CODE OF PRACTICE FOR THE CARE AND HANDLING OF DAIRY CATTLE: REVIEW OF SCIENTIFIC RESEARCH ON PRIORITY ISSUES

December 2020

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ACKNOWLEDGEMENTS

This report was a significant undertaking that benefited from the help and guidance of several people. The Scientific Committee wishes to thank Dr. Steven Roche and his team at ACER Consulting for their help with the entire report, particularly *Section 5: Lameness and Injuries*. We also thank Dr. Steve Mason (AgroMedia International Inc.) for his contributions to *Section 2: Cow-Calf Separation* and *Section 3: Optimal Management and Design of Indoor Systems,* Véronique Boyer (McGill University) for her contributions to *Section 3.1: Stall Design and Bedding* and Paige McDonald (University of British Columbia) for her contributions to *Section 3.3: Air Quality and Temperature*. The authors appreciate the valuable input from the four peer reviewers, whose comments greatly improved the quality of this report, and also extend their gratitude to Dr. Cassandra Tucker (University of California, Davis) who coordinated the peer review and provided valuable suggestions on the final manuscript.

Funding for this project was provided through the AgriAssurance Program under the Canadian Agricultural Partnership, a federal–provincial–territorial initiative.

Excerpt from Scientific Committee Terms of Reference

Background

It is widely accepted that animal welfare codes, guidelines, standards or legislation should take advantage of the best available knowledge. This knowledge is often generated from the scientific literature.

In re-establishing the Code of Practice development process, NFACC recognized the need for a more formal means of integrating scientific input into the Code of Practice process. A Scientific Committee review of priority animal welfare issues for the species being addressed provides valuable information to the Code Committee in developing or revising the Code of Practice. As the Scientific Committee report is publicly available, the transparency and credibility of the Code is enhanced.

For each Code of Practice being developed or updated, NFACC identifies a Scientific Committee. This committee will consist of a target number of 6 scientists familiar with research on the care and management of the animals under consideration. NFACC will request nominations from 1) Canadian Veterinary Medical Association, 2) Canadian Society of Animal Science, and 3) Canadian Chapter of the International Society for Applied Ethology. At least one representative from each of these professional scientific bodies will be named to the Scientific Committee. Other professional scientific organizations as appropriate may also serve on the Scientific Committee.

Purpose & Goals

The Scientific Committee will develop a report synthesizing the results of research relating to key animal welfare issues, as identified by the Scientific Committee and the Code Committee. The report will be used by the Code Committee in drafting the Code of Practice for the species in question. Some priority issues may not be addressed by the Scientific Committee for any number of reasons (e.g., inadequate available research, existing protocols provide good guidance). Welfare issues that are not addressed by the Scientific Committee should still be addressed in the Code's development.

Note: The Scientific Committee report will not contain recommendations following from any research results. Its purpose is to present a compilation of the scientific findings without bias.

The full Terms of Reference for the Scientific Committee can be found within the NFACC Development Process for Codes of Practice for the Care and Handling of Farm Animals, available at www.nfacc.ca/code-development-process#appendixc.

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Dairy Code of Practice Scientific Committee Report
December 2020

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1 Introduction

1.1 Purpose and Objectives

The purpose of this report is to review and summarize the scientific research on priority welfare issues for the Canadian dairy industry. The specific topics and scope of this report were collectively identified by the Code Development Committee and the Scientific Committee. The mandate of the Scientific Committee was to address the implications for dairy cattle welfare within the priority issues identified. The Code Development Committee, for which this report was prepared, represents considerable expertise in these areas and is tasked with considering such factors in its discussions.

In many cases, these specific topics have not had an adequate number of randomized clinical trials asking similar enough research questions to be combined in meta-analysis. This form of synthesis is needed to best determine the overall efficacy of treatments and explore potential methodologic or contextual heterogeneity to better understand the clinical implications of the specific intervention in a specific context. In light of a plethora of evidence for a given practice, it is important to weight the potential benefits with any potential risks. This report summarizes the available evidence, making use of use of meta-analyses where appropriate, to offer a review of the science and strength of evidence for current practices related to dairy cattle welfare.

