frequency trimmers (7.66 ± 0.66, 9.34 ± 0.79, and 13.70 ± 0.66 cows/h, respectively; n = 111; $P < 0.01$). This could be because trimmers who trim more frequently are better practiced or have better equipment than trimmers that trim less frequently. Alternatively, trimmers who trim more frequently may have regular clients, making trimming visits quicker (because the cows' hooves are in better shape) than a farm that is not visited by a hoof trimmer regularly.

Ninety-nine percent (n = 114) of hoof trimmer respondents billed per cow, rarely charging an extra fee (visit, daily, or set-up) of any kind (only 12% of respondents, mean ± SD = 87.9 ± 133.4, n = 14). The mean ± SD rate charged by hoof trimmers was $12.55 ± 2.38/cow (n = 113). Trimming rate ($/cow) differed by region and herd size served. Hoof trimmers from the Midwest charged a greater fee ($13.21 ± 0.31/cow) than hoof trimmers from either the Northeast ($11.73 ± 0.33/cow) or other regions in the United States ($10.89 ± 0.47/cow; n = 108; $P < 0.01$). A large portion of dairy farms in the United States are located in the Midwest (USDA, 2017b), potentially contributing to a greater demand for hoof trimmers and the ability to charge an increased fee. Hoof trimmers serving mostly large herds charged a reduced fee ($11.10 ± 0.43) compared to those serving mostly medium sized herds (\$12.54 ± 0.33/cow, $P = 0.04$). Neither was different from hoof trimmers serving mostly small herds (\$12.19 ± 0.35/cow). The effect of herd size on fees charged by hoof trimmers could be attributed to economies of scale where large farms would be charged less because the fixed costs of hoof trimming (e.g., travel expenses) could be spread over more cows. Although interactions weren't tested in the model, it was noted that the ranking of rates charged to different herd sizes differed numerically by region with hoof trimmers in the Midwest charging the most to large herds, hoof trimmers in the Northeast charging the most to medium herds, and hoof trimmers in other regions charging the most to small herds.

Condition-specific lameness

Prevalence of hoof diseases. Among treated cases over the past year, respondents estimated that digital dermatitis was most prevalent, followed by sole ulcers, white line disease, other lameness, foot rot, toe ulcers, and thin soles (Table 2). Very few studies identifying specific lesions have been conducted in the United States, making an estimate of actual hoof disease prevalence or incidence difficult. Bicalho et al. (2007) found in 459 cows on a New York dairy that the most common hoof diseases were a sole ulcer (52%), digital dermatitis (20%), white line disease (15%), other lameness (10%), toe ulcers (3%), and foot rot (1%). Similarly, other studies have identified sole ulcers as the most common condition causing lameness in dairy cows, but rarely do studies include identification of toe ulcers or thin soles (Amory et al., 2008, Gernand et al., 2012). Sanders et al. (2009) found in a Florida herd of 4,915 cows that 38% of lameness cases were attributed to other lameness (including digital dermatitis, foot rot, heel ulcers, leg injuries, sole punctures, and others), 20% to thin sole induced toe ulcers, 16% to sole ulcers, 13% to thin soles, 10% to white line disease, and 2% to toe ulcers.

Inconsistent with previous research, hoof trimmer respondents to this survey reported the percentage of treated cases attributed to digital dermatitis as much greater than the cases attributed to sole ulcers (44% vs. 16%). One factor that might contribute to this is that hoof trimmers conduct more preventive trimming and are more likely to see both lame and non-lame cows, thereby observing both mild and severe conditions. Additionally, the types and prevalence of hoof diseases present in a herd depend on both management and the environment (Cook and Nordlund, 2009). Therefore, variation among herds is expected and likely contributed to the variation in reported prevalence of hoof diseases seen in our study. Regardless, the viewpoint of the surveyed hoof trimmers likely does not represent the true occurrence of different hoof disease because they do not always examine every lame cow.

Region, herd size served, and trimming frequency did not influence the percent of treatments over the past 12 months classified as foot rot, thin soles, toe ulcers, white line disease, or other lameness ($P > 0.05$). The percent of digital dermatitis was influenced by herd size served ($P = 0.02$, n = 107) where hoof trimmers serving mostly large herds reported less digital dermatitis (31.6 ± 4.2%) than hoof trimmers serving mostly small or medium-sized herds (44.4 ± 3.4% and 46.7 ± 3.2%, respectively). One possible explanation for this observation is that large farms may have protocols and consistent labor available to prioritize footbath use. However, the exact reason for this observation cannot be extrapolated from the data available in this study. The percent of sole ulcers reported was influenced by region and herd size served ($P = 0.03$ and $P = 0.03$, respectively; n =

107). Respondents from the Northeast reported more sole ulcers (22.1 ± 2.3%) than respondents from other regions in the United States (12.4 ± 3.3%); neither differed from Midwestern respondents (15.2 ± 2.1%). It is possible that differences in style and age of housing contributed to these reported differences, however, an exact reason for this observation is not clear. Respondents serving mostly large herds reported more sole ulcers (23.1 ± 3.0%) than respondents serving either medium sized herds (13.3 ± 2.3%) or small sized herds (13.4 ± 2.4%). This could be because large herds from the Midwest and Northeastern regions (most respondents) are more likely to house cows on concrete (NAHMS, 2014), which is a risk factor for sole ulcer development (Zinpro, 2014).

Treatment time. Among all respondents, the mean time to treat a case of lameness was longest for toe ulcers, followed by white line disease, sole ulcers, thin soles, foot rot, and digital dermatitis (Table 2). Conditions requiring more remodeling of the foot, like ulcers and white line disease (Andrews et al., 2008), required more time to treat. Region, herd size served, and trimming frequency did not influence the time required to treat foot rot, sole ulcers, thin soles, toe ulcers, or white line disease ($P > 0.05$). The time to treat digital dermatitis differed by trimming frequency where hoof trimmers classified as high trimming frequency spent less time treating digital dermatitis (1.6 ± 0.3 min) than those with a low trimming frequency (3.0 ± 0.3 min; $P < 0.01$, n = 108). Hoof trimmers classified as medium trimming frequency fell in between the two extremes (2.1 ± 0.3 min). Although numerical differences were minimal, hoof trimmers with a high trimming frequency may be quicker because they have had more practice and additionally might have equipment that allows for quicker treatments.

Cost per case. The mean total charged per case of each hoof disease was greatest for toe ulcers, followed by sole ulcers, white line disease, thin sole, foot rot, and digital dermatitis (Table 2). Previous studies focused on veterinarian and hoof trimmer opinions about hoof disease costs are limited. Similar to our findings, Charfeddine and Pérez-Cabal (2017) found in a survey of Spanish hoof trimmers that the cost to treat sole ulcers and white line disease were similar to each other, with the treatment of digital dermatitis being less. We observed that many of the respondents indicated that they charged equal amounts for the two infectious diseases (digital dermatitis and foot rot) and identical, but larger, amounts for non-infectious diseases (sole ulcers, white line disease, thin soles, and toe ulcers). This observation is likely because similar supplies would be used to treat infectious (wrap) and non-infectious (block) hoof diseases. The hoof trimmer reported cost per case did not differ by region, herd size served, or trimming frequency for any of the hoof diseases ($P > 0.05$).

Costs attributed to labor vs. supplies. The percent of the total cost attributed to either labor or supplies by hoof disease is included in Table 2. The difference in the percent of the cost attributed to labor between diseases is likely the result of different treatment methods for different diseases. Traditional infectious lameness treatments often involve cleaning and topical application of antibiotics in a foot wrap whereas non-infectious lesions involve trimming and blocking the hoof to reduce weight bearing on the affected claw (Andrews et al., 2008). Some paper survey respondents wrote in comments about the cost per block or per wrap used. Mean wrap price was $3.92 ± 1.71 (n = 13) and mean block price was $16.00 ± 6.15 (n = 18). Therefore, it is not surprising that we found a greater percentage of costs attributed to labor for infectious diseases and a greater percentage of costs attribute to supplies for non-infectious diseases.

Region, herd size served, and trimming frequency did not influence the percent of total costs attributed to labor or supplies for digital dermatitis, sole ulcers, thin soles, toe ulcers, or white line disease ($P > 0.05$). The percent of the total cost of foot rot attributed to supplies did not differ by region, herd size served, or trimming frequency, but the percent of the total cost of foot rot attributed to labor differed by region ($P = 0.03$, $n = 81$). For unknown reasons, hoof trimmers from the Midwest attributed more of the foot rot costs to labor (75.6 ± 4.2%) than hoof trimmers from the Northeast (60.6 ± 4.2%).

Rank order responses

Hoof disease total costs. Respondents were asked to rank the selected hoof diseases based on the total cost per case to the producer (treatment and labor costs plus the reduction in milk yield, reduced reproductive performance, etc.) from most expensive (1) to least expensive (6). The frequency of responses is reported in Table 3. Hoof trimmer respondents most often ranked digital dermatitis total cost per case to the producer as greatest. Conversely, multiple previously published economic estimates of lameness costs agree that sole ulcers are the most expensive hoof disease per case whereas infectious conditions, including digital dermatitis and foot rot, tend to be the least expensive per case (Willshire and Bell, 2009, Cha et al., 2010, Charfeddine and Pérez-Cabal, 2017). The survey question about the cost ranking of different hoof diseases tried to emphasize the cost per case component, but the ranking of digital dermatitis total costs per case as first by hoof trimmers could indicate that some respondents focused more on the total cost to the herd. This is especially possible given that respondents reported charging producers more to treat either sole ulcers or white line disease than digital dermatitis (Table 2).

Interestingly, among hoof trimmer respondents that did not rank digital dermatitis as first, most ranked the total cost per case of digital dermatitis as last. This indicates that some of the respondents likely did consider the per-case portion of the question more seriously than others. Thin soles were most commonly ranked as the lowest cost per case to the producer. No previous lameness cost estimate studies have included either toe ulcers or thin soles and rarely have epidemiological studies included these conditions. Therefore, it is unclear if ranking of thin soles as having the least total cost per case is consistent with reality or not; more research on the effects of this condition on cow performance is needed.

Lameness reduction benefits. Respondents were asked to rank selected potential benefits of reducing lameness from most important (1) to least important (8). The frequency of responses is reported in Table 4. Among hoof trimmers, enhanced animal welfare and increased milk production were the most important benefits identified. Chapter 1 summarized that the top contributing categories to the total cost of lameness have traditionally been calculated as increased culling and death, reduced reproductive performance, and decreased milk yield. However, no previous literature has considered the costs of lameness attributed to negative animal welfare, excluding it from consideration in that study. In agreement with respondents to this survey, recent studies have highlighted the connection between animal welfare and lameness (Von Keyserlingk et al., 2009, Barkema et al., 2015).

Reduced veterinary and hoof trimmer fees were ranked as the least important potential benefit associated with reducing lameness. This was in agreement with Chapter 1 which found that previous total cost of lameness estimates have ranked reduced drug and supply costs, reduced outside labor, and reduced producer labor as less important cost categories. The second least important response was decreased incidence of other diseases. Evidence of the connection between lameness and other diseases is mixed (Chapter 1). Overall, respondent's answers indicate that hoof trimmers have a good understanding of the contribution of different cost categories to the total cost of lameness as defined in currently available literature. However, the voluntary survey strategy may have selected for hoof trimmers that are more interested in research and up-to-date on published literature, potentially influencing rank order responses.

Conclusions

The goal of this study was to collect information on hoof disease treatment costs charged by hoof trimmers and veterinarians to dairy producers. Low responses rates from veterinarians limited our study to hoof trimmer opinions only. Hoof trimmers reported that hoof disease treatment cost per case was greatest for toe ulcers, followed by sole ulcers, white line disease, thin sole, foot rot, and digital dermatitis. Additional insight was provided into hoof trimmers' general billing practices and views on the amount and importance of different hoof diseases and the value of reducing lameness incidence. Minimal effects of region, herd size served, or trimming frequency were found on responses. The treatment cost estimates found in this study can aid in improving economic estimates of the total cost per case of different hoof diseases. More accurate hoof disease total cost per case estimates could help improve decisions regarding the treatment of individual hoof disease cases and the adoption of lameness prevention strategies.

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Table 2.1 Distribution of respondents to a survey[1] about dairy hoof disease treatment costs by profession, survey type, region, herd size served, and trimming frequency

Category	Profession		Total
	Veterinarian	Hoof Trimmer	
Survey type			
Online	17	5	22
Paper	1	111	112
Region[2]			
Midwest	11	55	66
Northeast	3	41	44
Other	4	20	24
Herd size served[3]			
Small (< 100 cows)	7	45	52
Medium (100 to 500 cows)	7	42	49
Large (> 500 cows)	0	25	25
Trimming frequency[4]			
Low (< 150 cows/wk)	18	32	50
Medium (150 to 250 cows/wk)	0	41	41
High (>250 cows/wk)	0	42	42
Total	18	116	

[1]An online version of the survey was sent to the American Association of Bovine Practitioners listserv (n ≈ 2,000 members) and a paper version of the survey was mailed to 548 hoof trimmers identified by the Hoof Trimmers Association

[2]Midwest states represented included IA, IL, IN, KS, MI, MN, ND, NE, OH, SD, and WI; Northeast states represented included CT, MA, MD, ME, NH, NY, PA, RI, and VT; Other states represented included AL, AR, FL, GA, KY, MO, MS, TN, VA, NM, TX, CO, ID, MT, OR, and WA.

[3]Herd size served was categorized based on if the respondent's clients were mostly small herds (fewer than 100 lactating cows), medium herds (between 100 and 500 lactating cows), or large herds (over 500 lactating cows). Eight respondents did not provide sufficient information to classify them according to herd size served but were still included in descriptive statistics.

[4]Trimming frequency was categorized based on the calculated tertiles of responses used in linear regression analysis; 1 respondent did not provide sufficient information to classify hoof trimming frequency but was still included in descriptive statistics

Table 2.2 Hoof trimmer responses to a survey regarding dairy hoof disease prevalence, time to treat, treatment costs, and the percentage of costs attributed to labor or supplies

Hoof disease	Number of responses (n)	Response (mean ± SD)
Digital dermatitis		
% of total	112	43.9 ± 20.4†
Time to treat (min)	113	2.2 ± 1.9‡
Total charged ($/case)	98	7.5 ± 9.6
% attributed to labor	92	65.1 ± 21.8
% attributed to supplies	92	34.9 ± 21.8
Foot rot		
% of total	112	6.5 ± 7.0
Time to treat (min)	111	3.7 ± 2.7
Total charged ($/case)	90	8.0 ± 7.6
% attributed to labor	85	66.0 ± 21.8*
% attributed to supplies	85	32.8 ± 20.8
Sole ulcer		
% of total	112	15.9 ± 14.2*†
Time to treat (min)	114	6.2 ± 3.5
Total charged ($/case)	95	19.7 ± 8.6
% attributed to labor	90	58.8 ± 19.8
% attributed to supplies	90	41.2 ± 19.8
Thin sole		
% of total	112	5.3 ± 5.7
Time to treat (min)	107	5.1 ± 3.3
Total charged ($/case)	89	18.1 ± 8.1
% attributed to labor	82	56.7 ± 20.7
% attributed to supplies	82	43.3 ± 20.7
Toe ulcer		
% of total	112	5.3 ± 4.1
Time to treat (min)	111	7.1 ± 3.6
Total charged ($/case)	96	20.2 ± 8.5
% attributed to labor	91	57.5 ± 20.5
% attributed to supplies	91	42.5 ± 20.5
White line disease		
% of total	112	14.2 ± 10.2
Time to treat (min)	113	6.5 ± 3.1
Total charged ($/case)	96	19.5 ± 8.1
% attributed to labor	90	57.9 ± 21.2
% attributed to supplies	90	42.1 ± 21.2
Other lameness		
% of total treatments	112	8.9 ± 9.3

*Indicates a statistical difference between hoof trimmers by region (Midwest, Northeast, or other region of the United States; $P < 0.05$); further details included in the text

†Indicates a statistical difference between hoof trimmers by herd size served (small, medium, or large; $P < 0.05$); further details included in the text

‡Indicates a statistical difference between hoof trimmers by trimming frequency (low, medium, or high; $P < 0.05$); further details in the text

Table 2.3 Ranking frequency of the estimated total cost per case to the producer (treatment and labor costs plus the reduction in milk yield, reduced reproductive performance, etc.) of selected hoof diseases as evaluated by a survey of hoof trimmers. Ranking was from most expensive (1) to least expensive (6).

	Response frequency (%)						
Disease	n	1	2	3	4	5	6
Digital dermatitis	112	33.9	9.8	4.5	9.8	13.4	28.6
Toe ulcer	109	22.9	19.3	15.6	19.3	12.8	10.1
Foot rot	111	19.8	11.7	9.9	20.7	19.8	18.0
Sole ulcer	111	11.7	27.0	26.1	17.1	13.5	4.5
White line disease	112	7.1	23.2	30.4	20.5	8.9	9.8
Thin sole	111	6.3	7.2	13.5	12.6	30.6	29.7

Table 2.4 Ranking frequency of the potential benefits to producers of reducing dairy cow lameness as evaluated by a survey of hoof trimmers. Ranking was from most important (1) to least important (8).

		Response frequency (%)							
Potential benefit	n	1	2	3	4	5	6	7	8
Enhanced animal welfare	106	36.8	12.3	13.2	17.9	6.6	4.7	2.8	5.7
Increased milk production	105	32.4	24.8	18.1	7.6	6.7	1.0	3.8	4.8
Increased cow longevity	106	20.8	21.7	22.6	15.1	13.2	5.7	0.0	0.9
Reduced veterinary and hoof trimmer fees	103	4.9	1.0	2.9	8.7	14.6	17.5	21.4	29.1
Decreased incidence of other diseases (not lameness)	105	2.9	7.6	7.6	11.4	20.0	13.3	11.4	25.7
Increased reproductive performance	106	2.8	27.4	26.4	20.8	10.4	6.6	4.7	0.9
Reduced drug and supply costs	105	1.0	2.9	4.8	12.4	13.3	31.4	21.0	13.3
Reduced producer labor costs	106	0.0	3.8	3.8	6.6	14.2	18.9	34.9	17.9

CHAPTER 3

Use of a stochastic simulation model to estimate the cost per case of digital dermatitis, sole ulcer, and white line disease by severity, incidence timing, and parity group in dairy cattle

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Abstract

A farm-level stochastic simulation model was modified to estimate the cost per case of 3 hoof diseases (digital dermatitis, sole ulcer, and white line disease) by severity, incidence timing, and parity group. Disease expenditures considered within the model included therapeutics, outside labor, and on-farm labor. Disease losses considered within the model included discarded milk, reduced milk production, extended days open, an increased risk of culling, an increased risk of death (natural or euthanized), and disease recurrence. All estimates of expenditures and losses were defined using data from previously published research in stochastic distributions. Monte Carlo simulation was used to account for variation within the farm model; 1,000 iterations were run. Sensitivity of hoof disease costs to selected market prices (milk price, feed price, replacement heifer price, and slaughter price) and herd specific performance variables (rolling herd average milk production and pregnancy rate) was analyzed. Using our model assumptions, the cost per case of disease over all combinations of severity, incidence timing, and parity group was lowest for digital dermatitis (mean ± SD = \$137 ± 36), followed by white line disease (mean ± SD = \$203 ± 33), and sole ulcer (mean ± SD = \$227 ± 35). Disease costs were greater in severe vs. mild cases and multiparous vs. primiparous cows and were always highest at the beginning of lactation. The greatest contributing cost categories were decreased milk production, an increased risk of culling, disease recurrence, and, in severe cases, an increased risk of death. The contribution of cost categories to the total cost of disease varied by disease type, severity, incidence timing, and parity group. For all diseases, the average cost per case of disease increased as milk price, rolling herd average milk production, or replacement heifer price increased and decreased as feed price,

pregnancy rate, or slaughter price increased. Understanding how hoof disease costs change according to cow-specific conditions (i.e., severity level, DIM at incidence, and parity group) and herd-specific conditions (i.e., market prices and performance variables) can help improve on-farm decisions about treatment and prevention of hoof diseases.

Key Words: lameness, disease cost, hoof health, animal health economics

Introduction

Lameness is a widespread issue in the dairy industry, with prevalence ranging from 5.5% to 70.1% (mean = 27.2 ± 11.9%) on United States and Canadian dairy farms (Costa et al., 2017). Although often referred to as a disease itself, lameness is actually a clinical sign associated with multiple different hoof diseases. Each case of lameness, and the associated hoof disease that is causing it, is associated with both direct expenditures (e.g., on-farm labor, hoof trimmer labor, and therapeutics) and indirect losses (e.g., discarded milk, reduced milk production, reduced reproductive performance, increased risk of death, increased risk of culling, and disease recurrence; Chapter 1). Understanding the total cost per hoof disease case is valuable for improving management at both the cow and herd level by aiding in the selection of lameness treatment strategies, culling strategies, and prevention investments.

Most previous lameness cost estimates have focused on either the cost of lameness at the herd level (Kaneene and Hurd, 1990, Miller and Dorn, 1990), the cost per case of non-specific lameness (Harris et al., 1988, Guard, 2008, Liang et al., 2017), or the cost per case of lameness categorized as interdigital, digital, or sole ulcer (Esslemont and Peeler, 1993, Kossaibati and Esslemont, 1997, Esslemont, 2005). More recently, specific hoof diseases have been considered when calculating the cost per case of lameness (Willshire and Bell, 2009, Bruijnis et al., 2010, Cha et al., 2010, Charfeddine and Pérez-Cabal, 2017). However, Chapter 1 highlighted that these costs often still fail to consider how severity, incidence timing relative to calving, or parity affects the cost of the disease even though previous literature supports that these differences exist. Charfeddine and Pérez-Cabal (2017) identified differences in both direct (trimmer fees, treatment fees, producer labor, and discarded milk) and indirect (milk loss, days open, and length of productive life) negative consequences when comparing mild and severe lesions, emphasizing the need to account for this factor in cost estimates. Booth et al. (2004) demonstrated how the effect of hoof diseases on survival differed depending on disease diagnosis timing. Logically, incidence timing would also influence discarded milk and reduced milk production because of yield changes throughout lactation and reduced reproductive performance, assuming a reduced effect of lameness on reproduction after pregnancy is established. Liang et al. (2017) found that the total cost per case of non-specific lameness was 1.8 times greater in multiparous cows than primiparous cows. The authors attributed most of the difference to increased multiparous cow losses associated with reduced milk yield, culling, and extended days open.