The specific priority issues discussed within this report include:

- Cow-calf separation—effects of immediate or delayed separation
- Optimal management and design of indoor systems, as it relates to:
    - Stall design
    - Bedding
    - Spatial allowance/stocking density, including impact on social interactions
    - Air quality and temperature (for calves and cows)
    - Exercise and outdoor access
- Pain control for painful conditions and procedures
    - Main principles
    - Mastitis, metritis, diarrhea, and dystocia
    - Pain associated with caustic paste disbudding
    - Surgical and post-surgical considerations
- Lameness and injuries
    - Risk factors
    - Prevention strategies

  - Early identification and treatment, including pain control
  - Understanding farm-level barriers to reducing occurrence
- End-of-life management (culling, euthanasia, and fitness for transport)
  - Prognosis and decision-making for vulnerable cows
  - Nursing care for down cows
  - Link to dry off and culling

1.2 Approaches to Defining and Evaluating Animal Welfare

The scientific evaluation of animal welfare involves the use of empirical methods to obtain information about animals that can be used to inform ethical decision-making regarding their quality of life. One major challenge is that people have diverse views about what constitutes a good quality of life and, therefore, express a variety of ethical concerns and use different criteria for defining animal welfare. These have been grouped into three general categories: 1) biological functioning, 2) affective states, and 3) natural living and form the bases for different approaches to animal welfare research (Fraser et al., 1997). The biological functioning approach emphasizes basic health and normal function and includes measures having to do with health, productivity, and behavioural responses to stress (Broom, 1991). Animal welfare defined in terms of affective states, often referred to as the feelings-based approach, concerns the subjective experiences of animals with an emphasis on states of suffering (pain, fear, frustration), states of pleasure (comfort, contentment), and the notion that animals should be housed and handled in ways that minimize suffering and promote positive experiences (Duncan, 1993). The concept of natural living emphasizes the naturalness of the circumstances that the animal experiences and the ability of the animal to live according to its nature (Fraser, 2008). Much of the progress made in animal welfare relates to identifying behaviours that are important for animals to express (i.e., natural behaviours) and identifying environments and management practices that accommodate and promote these behaviours.

Since the field of animal welfare science has developed in response to societal concerns about the welfare of the animals in our care (Fraser, 2008), Weary and Robbins (2019) suggest that the evaluation of animal welfare should include consideration of public perceptions about animal welfare that may not fit well into the categories commonly used in scientific evaluations, described above. For example, perceived quality of life may involve more than simply facts about the animal and may incorporate a range of factors including the perceived value of a life, relationships with the animal's caregiver, and how an animal's life ends. Those authors advocate that future research should account for conceptions of animal care held by the general public by evaluating how ordinary people respond to scenarios describing alternative animal care scenarios.

Varying and evolving definitions of animal welfare have consequently resulted in a variety of different scientific approaches and corresponding results in the published literature. The authors of this report have made an attempt to be considerate of these various forms of animal welfare research but recognize that there may be gaps in current research based on the evolution of our understanding of and approaches to measuring dairy cattle welfare.

1.3 Public Perception of High Priority Issues

While an in-depth review of social science on the pre-identified priority welfare topics is not a specific focus of this report, it should be noted that numerous studies have begun to explore public perceptions of the dairy industry and specific husbandry practices. Acknowledging and understanding these concerns may help in adopting a broader and more holistic view of dairy cattle welfare and provide additional context when reviewing the evidence summarized herein.