The objective of this study was to build a stochastic simulation model capable of estimating hoof disease costs depending on disease type, severity level, incidence timing, and parity group. Other studies (Ettema and Østergaard, 2006, Bruijnis et al., 2010, Liang et al., 2017) have also used stochastic simulation to estimate disease costs which allows evaluation of how disease costs change with variation in farm specific and market values. To demonstrate usefulness, the model was used to calculate the cost per case of digital dermatitis, sole ulcer, and white line disease in an example United States dairy herd.

Materials and Methods

Model overview

A pre-existing farm-level, Monte Carlo simulation model was adapted for use in this study (Bewley et al., 2010, Liang et al., 2017). The model was created using Excel 2016 (Microsoft, Seattle, Washington) and stochastic features were applied using the @Risk add-in (Version 7, Palisade Corporation, Ithaca, New York). As described previously by Liang et al. (2017), the model worked by calculating the milk yield (estimated via the lactation curve described by Skidmore (1990)), body weight, dry matter intake (estimated via equations found in NRC (2001)), and pregnancy status of the average cow in the herd every day for 6 parities. This average cow was assumed to represent all cows in the herd and information about the cow was used to calculate disease costs.

The Monte Carlo simulation method is a technique that allows re-running of a simulation model repeatedly while key variables vary stochastically. When a variable was modeled stochastically, a distribution was defined for that variable based on previously published literature or industry averages. During each iteration of the model, a different value from that distribution was selected for use. For this study, variables assumed to influence the cost of lameness were modeled stochastically, resulting in unique cost per case estimates for each hoof disease each time the model was run.

Disease case definitions

For this study, three hoof diseases were selected for modeling: digital dermatitis, sole ulcer, and white line disease. These conditions were selected because they are considered the most prevalent lameness causing diseases in United States dairy herds

(DeFrain et al., 2013). Additionally, these 3 hoof diseases have the most published data available to be able to specify costs by severity, incidence timing, and parity group.

Based on the availability of data for modeling, severity was categorized as mild or severe. Most assumptions about differences between mild and severe cases were taken from Charfeddine and Pérez-Cabal (2017). In that study, severity was classified based on how deep or superficial the lesion was, the expected recovery time, and if further treatment was needed. To evaluate how incidence timing affected the cost of disease, 4 incidence periods were selected: 0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, and >240 DIM. These incidence timings were selected from Booth et al. (2004), who reported culling risk associated with different hoof diseases by incidence timing. Two parity groups were selected for inclusion: primiparous and multiparous. In some cases, no differences in disease affect by severity level, incidence timing, or parity group was modeled because of a lack of data rather than a belief that no difference existed.

Calculation of lameness expenditures and losses

The expenditures and losses associated with lameness were already reviewed in Chapter 1. For this study, only losses and expenditures with enough data to estimate for individual hoof diseases were incorporated, as determined by the authors. Modeled expenditures included outside (hoof trimmer) labor, therapeutics, and on-farm labor. Modeled losses included discarded milk, reduced milk production, extended days open, an increased risk of culling, an increased risk of death (natural or euthanized), and disease recurrence. All expenditure and loss categories were calculated individually for each combination of disease type (digital dermatitis, sole ulcer, or white line disease), severity level (mild or severe), incidence timing (0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, or

>240 DIM), and parity group (primiparous or multiparous) for a total of 48 case cost estimates. The total cost per case was the sum of all individual loss and expenditure categories. Separate modules within the model were used to calculate each cost category and necessary precursors for those categories.

Market prices module. Current market prices (milk price, feed price, replacement heifer price, slaughter price, heifer calf price, and bull calf price) were necessary to accurately calculate many of the disease-related losses. Historical price variation and future price baseline data were used to create stochastic predicted prices for 2017, identical to the process described by Bewley et al. (2010) and Liang et al. (2017). To summarize, the historical prices were used to create simulated error terms that could be added to the expected 2017 price to account for variation in the prediction. Additionally, a correlation matrix between historical values over the past 10 years was implemented to prevent unrealistic price combinations (e.g., high corn price and low soybean price).

Annual historical United States prices for milk, alfalfa, corn, soybean, slaughter, and replacement heifers from the previous 10 years (2007 to 2016) were collected from the Understanding Dairy Markets website (Gould and Bozic, 2017). Heifer and bull calf prices for 2007 to 2016 were collected from the USDA Agricultural Market Service website (USDA, 2017a). The expected 2017 prices for milk, alfalfa, corn, soybean, and slaughter price were collected from the Food and Agricultural Policy Research Institute's *2017 U.S. Baseline Briefing Book: Projections for Agricultural and Biofuel Markets* (FAPRI, 2017). Feed price was subsequently estimated from corn, soybean, and alfalfa prices using the equation published by Bailey and Ishler (2007).

Expected 2017 replacement heifer, heifer calf, and bull calf prices were calculated using regression analysis between historical values for each variable and other historical prices, similar to Bewley et al. (2010) and Liang et al. (2017). For our model, regressions were calculated using the REG procedure in SAS (version 9.4, SAS Institute, Inc., Cary, NC). Historical replacement heifer price records were found back to 1971 (Gould and Bozic, 2017); therefore, data from 1971 to 2016 was included in the regression equation. Historical calf price (bull and heifer) records were found back to 1991 (Robin L. Cusato-Wood, USDA Agricultural Marketing Service, Moses Lake, WA, personal communications and USDA (2017a)); therefore, data from 1991 to 2016 was included in those regression equations. All historical prices for slaughter, feed (calculated using alfalfa price, corn price, and soybean price), and milk that were included in each regression equation were collected from the Understanding Dairy Markets website (http://future.aae.wisc.edu/; Gould and Bozic, 2017).

Regression equations were built by offering each model the following variables: slaughter price, feed price, milk price, lag of slaughter price, lag of feed price, lag of milk price, and year where lag indicates the previous year's price for the specific variable. The regression equation for replacement heifer price was also offered the lag of heifer calf price and the lag of bull calf price. The regression equation for heifer calf price was also offered the lag of replacement heifer price and the lag of bull calf price. The regression equation for bull calf price was also offered the lag of replacement heifer price and the lag of heifer calf price. Year was forced into all models to account for time. Other covariates were removed when non-significant ($P \geq 0.05$) via backward step-wise elimination. The final equations generated adjusted R^2 values of 0.97, 0.78, and 0.85 for replacement heifer price, heifer calf price, and bull calf price, respectively:

Replacement heifer price (\$) = -23,161 (± 4,644.29) – 47.56 (± 11.79) × feed price (\$/cwt) + 48.79 (± 6.87) × milk price (\$/cwt) + 482.68 (± 95.55) × slaughter price lag (\$/lb) – 53.13 (± 14.23) × feed price lag (\$/cwt) + 37.52 (± 7.38) × milk price lag (\$/cwt) + 0.78 (± 0.10) × heifer calf price lag (\$) + 11.72 (± 2.37) × year

Heifer calf price (\$) = 6,447.10 (± 8,551.59) + 33.88 (± 8.67) × milk price (\$/cwt) – 59.99 (± 9.35) × feed price lag (\$/cwt) + 0.47 (± 0.10) × replacement price lag (\$) – 3.51 (± 4.38) × year

Bull calf price (\$) = 2,645.27 (± 1,213.77) + 442.60 (± 41.86) × slaughter price (\$/lb) – 15.31 (± 4.02) × feed price (\$/cwt) – 12.60 (± 5.03) × feed price lag (\$/cwt) + 8.50 (± 2.72) × milk price lag (\$/cwt) – 1.35 (± 0.62) × year

Retention pay-off module. The stochastic market prices and the daily simulated cow data (i.e., milk yield, body weight, dry matter intake, and pregnancy status) were combined to calculate the retention pay-off (RPO) value for every day over the lifetime of the average cow. Retention pay-off compares the value of the current cow with her potential replacement, considering both cows' expected future profits based on daily revenues (milk sales, calf value, and slaughter value) and costs (feed costs, veterinary costs, breeding costs, and disposal losses). The RPO value represents a cow's worth beyond her slaughter value and can be used to estimate losses resulting from early or non-optimal culling and death (Groenendaal et al., 2004). For additional details regarding how RPO is calculated, see Groenendaal et al. (2004). In this model, the RPO value was used in the calculation of losses associated with extended days open and an increased risk of culling.

Treatment module. The treatment module calculated expenditures associated with outside labor, on-farm labor, and therapeutics, and the losses associated with discarded milk. Expenditures on outside labor and therapeutics were disease-specific, expenditures on on-farm labor were disease and severity specific, and losses associated with discarded milk were disease, severity, incidence timing, and parity group specific. Estimates used in the model for outside labor and therapeutics were taken from a survey of hoof trimmers and veterinarians (Chapter 2; Table A5). The responses from hoof trimmers (n = 90 for digital dermatitis; n = 88 for sole ulcer and white line disease) to questions about the amount charged to a producer for labor and supplies per case by disease type were used to create stochastic distributions for disease-specific outside labor and therapeutic costs per case. This dataset was evaluated using the "distribution fitting" feature in @Risk and the best distribution was identified using the AIC value. An extreme values distribution, related to the Weibull distribution, was chosen to represent therapeutic costs associated with sole ulcer treatment. All other distributions for both outside labor and therapeutics were log logistic distributions. Log-logistic distributions are similar in shape to log-normal distributions, but have thicker tails. All distributions were truncated at a minimum of 0, meaning if a value less than 0 was drawn from the distribution, the distribution was resampled assuming there would never be decreased costs associated with outside labor or therapeutics resulting from a hoof disease case. Outside labor and therapeutic expenditures were assumed to be identical regardless of severity, incidence timing, and parity group.

Charfeddine and Pérez-Cabal (2017) reported the mean cost of on-farm labor per mild and severe case of digital dermatitis, sole ulcer, and white line disease. These means and corresponding standard deviations, calculated as a 10% coefficient of variation from the mean, were used in normal distributions to create stochastic disease and severity specific on-farm labor cost estimates (Table A5). All values drawn from these distributions were truncated at a minimum of 0, meaning if a value less than 0 was drawn from the distribution, the distribution was resampled assuming there would never be decreased costs associated with on-farm labor resulting from a hoof disease case. The cost associated with on-farm labor was assumed identical regardless of incidence timing and parity group.

Data from the survey conducted in Chapter 2 were also used to define discarded milk per case, as required after treatment with antibiotics. It was assumed that only digital dermatitis would result in discarded milk because antibiotic use was reported as rare for both sole ulcers and white line disease cases. Survey respondents were asked to indicate the number of days required for milk discard (on-average) for a case of digital dermatitis (n = 22 responses). The digital dermatitis days to discard milk data was fit to a single stochastic distribution using the “distribution fitting” feature in @Risk (Table A5). That stochastic distribution was chosen to represent severe digital dermatitis cases; an assumption was made that mild digital dermatitis cases would not require antibiotic treatment and, therefore, would require no milk discard. The fitted distribution for days to discard milk following a severe case of digital dermatitis was an exponential distribution. To account for differences in milk production, discarded milk losses associated with digital dermatitis were made both parity group and incidence timing specific. This was accomplished by multiplying the stochastic number of days of milk discard by the average milk production per day for a cow with digital dermatitis in the appropriate parity group (primiparous or multiparous) and time period (0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, and >240 DIM). Lastly, the resulting pounds of milk lost per case was multiplied by the stochastic milk price to calculate the value of discarded milk associated with each lameness event. In this study, we assumed discarded milk was not fed to calves. If discarded milk were fed to calves, losses associated with discarded milk would be reduced, therefore reducing the cost of a severe case of digital dermatitis.

Milk loss module. The milk loss module calculated the losses associated with the reduced production potential of cows experiencing hoof diseases. Milk losses were disease, severity, incidence timing, and parity group specific. Charfeddine and Pérez-Cabal (2017) reported the mean and SE ECM loss (kg/d) associated with a case of mild and severe digital dermatitis, sole ulcer, and white line disease for 4 weeks before and after disease occurrence for primiparous and multiparous cows separately. Those reported values were chosen for use in our model because other studies have not considered severity when calculating milk loss associated with specific hoof diseases. However, that study did not account for culling bias (i.e., culled cows were not included in all milk loss calculations) or the increased likelihood that a higher producing cow would get a hoof disease; therefore, the estimates for reduced milk production are likely biased low. As a result, we may have underestimated the losses associated with reduced milk production in our disease cost estimates and, therefore, underestimated the cost per case of each hoof disease.

The mean and SE ECM loss (kg/d) for each disease, severity, and parity combination from Charfeddine and Pérez-Cabal (2017) was used to calculate the expected 2.5th and 97.5th percentiles which were used in program evaluation and review technique (PERT) distributions to create stochastic estimates for milk loss associated with each hoof disease combination for each of the 4 weeks before and after occurrence (Table A6). The PERT distribution is a type of β distribution adjusted for skewness by defining the minimum, mean, and maximum values or, alternatively, the 5th and 95th percentile can be defined (Bewley et al., 2010). If the distribution parameters were positive, they were adjusted to zero, assuming this was because higher producing cows are more susceptible to disease rather than the disease actually increases milk production (Bewley et al., 2010). For all disease cases, an assumption was made that all weeks post-disease incidence ≥ 4 were identical. This meant that milk production potential was reduced for the remainder of the lactation after lameness incidence, making losses associated with reduced milk production incidence timing specific. Altogether, the total milk loss per case of hoof disease was the sum of milk loss for every week from 4 weeks before disease occurrence until the end of the lactation.

Milk loss per case for each incidence timing (0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, and >240 DIM) was calculated by summing the milk loss associated with a case occurring every day within that incidence timing and taking the average of all of those cases. Milk loss per case was multiplied by the 2017 stochastic milk price to calculate reduced milk revenues. The feed costs associated with producing that milk were subtracted from the total reduced milk revenue losses to account for the fact that the cow responds to reduced milk production by eating less. Reduced feed costs were calculated by multiplying the estimated reduction in dry matter intake (calculated as the average cow's daily intake over the lactation divided by the average cow's daily production over the lactation) by the stochastic feed price.

Days open module. The days open module calculated the losses associated with extended days open resulting from cows experiencing hoof diseases. Extended days open losses were disease, severity, incidence timing, and parity-specific. Charfeddine and Pérez-Cabal (2017) reported the mean and SE increase in days open associated with mild and severe digital dermatitis, sole ulcer, and white line disease for primiparous and multiparous cows combined. Similar to the milk loss module parameters, these reported values were chosen for use in our model because other studies have not considered severity when calculating days open losses associated with specific hoof diseases. However, culling bias also affected these estimates because Charfeddine and Pérez-Cabal (2017) only considered those cows that became pregnant within their analysis (i.e., the impact of cows who did not become pregnant was not included). As a result, we may have underestimated the losses associated with extended days open in our disease cost estimates and, therefore, further underestimated the cost per case of each hoof disease.

The mean and SE increase in days open for each disease and severity combination from Charfeddine and Pérez-Cabal (2017) was used to calculate the expected 2.5th and 97.5th percentiles which were used in PERT distributions to create stochastic estimates for the number of extended days open associated with each hoof disease and severity combination (Table A7). For each distribution, if the mean or 2.5th percentile were negative (indicating a decrease in days open) they were adjusted to zero, assuming no positive effect of disease on days open.

The losses associated with extended days open were calculated separately for parities 1, 2, and 3 using RPO values. For each parity, the RPO of an average cow in the herd on the first day of that parity was compared to the RPO of a diseased cow on the first day of that parity. The only difference between the two cows was the difference in days open during that parity, so the difference in RPO represented the total loss in the cow's value associated with extended days open for that case. For example, if the RPO of the average cow without any disease on day 1 of lactation 1 was $825 and the RPO of the average cow with a severe sole ulcer (+ 17 days open) on day 1 of lactation 1 was $800, then the total losses associated with extended days open for a parity 1 cow experiencing a severe sole ulcer were $25. This method has previously been described by Dolecheck et al. (2016) and was applied in the model by Liang et al. (2017).

The multiparous parity group extended days open cost per case was a weighted average of the calculated cost of extended days open per case for parity 2 cows and parity 3 cows, based on the assumed distribution of cows among parities (Table 3.1). To calculate costs by incidence timing, an assumption was made that disease cases occurring before the average cow became pregnant resulted in all losses associated with extended days open and disease cases occurring after the average cow became pregnant resulted in no losses associated with extended days open. For incidence timings that contained the average cow's DIM at conception, a portion of the losses associated with extended days open were included to account for some cases occurring before the average cow becomes pregnant and some cases occurring after the average cow becomes pregnant. For example, if the average cow's days open is 150 d and the days open losses per case are $20, then the losses per case associated with days open for the incidence timing 121 to 240 DIM would be $5

($20 x (150-121)/(240-121)). The DIM at conception for the average cow was calculated using the equation by Pecsok et al. (1994) with the voluntary waiting period and days in milk do not breed set deterministically at 60 and 250 DIM, respectively, and pregnancy rate calculated using stochastic distributions for estrus detection rate and conception rate defined by data from DairyMetrics (Dairy Records Management Systems, Raleigh, NC; Table 3.1 and Table 3.2).

Culling and death module. The culling and death module calculated the losses associated with an increased risk of culling and death resulting from hoof diseases. The losses associated with an increased risk of culling and death were disease, severity, incidence timing, and parity group specific. Mean, 5th percentiles, and 95th percentiles culling hazard ratios associated with digital dermatitis and sole ulcers were reported by Booth et al. (2004), specifically considering how the incidence of disease in one period (0 to 60 DIM, 61 to 150 DIM, 151 to 240 DIM, or > 240 DIM) influenced culling in both that time period and future time periods. These values were used to create stochastic distributions for disease-specific culling risk ratios, assuming white line disease culling risk ratios were identical to sole ulcers (Table A8). The assumption about similarities between sole ulcer and white line disease were made because they are both non-infectious hoof diseases and Charfeddine and Pérez-Cabal (2017) reported similar effects of both diseases on the length of productive life.

To account for severity, two different stochastic distributions were created for each disease using PERT distributions. For the "mild" distributions, a mean 0.5 times that of the mean reported by Booth et al. (2004) was used whereas for the "severe" distributions, a mean 1.5 times that of the reported mean was used. The same 5^{th} and 95^{th} percentiles were used in both mild and severe distributions for each disease. This method allowed for the same minimum and maximum values, regardless of severity, but skewed the distributions to the lower or upper ends for mild and severe cases, respectively. All distributions were truncated at a minimum of 1.0, meaning if a value less than 1.0 was drawn from the distribution (indicating a decreased risk of culling) the distribution was resampled, assuming no positive effect of disease on culling. The culling risk ratios were used to calculate the number of extra culls resulting from each hoof disease case, as previously described by Bewley et al. (2010). To calculate losses associated with the extra culls, the RPO value of the average cow for each combination of parity and incidence timing was multiplied by the number of extra culls per case in that parity and incidence timing. Culling losses per case were calculated separately for parities 1, 2, 3, 4, 5, and 6. The weighted average of parities ≥ 2, based on the distribution of cows among parities (Table 3.1), was used to represent culling losses associated with the multiparous parity group.

An assumption was made in this model that only severe lameness cases would have the potential to result in death and that no cases of digital dermatitis would result in death. Therefore, losses associated with an increased risk of death for all mild conditions and severe digital dermatitis cases were $0. No previous research has estimated the percentage of hoof disease cases resulting in death so for other severe conditions (sole ulcer and white line disease) an assumption was made that 5% of cases occurring at any incidence timing would result in death. Disease related death losses were calculated for each incidence timing and parity (1, 2, 3, 4, 5, or 6). To summarize, the number of deaths per case for each incidence timing and parity was multiplied by the mean slaughter value (calculated as the body weight of the cow multiplied by the stochastic slaughter price) for that specific time period in that specific lactation. Death losses per case for multiparous cows were the weighted average of each parity, based on the assumed distribution of cows among parities (Table 3.1).

Disease recurrence module. The disease recurrence module calculated losses linked to cases recurring in the same animal. Disease recurrence losses were disease, severity, incidence timing, and parity group specific. Charfeddine and Pérez-Cabal (2017) reported mean relapse rates (episodes per infected cow) for both primiparous and multiparous cows experiencing either mild or severe digital dermatitis, sole ulcers, and white line disease. Each of these assumptions was modeled stochastically using a PERT distribution (Table A9) with minimum and maximum values assumed identical for all hoof diseases using the general lameness relapse rate values reported by Ettema and Østergaard in 2006 (min = 1.5, max = 4.0). The stochastic relapse rate minus 1 was the number of repeat cases expected per original case. However, incidence timing and disease length logically influence how many repeat cases per original case can occur within the same lactation. Therefore, disease length estimates were incorporated into the model.

Bruijnis et al. (2010) reported mean, 5^{th} percentile, and 95^{th} percentile disease length for subclinical and clinical digital dermatitis, sole ulcer, and white line disease. An assumption was made that subclinical would represent mild cases and clinical would represent severe cases. These values were used in PERT distributions to create stochastic estimates for disease length for each hoof disease (Table A9). By multiplying the disease length by the relapse rate, the length of time (d) required for all cases (original plus relapse cases) to occur was calculated.

To make losses associated with disease recurrence incidence timing specific, a comparison was made between the length of time required for all cases (original and relapse) to occur and the number of days remaining in the lactation. An assumption was made that a new case occurring within each incidence timing occurred at the midpoint of that period (e.g., for incidence timing 0 to 60 DIM, incidence occurred at 30 DIM). The remaining days left in the lactation were calculated by subtracting the incidence timing from the average cow's length of lactation, as determined by the calving interval. For example, if the average cow's length of lactation was 375 days, then there would be 345 d left in the lactation for the incidence timing 0 to 60 DIM (375 to 30). By comparing this to the time required for all lameness cases (original and relapse) to occur, we could calculate the number of actual recurrences that would happen within a lactation. Using this method, more recurring cases were assumed for a case of lameness occurring in early lactation than a case occurring in later lactation, simply because the days remaining in the lactation would not permit the case to recur at the same rate. We assumed no adverse effects of hoof diseases occurring in late lactation on the subsequent lactation because of lacking published data on this relationship.

For recurring cases, treatment, labor, and discarded milk costs were assumed to reoccur at 100% of the price of the first episode whereas no extra losses were associated with reduced milk production, extended days open, an increased risk of culling, or an increased risk of death. This assumption is likely conservative but was necessary considering the lack of data available to show how recurring cases influence a cow's milk yield, reproductive performance, risk of culling, and risk of death. As a result of this assumption, we may have underestimated the losses associated with disease recurrence in our disease cost estimates and, therefore, underestimated the cost per case of each hoof disease.

Model demonstration

To demonstrate model usefulness, 1,000 iterations of the model were run using Latin Hypercube sampling. The mean ± SD cost per case of hoof disease across all disease type, severity level, incidence timing, and parity group combination was reported. Default deterministic variable assumptions used to define the herd and the average cow were collected from Dairy Records Management Systems (Raleigh, NC) using limitations of only Holstein herds with ≥ 200 cows, published literature, or the authors' expertise (Table 3.1). The resulting distributions of herd-level stochastic variables can be found in Table 3.2. Inputs used in the model for this study were meant to represent a United States dairy herd. However, model inputs could be adjusted to herd-specific values to calculate the cost of hoof diseases for a specific herd.

Sensitivity analysis

As described for each module, many variables were stochastic within the model including labor costs, therapeutic costs, days of discarded milk, expected milk loss, extended days open, culling risk ratios, disease recurrence rates, and disease length. However, only selected market prices and herd specific performance variables were included in a sensitivity analysis to test how they affected the disease costs because these variables are either more controllable by or more readily available to the producer. The selected variables included: milk price, feed price, replacement heifer price, slaughter price, rolling herd average milk production, and pregnancy rate (calculated as the multiplication of estrus detection rate and conception rate). Using the @Risk sensitivity analysis function, a multivariate regression analysis was conducted between these stochastic variables and the mean total cost per case of each hoof disease across all combinations of severity level, incidence timing, and parity group. The results of this analysis show how the cost per case of disease changes with a 1 standard deviation increase in each stochastic factor.

Results and Discussion

The objective of this study was to build a stochastic simulation model capable of estimating hoof disease costs per case depending on disease, severity level, incidence timing, and parity group. This was accomplished by incorporating modules to account for outside (hoof trimmer) labor, therapeutics, on-farm labor, discarded milk, reduced milk production, extended days open, an increased risk of culling, an increased risk of death (natural or euthanized), and disease recurrence into a pre-existing stochastic simulation model. Model accuracy may be limited by the fact that few previous studies have considered hoof disease expenditure and loss estimates specific to disease, severity level, incidence timing, and parity group. In particular, estimates used in this study for reduced milk production, extended days open, and disease recurrence may underestimate the total effects of hoof diseases. Additionally, little data exists on the effects of hoof diseases beyond the current lactation. Therefore, our hoof disease cost estimates only included expenditures and losses within the same lactation as disease occurrence. The disease cost estimates from our model demonstration should be interpreted carefully while keeping these limitations in mind.

Disease cost estimates

Digital dermatitis. The simulated mean ± SD cost per case of digital dermatitis by severity, incidence timing, and parity group is presented in Table 3.3 and patterns among results are presented in Figure 3.1a. Over all combinations, the mean ± SD cost per case of digital dermatitis was \$137 ± 36, ranging from a low of \$30 ± 21 for a mild case in a post-peak lactation (121 to 240 DIM), primiparous cow to a high of \$399 ± 116 for a severe case in an early lactation, multiparous cow. Previous estimates of the cost of digital dermatitis have been similar to the mean found in this study (\$133 and \$149/case after adjustment to 2017 USD; Willshire and Bell, 2009; Cha et al., 2010); although those estimates did not differentiate by severity or parity and did not include the cost of recurring cases within the same cow.

Charfeddine and Pérez-Cabal (2017) estimated a mild and severe case of digital dermatitis to be \$53 and \$402 (adjusted to 2017 USD), respectively, including the cost of recurrence. The mean ± SD mild or severe cost per case of digital dermatitis in our study, regardless of parity group or incidence timing, was \$59 ± 40 and \$215 ± 117, respectively. It is difficult to compare estimates from Charfeddine and Pérez-Cabal (2017) to the current study because 1) our study breaks costs down by not only severity but also incidence timing and parity group and 2) Charfeddine and Pérez-Cabal (2017) included recurrence costs within the other cost categories whereas recurrence costs were a separate category within our estimates. However, some major differences in calculations likely contributed to our difference in severe case cost estimates. First, our study did not differentiate expenditures on therapeutics or outside labor by severity level, whereas Charfeddine and Pérez-Cabal (2017) did. Additionally, the estimates for therapeutics and outside labor assumed in this study (from Chapter 2) were lesser than those found by Charfeddine and Pérez-Cabal (2017), likely because of differences in study location (United States vs. Spain) and the increased likelihood of veterinary involvement in Spain as compared to the United States. Second, discarded milk was assumed to be minimal in our study compared to Charfeddine and Pérez-Cabal (2017) who reported that antibiotic use was standard for all severe lesions. Third, our study assumed that the cost of a recurring case only included direct costs (therapeutics, outside labor, on-farm labor, and discarded milk) because minimal evidence exists to differentiate milk loss, extended days open, risk of culling, and risk of death associated with the first vs. second case of a hoof disease. Comparatively, Charfeddine and Pérez-Cabal (2017) assumed recurring cases to have the same cost as the first case.

As shown in Figure 3.1a, cases in primiparous cows were less expensive than comparable cases (same severity level and incidence timing) in multiparous cows. Compared to multiparous cows, primiparous cows experienced less milk production losses, losses associated with extended days open, losses associated with an increased risk of culling, and recurrence losses (Table 3.3). Within parity group, severe cases were more expensive than mild cases, regardless of incidence timing. Mild cases were associated with less on-farm labor, less milk production losses (from both discarded milk and reduced yield), lower costs associated with extended days open, lower losses associated with an increased risk of culling, and fewer recurrence costs. Across incidence timing, mean severe case costs decreased over the lactation of the cow whereas mean mild case costs were bimodal, peaking at the beginning and end of the lactation but with minimal variation among incidence timings (Figure 3.1a). All variable cost categories decreased as DIM at incidence increased except for culling losses. Losses associated with culling were bimodal, peaking in both early and late lactation. Our assumptions about the effects of hoof diseases on culling were taken from Booth et al. (2004), who found that the 95% confidence interval for the risk of culling when hoof diseases occurred in later lactation was wider than the 95% confidence interval for the risk of culling when hoof diseases occurred in earlier lactation. This resulted in our model estimating an increased risk of culling for cases occurring in later lactation, which may be overestimated. More research is needed to accurately estimate the effects of hoof disease timing on culling.

For mild digital dermatitis cases, losses associated with an increased risk of culling represented the greatest contribution to the total cost per case (mean = 55% of the total cost) in both parities and at all incidence timings except for multiparous cows in the post-peak period (121 to 240 DIM). During that period, losses associated with decreased milk production represented the largest portion of the total cost (mean = 39% of the total cost). For severe digital dermatitis cases, regardless of parity group, losses associated with decreased milk production represented the greatest contribution to the total cost per case at all incidence timings except late lactation (mean = 43% of the total cost). During late lactation, losses associated with an increased risk of culling contributed the most to the total cost per case (mean = 38% of the total cost). The remaining contributions of each cost category varied by severity, parity group, and incidence timing (Table 3.3). Charfeddine and Pérez-Cabal (2017) found that expenditures on outside labor and losses associated with reduced milk production contributed the most to the cost per affected cow in mild digital dermatitis cases (43% and 34%, respectively) and losses associated with an increased risk of death and culling and discarded milk contributed the most to the cost per affected cow in severe digital dermatitis cases (37% and 24%, respectively). As previously mentioned, recurrence losses were not considered as their own category by Charfeddine and Pérez-Cabal (2017), making direct comparisons difficult.

It is worth noting that none of the current cost estimates for digital dermatitis, including those in this study, have included the cost of transmission. Digital dermatitis is a contagious disease and ignoring the costs of additional cases of digital dermatitis resulting from one original case ignores the full economic losses of the disease. Döpfer et al. (2012) estimated the reproductive ratio of digital dermatitis to be between 0.5 and 3.3, depending on the prevention strategy used. Therefore, this cost category could make up a large portion of the cost per case of digital dermatitis, depending on herd level prevention strategies in place. Modeling of contagious diseases is complex, which is why this cost category is typically not included in digital dermatitis case cost estimates.

Sole ulcer. The simulated mean ± SD cost per case of a sole ulcer by severity, incidence timing, and parity group is presented in Table 3.4 and patterns among results are presented in Figure 3.1b. Over all combinations, the mean cost per case of sole ulcers was \$227 ± 35, ranging from a low of \$111 ± 41 for a mild case in a late lactation, primiparous cow to a high of \$486 ± 87 for a severe case in an early lactation, multiparous cow. Our reported mean was similar to the sole ulcer cost estimate of \$243 (adjusted to 2017 USD) by Cha et al. (2010). The mean ± SD mild or severe cost per case of sole ulcer in our study, regardless of parity group or incidence timing, was \$170 ± 65 and \$283 ± 109, respectively. Charfeddine and Pérez-Cabal (2017) estimated the cost per case of a mild and severe sole ulcer to be \$232 and \$622, respectively (adjusted to 2017 USD). The lower cost estimates found in our study, especially for severe cases, may be for similar reasons as the differences found for digital dermatitis.

Unlike digital dermatitis, parity group appeared to minimally affect the cost per case of mild sole ulcer (Figure 3.1b). In fact, mild cases occurring at any incidence timing except early lactation were within $15 of each other (Table 3.4). Parity group did affect the cost per case of severe sole ulcers with severe sole ulcers in multiparous cows resulting in greater losses associated with decreased milk production throughout lactation and greater losses associated with increased culling or death in early lactation. Within parity group, severe cases were always more expensive than mild cases occurring at the same incidence timing. Mild cases were associated with less on-farm labor and fewer losses associated with extended days open, disease recurrence, and an increased risk of culling or death. Milk production losses were greater in severe cases compared to mild cases for multiparous cows, but in primiparous cows, mild cases resulted in greater (though numerically similar) decreased milk production losses than severe cases. This was because milk production losses for week 4 post-diagnosis were estimated by Charfeddine and Pérez-Cabal (2017) to be greater in mild cases than severe cases, and week 4 post-diagnosis losses were assumed to continue until the end of lactation. Unfortunately, no alternative literature sources were identified that considered milk loss associated with hoof diseases while also considering severity of the disease and parity group of the affected animal. However, it is possible that a mild case of lameness might go undetected (and untreated) longer than a severe case of lameness, potentially increasing losses associated with reduced milk production.

Across incidence timing, both mild and severe case costs decreased over the lactation of the cow (Figure 3.1b). The decrease in mild case costs for sole ulcers over the lactation of the cow was more apparent than the decrease in mild case costs for digital dermatitis over the lactation of the cow. Compared to digital dermatitis, sole ulcers were associated with more extreme effects on reduced milk yield, extended days open, and an increased risk of culling or death, which were all influenced by stage of lactation. Similar to digital dermatitis, all variable cost categories decreased further in lactation except for those associated with an increased risk of culling or death. The peak in losses associated with an increased risk of death differed by parity group, but was bimodal in both cases with losses being highest at the beginning and end of lactation. This resulted from the slaughter value of the cow being highest at the beginning and end of lactation, following body weight patterns.

Across all sole ulcer cases, regardless of severity, the losses associated with reduced milk production, an increased risk of culling, and disease recurrence made up most of the total cost per case (mean = 24%, 24%, and 23% of the total cost, respectively). In severe sole ulcer cases, losses associated with an increased risk of death were also a top contributor to the total cost per case (mean = 18% of the total cost). The remaining contributions of each cost category varied by parity group (Table 3.4). Similarly, Kossaibati and Esslemont (1997) and Esslemont (2005) estimated that the combined costs of culling and death contributed most to the total cost of sole ulcers (33% to 36%). However, they estimated reduced reproductive performance to contribute the second most to total sole ulcer costs (30% to 32%). Losses associated with extended days open in this study were based on the assumption that mild and severe sole ulcers resulted in 2.1 ± 1.1 and 17.4 ± 6.0 extended days open, respectively, whereas both Kossaibati and Esslemont (1997) and Esslemont (2005) assumed sole ulcers resulted in 40 extended days open, which partially explains our difference in findings. Additionally, our method of calculating the cost per day open tends to be more conservative than other estimates (Dolecheck et al., 2016). Charfeddine and Pérez-Cabal (2017) estimated that the losses associated with an increased risk of culling contributed most (40% and 23% for mild and severe cases, respectively) to the total cost of a sole ulcer, followed by discarded milk (20% in severe cases) and reduced milk yield (18% and 16% for mild and severe cases, respectively).

White line disease. The simulated mean ± SD cost per case of white line disease by severity, incidence timing, and parity group is presented in Table 3.5 and patterns among results are presented in Figure 3.1c. Over all combinations, the mean cost per case of white line disease was \$203 ± 33, ranging from a low of \$97 ± 39 for a mild case in a late lactation, primiparous cow to a high of \$471 ± 90 for a severe case in an early lactation, multiparous cow. Willshire and Bell (2009) estimated costs associated with white line disease to be greater (\$555/case after adjustment to 2017 USD), but assumed 30 extended days open resulting from the disease, whereas our assumed mean extended days open for a mild and severe case of white line disease was 3.3 ± 1.5 d and 10.3 ± 5.0 d, respectively. The mean ± SD mild or severe cost per case of white line disease in our study, regardless of parity group or incidence timing, was \$135 ± 55 and \$271 ± 106, respectively. These estimates are less than those of Charfeddine and Pérez-Cabal (2017), who found a mild case of white line disease to cost \$221 and a severe case to cost \$590 assuming greater therapeutic and supply costs, as well as the possibility of discarded milk losses, which were not included in our study.

Similar to sole ulcers, parity group appeared to minimally affect the cost per case of mild white line disease while having greater effects on severe white line disease. In severe cases, multiparous cows had increased losses associated with reduced milk production throughout lactation and increased losses associated with an increased risk of culling or death in early lactation. Within parity group, severe cases were always more expensive than mild cases. Losses associated with decreased milk production were greater in severe cases compared to mild cases regardless of parity group, but within mild cases were greater for primiparous cows than multiparous cows for similar reasons as for our sole ulcers estimates. Across incidence timing, both mild and severe case costs generally decreased over the lactation of the cow (Figure 3.1c).

For mild cases of white line disease, regardless of parity group, the cost categories that contributed the most to the total cost per case were losses associated with an increased risk of culling (mean = 33% of the total cost) and disease recurrence (mean = 23% of the total cost). For severe cases of white line disease, losses attributed to disease recurrence and an increased risk of culling contributed most to the cost per case in primiparous cows (mean = 22% and 21% of the total cost, respectively) whereas losses attributed to decreased milk production and an increased risk of culling contributed most to the cost per case in multiparous cows (mean = 27% and 22% of the total cost, respectively). Losses associated with an increased risk of death were also a large contributor to the total cost per case of severe white line disease (mean = 18% of the total cost). The remaining contributions of each cost category varied by parity group (Table 3.5). Only Charfeddine and Pérez-Cabal (2017) have previously broken down cost categories for white line disease, with very similar estimates to sole ulcers (30% to 39% increased risk of culling or death, 13% to 17% reduced milk production, and 20% discarded milk in severe cases).

Sensitivity Analysis. The change in the mean (across all severity level, incidence timing, and parity group combinations) total cost per case of each disease as selected market prices and herd specific performance variables increased by 1 standard deviation is displayed in Figure 3.2. Across all diseases, the cost per case of hoof disease increased in response to a 1 standard deviation increase in milk price, rolling herd average milk production, or replacement heifer price. As either milk price or rolling herd average milk production increased the cost per case increased because there was more potential income from milk production being lost through both discarded milk and reduced milk yield. Milk price and the rolling herd average milk production level influenced the cost per case more in higher milk production potential situations: multiparous cows, severe cases, and earlier incidence timing (because milk loss would continue throughout lactation). As replacement price increased, the cost to replace an animal that was culled or died increased, thereby increasing the cost of disease. The change in the cost per case in response to changing replacement price was greatest in severe cases when culling or death was more likely.

Across all diseases, the cost per case of hoof disease decreased in response to a 1 standard deviation increase in feed price, pregnancy rate, or slaughter price. In response to disease and the resulting lower milk production, cows were assumed to eat less. Therefore, a cow with a disease would have lower feed costs and the cost of disease would be lowered when feed costs are high. As with milk price, the feed price influenced the cost per case more in higher milk production potential situations. As pregnancy rate increased, the adverse effects of disease on reproduction became less detrimental, therefore lowering the cost of disease. In other words, if a herd was already getting cows pregnant quickly, adding a few more days open would be less detrimental than in a herd that was already struggling to get cows pregnant. Finally, as slaughter price increased, the cost of culling a cow decreased, therefore lowering the cost of disease.

The two most important of the selected market prices and herd specific performance variables appeared to be the milk price and replacement price. Changing milk price resulted in the largest change in the mean cost of either digital dermatitis or sole ulcer ($15.3 and $17.1 increase, respectively) whereas changing replacement price resulted in the largest change in the mean cost of white line disease ($13.5 increase). The reason these two market prices had the greatest influence on the cost of hoof diseases is likely linked to their heavy involvement in calculating losses associated with reduced milk production, an increased risk of culling, and an increased risk of death; these 3 cost categories were among the largest contributors in all cost per case estimates.

Hoof disease cost estimates summary. Across all 3 hoof diseases considered in this study, severity had the largest effect on the total cost per case. The percent increase from mild to severe cases within the same incidence timing and parity group ranged from 45% to 364%. Understanding the differences between the cost of a mild and severe hoof disease highlights the need for early intervention when a cow becomes lame. For digital dermatitis, parity group had a greater effect on the total cost per case than incidence timing. For sole ulcers and white line disease, both incidence timing and parity group affected the total cost per case of disease. Understanding the cost per case of disease for different categories of animals (e.g., parity group, DIM) can help guide treatment and culling decisions at the individual animal level. Understanding how incidence timing influences the cost of a disease can additionally help focus prevention strategies on certain groups of animals within a herd (i.e., early vs. late lactation) if prevention is not implemented across the whole herd. Based on results using the assumptions in this study, implementing hoof disease prevention strategies would be most beneficial in early lactation. Additionally, this might indicate that prevention in the dry and close-up periods would also be beneficial.

The results from the sensitivity analysis highlight the importance of considering the cost of hoof diseases at the herd level as changes in market prices and herd performance can change the cost of disease. In the future, models like this one could aid in the construction of decision support tools to improve herd and cow level decisions regarding lameness treatment and prevention.

Conclusions

The ability to estimate the cost per case of 3 hoof diseases (digital dermatitis, sole ulcer, and white line disease) was incorporated into a pre-existing stochastic simulation model. Through this process, missing data in the literature was identified, indicating potential areas for future research. In particular, expenditures and losses specific to individual hoof diseases, severity of disease, timing of disease, and parity group affected by the disease should be considered.

Using assumptions meant to represent a United States dairy herd, disease cost estimates calculated using the model varied by not only disease type, but also severity, incidence timing, and parity group. These differences indicate that the cost per case of hoof disease differs by cow. This knowledge could help guide on-farm decisions about hoof disease treatment, culling strategies, and investment in lameness prevention. Hoof disease costs were also influenced by market prices and herd specific performance variables, indicating that hoof disease costs should be considered at the individual herd level.