Increasing public concern with the welfare of farmed animals is well documented (Clark et al., 2016). In some cases, the industry has been dismissive of these concerns on the basis that the concerns of citizens are misinformed (Spooner et al., 2012; Ventura et al., 2016). However, there is a growing recognition that societal values are a critical construct that the dairy industry and other livestock commodities must integrate into their concept of a sustainable industry (Thornton, 2010; Weary & von Keyserlingk, 2017).

Much of the research on this topic has used social science techniques (interviews, surveys, experimental interventions using pre-post educational interventions) to understand how members of the public react to learning about or viewing certain practices common on commercial dairies. These studies have highlighted that the most contentious practices appear to relate to early cow-calf separation, tail docking, disbudding/dehorning without pain mitigation, culling of male dairy calves, and zero-grazing (lack of pasture access) and/or tie-stall housing systems (Weary et al., 2011; Ventura et al., 2013; Schuppli et al., 2014; Robbins et al., 2015; Widmar et al., 2017; Hötzel et al., 2017; Cardoso et al., 2017; Robbins et al., 2019). For example, Ventura et al. (2016) explored citizens' concerns about farm animal welfare before and after a self-guided tour of a 500-head dairy farm in British Columbia. The authors concluded that the visit appeared to address some concerns (e.g., provision of adequate feed and water, humane handling), while reinforcing others (e.g., lack of pasture access, early cow-calf separation). Collectively, the growing body of evidence on public perception of on-farm practices suggests that the public typically emphasize natural living and care, and that citizens are often unaware of many of the common on-farm practices but have a negative reaction when informed about them. While there are a wide range of values expressed among these studies, there appear to be important disconnects between current dairy production practices and public perceptions and values.

While there is some evidence to suggest the dairy industry is adapting to growing public concerns (de Rooij et al., 2010), the social science literature provides a growing set of recommendations to engage the public as an important industry stakeholder (Weary & von Keyserlingk, 2017; Hötzel et al., 2017; Cardoso et al., 2017; Beaver et al., 2020). More specifically, these recommendations advocate for a more explicit engagement of the public in discussions about the future of the industry in an effort to better understand their attitudes, identify contentious issues, and relate industry practices with societal expectations (Weary & von Keyserlingk, 2017).

1.4 References

Beaver A., Proudfoot K.L. & von Keyserlingk M.A.G. (2020) Symposium review: Considerations for the future of dairy cattle housing: an animal welfare perspective.

Broom D.M. (1991) Animal welfare: Concepts and measurement. *Journal of Animal Science* 69:4167–4175.

Cardoso C.S., von Keyserlingk M.A.G. & Hötzel M.J. (2017) Brazilian citizens: expectations regarding dairy cattle welfare and awareness of contentious practices. *Animals* 7:89.

Clark B., Stewart G.B., Panzone L.A., Kyriazakis I. & Frewer L.J. (2016) A systematic review of public attitudes, perceptions and behaviors towards production diseases associated with farm animal welfare. *Journal of Agricultural and Environmental Ethics* 29:455–478.

de Rooij S.J.G., De Lauwere C.C. & Van Der Ploeg J.D. (2010) Entrapped in group solidarity? Animal welfare, the ethical positions of farmers and the difficult search for alternatives. *Journal of Environmental Policy and Planning* 12:341–361.

Duncan I.J.H. (1993) Welfare is to do with what animals feel. *Journal of Agricultural and Environmental Ethics* 6(Suppl. 2):8–14.

Fraser D. (2008) *Understanding Animal Welfare: The Science in Its Cultural Context*. Ames IA: Wiley-Blackwell.

Fraser D., Weary D.M., Pajor E.A. & Milligan B.N. (1997) A scientific conception of animal welfare that reflects ethical concerns. *Animal Welfare* 6:187–2.

Hötzel M.J., Cardoso C.S. Roslindo A. & von Keyserlingk M.A.G. (2017) Citizens' views on the practices of zero-grazing and cow-calf separation in the dairy industry: Does providing information increase acceptability? *Journal of Dairy Science* 100:4150–4160.