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Table 3.1 Deterministic farm performance and financial inputs used in a stochastic model to estimate the cost of 3 different dairy cow hoof diseases

Input	Value	Source[1]
Age at first calving (m)	24.3	DairyMetrics
Baseline culling rate (%)	13.0	Bewley et al. (2010)
Breeding costs ($/insemination)	15.51[2]	VanRaden and Cole (2014)
Butterfat yield (%)	3.7	DairyMetrics
Calf birth weight (kg)	41.7	Kertz et al. (1997)
Close up dry cow feed price ($/kg DM)	0.22	Authors' expertise
Close up dry period length (d)	21	Authors' expertise
Days dry	56.2	NAHMS (2014)
Days in milk designated do not breed	250	Bewley et al. (2010)
Discount rate (%)	8.0	Hyde and Engel (2002)
Disposal losses ($)	65[2]	Groenendaal et al. (2004)
Far off dry cow feed price ($/kg DM)	0.15	Authors' expertise
Gestation length (d)	280	Norman et al. (2007)
Mature cow live weight (kg)	723	NRC (2001)
Percent heifer calves	46.7	Del Río et al. (2007)
Percent of herd in 1st parity	36.1	Dhuyvetter et al. (2007)
Percent of herd in 2nd parity	26.0	Dhuyvetter et al. (2007)
Percent of herd in 3rd parity	17.7	Dhuyvetter et al. (2007)
Percent of herd in 4th parity	11.0	Dhuyvetter et al. (2007)
Percent of herd in 5th parity	5.8	Dhuyvetter et al. (2007)
Percent of herd in 6th (or greater) parity	3.4	Dhuyvetter et al. (2007)
Protein yield (%)	3.1	DairyMetrics
Voluntary waiting period (d)	59.3	DairyMetrics

[1]DairyMetrics information was collected on October 1, 2017 from Dairy Records Management Systems (Raleigh, NC). Values gathered from DairyMetrics included 1,987 United States Holstein herds with at least 200 cows.
[2]Adjusted for inflation to 2017 prices

Table 3.2 Simulated market price and farm performance inputs used in a stochastic model to estimate the cost of 3 different dairy cow hoof diseases

Input	Simulated range (min – max)	Simulated mean ± SD	Source[1]
Calf value ($/bull)	72.35 – 224.25	130.74 ± 41.27	Regression model
Calf value ($/heifer)	234.00 – 674.92	395.16 ± 143.51	Regression model
Slaughter value ($/kg)	1.03 – 1.78	1.43 ± 0.20	FAPRI (2017)
Milk price ($/kg)	0.29 – 0.50	0.40 ± 0.06	FAPRI (2017)
Lactating feed price ($/kg DM)	0.21 – 0.38	0.29 ± 0.04	FAPRI (2017)
Replacement heifer price ($)	1,437 – 2,122	1,718 ± 216	Regression model
RHA milk production (kg)	4,899 – 18,113	11,459 ± 2,002	DairyMetrics
Pregnancy rate (%)	2.8 – 74.7	22.5 ± 11.4	DairyMetrics

[1]DairyMetrics information was collected on October 1, 2017 from Dairy Records Management Systems (Raleigh, NC). Values gathered from DairyMetrics included 1,987 United States Holstein herds with at least 200 cows.

Table 3.3 Mean ± SD expenditures, losses, and total cost per case of digital dermatitis by severity, incidence timing, and parity group as estimated using a stochastic simulation model (n = 1,000 iterations). Bolded values indicate the cost category contributing most to the total cost per case for each combination of severity, incidence timing, and parity group.

	Expenditures ($/case)			Losses[1] ($/case)					Total ($/case)
	Therapeutics	Outside labor	On-farm labor	Discarded milk	Decreased milk production	Extended days open	Recurrence	Culling	
Primiparous (mild)									
0 to 60 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	0.59 ± 0.35	0.67 ± 0.70	10.41 ± 13.77	**27.10 ± 18.33**	47.39 ± 28.42
61 to 120 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	0.59 ± 0.35	0.61 ± 0.62	9.88 ± 12.93	**26.84 ± 23.47**	46.55 ± 31.71
121 to 240 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	0.59 ± 0.35	0.12 ± 0.18	7.54 ± 9.05	**12.71 ± 11.23**	29.57 ± 21.23
>240 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	0.55 ± 0.33	0.00 ± 0.00	2.58 ± 3.11	**31.77 ± 27.21**	43.52 ± 29.61
Primiparous (severe)									
0 to 60 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	14.99 ± 16.57	**81.34 ± 50.81**	11.31 ± 9.66	53.15 ± 35.66	28.95 ± 18.93	217.45 ± 76.73
61 to 120 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	14.78 ± 16.33	**67.53 ± 40.36**	10.56 ± 9.18	50.30 ± 32.31	27.07 ± 20.81	197.95 ± 67.36
121 to 240 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	12.46 ± 13.75	**45.95 ± 24.96**	2.17 ± 3.38	36.70 ± 21.90	12.14 ± 10.04	137.11 ± 47.65
>240 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	9.02 ± 10.02	17.43 ± 7.19	0.00 ± 0.00	11.54 ± 6.82	**41.48 ± 25.94**	107.17 ± 33.38
Multiparous (mild)									
0 to 60 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	31.47 ± 14.58	0.97 ± 0.70	11.81 ± 14.20	**66.36 ± 33.51**	119.23 ± 44.11
61 to 120 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	27.56 ± 12.02	0.91 ± 0.66	10.97 ± 12.86	**27.91 ± 17.97**	75.96 ± 31.94
121 to 240 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	**20.13 ± 8.07**	0.20 ± 0.28	8.07 ± 9.01	13.97 ± 11.41	50.98 ± 23.40
>240 DIM	1.98 ± 2.41	4.91 ± 8.99	1.73 ± 0.43	NA	10.15 ± 3.26	0.00 ± 0.00	2.75 ± 3.12	**39.92 ± 28.35**	61.42 ± 31.30
Multiparous (severe)									
0 to 60 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	19.60 ± 21.31	**194.33 ± 76.00**	15.00 ± 12.22	74.72 ± 47.56	67.96 ± 31.66	399.30 ± 115.94
61 to 120 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	17.98 ± 19.54	**162.85 ± 62.21**	14.07 ± 11.63	65.83 ± 40.55	28.58 ± 14.97	316.99 ± 94.36
121 to 240 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	12.10 ± 13.10	**110.66 ± 41.56**	3.06 ± 4.67	41.50 ± 23.32	13.42 ± 9.42	208.43 ± 62.76
>240 DIM	1.98 ± 2.41	4.91 ± 8.99	20.81 ± 5.20	5.80 ± 6.32	41.57 ± 14.81	0.00 ± 0.00	11.83 ± 6.42	**51.99 ± 26.00**	138.88 ± 36.66

[1]NA indicates a cost category that was assumed not applicable to the total cost for that specific severity, incidence timing, and parity group combination

Table 3.4 Mean ± SD expenditures, losses, and total cost per case of sole ulcer by severity, incidence timing, and parity group as estimated using a stochastic simulation model (n = 1,000 iterations). Bolded values indicate the cost category contributing most to the total cost per case for each combination of severity, incidence timing, and parity group.

	Expenditures ($/case)			Losses[1] ($/case)					Total ($/case)
	Therapeutics	Outside labor	On-farm labor	Decreased milk production	Extended days open	Recurrence	Culling	Death	
Primiparous (mild)									
0 to 60 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	**75.30 ± 30.68**	1.98 ± 1.33	51.03 ± 21.18	45.47 ± 33.00	NA	207.68 ± 50.60
61 to 120 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	**62.96 ± 25.18**	1.84 ± 1.27	50.35 ± 20.43	40.23 ± 30.59	NA	189.29 ± 46.76
121 to 240 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	42.72 ± 16.94	0.38 ± 0.53	**43.74 ± 17.50**	18.02 ± 15.35	NA	138.77 ± 33.80
>240 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	15.82 ± 5.97	0.00 ± 0.00	16.58 ± 7.65	**44.20 ± 37.30**	NA	110.51 ± 40.57
Primiparous (severe)									
0 to 60 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	55.92 ± 35.06	21.59 ± 11.03	**80.91 ± 25.67**	62.16 ± 38.73	39.25 ± 5.68	300.66 ± 60.58
61 to 120 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	49.42 ± 28.42	20.07 ± 10.55	**77.90 ± 24.58**	58.18 ± 34.68	40.12 ± 5.80	286.53 ± 53.97
121 to 240 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	36.42 ± 18.35	3.99 ± 4.70	**62.95 ± 22.07**	21.87 ± 16.76	41.70 ± 6.04	207.76 ± 39.63
>240 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	18.85 ± 6.81	0.00 ± 0.00	22.32 ± 9.26	**53.17 ± 35.76**	46.63 ± 6.84	181.81 ± 39.76
Multiparous (mild)									
0 to 60 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	70.72 ± 22.99	2.77 ± 1.69	52.67 ± 21.14	**99.59 ± 52.71**	NA	259.65 ± 66.11
61 to 120 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	**61.12 ± 19.64**	2.60 ± 1.66	51.69 ± 20.09	43.33 ± 25.41	NA	192.64 ± 43.50
121 to 240 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	43.43 ± 14.08	0.57 ± 0.80	**44.24 ± 16.53**	19.19 ± 14.99	NA	141.34 ± 32.34
>240 DIM	8.01 ± 4.69	12.01 ± 6.16	13.88 ± 3.48	19.89 ± 6.20	0.00 ± 0.00	16.72 ± 7.37	**53.25 ± 36.20**	NA	123.76 ± 40.08
Multiparous (severe)									
0 to 60 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	114.67 ± 45.21	27.35 ± 13.96	81.51 ± 26.66	**137.67 ± 51.36**	84.38 ± 12.20	486.41 ± 87.49
61 to 120 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	**100.30 ± 37.88**	25.54 ± 13.61	78.53 ± 25.05	62.33 ± 23.93	41.63 ± 6.02	349.15 ± 63.35
121 to 240 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	**72.41 ± 26.12**	5.30 ± 6.46	62.91 ± 21.64	22.65 ± 14.13	41.91 ± 6.08	246.02 ± 46.45
>240 DIM	8.01 ± 4.69	12.01 ± 6.16	20.81 ± 5.20	35.08 ± 10.91	0.00 ± 0.00	22.27 ± 9.06	**64.41 ± 34.06**	44.10 ± 6.41	206.70 ± 41.52

[1]NA indicates a cost category that was assumed not applicable to the total cost for that specific severity, incidence timing, and parity group combination

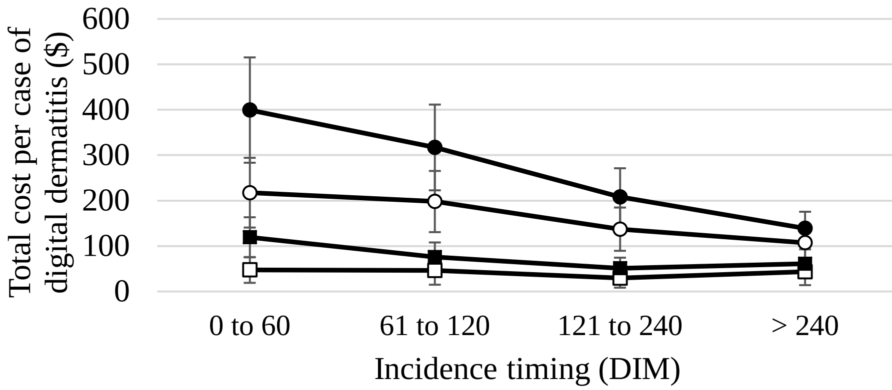
Table 3.5 Mean ± SD expenditures, losses, and total cost per case of white line disease by severity, incidence timing, and parity group as estimated using a stochastic simulation model (n = 1,000 iterations). Bolded values indicate the cost category contributing most to the total cost per case for each combination of severity, incidence timing, and parity group.

	Expenditures ($/case)			Losses[1] ($/case)					Total ($/case)
	Therapeutics	Outside labor	On-farm labor	Decreased milk production	Extended days open	Recurrence	Culling	Death	
Primiparous (mild)									
0 to 60 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	36.63 ± 20.87	3.09 ± 1.76	**46.96 ± 17.59**	45.10 ± 32.12	NA	165.72 ± 45.78
61 to 120 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	31.32 ± 16.90	2.88 ± 1.69	**40.99 ± 15.30**	40.05 ± 30.08	NA	149.19 ± 39.75
121 to 240 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	21.99 ± 10.89	0.57 ± 0.71	**28.45 ± 11.09**	18.39 ± 16.81	NA	103.34 ± 27.65
>240 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	9.60 ± 4.11	0.00 ± 0.00	9.60 ± 4.11	**43.90 ± 37.13**	NA	97.03 ± 39.01
Primiparous (severe)									
0 to 60 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	56.68 ± 38.89	11.30 ± 7.35	**71.58 ± 26.16**	62.60 ± 39.74	39.25 ± 5.68	282.28 ± 62.39
61 to 120 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	50.60 ± 31.52	10.53 ± 6.98	**66.67 ± 25.34**	58.09 ± 35.37	40.12 ± 5.80	266.88 ± 56.01
121 to 240 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	37.63 ± 20.26	2.15 ± 2.91	**52.29 ± 23.37**	22.12 ± 16.55	41.70 ± 6.04	196.76 ± 40.57
>240 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	20.20 ± 7.44	0.00 ± 0.00	18.92 ± 10.22	**53.73 ± 36.74**	46.63 ± 6.84	180.35 ± 40.95
Multiparous (mild)									
0 to 60 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	23.34 ± 11.42	4.23 ± 2.27	48.97 ± 17.49	**99.60 ± 51.62**	NA	210.09 ± 60.89
61 to 120 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	22.06 ± 9.63	3.96 ± 2.24	42.37 ± 15.16	**42.85 ± 24.44**	NA	145.19 ± 35.66
121 to 240 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	17.24 ± 6.61	0.83 ± 1.04	**29.17 ± 11.17**	19.31 ± 15.78	NA	100.50 ± 26.63
>240 DIM	8.20 ± 6.74	11.86 ± 5.85	13.88 ± 3.47	10.74 ± 3.18	0.00 ± 0.00	9.85 ± 4.23	**53.32 ± 36.38**	NA	107.85 ± 39.08
Multiparous (severe)									
0 to 60 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	120.36 ± 51.15	14.70 ± 9.51	73.16 ± 25.32	**137.65 ± 53.18**	84.38 ± 12.20	471.13 ± 89.89
61 to 120 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	**104.92 ± 42.39**	13.74 ± 9.04	67.76 ± 24.50	62.44 ± 24.64	41.63 ± 6.02	331.36 ± 65.46
121 to 240 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	**75.33 ± 28.62**	2.92 ± 4.02	52.58 ± 22.16	22.72 ± 13.91	41.91 ± 6.08	236.33 ± 47.55
>240 DIM	8.20 ± 6.74	11.86 ± 5.85	20.81 ± 5.20	35.91 ± 11.56	0.00 ± 0.00	19.12 ± 10.25	**64.62 ± 34.40**	44.10 ± 6.41	204.62 ± 43.17

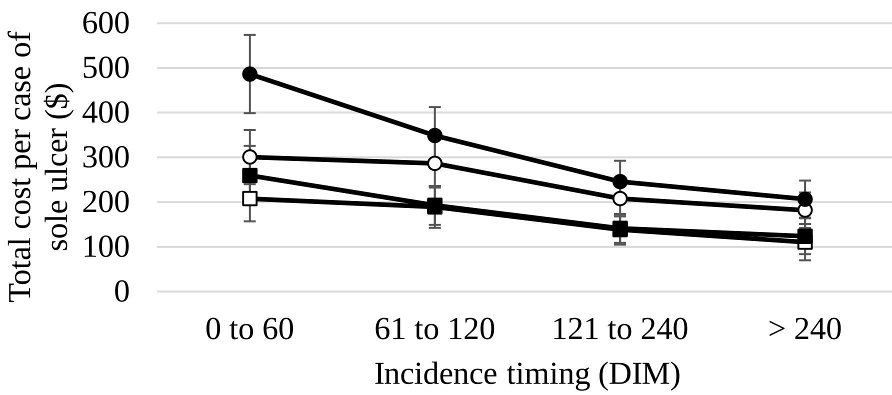
[1]NA indicates a cost category that was assumed not applicable to the total cost for that specific severity, incidence timing, and parity group combination

Figure 3.1 Variation in the total cost per case of a) digital dermatitis, b) sole ulcer, and c) white line disease by severity, incidence timing, and parity group as estimated using a stochastic simulation model (n = 1,000 iterations). Incidence timing represents the timing of diseases occurrence. Open squares (□) represent mild cases in primiparous cows, solid squares (■) represent severe cases in primiparous cows, open circles (○) represent mild cases in multiparous cows, and solid circles (●) represent severe cases in multiparous cows.

a)



b)



c)

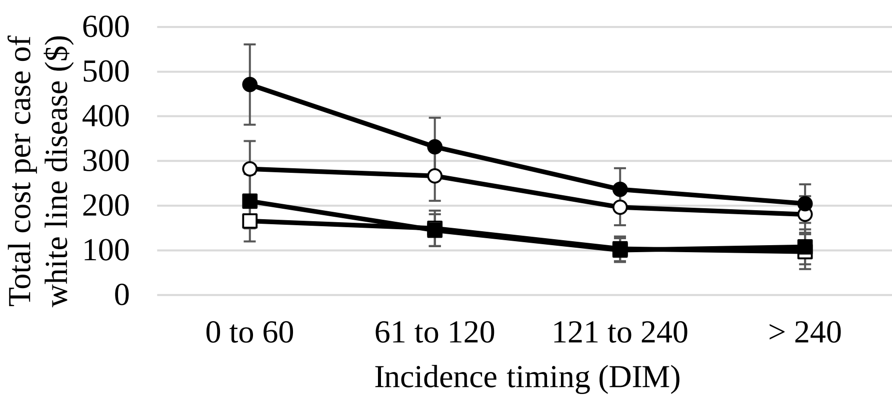
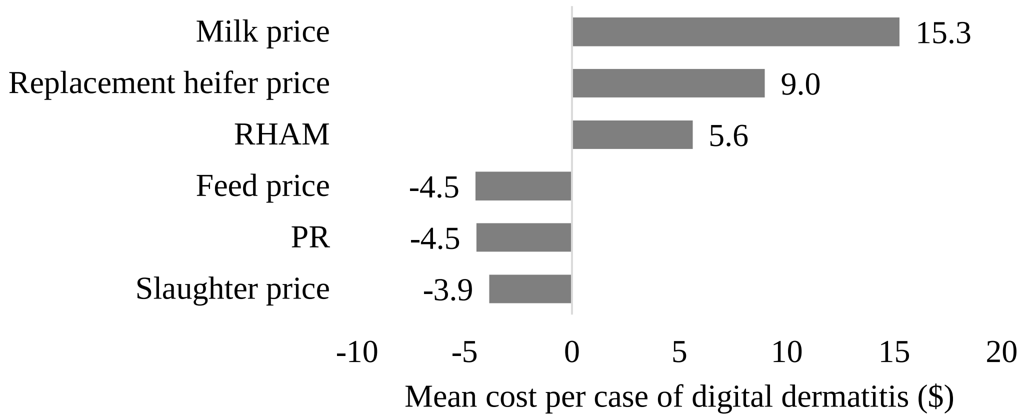
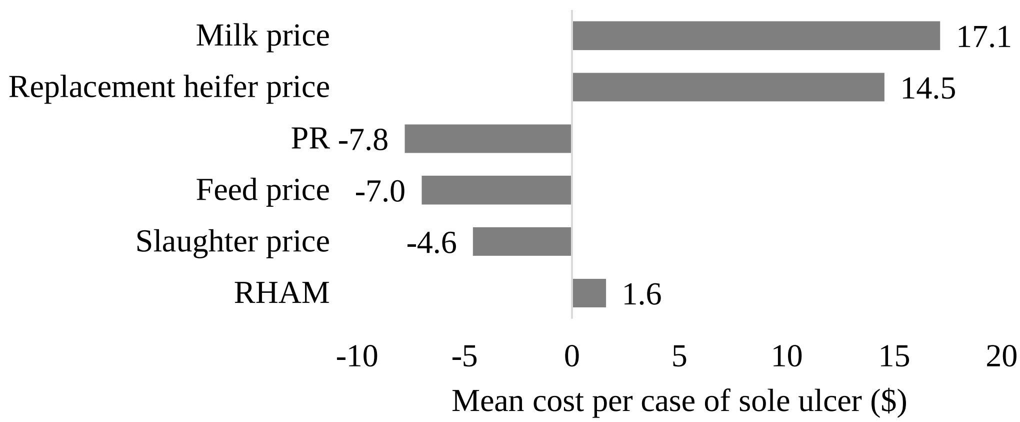


Figure 3.2 Tornado graphs indicating the change ($) in digital dermatitis (a), sole ulcer (b), and white line disease (c) mean total cost per case with a 1 SD increase in selected stochastic market prices and herd specific performance variables (RHAM = rolling herd average milk production, PR = pregnancy rate) as estimated using a stochastic simulation model (n = 1,000 iterations).

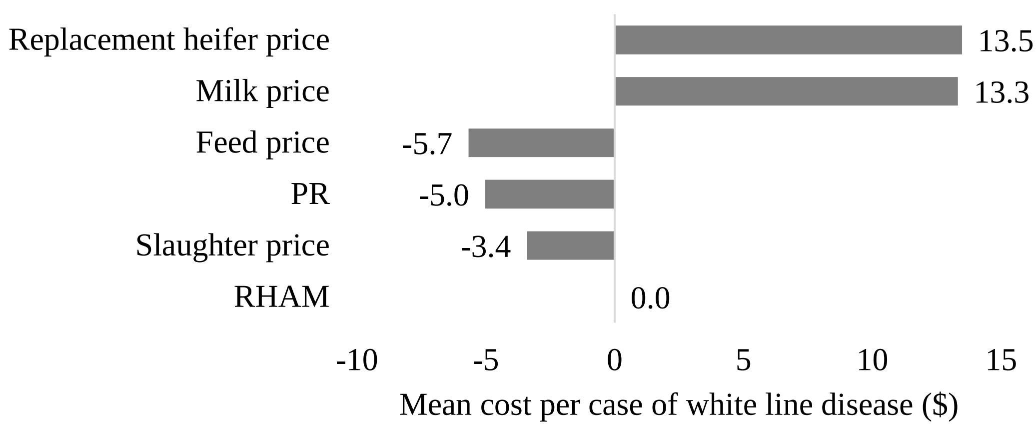
a)



b)



c)



CHAPTER 4

Estimating the dairy farm value of infectious or non-infectious lameness prevention strategies, as influenced by pre-prevention hoof disease incidence rates and prevention effectiveness

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Abstract

A farm-level stochastic simulation model was adapted to estimate the value of implementing lameness prevention on a dairy farm by calculating the change in the herd-level total cost of lameness from pre- to post- lameness prevention implementation. Two potential lameness prevention strategies were tested: strategy 1 was prevention focused on reducing the infectious hoof diseases in the model (digital dermatitis) and strategy 2 was prevention focused on reducing the non-infectious hoof diseases in the model (sole ulcer and white line disease). For each strategy, the effect of the pre-prevention investment hoof disease incidence on prevention value was evaluated by setting pre-prevention incidence of hoof diseases at 3 different levels. For strategy 1, digital dermatitis incidence level pre-prevention investment was 20%, 40%, or 60% while the incidence level of the non-infectious hoof diseases in the model were held constant. For strategy 2, sole ulcer and white line disease incidence level pre-prevention investment were both 5%, 15%, or 25% while the incidence level of the infectious hoof diseases included in the model were held constant. Overall, 6 different scenarios were run; 1 scenario for each prevention strategy and pre-prevention investment hoof disease incidence rate combination. To evaluate how the effectiveness of each prevention strategy would influence the investment value, the effectiveness of prevention was allowed to vary from a disease incidence risk ratio of 0.0 (100% reduction in disease incidence) to 1.0 (0% reduction in disease incidence). For both prevention strategies, the value of prevention (i.e., change in the herd-level total cost of lameness) increased as the pre-prevention incidence rate of hoof diseases and the effectiveness of prevention increased (i.e., the disease incidence risk ratio became smaller). However, the profitability of investing in lameness prevention would depend on the cost

of the prevention strategy and the other benefits association with the selected prevention strategy. If a herd manager knows the current herd-level incidence of hoof diseases and the expected effectiveness of a potential lameness prevention strategy, this model could be used as a decision support tool to help identify the amount that could be paid to implement that prevention strategy.

Key words: lameness, hoof health, decision support, animal health economics

Introduction

Lameness is considered one of the most important animal welfare issues in the dairy industry today (Von Keyserlingk et al., 2009) and is also estimated to be one of the most expensive dairy diseases per case (Liang et al., 2017). In North American herds, reported lameness prevalence has ranged from 10% (Adams et al., 2016) to 55% (Von Keyserlingk et al., 2012) between 2012 and 2017.

There are many lameness prevention strategies available for dairy herds to use, including footbaths (Speijers et al., 2012) and preventive hoof trimming (Manske et al., 2002). Yet a recent survey of 184 United States dairies indicated that producers are not consistently using recommended lameness prevention and control strategies (Adams et al., 2016). Thirty-five percent of surveyed farms never used a footbath and 13% of farms only used a footbath seasonally or occasionally. Additionally, 7% of herds never performed preventive hoof trimming, 20% of farms only conducted trimming when cows were visibly lame, and 36% of farms only performed preventive hoof trimming once per lactation.

Leach et al. (2010a) found that the reasons producers did not focus on lameness prevention included a false perception that no lameness problem existed in their herd, a lack of time, or a lack of understanding surrounding the economic consequences of lameness. Further, when producers were asked what could motivate other farms to reduce lameness, the most frequent response was to provide more information on lameness costs (Leach et al., 2010b). Disease costs are difficult to understand because the total cost is composed of 2 different components: expenditures and losses (McInerney et al., 1992). Expenditures are the direct costs associated with treatment (i.e., labor and therapeutics) and prevention of disease. These are the costs producers often recall because they are obvious. Losses are the indirect costs associated with existing disease. For example, reduced milk yield, reduced reproductive performance, increased risk of culling, increased risk of death, and risk of disease recurrence are all disease losses.

Morris (1969) defined optimum disease management as increasing disease prevention expenditures only to the point that the additional money spent would be equal to the resulting additional returns (i.e., reduced losses). In this study, we used a pre-existing farm-level stochastic simulation model to estimate the change in the herd-level total cost of lameness when prevention strategies were implemented. By doing this, the model could be used to calculate the amount a producer should be willing to spend on prevention, given the expected returns (i.e., reduced hoof disease losses). Our objective was to estimate the value of infectious or non-infectious lameness prevention strategies when pre-prevention hoof disease incidence rates and prevention effectiveness varied.

Materials and Methods

Model overview

The herd-level stochastic simulation model used in this study was previously described in Chapter 3. The deterministic portion of the model was created using Excel 2016 (Microsoft, Seattle, Washington) and was supplemented with stochastic features using the @Risk add-in (Palisade Corporation, Ithaca, New York). The model calculates the revenues (milk sales, calf value, and slaughter value) and expenses (feed costs, veterinary costs, breeding costs, and disposal losses) associated with the average cow in the herd every day for 6 lactations. Information about the average cow is used to estimate the herd-level revenues and expenses over a year-long period.

Within the model, the cost per case of 3 hoof diseases (digital dermatitis, sole ulcer, and white line disease) was calculated based on assumed changes in cow performance in response to disease, as collected from previously published research (Chapter 3). The cost per case of hoof disease varied by not only disease type, but also severity level (mild or severe), incidence timing (0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, or >240 DIM), and parity group (primiparous or multiparous). The total cost per case of each hoof disease included the current lactation expenditures associated with outside (hoof trimmer) labor, therapeutics, and on-farm labor, and losses associated with discarded milk, reduced milk production, extended days open, an increased risk of culling, an increased risk of death (natural or euthanized), and disease recurrence (within the same animal). Variables assumed to influence the cost of hoof diseases were modeled stochastically to account for variation among herds or uncertainty in their values. For stochastically modeled variables, a distribution was defined using previously published literature or industry averages (Table 4.1). Each time the model was run, a value from that distribution was selected and used in the model to calculate a unique cost per case of hoof disease.

Lameness prevention assumptions

In this study, the pre-existing model was adapted to estimate the economic outcome associated with implementing lameness prevention strategies on a dairy farm. As an example, we focused on two potential lameness prevention methods: strategy 1 was assumed to reduce infectious hoof diseases only (i.e., digital dermatitis) and strategy 2 was assumed to reduce both non-infectious hoof diseases only (i.e., sole ulcer and white line disease). To calculate the value of implementing strategies which prevented each type of lameness, the herd-level total cost of lameness would need to be calculated pre- and post-lameness prevention implementation. To calculate the herd-level total cost of lameness from the cost per case of lameness estimates already provided by the model, the following additional information was needed in the model: pre- and post- lameness prevention implementation hoof disease incidence rates and the distribution of hoof diseases among different classifications (i.e., mild vs. severe cases, the distribution of disease occurrence across the lactation, and the distribution of cases among parities).

Hoof disease incidence rates. For the base scenario, when no lameness prevention was used, an estimate of the incidence of each hoof disease was needed. No United States studies were identified that evaluated incidence levels of specific hoof diseases while reporting the prevention strategies used on the evaluated herds. Additionally, incidence rates will vary across farms. Therefore, in this study we tested 3 possible pre-prevention implementation incidence rates of hoof diseases within each strategy to see how variation would influence the investment outcome. Each different pre-prevention incidence rate was run as a separate simulation within the model. For strategy 1, the incidence of digital dermatitis was assumed to be 20%, 40%, or 60%, while the incidence of sole ulcer and white line disease were held constant (15%). For strategy 2, the incidence of both sole ulcers and white line disease was assumed to be 5%, 15%, or 25%, while the incidence of digital dermatitis was held constant (30%). To summarize, 6 different scenarios were tested: in 3 scenarios the economic effect of implementing infectious hoof disease prevention was tested, assuming 3 different pre-prevention incidence rates for digital dermatitis and in 3 scenarios the economic effect of implementing non-infectious hoof disease prevention was tested, assuming 3 different pre-prevention incidence rates for sole ulcers and white line disease. The values chosen to represent pre-prevention implementation incidence rates for all diseases were selected to represent variation around the mean prevalence rates reported by DeFrain et al. (2013), but do not necessary represent the true incidence rates found on farms in the United States.

When lameness prevention strategies were used, we assumed that lameness incidence would be affected. Disease incidence risk ratios (RR) were used to adjust the base incidence of each hoof disease as prevention strategies were implemented. Limited published data on how different lameness prevention strategies change hoof disease incidence exists. Therefore, instead of assuming a particular prevention strategy, we allowed the effect of prevention strategies on hoof disease incidence (disease risk ratios) to vary stochastically. Hoof disease risk ratios were modeled using a triangle distribution with the minimum, most likely, and maximum values set to 0.0, 0.5, and 1.0, respectively, for all simulations. The hoof disease risk ratio distributions were truncated at a minimum of 0.0 and a maximum of 1.0, meaning the model input was re-drawn from the distribution if a value outside of that range was selected, assuming that lameness prevention strategy implementation would never increase the risk of diseases incidence. To summarize, the effect of prevention in all 6 scenarios varied from no effect (risk ratio = 1.0) to 100% reduction in the selected hoof diseases (risk ratio = 0.0). For the first 3 scenarios, this risk ratio was applied to the incidence of digital dermatitis (to allow analysis of the value of infectious hoof disease prevention) and for the remaining 3 scenarios, this risk ratio was applied to the incidence of sole ulcers and white line disease (to allow analysis of the value of non-infectious hoof disease prevention). Allowing variation in the disease incidence risk ratios allowed us to evaluate the value of lameness prevention strategies with varying levels of effectiveness.

Hoof disease case classification. The model calculated the cost per case of hoof disease by disease type, severity level, incidence timing, and parity. Therefore, the distribution of occurring hoof disease cases among these combinations was needed for an accurate estimation of herd-level lameness costs. The same hoof disease incidence rates were assumed for primiparous and multiparous cows and parities 1, 2, 3, 4, 5, and 6 were modeled to represent 36.1%, 26.0%, 17.7%, 11.0%, 5.8%, and 3.4% of the herd, respectively (Table 4.1; Dhuyvetter et al., 2007). The percent of severe vs. mild cases was defined by observations from Charfeddine and Pérez-Cabal (2017) who estimated severe cases to represent 6%, 14%, and 16% of primiparous digital dermatitis, sole ulcer, and white line disease, and 6%, 13%, and 14% of multiparous digital dermatitis, sole ulcer, and white line disease, respectively. Disease incidence timing was modeled to match timing as reported by Booth et al. (2004), assuming white line disease to follow a similar pattern to sole ulcer because both are non-infectious diseases. The percentage of digital dermatitis cases occurring at ≤ 60 DIM, 61 to 120 DIM, 121 to 240 DIM, and >240 DIM was 27%, 31%, 30%, and 12%, respectively. The percentage of sole ulcer and white line disease cases occurring at ≤ 60 DIM, 61 to 120 DIM, 121 to 240 DIM, and >240 DIM was 26%, 32%, 31%, and 10%, respectively.

Calculation of lameness prevention value

In both pre- and post- lameness prevention implementation simulations, hoof disease incidence rates were multiplied by the number of cows in each parity to calculate the number of cases of each hoof disease occurring in one year. To find the number of cows in each parity, the percent of cows in each parity (Table 4.1) was multiplied by the milking herd size. Milking herd size was modeled stochastically using a PertAlt distribution with the 5th percentile, mean, and 95th percentile set to 50, 250, and 1,000 cows to represent a wide range of herd sizes (Table 4.2). These calculations resulted in the total number of cases of each hoof disease in each parity per year in both the pre- and post-lameness prevention implementation scenarios. The number of cases within each parity per year were then classified by severity and incidence timing using model assumptions, and a cost was assigned to each case by calculating the lameness associated expenditures and losses as described in Chapter 3.

In each scenario, the herd-level total cost of lameness was calculated as the sum of all expenditures (outside labor, therapeutics, on-farm labor, and prevention) and losses (discarded milk, reduced milk production, increased days open, an increased risk of culling, an increased risk of death, and disease recurrence) for all 3 hoof diseases over a one-year period. This value was converted to the total cost of lameness per lactating cow-year by dividing the herd-level total cost of lameness by the lactating herd size. Within this cost of lameness, we did not include the cost of prevention since we were not attempting to model specific prevention strategies. Instead, by comparing the herd-level total cost of lameness per cow-year pre- and post - lameness prevention implementation, the change in the herd-level total cost of lameness per cow-year can be calculated, which would represent the maximum amount that could be spent on the lameness prevention strategy in each scenario to breakeven. How this value varied with varying pre-prevention incidence rate of hoof diseases and effectiveness of the implemented prevention strategy was also considered.

Simulation methods

For this study, 12 simulations of the model were run as described in Table 4.3. In 6 simulations, the value of infectious hoof disease prevention was estimated (strategy 1) assuming varying pre-prevention implementation digital dermatitis incidence levels (20%, 40%, and 60% for simulations 1 and 2, 3 and 4, and 5 and 6, respectively, where odd numbered simulations were pre-prevention implementation and even numbered simulations were post-prevention implementation) . In the remaining 6 simulations, the value of non-infectious hoof disease prevention was estimated (strategy 2) assuming varying pre-prevention implementation sole ulcer and white line disease incidence levels (5%, 15%, and 25% for simulations 7 and 8, 9 and 10, and 11 and 12, respectively, where odd numbered simulations were pre-prevention implementation and even numbered simulations were post-prevention implementation). For each simulation, 300 iterations were run using Latin Hypercube sampling. To confirm that all simulations used the same drawn stochastic variables for each iteration (making them comparable) a static seed was set to 31,517. Default deterministic variable assumptions used to define the herd and the average cow were collected from Dairy Records Management Systems (Raleigh, NC) using limitations of only Holstein herds with $\geq$ 200 cows, published literature, or the authors' expertise (Table 4.2). The resulting distributions of herd-level stochastic variables can be found in Table 4.1. Inputs used in the model for this study were meant to represent a United States dairy herd. However, model inputs could be adjusted to herd-specific values to calculate the cost of hoof diseases for a specific herd.

Results and Discussion

The objective of this study was to use an existing stochastic simulation model to estimate the value of lameness prevention strategies when pre-prevention hoof disease incidence rates and prevention effectiveness varied. The mean ± SD total herd-level cost of lameness per cow-year for each simulation is presented in Table 4.3. Over the 12 simulations, the herd-level total cost of lameness varied depending on the assumed pre-prevention disease incidence rates, if lameness prevention was used or not, and how effective the lameness prevention method was. The change in the herd-level total cost of lameness per cow-year between simulations using and not using prevention could be used to identify the maximum amount a producer should be willing to pay for implementing a prevention strategy.

Infectious hoof disease prevention

Figure 4.1 shows the change in the herd-level total cost of lameness per cow-year when infectious hoof disease prevention was implemented as affected by prevention effectiveness across the 3 different pre-prevention digital dermatitis incidence rates. Regardless of pre-prevention digital dermatitis incidence rate, the value of prevention (i.e., change in the herd-level total cost of lameness) increased as the effectiveness of prevention increased (i.e., the disease incidence risk ratio became smaller) because less lameness cases were occurring and, therefore, there were less expenditures and losses associated with lameness. Additionally, as the pre-prevention incidence rate of digital dermatitis increased, the value of prevention (i.e., change in the herd-level total cost of lameness between preand post- lameness prevention implementation) increased. The mean ± SD change in the herd-level total cost of lameness per cow-year when digital dermatitis was original 20%, 40%, or 60% was \$6.9 ± 3.3, \$13.8 ± 6.5, and \$20.6 ± 9.8, respectively. In this example, we assumed prevention focused on infectious hoof diseases would reduce the incidence of digital dermatitis only so changes in the herd-level total cost of lameness per cow-year were not affected by changes in the cost of other hoof diseases included in the model (i.e., sole ulcer and white line disease). The pre-prevention incidence rate of digital dermatitis influences the value of prevention because as pre-prevention incidence increases, the potential to reduce lameness costs increases.

Although the herd-level total cost of lameness per cow-year always decreased when infectious hoof disease prevention was implemented, this is only beneficial to the herd if the decrease in costs is greater than or equal to the cost of prevention. In the simulation where pre-prevention incidence of digital dermatitis was 20%, the maximum decrease in the herd-level total cost of lameness per cow-year was \$17 when the digital dermatitis incidence risk ratio associated with prevention was 0.20 and the minimum decrease in the herd-level total cost of lameness per cow-year was \$0.1 when the digital dermatitis incidence risk ratio associated with prevention was 0.99. This indicates that, using our model assumptions, the most that could be spent on prevention per cow-year when your herd has a pre-prevention incidence rate of 20% is \$17, but only if the prevention strategy is highly effective (reduces digital dermatitis incidence by > 80%). If the prevention strategy is not very effective, a herd in this scenario could only spend up to \$0.1 per cow-year before the benefits of prevention are not paying for the prevention strategy itself. Similarly, if pre-prevention incidence rate of digital dermatitis was 40%, the maximum that could be paid for prevention was $34, but if the effectiveness of prevention was low then the maximum that could be paid for prevention was only $0.3. Finally, if pre-prevention incidence rate of digital dermatitis was 60%, the maximum that could be paid for prevention was $51, but if the effectiveness of prevention was low then the maximum that could be paid for prevention was only $0.4.

The most common infectious lameness disease prevention strategy in the United States dairy industry is footbaths. Multiple options exist for footbath solutions, with the 2 most common being 5% copper sulfate and formalin. If we assume that a 5% copper sulfate solution footbath costing $50 per bath is utilized 1 time per day, 3 times per week, and changed after 200 cow passes, 0.78 baths would be needed per cow-year, for a total cost of prevention of $39/cow-year. In our model, the mean change in the herd-level total cost of lameness per cow-year was not enough to pay for using this prevention strategy, regardless of the pre-prevention incidence level of digital dermatitis. Even if copper sulfate footbath use was highly effective at reducing digital dermatitis, the maximum change in the herd-level total cost of lameness per-cow year was only high enough to pay for prevention if pre-prevention incidence rate of digital dermatitis was 60%; there were no scenarios when pre-prevention incidence of digital dermatitis was 20% or 40% that the value of prevention was enough to offset the cost of this prevention strategy, regardless of prevention effectiveness. However, reduced footbath frequency or a less expensive supply of copper sulfate could change these results if no negative effects on footbath effectiveness were seen. Additionally, if more benefits beyond digital dermatitis reduction are seen after footbath implementation (e.g., reduced foot rot) the footbath could still be profitable. Alternatively, if we assume a formalin footbath costing $12 per bath and utilized at the same rate as we assumed for the 5% copper sulfate bath, the total cost of prevention would be $9/cow-year. In our model, the mean change in the herd-level total cost of lameness per cow-year would cover the cost of this prevention method if pre-prevention incidence of digital dermatitis was 40% or 60%. Additionally, implementation of this prevention strategy would be economically beneficial when pre-prevention digital dermatitis incidence was only 20% if prevention effectiveness was high.

Non-infectious hoof disease prevention

Figure 4.2 shows the change in the herd-level total cost of lameness per cow-year when non-infectious hoof disease prevention was implemented, as affected by prevention effectiveness across the 3 different pre-prevention non-infectious hoof disease incidence rates. Similar to the infectious hoof disease prevention scenario, the value of prevention (i.e., change in the herd-level total cost of lameness from pre- to post- lameness prevention implementation) increased as the effectiveness of prevention increased (i.e., the disease incidence risk ratio became smaller) and as the pre-prevention incidence rate of non-infectious diseases increased. The mean ± SD change in the herd-level total cost of lameness per cow-year when non-infectious hoof disease incidence levels were original 5%, 15%, or 25% was $8.7 ± 3.9, $26.2 ± 11.6, and $43.6 ± 19.3, respectively. Compared to when infectious hoof disease prevention was used, the value of prevention was greater in this scenario even though the pre-prevention incidence rate of selected disease was lower. This resulted from non-infectious diseases costing more per case (Table 4.1) and the prevention strategy impacting the incidence of more than just 1 disease.

Using our model assumptions in the simulation where pre-prevention incidence of non-infectious hoof diseases was 5%, the most that could be spent on prevention per cow-year was $20, but only if the prevention strategy was highly effective (risk ratio = 0.05). If the prevention strategy effectiveness was poor (risk ratio = 0.99) then the most that could be spent on prevention per cow-year was only $0.2. Similarly, if pre-prevention incidence rate of non-infectious diseases was 15%, the maximum that could be paid for prevention was $59, but if the effectiveness of prevention was low then the maximum that could be paid for prevention was only $0.7. Finally, if the pre-prevention incidence rate of non-infectious hoof diseases was 25%, the maximum that could be paid for prevention was $98, but if the effectiveness of prevention was low then the maximum that could be paid for prevention was only $1.

Multiple non-infectious hoof disease prevention strategies exist; for example, preventive hoof trimming, biotin supplementation, and rubber flooring (Ettema and Østergaard, 2006). An estimated cost of preventive hoof trimming could be taken from the survey of hoof trimmers in Chapter 2 where the mean ± SD charged for trimming per cow was $12.55 ± 2.39 (n = 113 survey respondents). Assuming the implementation of one additional trimming per cow-year, the mean value of this prevention strategy would be positive if pre-prevention incidence of non-infectious diseases was either 15% or 25%. Only in cases where this prevention strategy was highly effective was the change in the herd-level total cost of lameness per cow-year enough to pay for implementation if pre-prevention incidence of non-infectious hoof diseases was only 5%. Other non-infectious hoof disease prevention strategies are more difficult to calculate the cost of because they are typically not charged per cow. For example, reduction in lameness may be seen after installing rubber flooring (Vanegas et al., 2006) or redesigning poorly constructed freestalls (Ito et al., 2010), but the cost of doing so is a long-term investment that will also have benefits beyond lameness incidence reduction (e.g., reduced mastitis incidence, improved cow longevity). Correctly identifying what portion of this cost should be considered expenditures on lameness prevention will influence if the prevention investment is beneficial or not.

Interpretation of results

Within this study we focused on estimating the value of implementing either infectious or non-infectious lameness prevention. Based on the results in this study, the value of lameness prevention strategies depends on the pre-prevention incidence rate of hoof diseases, the effectiveness of the prevention strategy implemented, and the cost of the prevention strategy implemented.

This model could be useful as a decision support tool to help guide decisions about investment in lameness prevention strategies. However, some limitations exist within the model. First, the model only accounted for 3 hoof diseases. These hoof diseases were selected because they are the most prevalent lameness causing diseases in United States dairy herds (DeFrain et al., 2013) and have had their effects on cow productivity studied more extensively than other hoof diseases. However, by not including other hoof diseases (e.g., foot rot, toe ulcers, thin soles) we may be underestimating the herd-level total cost of lameness and, therefore, the value of lameness prevention strategies.