Robbins J.A., Roberts C., Weary D.M., Franks B. & von Keyserlingk M.A.G. (2019) Factors influencing public support for dairy tie stall housing. *PLoS ONE* 14:5.

Robbins J.A., Weary D.M., Schuppli C.A. & von Keyserlingk M.A.G. (2015) Stakeholder views on treating pain due to dehorning dairy calves. *Animal Welfare* 24:399–406.

Schuppli C.A., von Keyserlingk M.A.G & Weary D.M. (2014) Access to pasture for dairy cows: Responses from an online engagement. *Animal Science* 92:5185–519.

Spooner J.M., Schuppli C.A., Fraser D. (2012) Attitudes of Canadian beef producers toward animal welfare. *Animal Welfare* 21:273–283.

Thornton P.K. (2010) Livestock production: Recent trends, future prospects. *Philosophical Transactions of the Royal Society B* 365:2853–2867.

Ventura B.A., von Keyserlingk M.A.G., Schuppli C.A. & Weary D.M. (2013) Views on contentious practices in dairy farming: The case of early cow-calf separation. *Journal of Dairy Science* 96:6105–6116.

Ventura B.A., von Keyserlingk M.A.G., Wittman H. & Weary D.M. (2016) What difference does a visit make? Changes in animal welfare perceptions after interested citizens tour a dairy farm. *PLoS ONE* 11(5).

Weary D.M. & Robbins J.A. (2019) Understanding the multiple conceptions of animal welfare. *Animal Welfare* 28:33–40.

Weary D.M., Schuppli C.A. & von Keyserlingk M.A.G. (2011) Tail docking dairy cattle: Responses from an online engagement. *Animal Science* 89:3831–3837.

Weary D.M. & von Keyserlingk M.A.G. (2017) Public concerns about dairy-cow welfare: How should the industry respond? *Animal Production Science* 57:1201–1209.

Widmar N.O., Morgan C.J., Wolf C.A., Yeager E.A., Dominick S.R. & Croney C.C. (2017) US resident perceptions of dairy cattle management practices. *Agricultural Sciences* 8:645–656.

2 Cow-Calf Separation

Conclusions:

1. **There is no consistent scientific evidence that early separation versus a prolonged period of contact with the dam:**
    a. **Affects the risk of calf scours. Available studies do not make it possible to distinguish the effects of pathogen exposure, the quantity and quality of milk provided, and other aspects of management and housing.**
    b. **Affects the risk of Johne's disease. Rather, risk of infection increases with poor cow hygiene, colostrum management, and calving area and maternity pen cleanliness.**
    c. **Affects the risk of respiratory disease in calves.**
    d. **Affects the risk failure of transfer of immunoglobulins to the calf.**
    e. **Affects the risk of calf morbidity or mortality.**
    f. **Affects milk yield. Any loss in harvestable milk must be weighed against the cost or value of alternative liquid feeds and the possible benefit of increased weight gains in suckled calves.**
2. **Cows allowed a prolonged period of contact with the calf are at reduced risk of mastitis, but there is no consistent evidence of any other effects on cow health.**
3. **Calves separated within 24 hours of birth show reduced indicators of distress compared with calves separated later in life.**
4. **Calves allowed extended contact with their dams exhibit consistently reduced abnormal oral behaviour compared with calves separated from their dam soon after birth.**
5. **Calves able to suckle their dams gain weight more rapidly than their artificially reared peers. Depending upon how weaning is managed, calves may experience a growth check, but even then the weight gain advantage for suckled calves is generally maintained.**