Secondly, we did not account for the possibility that the proportion of mild and severe cases could change with lameness prevention implementation. If prevention strategies do reduce the proportion of severe hoof diseases, we may have underestimated the value of prevention. Third, the model did not account for a herd potentially improperly implementing prevention strategies. In reality, a positive response to prevention implementation will only be seen in herds with correct stocking density, appropriate time budgets, and proper implementation of the prevention strategies. Poor implementation, including improper hoof trimming practices or footbath design, could lead to increased rather than decreased hoof disease incidence.

Finally, the accuracy of model results is limited by the accuracy of the information provided to it. To accurately calculate the value of lameness prevention strategies, correct estimates are needed for the cost of hoof diseases, the pre-prevention hoof disease incidence rates within a herd, and the effectiveness of prevention. Although our cost estimates were taken from Chapter 3, those did not account for the animal welfare impact of lameness, which could be an economic contributor in the future. Improved on-farm records of hoof disease incidence at the cow level, further research considering the effects of specific hoof diseases on cow performance, and further research on the effects of prevention strategies on hoof disease incidence is needed.

Acknowledgements

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Table 4.1 Simulated market price and herd performance inputs used in a stochastic model to estimate the value of infectious and non-infectious lameness prevention strategies

Input	Simulated range (min – max)	Simulated mean ± SD	Source[1]
Calf value ($/bull)	72 – 224	131 ± 41	Chapter 3
Calf value ($/heifer)	234 – 675	395 ± 144	Chapter 3
Milking herd size (c)	68 – 968	434 ± 205	Authors' expertise
Slaughter value ($/kg)	1.03 – 1.78	1.43 ± 0.20	FAPRI (2017)
Milk price ($/kg)	0.29 – 0.50	0.40 ± 0.06	FAPRI (2017)
Lactating cow feed price ($/kg)	0.21 – 0.37	0.29 ± 0.04	FAPRI (2017)
Replacement heifer price ($)	1,437 – 2,122	1,718 ± 217	Chapter 3
RHA milk production (kg)	5,993 – 17,136	11,461 ± 1,994	DairyMetrics
Pregnancy rate (%)	3.3 – 72.6	22.1 ± 11.0	DairyMetrics
Cost of digital dermatitis ($/case)[1]	64 – 248	137 ± 31	Chapter 3
Cost of sole ulcer ($/case)[1]	130 – 325	227 ± 37	Chapter 3
Cost of white line disease ($/case)[1]	138 – 435	202 ± 33	Chapter 3
Prevention effect on hoof diseases (risk ratio)	0.01 – 0.99	0.50 ± 0.20	Authors' expertise

[1]Mean cost per case across all combinations of severity level, incidence timing, and parity group

Table 4.2 Deterministic herd performance and financial inputs used in a stochastic model to estimate the value of infectious and non-infectious lameness prevention strategies

Input	Value	Source[1]
Age at first calving (m)	24.3	DairyMetrics
Baseline culling rate (%)	13.0	Bewley et al. (2010)
Breeding costs ($/insemination)[2]	15.51	VanRaden and Cole (2014)
Butterfat yield (%)	3.7	DairyMetrics
Calf birth weight (kg)	41.7	Kertz et al. (1997)
Close up dry cow feed price ($/kg DMI)	0.22	Model input
Close up dry period length (d)	21	Model input
Days dry	56.2	NAHMS (2014)
Days in milk designated do not breed	250	Bewley et al. (2010)
Discount rate (%)	8.0	Hyde and Engel (2002)
Disposal losses ($)[2]	65	Groenendaal et al. (2004)
Far off dry cow feed price ($/kg DMI)	0.15	Model input
Gestation length (d)	280	Norman et al. (2007)
Mature cow live weight (kg)	723	NRC (2001)
Percent heifer calves	46.7	Del Río et al. (2007)
Percent of herd in 1st parity	36.1	Dhuyvetter et al. (2007)
Percent of herd in 2nd parity	26.0	Dhuyvetter et al. (2007)
Percent of herd in 3rd parity	17.7	Dhuyvetter et al. (2007)
Percent of herd in 4th parity	11.0	Dhuyvetter et al. (2007)
Percent of herd in 5th parity	5.8	Dhuyvetter et al. (2007)
Percent of herd in 6th (or greater) parity	3.4	Dhuyvetter et al. (2007)
Protein yield (%)	3.1	DairyMetrics
Voluntary waiting period (d)	59.3	DairyMetrics

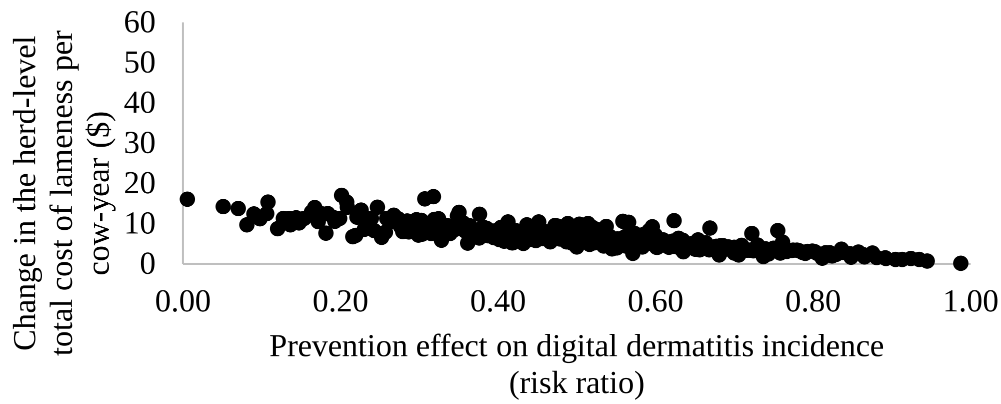
[1]DairyMetrics information was collected on October 1, 2017 from Dairy Records Management Systems (Raleigh, NC). Values gathered from DairyMetrics included 1,987 United States Holstein herds with at least 200 cows.
[2]Adjusted for inflation to 2017 prices

Table 4.3 Outline of simulations run to estimate the value of either infectious or non-infectious hoof disease prevention strategies, as influenced by pre-prevention hoof disease incidence rates and prevention effectiveness. The mean ± SD total herd-level total cost of lameness per cow-year as estimated using a stochastic simulation model is reported for each simulation (n = 300 iterations).

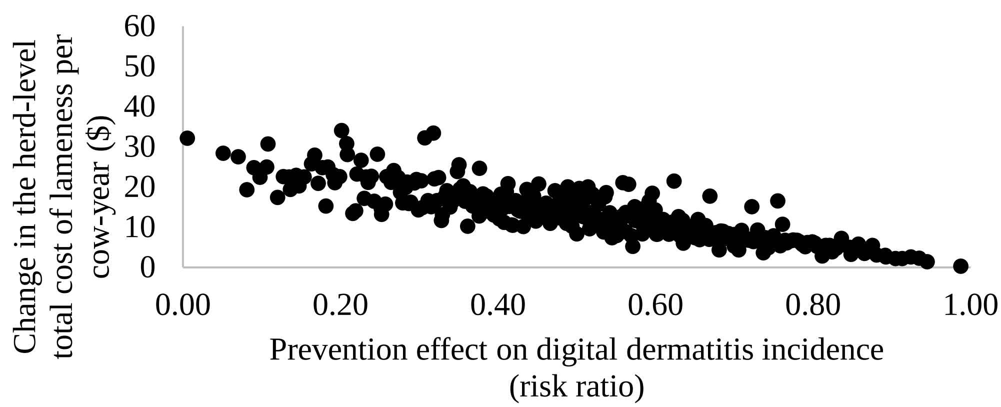
Simulation number	Prevention focus	Pre-prevention disease incidence rate (%)			Prevention implemented (Yes or No)	Herd-level total cost of lameness (mean ± SD $/cow-year)
		Digital dermatitis	Sole ulcer	White line disease		
1	Infectious diseases	20	15	15	No	66.3 ± 10.5
2	Infectious diseases	20	15	15	Yes	59.5 ± 9.9
3	Infectious diseases	40	15	15	No	80.2 ± 66.4
4	Infectious diseases	40	15	15	Yes	66.4 ± 12.3
5	Infectious diseases	60	15	15	No	94.0 ± 16.4
6	Infectious diseases	60	15	15	Yes	73.4 ± 9.8
7	Non-infectious diseases	30	5	5	No	38.3 ± 7.1
8	Non-infectious diseases	30	5	5	Yes	29.5 ± 7.3
9	Non-infectious diseases	30	15	15	No	73.3 ± 11.8
10	Non-infectious diseases	30	15	15	Yes	47.1 ± 13.9
11	Non-infectious diseases	30	25	25	No	108.2 ± 17.1
12	Non-infectious diseases	30	25	25	Yes	64.6 ± 21.3

Figure 4.1 Change in the total herd-level total cost of lameness per cow-year when infectious hoof disease prevention was implemented, as calculated using a stochastic simulation model (n = 300 iterations). Three pre-prevention herd-level digital dermatitis incidence rates were tested: 20% (a), 40% (b), and 60% (c). The prevention effect on digital dermatitis incidence (risk ratio) was allowed to vary between 0.0 and 1.0.

a)



b)



c)

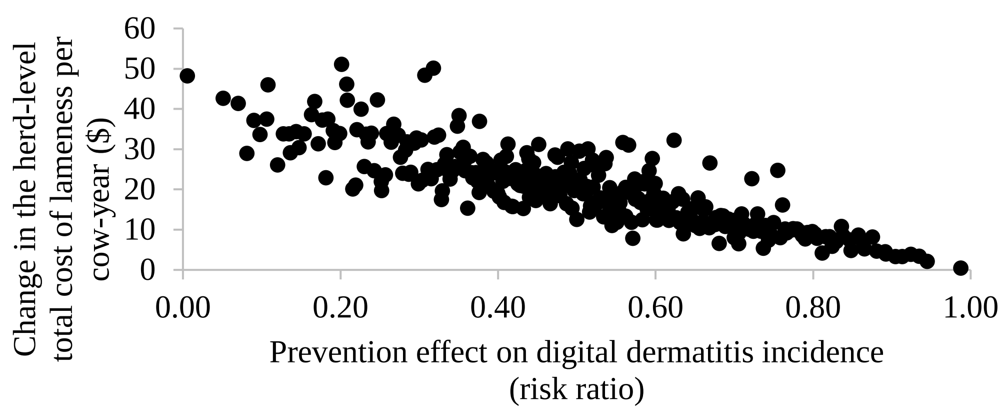
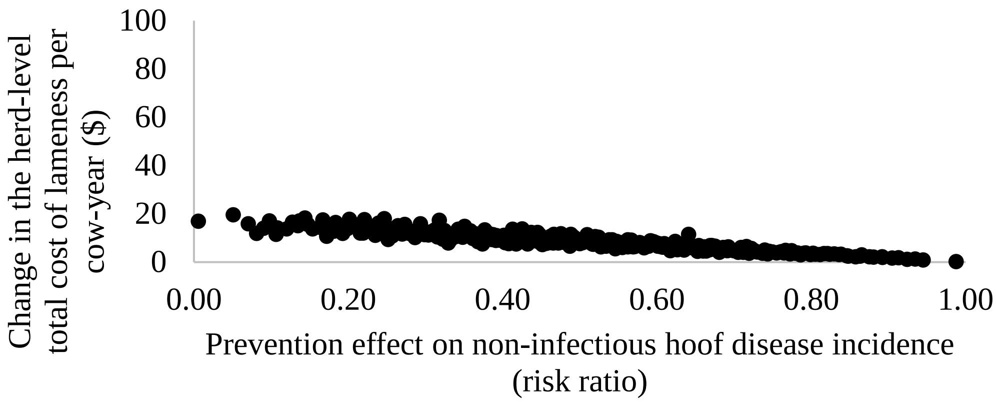
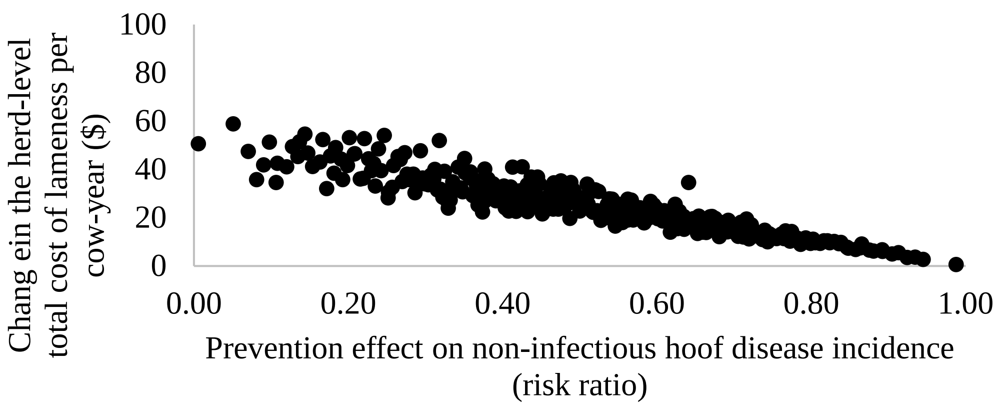


Figure 4.2 Change in the total herd-level total cost of lameness per cow-year when non-infectious hoof disease prevention was implemented, as calculated using a stochastic simulation model (n = 300 iterations). Three pre-prevention herd-level non-infectious hoof disease (sole ulcer and white line disease) incidence rates were tested: 5% (a), 15% (b), and 25% (c). The prevention effect on non-infectious hoof disease incidence (risk ratio) was allowed to vary between 0.0 and 1.0.

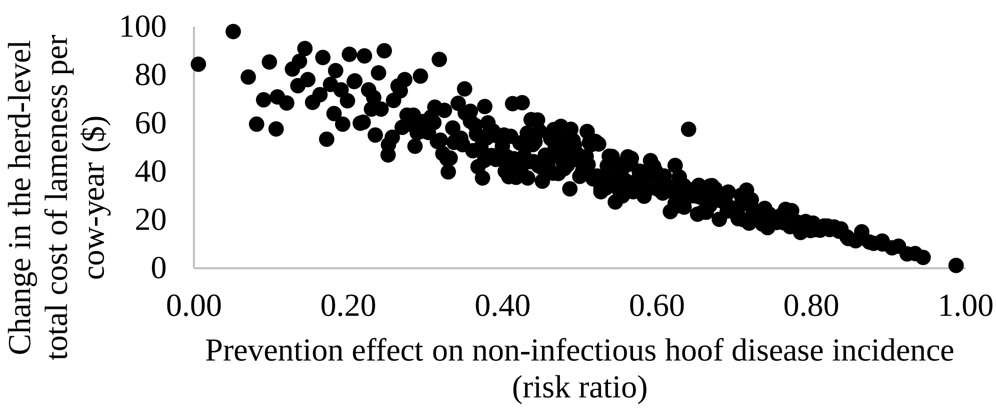
a)



b)



c)



CHAPTER 5

Research Summary

Two objectives were focused on throughout this research. The first was to calculate the costs associated with hoof diseases causing lameness in dairy cattle. To accomplish this, we had to collect estimates for all disease associated expenditures (therapeutics, outside labor, and on-farm labor) and losses (discarded milk, reduced milk production, extended days open, increased risk of culling, increased risk of death, and disease recurrence) from previously published epidemiological studies. Many gaps in the literature were identified through our search. In particular, very few studies have focused on the expenditures and losses associated with lameness at the hoof disease level. Originally we had planned to estimate the costs per case for 6 different hoof diseases (digital dermatitis, foot rot, sole ulcer, thin sole, toe ulcer, and white line disease), but missing data narrowed our focus to 3 hoof diseases (digital dermatitis, sole ulcer, and white line disease). Further research considering the many different conditions classified as lameness, rather than lameness as a disease itself, is needed. This area of focus is especially necessary given the prevalence of lameness reported in many recent studies and the increasing animal welfare concerns for the dairy industry.

One hole identified in the literature was a lack of estimates for disease-specific therapeutic and outside labor costs (fees charged by hoof trimmers or veterinarians to visit and treat lameness cases) in the United States. Therefore, a survey of hoof trimmers and veterinarians was conducted to estimate those costs for the 3 hoof diseases of interest, along with additional hoof diseases (foot rot, toe ulcers, and thin soles). Answers from 116 hoof trimmers and 18 veterinarians were obtained through both online and paper survey methods. Because of the low response rates from veterinarians, our analysis focused on hoof trimmer respondents only. Hoof trimmers indicated that digital dermatitis, sole ulcer, and white line disease were the most commonly treated hoof diseases, confirming our decision to focus our research on those 3 diseases. However, toe ulcers were identified as the most expensive hoof disease to treat. This is interesting given the lack of published literature on toe ulcers. Further research into less understood hoof diseases, like toe ulcers and thin soles, could increase understanding of those diseases and potentially reduce their treatment costs.

Survey estimates for therapeutics and outside labor were combined with other literature-derived values in a stochastic simulation model used to estimate cost of 3 specific hoof diseases. To improve on previous studies, costs per case were differentiated not only by disease, but also by severity (mild vs. severe), incidence timing (0 to 60 DIM, 61 to 120 DIM, 121 to 240 DIM, or >240 DIM), and parity group (primiparous or multiparous). Our results indicate similar mean costs per case to previous hoof disease cost estimates, but provide beneficial insight into how costs vary by severity, incidence timing, and parity group. Having an understanding of how disease costs differ by cow (depending on parity, DIM, etc.) could help producers make cow specific treatment decisions. Additionally, this knowledge can help prioritize investment in prevention to focus on cases that are most costly to the producer. The sensitivity of hoof disease costs to market prices (milk price, feed price, replacement price, and slaughter price) and herd performance factors (rolling herd average milk production and pregnancy rate) highlights the need to consider lameness costs at the herd level rather than the industry level. In other words, a good treatment or prevention decision for one herd may be a poor treatment or prevention decision for another herd. Future efforts could be made to incorporate our hoof disease cost estimates into decision support tools that could be used at the herd level to aid in treatment and prevention investment decisions.

A variety of lameness prevention recommendations are made to dairy producers with little scientific evidence supporting their economic benefits. Therefore, the second objective of this research was to estimate the economic value of investing in different lameness prevention strategies. For our study, we chose to focus on 2 broad categories of lameness prevention: infectious hoof disease prevention and non-infectious hoof disease prevention. The same stochastic simulation model used for estimating hoof disease costs was used to calculate the herd-level total cost of digital dermatitis, sole ulcer, and white line disease with and without prevention implementation. We also evaluated how changes in pre- lameness prevention implementation hoof disease incidence and the effectiveness of the prevention strategy changed the estimated value of lameness prevention.

Overall, the greater the incidence of hoof diseases and the more effective the prevention strategy, the greater the value of implementing lameness prevention strategies. However, each lameness prevention strategy would only be economically beneficial if the change in the herd-level total cost of lameness was enough to offset the cost of the selected prevention strategy or if non-economic factors (like improved animal welfare) could be used to justify implementation. Individual farm managers could use this model to help identify the potential value of different lameness prevention strategies if they know the current herd-level incidence of hoof diseases and the expected effectiveness of the lameness prevention strategy of interest.

Compared to other dairy diseases, hoof diseases are understudied. Many opportunities exist for further research in this area; particularly field trials focused on the direct effect of individual hoof diseases on cow performance and on how prevention strategies effect specific hoof diseases, including those beyond digital dermatitis, sole ulcers, and white line disease.

APPENDIX

Table A1. Questions included in a survey of hoof trimmers and veterinarians aimed at collecting and summarizing information on hoof disease treatment costs

Question number	Question
Q1	What role do you serve for dairy farmers? (hoof trimmer, veterinarian, other)
Q2	If in the United States, which states do you practice in? If outside the United States, in which country/countries do you practice?
Q3	Estimate the ***number of farms*** you perform preventative or corrective trimming for each year that would fall under each category: Small herds (fewer than 100 lactating cows): __________ Medium herds (between 100 and 500 lactating cows): __________ Large herds (over 500 lactating cows): __________
Q4	What is the smallest herd size for which you perform preventative or corrective trimming? ___________ lactating cows
Q5	What is the largest herd size for which you perform preventative or corrective trimming? ____________ lactating cows
Q6	On average, how many dairy cows do you conduct preventative trimming for weekly (i.e. routine trimming)? __________
Q7	On average, how many dairy cows do you treat for lameness weekly (i.e. treatment of existing lameness)? __________
Q8	Do you charge a set-up fee, visit fee, or set daily rate to come to a dairy farm? Circle one: NO YES If yes, what is your rate: $__________ set-up fee (on average) $__________ visit fee (on average) $__________ set daily rate (on average)
Q9	What is your on-farm rate for dairy preventative trimming (i.e. routine trimming)? _________ $/hour OR _________ $/cow
Q10	On average, how many dairy cows do you trim per hour when conducting preventative trims? __________
Q11	In your opinion, rank the following dairy lameness diseases from (1) most costly to (6) least costly in terms of ***total costs per case*** to the producer (treatment and labor costs plus reduction in milk yield, reduced reproductive performance, etc.). Use each number only once. _______ Digital Dermatitis _______ Foot Rot _______ Sole Ulcer _______ Thin Sole _______ Toe Ulcer _______ White Line Lesion
Q12	In your opinion, rank the following potential benefits of reducing dairy cow lameness to dairy producers from (1) most important to (8) least important. Use each number only once. ____ Decreased incidence of other diseases (not lameness) ____ Enhanced animal welfare ____ Increased milk production ____ Increased reproductive performance ____ Increased cow longevity ____ Reduced drug and supply costs ____ Reduced producer labor costs ____ Reduced veterinary/hoof trimmer fees

Table A1. Continued

Q13	Of all dairy cow lameness cases that you have treated in the past 12 months, what is your best estimate of the percent that would fall under each of the following classifications (the total should equal 100%).

Q13 Of all dairy cow lameness cases that you have treated in the past 12 months, what is your best estimate of the percent that would fall under each of the following classifications (the total should equal 100%).

_________% Digital Dermatitis
_________% Foot Rot
_________% Sole Ulcer
_________% Thin Sole
_________% Toe Ulcer
_________% White Line Lesion
_________% Other (For example: corkscrew, axial wall cracks, overgrowth, and corns)
100 % = TOTAL OF ALL

Q14 Approximately how much time do you spend per hoof to treat a case of:

Digital Dermatitis: _________ minutes
Foot Rot: _________ minutes
Sole Ulcer: _________ minutes
Thin Sole: _________ minutes
Toe Ulcer: _________ minutes
White Line Lesion: _________ minutes

Q15 Do you generally recommend milk withholding following treatment of each of the following diseases (mark "Yes" or "No")? If "Yes", indicate for how many days milk withholding is recommended:

Disease	**No**	**Yes**	**If yes, days withhold is recommended after treatment:**
Digital Dermatitis			
Foot Rot			
Sole Ulcer			
Thin Sole			
Toe Ulcer			
White Line Lesion			

Q16 In the first blank column, list how much you charge a dairy producer to treat one case of each of the diseases listed.

Then indicate what percent of the total charge of each case is for labor vs. supplies. The total of "% Labor" and "% Supplies" for each row should equal 100%.

Disease	**Total amount charged to the producer $**	**% Labor**	**% Supplies**	**Total %**
Digital Dermatitis				100%
Foot Rot				100%
Sole Ulcer				100%
Thin Sole				100%
Toe Ulcer				100%
White Line Lesion				100%

Table A2. Veterinarian responses to a survey regarding dairy hoof disease prevalence, time to treat, treatment costs, and the percentage of costs attributed to labor or supplies

Hoof disease	Number of responses (n)	Response (mean ± SD)
Digital dermatitis		
% of total	16	24.7 ± 12.7
Time to treat (min)	12	11.4 ± 6.8
Total charged ($/case)	12	46.3 ± 26.5
% attributed to labor	12	75.6 ± 16.7
% attributed to supplies	12	24.4 ± 16.7
Foot rot		
% of total	16	17.0 ± 10.4
Time to treat (min)	12	11.4 ± 6.1
Total charged ($/case)	12	65.1 ± 38.1
% attributed to labor	12	57.5 ± 23.6
% attributed to supplies	12	42.5 ± 23.6
Sole ulcer		
% of total	16	27.4 ± 14.3
Time to treat (min)	12	21.3 ± 10.1
Total charged ($/case)	12	69.8 ± 30.8
% attributed to labor	12	73.4 ± 18.3
% attributed to supplies	11	26.6 ± 18.3
Thin sole		
% of total	16	3.3 ± 5.0
Time to treat (min)	12	9.6 ± 6.2
Total charged ($/case)	10	53.1 ± 35.8
% attributed to labor	12	64.8 ± 37.1
% attributed to supplies	12	18.5 ± 23.1
Toe ulcer		
% of total	16	2.8 ± 3.0
Time to treat (min)	12	16.9 ± 8.0
Total charged ($/case)	11	78.2 ± 48.9
% attributed to labor	12	66.7 ± 27.1
% attributed to supplies	12	25.0 ± 18.8
White line disease		
% of total	16	18.3 ± 14.8
Time to treat (min)	12	18.8 ± 7.6
Total charged ($/case)	12	65.3 ± 33.6
% attributed to labor	12	77.1 ± 17.2
% attributed to supplies	12	22.9 ± 17.2
Other lameness		
% of total treatments	16	6.6 ± 6.7

Table A3. Ranking frequency of the estimated total cost per case to the producer (treatment and labor costs plus the reduction in milk yield, reduced reproductive performance, etc.) of selected hoof diseases as evaluated by a survey of veterinarians. Ranking was from most expensive (1) to least expensive (6).

	Response frequency (%)						
Disease	n	1	2	3	4	5	6
Sole ulcer	16	31.3	31.3	6.3	18.8	12.5	0.0
Digital dermatitis	16	25.0	37.5	25.0	6.3	0.0	6.3
Foot rot	16	18.8	0.0	43.8	12.5	12.5	12.5
Toe ulcer	16	12.5	12.5	0.0	25.0	18.8	31.3
White line disease	16	6.3	18.8	18.8	25.0	18.8	12.5
Thin sole	16	6.3	0.0	6.3	12.5	37.5	37.5

Table A4. Ranking frequency of the potential benefits to producers of reducing dairy cow lameness as evaluated by a survey of veterinarians. Ranking was from most important (1) to least important (8).

		Response frequency (%)							
Potential benefit	n	1	2	3	4	5	6	7	8
Enhanced animal welfare	16	50.0	18.8	6.3	6.3	6.3	0.0	0.0	12.5
Increased milk production	16	37.5	25.0	25.0	6.3	6.3	0.0	0.0	0.0
Increased cow longevity	16	12.5	25.0	6.3	18.8	31.3	63.0	0.0	0.0
Increased reproductive performance	16	0.0	18.8	37.5	37.5	6.3	0.0	0.0	0.0
Decreased incidence of other diseases (not lameness)	16	0.0	6.3	18.8	18.8	31.3	18.8	6.3	0.0
Reduced veterinary and hoof trimmer fees	16	0.0	6.3	0.0	0.0	12.5	0.0	25.0	56.3
Reduced drug and supply costs	16	0.0	0.0	6.3	0.0	6.3	75.0	12.5	0.0
Reduced producer labor costs	16	0.0	0.0	0.0	12.5	0.0	0.0	56.3	31.3

Table A5. Input assumptions and resulting simulated distributions of values used in the treatment module of a stochastic simulation model developed to estimate the cost per case of 3 hoof diseases.

Variable	Input assumption (mean ± SD)	Input source	Simulation distribution type	Simulated data[1] (mean ± SD)
Outside labor ($/case)				
Digital dermatitis	4.67 ± 4.61	Survey of hoof trimmers (Chapter 2)	Log logistic	4.91 ± 8.99
Sole ulcer	11.81 ± 6.74	Survey of hoof trimmers (Chapter 2)	Log logistic	12.01 ± 6.16
White line disease	11.60 ± 6.49	Survey of hoof trimmers (Chapter 2)	Log logistic	11.86 ± 5.85
Therapeutics ($/case)				
Digital dermatitis	2.74 ± 8.92	Survey of hoof trimmers (Chapter 2)	Log logistic	1.98 ± 2.41
Sole ulcer	8.13 ± 5.07	Survey of hoof trimmers (Chapter 2)	Extreme values	8.01 ± 4.69
White line disease	8.16 ± 5.47	Survey of hoof trimmers (Chapter 2)	Log logistic	8.19 ± 6.74
On-farm labor ($/case)[2]				
Mild digital dermatitis	1.73 ± 0.43	Charfeddine and Pérez-Cabal (2017)	Normal	1.73 ± 0.43
Severe digital dermatitis	20.81 ± 5.20	Charfeddine and Pérez-Cabal (2017)	Normal	20.81 ± 5.20
Mild sole ulcer	13.88 ± 3.47	Charfeddine and Pérez-Cabal (2017)	Normal	13.88 ± 3.48
Severe sole ulcer	20.81 ± 5.20	Charfeddine and Pérez-Cabal (2017)	Normal	20.81 ± 5.20
Mild white line disease	13.88 ± 3.47	Charfeddine and Pérez-Cabal (2017)	Normal	13.88 ± 3.47
Severe white line disease	20.81 ± 5.20	Charfeddine and Pérez-Cabal (2017)	Normal	20.81 ± 5.20
Days of discarded milk (per case)[3]				
Severe digital dermatitis	0.95 ± 1.86	Survey of hoof trimmers (Chapter 2)	Exponential	0.91 ± 0.96

[1]n = 1,000 iterations
[2]Input source only reported a mean; the SD was calculated as a 10% coefficient of variation from the mean
[3]An assumption was made that only severe cases of digital dermatitis would result in discarded milk; no discarded milk was assumed for mild digital dermatitis cases or cases of other diseases

Table A6. Input assumptions and resulting simulated distributions of values used in the milk loss module of a stochastic simulation model developed to estimate the cost per case of 3 hoof diseases. Input assumptions were taken from Charfeddine and Pérez-Cabal (2017) and used in PERT (program evaluation and review technique) distributions to calculate the simulated data (n = 1,000 iterations).

Variable	Input assumption[1] (mean ± SE)	Simulated data (mean ± SD)
Primiparous mild digital dermatitis (ECM kg lost/d)		
28 to 15 d before incidence	NA	
14 to 1 d before incidence	NA	
1 to 14 d after incidence	-0.07 ± 0.25	-0.20 ± 0.15
≥ 15 d after incidence	NA	
Primiparous severe digital dermatitis (ECM kg lost/d)		
28 to 15 d before incidence	NA	
14 to 1 d before incidence	-0.37 ± 1.27	-1.03 ± 0.77
1 to 14 d after incidence	-0.56 ± 1.34	-1.20 ± 0.86
≥ 15 d after incidence	-0.64 ± 1.14	-1.14 ± 0.77
Multiparous mild digital dermatitis (ECM kg lost/d)		
28 to 15 d before incidence	-0.52 ± 0.19	-0.52 ± 0.20
14 to 1 d before incidence	-0.77 ± 0.18	-0.77 ± 0.19
1 to 14 d after incidence	-0.90 ± 0.20	-0.90 ± 0.21
≥ 15 d after incidence	-0.39 ± 0.18	-0.39 ± 0.19
Multiparous severe digital dermatitis (ECM kg lost/d)		
28 to 15 d before incidence	-1.52 ± 1.08	-1.71 ± 0.97
14 to 1 d before incidence	-2.22 ± 0.95	-2.22 ± 1.00
1 to 14 d after incidence	-0.54 ± 1.07	-1.03 ± 0.71
≥ 15 d after incidence	-2.77 ± 0.90	-2.77 ± 0.94
Primiparous mild sole ulcer (ECM kg lost/d)		
28 to 15 d before incidence	-0.72 ± 0.30	-0.72 ± 0.31
14 to 1 d before incidence	-0.42 ± 0.29	-0.47 ± 0.26
1 to 14 d after incidence	-0.63 ± 0.31	-0.63 ± 0.32
≥ 15 d after incidence	-1.07 ± 0.35	-1.07 ± 0.37
Primiparous severe sole ulcer (ECM kg lost/d)		
28 to 15 d before incidence	-1.16 ± 0.82	-1.30 ± 0.74
14 to 1 d before incidence	-0.87 ± 0.80	-1.09 ± 0.65
1 to 14 d after incidence	-1.80 ± 0.83	-1.80 ± 0.87

Table A6. Continued

≥ 15 d after incidence	-0.23 ± 0.86	-0.69 ± 0.52
Multiparous mild sole ulcer (ECM kg lost/d)		
28 to 15 d before incidence	-1.14 ± 0.14	-1.14 ± 0.15
14 to 1 d before incidence	-1.52 ± 0.14	-1.52 ± 0.15
1 to 14 d after incidence	-1.04 ± 0.15	-1.04 ± 0.16
≥ 15 d after incidence	-0.93 ± 0.17	-0.93 ± 0.18
Multiparous severe sole ulcer (ECM kg lost/d)		
28 to 15 d before incidence	-2.48 ± 0.44	-2.48 ± 0.46
14 to 1 d before incidence	-2.28 ± 0.43	-2.28 ± 0.45
1 to 14 d after incidence	-2.36 ± 0.44	-2.36 ± 0.46
≥ 15 d after incidence	-1.47 ± 0.50	-1.47 ± 0.52
Primiparous mild white line disease (ECM kg lost/d)		
28 to 15 d before incidence	-0.36 ± 0.34	-0.46 ± 0.27
14 to 1 d before incidence	-0.68 ± 0.32	-0.68 ± 0.33
1 to 14 d after incidence	-0.41 ± 0.35	-0.50 ± 0.29
≥ 15 d after incidence	-0.38 ± 0.38	-0.49 ± 0.30
Primiparous severe white line disease (ECM kg lost/d)		
28 to 15 d before incidence	-1.24 ± 1.02	-1.48 ± 0.86
14 to 1 d before incidence	-1.29 ± 0.93	-1.46 ± 0.83
1 to 14 d after incidence	-1.71 ± 0.92	-1.74 ± 0.93
≥ 15 d after incidence	-0.07 ± 1.02	-0.68 ± 0.56
Multiparous mild white line disease (ECM kg lost/d)		
28 to 15 d before incidence	-1.16 ± 0.16	-1.16 ± 0.17
14 to 1 d before incidence	-1.02 ± 0.16	-1.02 ± 0.17
1 to 14 d after incidence	-0.65 ± 0.17	-0.65 ± 0.18
≥ 15 d after incidence	-0.20 ± 0.19	-0.25 ± 0.15
Multiparous severe white line disease (ECM kg lost/d)		
28 to 15 d before incidence	-2.37 ± 0.58	-2.37 ± 0.61
14 to 1 d before incidence	-2.66 ± 0.54	-2.66 ± 0.57
1 to 14 d after incidence	-2.07 ± 0.57	-2.07 ± 0.60
≥ 15 d after incidence	-1.56 ± 0.61	-1.56 ± 0.64

[1]NA indicates that the value reported by the input source was positive (indicating an increase in milk yield); positive values were adjusted to 0 (i.e. no change in milk production)

Table A7. Input assumptions and resulting simulated distributions of values used in the days open module of a stochastic simulation model developed to estimate the cost per case of 3 hoof diseases. Input assumptions were taken from Charfeddine and Pérez-Cabal (2017) and used in PERT (program evaluation and review technique) distributions to calculate the simulated data (n = 1,000 iterations).

Variable	Input assumption[1] [mean (min – max)]	Simulated data (mean ± SD)
Increase in days open (d)		
Mild digital dermatitis	0.0 (0.0 – 3.6)	0.6 ± 0.5
Severe digital dermatitis	5.4 (0.0 – 39.5)	10.2 ± 6.6
Mild sole ulcer	1.6 (0.0 – 6.3)	2.1 ± 1.1
Severe sole ulcer	17.4 (1.4 – 33.3)	17.4 ± 6.0
Mild white line disease	3.0 (0.0 – 7.7)	3.3 ± 1.5
Severe white line disease	8.6 (0.0 – 27.4)	10.3 ± 5.0

[1]If parameters (mean, min, or max) reported by the input source were positive (indicating an improvement in reproductive performance) they were adjusted to 0 (i.e. no change in days open)

Table A8. Input assumptions and resulting simulated distributions of values used in the culling module of a stochastic simulation model developed to estimate the cost per case of 3 hoof diseases. Input assumptions were taken from Booth et al. (2004)[1] who reported culling hazard ratios based on both time of disease incidence and time of culling. Input assumptions were used in PERT (program evaluation and review technique) distributions[2] to calculate the simulated data (n = 1,000 iterations).

		Time interval of culling			
Disease and data type	Incidence timing	≤60	61 to 120	121 to 240	>240
Digital dermatitis input assumptions [HR (95% CI)]	≤ 60	0.4 (0.0 – 2.5)	0.9 (0.3 – 2.8)	1.4 (0.6 - 2.9)	0.8 (0.3 – 2.1)
	61 to 120		2.7 (1.3 – 6.0)	1.5 (0.8 – 3.0)	1.9 (1.0 – 3.6)
	121 to 240			1.5 (0.8 – 3.5)	1.1 (0.5 – 2.5)
	> 240				2.2 (0.7 – 7.1)
Mild digital dermatitis simulated data (mean ± SD)	≤ 60	1.7 ± 0.6	1.8 ± 0.7	1.8 ± 0.7	1.5 ± 0.5
	61 to 120		2.9 ± 1.5	1.4 ± 0.4	1.5 ± 0.4
	121 to 240			1.6 ± 0.5	1.5 ± 0.4
	> 240				2.7 ± 1.3
Severe digital dermatitis simulated data (mean ± SD)	≤ 60	1.7 ± 0.6	1.9 ± 0.6	2.0 ± 0.6	1.5 ± 0.4
	61 to 120		2.9 ± 1.4	1.4 ± 0.3	1.5 ± 0.3
	121 to 240			1.6 ± 0.5	1.4 ± 0.3
	> 240				3.2 ± 1.2
Sole ulcer and white line disease input assumptions [HR (95% CI)]	≤ 60	2.0 (0.9 – 4.3)	2.4 (1.2 – 5.0)	2.6 (1.4 – 4.9)	1.3 (0.5 – 3.1)
	61 to 120		2.7 (1.3 – 6.0)	1.5 (0.8 – 3.0)	1.9 (1.0 – 3.6)
	121 to 240			1.5 (0.8 – 3.5)	1.1 (0.5 – 2.5)
	> 240				2.2 (0.7 – 7.1)
Mild sole ulcer and white line disease simulated data (mean ± SD)	≤ 60	1.8 ± 0.6	2.6 ± 1.2	2.7 ± 1.1	1.9 ± 0.7
	61 to 120		3.0 ± 1.5	1.8 ± 0.7	2.0 ± 0.8
	121 to 240			2.0 ± 0.8	1.7 ± 0.6
	> 240				3.5 ± 1.9
Severe sole ulcer and white line disease simulated data (mean ± SD)	≤ 60	2.4 ± 0.5	3.3 ± 1.1	3.4 ± 1.0	2.1 ± 0.6
	61 to 120		3.9 ± 1.3	2.1 ± 0.6	2.6 ± 0.7
	121 to 240			2.3 ± 0.7	1.8 ± 0.5
	> 240				4.0 ± 1.8

[1]White line disease culling hazard ratio inputs were assumed identical to sole ulcers

[2] To account for severity, two different stochastic distributions were created for each disease. For the mild distributions, a mean 0.5 times that of the mean reported by Booth et al. (2004) was used whereas for the severe distributions, a mean 1.5 times that of the reported mean was used. The same 5th and 95th percentiles were used in both mild and severe distributions for each disease.

Table A9. Input assumptions and resulting simulated distributions of values used in the disease recurrence module of a stochastic simulation model developed to estimate the cost per case of 3 hoof diseases. Input assumptions for relapse rates were collected from Charfeddine and Pérez-Cabal (2017) and used in PERT (program evaluation and review technique) distributions to calculate the simulated data (n = 1,000 iterations). Input assumptions for disease length were collected from Bruijnis et al. (2010) and used in PERT (program evaluation and review technique) distributions to calculate the simulated data (n = 1,000 iterations).

Variable	Input assumption	Simulated data (mean ± SD)
Relapse rate (episodes per infected cow)	Mean[1]	
Primiparous mild digital dermatitis	1.97	2.23 ± 0.43
Primiparous severe digital dermatitis	2.02	2.26 ± 0.44
Multiparous mild digital dermatitis	2.24	2.41 ± 0.46
Multiparous severe digital dermatitis	2.60	2.65 ± 0.47
Primiparous mild sole ulcer	2.38	2.50 ± 0.46
Primiparous severe sole ulcer	3.13	3.00 ± 0.46
Multiparous mild sole ulcer	2.46	2.56 ± 0.47
Multiparous severe sole ulcer	3.14	3.01 ± 0.46
Primiparous mild white line disease	2.50	2.58 ± 0.47
Primiparous severe white line disease	2.89	2.84 ± 0.47
Multiparous mild white line disease	2.65	2.68 ± 0.47
Multiparous severe white line disease	2.98	2.90 ± 0.47
Disease length (months)[2]	Mean (5^{th} – 95^{th} percentile)	
Mild digital dermatitis	3.65 (2.68 – 4.78)	3.68 ± 0.40
Severe digital dermatitis	3.54 (2.38 – 5.00)	3.59 ± 0.49
Mild sole ulcer	2.50 (1.37 – 4.00)[3]	2.56 ± 0.50
Severe sole ulcer	2.50 (1.37 – 4.00)	2.56 ± 0.50
Mild white line disease	4.43 (2.50 – 6.42)	4.44 ± 0.74
Severe white line disease	2.90 (1.00 – 6.33)	3.16 ± 0.99

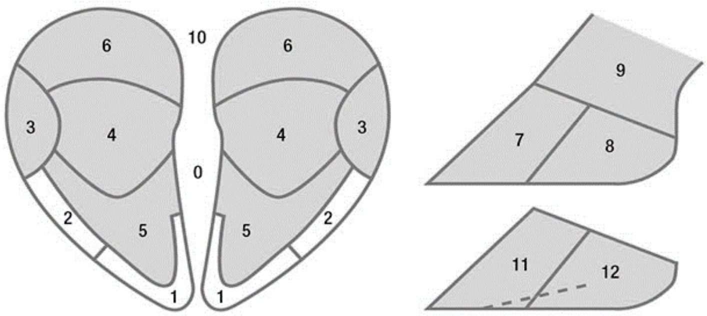
[1]The input assumption source only reported mean relapse rates. Relapse rate minimum and maximum values were assumed the same for all diseases and severity levels for stochastic modeling purposes. Minimum and maximum were set to 1.50 and 4.00 based on results from Ettema et al. (2010).

[2]The input assumption source reported disease length for subclinical and clinical cases of each disease. For this study, subclinical cases were assumed to represent mild cases and clinical cases were assumed to represent severe cases.

[3]The input assumption source did not report disease length for subclinical sole ulcers; an assumption was made that this length would be identical to clinical sole ulcers.