2.1 Effects on Cow and Calf Health

A comprehensive systematic review of the effects of early separation on dairy cow and calf health was published in the July 2019 issue of the *Journal of Dairy Science*, based on a search of the scientific literature published before May 18, 2018 (Beaver et al., 2019). From a total of 125 refereed articles initially identified, 70 were deemed appropriate for further review. The review protocol and quality assessment protocols for the included studies are described in the review (Beaver et al., 2019). Details of each study included in the review are also summarized in a number of tables in the review article. A feature of this literature is that studies varied widely in methodology. For example, although "early-separation" treatments involved separating cow and calf within 24 h of birth, the "delayed separation" treatments varied widely, both in the duration of contact (ranging from just a few days to weeks or months) and the type of contact (ranging from continuous to different forms of partial contact). More details about these papers are summarized in the tables of the review article we cite. The summary conclusions described here are derived directly from that review:

Scours. Of the 70 articles included in the review, 16 examined the effects of cow-calf separation on dairy calf scours attributable to unspecified or multiple causes. 6 of these studies reported that allowing calves to suckle reduced scours; 2 reported increased scours; 8 reported no evidence of an association. In a number of these studies, diagnosis of scours was based only on fecal consistency rather than identification of pathogens; the well-established effect of consuming high volumes of milk on production of loose manure was often not accounted for.

An additional 9 studies that addressed scours specifically due to Cryptosporidia also reported mixed results: 2 reported a protective effect of cow-calf contact; 3 reported increased risk; 4 reported no difference.

Johne's disease. 14 of the 70 articles reviewed examined the relationship between the duration of cow-calf contact and the prevalence in calves of the pathogen causing Johne's disease (*Mycobacterium avium* subspecies *paratuberculosis*; MAP). Only 1 of these studies reported increased MAP prevalence among herds that did not separate cow and calf immediately after birth. For most of these herds, time of separation varied greatly, ranging from more than 1 hour after birth to more than 24 hours after birth.

Respiratory health. Of the 70 articles reviewed, 7 addressed the relationship between cow-calf contact or nursing on calf respiratory health. 5 of these studies reported no relationship; 1 reported a higher risk of pneumonia when calves remained with their dams for more than 24 hours; 1 study reported a lower incidence of pneumonia in suckling calves.

Calf immunity. 9 of the 70 articles examined acquired immunity in suckled calves compared with those fed artificially. Immunity in the neonatal calf is acquired through the consumption of an adequate amount of immunoglobulin-containing colostrum within the first hours of life. The common criterion used to assess acquired immunity in the articles reviewed was failed passive transfer of immunity (FPT), reflecting the failure to consume sufficient colostrum containing minimal bacterial loads and adequate levels of immunoglobulin. FPT was variously assessed by measuring serum levels of lactoglobulin, immunoglobulin, or total protein. Due to variation in the source, timing, method, amount and quality of colostrum fed, lack of control of the timing, amount and quality of colostrum received through suckling, and method used to assess FPT, the articles reviewed do not provide conclusive evidence in support of either suckling or artificial provision of colostrum.

Calf morbidity and mortality. 10 of the 70 reviewed articles attempted to address the effect of early cow-calf separation on calf mortality; 2 addressed the effect on general calf morbidity. Again, the combined weight of the evidence is inconclusive, likely due to many of the same factors that influenced the results of the calf immunity studies.

Cow health. 18 articles were reviewed for evidence of the effect of suckling on mastitis. 10 reported reduced risk in suckled cows, 6 reported no evidence of an association, and 1 study noted increased teat damage with duration of suckling.

2.2 Effects on Behaviour, Welfare, and Productivity

A comprehensive review of the effects of early separation on dairy cow and calf behaviour, welfare, and productivity was published in the July 2019 issue of the *Journal of Dairy Science*, based on a search of the scientific literature published before May 31, 2018 (Meagher et al., 2019). From a total of 108 refereed articles deemed eligible, 53 were included in the review. The review protocol and quality assessment protocols for the included studies are described in the review (Meagher et al., 2019). Details of each study included in the review are also summarized in a number of tables in the review article. The summary conclusions described here are derived directly from that review:

Behavioural indicators of distress. Only 3 of the eligible studies compared separation of cow and calf at 1 day or less with later separation. All of these reported that calves separated within 24 hours exhibited reduced indicators of distress (such as vocalizations and time looking out of the pen).