Figure A1. Hoof disease definitions provided to respondents in a survey of hoof trimmers and veterinarians aimed at collecting and summarizing information on hoof disease treatment costs

Lesion Descriptions: For the remaining questions, please consider the below dairy lameness disease definitions and refer to the "Claw Zones" indicated in the figure:



Digital Dermatitis (also called Hairy Heel Warts or Mortellaro Disease)

Claw Zones affected: any zones along the coronary band including zones 0, 9, and 10

Common signs include:

- Typically located at the end of the interdigital cleft
- Acute cases have bright-red lesions > 0.75 inches (2 cm) that are painful and raw
- Chronic cases have lesions with lots of skin/hair around them, but are not painful

Foot Rot (also called Foot Foul, Interdigital Phlegmon, or Interdigital Necrobacillosis)

Claw Zones affected: 9

Common signs include:

- Symmetrical hard swelling of tissue above the claws (acute onset, "overnight")
- Can occur with dead, smelly skin between the claws

Sole ulcer (also called Pododermatitis Circumscripta, Rusterholz Disease)

Claw Zones affected: 4

Common signs include:

- Localized defect in sole horn that exposes corium
- Can also be a hemorrhage that is painful to hoof test
- Typically occurs on the inner side of the sole on the outer claw, but can occur in the heel

Thin Sole

Claw Zones affected: 4, 5

Common signs include:

- Sole moves when thumb pressure is applied at the toe
- Dorsal wall length is < 3 inches (7.5 cm)

Toe Ulcer

Claw Zones affected: 1

Common signs include:

- Penetration or separation of the horn in the toe triangle that results in exposure or infection of the corium

White line lesion (also called White Line Separation or White Line Disease)

Claw Zones affected: 1, 2, 3

Common signs include:

- Separation of the white line, which may result in abscesses (pus filled cavity) in the white line region

If severe this can be accompanied by swelling of the affected claw

REFERENCES

Adams, A., J. Lombard, C. Fossler, I. Román-Muñiz, and C. Kopral. 2016. Associations between housing and management practices and the prevalence of lameness, hock lesions, and thin cows on US dairy operations. J. Dairy Sci. 100:2119-2136.

Amory, J., Z. Barker, J. L. Wright, S. Mason, R. Blowey, and L. E. Green. 2008. Associations between sole ulcer, white line disease and digital dermatitis and the milk yield of 1824 dairy cows on 30 dairy cow farms in England and Wales from February 2003–November 2004. Prev. Vet. Med. 83:381-391.

Andrews, A. H., R. Blowey, H. Boyd, and R. Eddy. 2008. Bovine medicine: diseases and husbandry of cattle. John Wiley & Sons, Hoboken, NJ.

Archer, S. C., M. J. Green, and J. Huxley. 2010. Association between milk yield and serial locomotion score assessments in UK dairy cows. J. Dairy Sci. 93:4045-4053.

Bailey, K. and V. Ishler. 2007. Tracking milk prices and feed costs. Department of Agricultural Economics and Rural Sociology. Penn State University, Park City, PA.

Barkema, H., J. Westrik, K. Van Keulen, Y. Schukken, and A. Brand. 1994. The effects of lameness on reproductive performance, milk production and culling in Dutch dairy farms. Prev. Vet. Med. 20:249-259.

Barkema, H. W., M. A. G. von Keyserlingk, J. P. Kastelic, T. J. G. M. Lam, C. Luby, J. P. Roy, S. J. LeBlanc, G. P. Keefe, and D. F. Kelton. 2015. Invited review: Changes in the dairy industry affecting dairy cattle health and welfare. J. Dairy Sci. 98:7426-7445.

Bell, N., D. Main, H. Whay, T. Knowles, M. Bell, and A. Webster. 2006. Herd health planning: farmers' perceptions in relation to lameness and mastitis. Vet. Rec. 159:699-705.

Bennett, R. M., K. Christiansen, and R. S. Clifton-Hadley. 1999. Estimating the costs associated with endemic diseases of dairy cattle. J. Dairy Res. 66:455-459.

Bergsten, C., P. Greenough, J. Gay, W. Seymour, and C. Gay. 2003. Effects of biotin supplementation on performance and claw lesions on a commercial dairy farm. J. Dairy Sci. 86:3953-3962.

Bewley, J., M. Boehlje, A. W. Gray, H. Hogeveen, S. Kenyon, S. Eicher, and M. Schutz. 2010. Stochastic simulation using @Risk for dairy business investment decisions. Agr. Finance Rev. 70:97-125.

Bicalho, R., S. Cheong, G. Cramer, and C. Guard. 2007. Association between a visual and an automated locomotion score in lactating Holstein cows. J. Dairy Sci. 90:3294-3300.

Booth, C., L. Warnick, Y. Gröhn, D. Maizon, C. Guard, and D. Janssen. 2004. Effect of lameness on culling in dairy cows. J. Dairy Sci. 87:4115-4122.

Bruijnis, M., H. Hogeveen, and E. Stassen. 2010. Assessing economic consequences of foot disorders in dairy cattle using a dynamic stochastic simulation model. J. Dairy Sci. 93:2419-2432.

Cha, E., J. Hertl, D. Bar, and Y. Gröhn. 2010. The cost of different types of lameness in dairy cows calculated by dynamic programming. Prev. Vet. Med. 97:1-8.

Charfeddine, N. and M. A. Pérez-Cabal. 2017. Effect of claw disorders on milk production, fertility, and longevity, and their economic impact in Spanish Holstein cows. J. Dairy Sci. 100:653-665.
Collick, D., W. Ward, and H. Dobson. 1989. Associations between types of lameness and fertility. Vet. Rec. 125:103-106.
Cook, N. B. and K. V. Nordlund. 2009. The influence of the environment on dairy cow behavior, claw health and herd lameness dynamics. Vet. J. 179:360-369.
Costa, J. H. C., D. M. Weary, and M. A. G. v. Keyserlingk. 2017. Prevalence of lameness and leg injuries on US freestall dairies. J. Dairy Sci. 100 (Suppl. 2): 26. (Abstr.).
Cramer, G., K. D. Lissemore, C. L. Guard, K. E. Leslie, and D. F. Kelton. 2009. The association between foot lesions and culling risk in Ontario Holstein cows. J. Dairy Sci. 92:2572-2579.
DeFrain, J., M. Socha, and D. Tomlinson. 2013. Analysis of foot health records from 17 confinement dairies. J. Dairy Sci. 96:7329-7339.
Del Río, N. S., S. Stewart, P. Rapnicki, Y. Chang, and P. Fricke. 2007. An observational analysis of twin births, calf sex ratio, and calf mortality in Holstein dairy cattle. J. Dairy Sci. 90:1255-1264.
Dhuyvetter, K. C., T. L. Kastens, M. Overton, and J. Smith. 2007. Cow Culling Decisions: Costs or Economic Opportunity? Pages 173-187 in Proc. of the Western Dairy Management Conference. Reno, NV.
Dijkhuizen, A., R. Huirne, and A. Jalvingh. 1995. Economic analysis of animal diseases and their control. Prev. Vet. Med. 25:135-149.
Dobson, H. and R. Smith. 2000. What is stress, and how does it affect reproduction? Anim. Reprod. Sci. 60:743-752.
Dolecheck, K. A., G. Heersche, Jr., and J. M. Bewley. 2016. Retention payoff-based cost per day open regression equations: Application in a user-friendly decision support tool for investment analysis of automated estrus detection technologies. J. Dairy Sci. 99:10182-10193.
Döpfer, D., M. Holzhauer, and M. van Boven. 2012. The dynamics of digital dermatitis in populations of dairy cattle: Model-based estimates of transition rates and implications for control. Vet. J. 193:648-653.
Enting, H., D. Kooij, A. Dijkhuizen, R. Huirne, and E. Noordhuizen-Stassen. 1997. Economic losses due to clinical lameness in dairy cattle. Livest. Prod. Sci. 49:259-267.
Espejo, L., M. Endres, and J. Salfer. 2006. Prevalence of lameness in high-producing Holstein cows housed in freestall barns in Minnesota. J. Dairy Sci. 89:3052-3058.
Esslemont, R. and E. Peeler. 1993. The scope for raising margins in dairy herds by improving fertility and health. Brit. Vet. J. 149:537-547.
Esslemont, R. J. 2005. The costs of lameness in dairy herds. UK Vet Livestock 10:41-49.
Ettema, J., S. Østergaard, and A. R. Kristensen. 2010. Modelling the economic impact of three lameness causing diseases using herd and cow level evidence. Prev. Vet. Med. 95:64-73.
Ettema, J. F. and S. Østergaard. 2006. Economic decision making on prevention and control of clinical lameness in Danish dairy herds. Livest. Sci. 102:92-106.
FAPRI. 2017. U.S. Baseline Briefing Book: Projections for Agricultural and Biofuel Markets. Food and Agricultural Policy Research Institute (FAPRI) at the

University of Missouri, https://www.fapri.missouri.edu/wp-content/uploads/2017/03/FAPRI-MU-Report-01_17.pdf.
Fjeldaas, T., Å. Sogstad, and O. Østerås. 2006. Claw trimming routines in relation to claw lesions, claw shape and lameness in Norwegian dairy herds housed in tie stalls and free stalls. Prev. Vet. Med. 73:255-271.
Gernand, E., P. Rehbein, U. Von Borstel, and S. König. 2012. Incidences of and genetic parameters for mastitis, claw disorders, and common health traits recorded in dairy cattle contract herds. J. Dairy Sci. 95:2144-2156.
González, L., B. Tolkamp, M. Coffey, A. Ferret, and I. Kyriazakis. 2008. Changes in feeding behavior as possible indicators for the automatic monitoring of health disorders in dairy cows. J. Dairy Sci. 91:1017-1028.
Gould, B. W. and M. Bozic. 2017. Understanding Dairy Markets. University of Wisconsin-Madison and University of Minnesota, http://future.aae.wisc.edu/.
Green, L. E., V. J. Hedges, Y. H. Schukken, R. W. Blowey, and A. J. Packington. 2002. The Impact of Clinical Lameness on the Milk Yield of Dairy Cows. J. Dairy Sci. 85:2250-2256.
Groenendaal, H., D. Galligan, and H. Mulder. 2004. An economic spreadsheet model to determine optimal breeding and replacement decisions for dairy cattle. J. Dairy Sci. 87:2146-2157.
Guard, C. 2008. The costs of common diseases of dairy cattle. In Proceedings of the California Veterinary Conference, pp. 695-700. Advanstar Communications, Lenexa, KS, USA.
Harris, D., C. Hibburt, G. Anderson, P. Younis, D. Fitspatrick, A. Dunn, I. Parsons, and N. McBeath. 1988. The incidence, cost and factors associated with foot lameness in dairy cattle in south-western Victoria. Aust. Vet. J. 65:171-176.
Hernandez, J. A., E. J. Garbarino, J. K. Shearer, C. A. Risco, and W. W. Thatcher. 2005. Comparison of the calving-to-conception interval in dairy cows with different degrees of lameness during the prebreeding postpartum period. J. Am. Vet. Med. Assoc. 227:1284-1291.
Hogeveen, H., K. Huijps, and T. Lam. 2011. Economic aspects of mastitis: New developments. N. Z. Vet J. 59:16-23.
Horseman, S., H. Whay, J. Huxley, N. Bell, and C. Mason. 2013. A survey of the on-farm treatment of sole ulcer and white line disease in dairy cattle. Vet. J. 197:461-467.
Huxley, J. 2013. Impact of lameness and claw lesions in cows on health and production. Livest. Sci. 156:64-70.
Hyde, J. and P. Engel. 2002. Investing in a robotic milking system: A monte carlo simulation analysis. J. Dairy Sci. 85:2207-2214.
Ito, K., M. Von Keyserlingk, S. LeBlanc, and D. Weary. 2010. Lying behavior as an indicator of lameness in dairy cows. J. Dairy Sci. 93:3553-3560.
Kaneene, J. B. and H. S. Hurd. 1990. The national animal health monitoring system in Michigan. III. Cost estimates of selected dairy cattle diseases. Prev. Vet. Med. 8:127-140.
Kertz, A., L. Reutzel, B. Barton, and R. Ely. 1997. Body weight, body condition score, and wither height of prepartum Holstein cows and birth weight and sex of calves by parity: A database and summary. J. Dairy Sci. 80:525-529.

Kleinhenz, K., P. Plummer, J. Danielson, R. G. Burzette, P. J. Gorden, J. Coetzee, J. A. Schleining, V. Cooper, B. Leuschen, and A. Krull. 2014. Survey of veterinarians and hoof trimmers on methods applied to treat claw lesions in dairy cattle. Bovine Pract. 48:47-52.

Kossaibati, M. and R. Esslemont. 1997. The costs of production diseases in dairy herds in England. Vet. J. 154:41-51.

Laven, R. and H. Hunt. 2002. Evaluation of copper sulphate, formalin and peracetic acid in footbaths for the treatment of digital dermatitis in cattle. Vet. Rec. 151:144-146.

Leach, K. A., H. R. Whay, C. M. Maggs, Z. E. Barker, E. S. Paul, A. K. Bell, and D. C. Main. 2010a. Working towards a reduction in cattle lameness: 1. Understanding barriers to lameness control on dairy farms. Research in Veterinary Science 89:311-317.

Leach, K. A., H. R. Whay, C. M. Maggs, Z. E. Barker, E. S. Paul, A. K. Bell, and D. C. Main. 2010b. Working towards a reduction in cattle lameness: 2. Understanding dairy farmers' motivations. Research in Veterinary Science 89:318-323.

Liang, D., L. M. Arnold, C. J. Stowe, R. J. Harmon, and J. M. Bewley. 2017. Estimating US dairy clinical disease costs with a stochastic simulation model. J. Dairy Sci. 100:1472-1486.

Lucey, S., G. Rowlands, and A. Russell. 1986. The association between lameness and fertility in dairy cows. Vet. Rec. 118:628-631.

McConnel, C., J. Lombard, B. Wagner, C. Kopral, and F. Garry. 2015. Herd factors associated with dairy cow mortality. Animal 9:1397-1403.

McInerney, J. 1996. Old economics for new problems-Livestock disease: presidential address. J. Agric. Econ. 47:295-314.

McInerney, J., K. Howe, and J. Schepers. 1992. A framework for the economic analysis of disease in farm livestock. Prev. Vet. Med. 13:137-154.

Melendez, P., J. Bartolome, L. Archbald, and A. Donovan. 2003. The association between lameness, ovarian cysts and fertility in lactating dairy cows. Theriogenology 59:927-937.

Mill, J. and W. Ward. 1994. Lameness in dairy cows and farmers' knowledge, training and awareness. Vet. Rec. 134:162-164.

Miller, G. Y. and C. R. Dorn. 1990. Costs of dairy cattle diseases to producers in Ohio. Prev. Vet. Med. 8:171-182.

Morris, M., K. Kaneko, S. Walker, D. Jones, J. Routly, R. Smith, and H. Dobson. 2011. Influence of lameness on follicular growth, ovulation, reproductive hormone concentrations and estrus behavior in dairy cows. Theriogenology 76:658-668.

Morris, R. 1969. Assessing the economic value of veterinary services to primary industries. Aust. Vet. J. 45:295-300.

NAHMS. 2014. Dairy Cattle Management Practices in the United States. USDA-APHIS-VS, ed. National Animal Health Monitoring System, Fort Collins, CO.

NMPF. 2016. Animal Care Reference Manual for the Farmers Assuring Responsible Management National Dairy Farm Program. Retreived on 7 July 2017, from http://www.nationaldairyfarm.com/sites/default/files/Version-3-Manual.pdf.

Norman, H., J. Wright, M. Kuhn, S. Hubbard, and J. Cole. 2007. Genetic and environmental factors that affect gestation length. J. Dairy Sci. 90:264.

NRC. 2001. Nturient Requirements of Dairy Cattle. 7th Rev. Ed. Natl. Acad. Press, Washington, DC.

Pecsok, S. R., M. L. McGilliard, and R. L. Nebel. 1994. Conception Rates. 1. Derivation and Estimates for Effects of Estrus Detection on Cow Profitability. J. Dairy Sci. 77:3008-3015.

Peeler, E., M. Otte, and R. Esslemont. 1994. Inter-relationships of periparturient diseases in dairy cows. Vet. Rec. 134:129-132.

Pritchard, T., M. Coffey, R. Mrode, and E. Wall. 2013. Genetic parameters for production, health, fertility and longevity traits in dairy cows. Animal 7:34-46.

Rollin, E., K. Dhuyvetter, and M. Overton. 2015. The cost of clinical mastitis in the first 30 days of lactation: an economic modeling tool. Prev. Vet. Med. 122:257-264.

Rutten, C. J., W. Steeneveld, C. Inchaisri, and H. Hogeveen. 2014. An ex ante analysis on the use of activity meters for automated estrus detection: To invest or not to invest? J. Dairy Sci. 97:6869-6887.

Sanders, A., J. Shearer, and A. De Vries. 2009. Seasonal incidence of lameness and risk factors associated with thin soles, white line disease, ulcers, and sole punctures in dairy cattle. J. Dairy Sci. 92:3165-3174.

Skidmore, A. L. 1990. Development of a simulation model to evaluate effectiveness of dairy herd management. Cornell University, Aug.

Sood, P., A. Singh Nanda, and N. Singh. 2009. Effect of lameness on follicular dynamics in postpartum anestrous crossbred cows. Vet. Arhiv. 79:531-542.

Thomsen, P. T., A. M. Kjeldsen, J. T. Sørensen, and H. Houe. 2004. Mortality (including euthanasia) among Danish dairy cows (1990–2001). Prev. Vet. Med. 62:19-33.

USDA. 2007. Dairy 2007 Part I: Reference of dairy cattle health and management practices in the United States. Retrieved 7 July 2017 from, https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/monitoring-and-surveillance/nahms/nahms_dairy_studies.

USDA. 2017a. Agricultural Marketing Service - Market News Custom Report. Accessed June 20, 2017. https://www.ams.usda.gov/market-news/custom-reports.

USDA. 2017b. Dairy Data: Milk cows and production by state and region (Annual). Accessed Oct. 16, 2017. https://www.ers.usda.gov/data-products/dairy-data.aspx.

Van Nuffel, A., I. Zwertvaegher, L. Pluym, S. Van Weyenberg, V. M. Thorup, M. Pastell, B. Sonck, and W. Saeys. 2015a. Lameness detection in dairy cows: Part 1. How to distinguish between non-lame and lame cows based on differences in locomotion or behavior. Animal 5:838-860.

Van Nuffel, A., I. Zwertvaegher, S. Van Weyenberg, M. Pastell, V. M. Thorup, C. Bahr, B. Sonck, and W. Saeys. 2015b. Lameness detection in dairy cows: Part 2. Use of sensors to automatically register changes in locomotion or behavior. Animal 5:861-885.

Vanegas, J., M. Overton, S. Berry, and W. Sischo. 2006. Effect of rubber flooring on claw health in lactating dairy cows housed in free-stall barns. J. Dairy Sci. 89:4251-4258.

VanRaden, P. M. and J. B. Cole. 2014. Lifetime Net Merit 2014. USDA. Accessed July 3, 2017. http://aipl.arsusda.gov/reference/nmcalc-2014.htm.

Von Keyserlingk, M., A. Barrientos, K. Ito, E. Galo, and D. Weary. 2012. Benchmarking cow comfort on North American freestall dairies: Lameness, leg injuries, lying

time, facility design, and management for high-producing Holstein dairy cows. J. Dairy Sci. 95:7399-7408.
Von Keyserlingk, M., J. Rushen, A. M. de Passillé, and D. M. Weary. 2009. Invited review: The welfare of dairy cattle—Key concepts and the role of science. J. Dairy Sci. 92:4101-4111.
Walker, S., R. Smith, D. Jones, J. Routly, and H. Dobson. 2008. Chronic stress, hormone profiles and estrus intensity in dairy cattle. Horm. Behav. 53:493-501.
Whay, H. R., A. E. Waterman, A. J. F. Webster, and J. K. O'Brien. 1998. The influence of lesion type on the duration ofhyperalgesia associated with hindlimb lameness in dairy cattle. Vet. J. 156:23-29.
Willshire, J. and N. Bell. 2009. An economic review of cattle lameness. Cattle Pract. 17:136-141.
Zinpro. 2014. Cattle lameness claw lesions: Identify, Prevent, Control. Zinpro Corporation, Eden Prairie, MN.

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Professional Positions

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Scholastic and Professional Honors

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2015 National Dairy Leadership Scholarship
National Milk Producers Federation, Arlington VA, USA
2015 Best Paper Award
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Peer Reviewed Publications

1. Dolecheck, K.A. and J.M. Bewley. Accepted for publication in February 2018. Invited review: Dairy cow lameness expenditures, losses, and total cost. Animal.

2. Stygar, A.H., K.A. Dolecheck, A.R. Kristensen. 2018. Analyses of body weight patterns in growing pigs - A new view on body weight in pigs for frequent monitoring. *Animal* 12: 295-302.

3. Dolecheck, K.A., G. Heersche, Jr., and J.M. Bewley. 2016. Retention pay-off based cost of days open regression equations: Application in a user-friendly decision support tool for investment analysis of automated estrus detection technologies. *Journal of Dairy Science* 99: 10182-10193.

4. Dolecheck, K.A., W.J. Silvia, G. Heersche, Jr., C.L. Wood, K.J. McQuerry, and J.M. Bewley. 2015. A comparison of timed artificial insemination and automated activity monitoring with hormone intervention in three commercial dairy herds. *Journal of Dairy Science* 99: 1506-1514.

5. Dolecheck, K.A., W.J. Silvia, G. Heersche, Jr., Y.M. Chang, D.L. Ray, A.E. Stone, B.A. Wadsworth, and J.M. Bewley. 2015. Behavioral and physiological changes around estrus events identified using multiple automated monitoring technologies. *Journal of Dairy Science* 98: 8723-8731.

6. Lawson, B.D., A.H. Shahzad, K.A. Dolecheck, E.L. Martel, K.A. Velek, D.L. Ray, J.C. Lawrence, and W.J. Silvia. 2014. A pregnancy detection assay using milk samples: Evaluation and considerations. *Journal of Dairy Science* 97: 6316-6325.