Social behaviour. Of the 12 studies that examined effects on social behaviour, 10 reported that extended cow-calf contact promoted increased social interaction between calves after separation.

Abnormal oral behaviour. 8 of the eligible studies recorded cross-sucking, non-nutritive sucking, and tongue rolling. 6 of these studies reported reduced abnormal oral behaviour when calves were allowed extended contact with their dams (including suckling); the 2 other studies reported no evidence of an association.

Response to stressors. 7 eligible papers measured responses to stressors by offspring varying in age from preweaning to 2.5 years. All except 2 of these studies reported somewhat reduced stress responses by animals that had spent a prolonged period with their dam.

Milk yield. 16 papers were identified that measured the effect of suckling on milk yield while calves were still suckling. 7 of these reported decreases in harvested milk, 7 reported increases, and 2 reported no differences. The reviewers point out that any reduction in harvested milk is likely accounted for by consumption of the calf, and thus may not represent a loss of revenue from saleable milk when weighed against the cost or value of alternative liquid feeds (e.g., milk replacer or previously harvested milk) and the value of increased weight gains in suckled calves.

14 papers evaluated the effect of suckling on milk yield after separation of the calf. 1 of these reported a decrease in yield over the full lactation in multiparous cows; 3 other papers reported increases. The remaining 10 studies reported no statistically significant differences in milk yield.

Calf growth. 22 studies compared weight gain of calves with or without contact with the dam or a foster cow. 14 of those studies reported increased gains in suckled calves; 6 reported no differences. 2 studies reported mixed results among treatment groups. Intake of solid feed while being fed milk was generally lower by suckled versus artificially reared calves.

4 studies that measured post-weaning weight gain reported reduced gains by suckled calves after separation from their dams. However, in the studies that continued to monitor growth, the

advantage of greater gains during the suckling period was maintained despite the post-weaning reduction.

2.3 References

Beaver A., Meagher R.K., von Keyserlingk M.A.G. & Weary D.M. (2019) Invited review: A systematic review of the effects of early separation on dairy cow and calf health. *Journal of Dairy Science* 102(7):5784–5810.

Meagher R.K., Beaver A., Weary D.M. & von Keyserlingk M.A.G. (2019) Invited review: A systematic review of the effects of prolonged cow-calf contact on behavior, welfare, and productivity. *Journal of Dairy Science* 102(7):5765–5783.

3 Optimal Management and Design of Indoor Systems

Conclusions:

Stall Design and Bedding

1. **Recent large-scale studies assessing cow comfort on Canadian dairies have reported that a significant proportion of cows are housed in stalls that do not fit their body dimensions or current guidelines in the 2009 Code of Practice. Stall configuration was reported to have a major impact on cow welfare outcomes.**
2. **Some of the current guidelines on stall configuration are based only on observational studies, with no experimental research available to offer stronger evidence that current guidelines achieve optimal results.**
3. **Modifying stalls to meet the current guidelines for free-stall and tie-stall farms may improve animal-based outcome measures of welfare but may slightly decrease cow cleanliness if barn hygiene practices are not sufficient. Recent studies investigating the impact of going beyond the current guidelines suggest that these changes may allow farms to realize a number of improved animal welfare outcomes. Though results are dependent on cow- and herd-level factors, some general conclusions that can be made include:**
    a. **The provision of large amounts of bedding yields the best outcomes of all stall improvements in terms of welfare, from increased lying times to healing of body injuries. The combination of stall base and bedding together contribute to the softness and good traction of the stall bed.**
    b. **Bedding quality, namely dryness, is a key component of stalls. Drier laying surfaces are preferred by cows and calves, improve the quantity and quality of rest, and help maintain cow cleanliness, health, and production.**
    c. **Longer stalls are associated with greater lying times and decreased injuries and lameness, but a slight decrease in cow cleanliness.**
    d. **Wider stalls are associated with greater lying times, increased ease of movement, and, in the case of tie-stalls, decreased injuries and lameness.**
    e. **Positioning the tie-rail or the neck-rail further away from the curb has been associated with decreased injuries and lameness and improved ease of movement in the stall, but a slight decrease in cow cleanliness. Yet, even at the current guidelines, cows continue to put pressure on their necks, leading to injuries.**
    f. **Lower manger walls or brisket boards do not necessarily facilitate cow ease of movement. Instead, they work in conjunction with other stall components to define the space available to the cow and modulate the ease at which she can move within her stall.**
    g. **In tie-stalls, longer chains were reported to improve ease of movement at the stall, with shorter durations of intention movements before lying down and increased use of the stall environment.**

  h. **Electric trainers used in tie-stalls may impair hygiene and increase hock and foot injuries, but results are inconsistent, indicating that the proper placement of the trainer is imperative to its efficacy.**

Spatial Allowance and Stocking Density

4. **A substantial body of literature has been focused on examining the effects of stocking density at the free-stalls and the feed bunk, resources in loose housing systems that may be overstocked on Canadian farms.**
   a. **The research on free-stall availability shows that overstocking (i.e., more than one cow per stall) reduces lying time and increases competition for stalls. Overstocking at the feed bunk (i.e., more than one cow per suitable feeding position at the feed bunk) also has detrimental effects on cows, especially in terms of increased competition and competitive displacements.**
   b. **Research on both resources shows that more vulnerable animals, including lame cows and transition cows, are most susceptible to the negative effects of this competition.**
   c. **Other resources like water, milking, and brushing opportunities are also important to cows and need to be considered in stocking calculations.**

Air Quality and Temperature

5. **Heat stress is a serious problem for dairy cows, causing a number of harmful physiological and behavioural effects. Given their body size and metabolic rate, cold stress is much less of a problem for dairy cows under most conditions.**
6. **A number of approaches can be used to reduce heat load, including the provision of shade, sprinklers, fans, and barn designs that improve natural ventilation.**
7. **Dairy calves are more susceptible to cold stress at low ambient temperatures; increased milk rations, copious quantities of dry bedding, heat lamps, and insulating coats can help keep calves warm.**

Exercise and Outdoor Access

8. **Increased movement opportunity through less restrictive indoor housing and/or outdoor access (i.e., access to an outdoor bedded pack, paddock, and/or to pasture) has a number of benefits to dairy cow health, behaviour, performance, and welfare. Numerous factors relating to access to the outdoors (e.g., time of year, cleanliness, optional access versus forced access) must be carefully managed to achieve positive welfare outcomes.**

3.1 Stall Design and Bedding

Canadian dairy cows are primarily housed in stall-based systems, with 72.9% of herds housed in tie-stall barns and 27.1% in free-stall barns (CDIC, 2019). Welfare issues associated with housing were identified in a recent large-scale study assessing cow comfort on 230 Canadian dairies (Vasseur et al., 2015). In free-stall farms, prevalence of hock, knee, and neck injuries was 47, 24, and 9% (ranges not reported), respectively (Zaffino-Heyerhoff et al., 2014); lameness was 21% (range: 0 to 69%) (Solano et al., 2015). In tie-stall barns, prevalence of hock, knee, and neck injuries was 56, 43, and 33% (ranges not reported), respectively (Nash et al., 2016); lameness was 25% (Bouffard et al., 2017); and the prevalence of dirty cows was low (udder: 4%; flank: 11%; legs: 4%; Bouffard et al., 2017). For tie-stall farms, these results were in general agreement with the only two other epidemiological studies conducted previously on Canadian tie-stall farms (Zurbrigg et al., 2005a; Lapointe, 2010). In free-stall farms, these numbers were also similar to previously published data from Canadian and American herds (von Keyserlingk et al., 2012). The data from these studies demonstrated that, on average, less than half of the cows on tie-stall farms were housed in stalls that met the current recommendations set by the 2009 Canadian Code of Practice (NFACC-DFC, 2009), which are based on average body dimensions (Bouffard et al., 2017), supporting the results from previous studies (Zurbrigg et al., 2005a; Lapointe, 2010). Similarly, in free-stall farms, it was estimated that about 35% of cows would fit in the average stall, for stall length and width (Vasseur et al., 2015), based on the current recommendations set by the 2009 Canadian Code of Practice (NFACC-DFC, 2009). A number of the problems identified in tie-stall and free-stall farms are likely due to many cows being housed in stalls not fitting their body dimensions. Stall configuration has a significant impact on cows' welfare status.

3.1.1 Function of Stall Elements and Rationale of Current Recommendations for Stall Configuration

Stall length. The length of the lying surface is known as stall length in tie-stalls and bed length in free-stalls; in free-stalls, the total length of the stall is comprised of the bed length and the lunge space. The front of the stall is confined by the manger wall/curb in tie-stalls or by the brisket board/barrier in free-stalls. The current basis for the recommended length is the imprint length (Ceballos et al., 2004), aiming for the cow to be able to lay fully in the stall with her front legs tucked and her back legs and tail lying on the base of the stall (Anderson, 2014, 2016). The current stall length recommendation for both tie-stalls and free-stalls corresponds to 1.2 x the height of the cow's rump (Anderson, 2014, 2016; Valacta, 2014).

Stall width. The current recommendation for the width of stalls is common to both tie-stalls and free-stalls and is based off of cows' body dimensions (Anderson, 2014, 2016; Valacta, 2014). The current basis for the recommended width is the imprint width (Ceballos et al., 2004), or the space occupied by the cow when lying down in the narrow posture with all legs tucked near the body (Anderson, 2014, 2016), and corresponds to 2 x hip bone width of the cow (Anderson, 2014, 2016; Valacta, 2014). Specifically, for tie-stalls it is recommended to add another 6–8 inches (15.24–20.32 cm) in width, depending upon the design of the side dividers and the clearance they allow for the hips (Valacta, 2014).

Position of the tie-rail and of the neck-rail. Both the tie-rail in tie-stalls and the neck-rail in free-stalls act as a barrier at the front of the stall to help cows position themselves so that they do not leave the confines of their stall (i.e., entering the manger area, another stall, or coming into contact with the front wall) during lying and rising events. Another function of the tie-rail and neck-rail is to facilitate stall cleanliness and manure management, as it is positioned in a way that causes cows to eliminate in the gutter or alley and not in the stall. Tie-rails have an additional function of separating cows from the manger area. Because of their function (i.e., positioning the cow in her stall), most of the recommendations for tie-rail and neck-rail height and forward position are based on the cow's body dimensions. Recommendations for height and forward positions are similar for tie-rails (height: 0.7–0.8 x height of the cow's rump; forward position: 14 inches [35.56 cm] outside of the stall; Anderson, 2014) and neck-rails (height: 0.83 x height of the cow's rump; forward position: 2 inches [5.08 cm] inside of the stall; Anderson, 2016), although tie-rail forward position in tie-stalls is recommended to be further from the cow compared to neck-rails in free-stalls.

Height of the manger wall and of the brisket board. The manger wall is the structure in tie-stalls that separates the bed of the stall from the manger and represents the front limit of the stall. As the front limit of the stall bed, the manger wall determines how far forward in the stall the cow is able to lie and how she is able to position herself in the stall (Tucker et al., 2006). Another function of the manger wall in tie-stalls is to prevent the bedding from the stall and the feed from the manger from mixing. The analogous structure in free-stalls, the brisket board, serves the same purpose of determining how far forward in the stall the cow can lie. However, the brisket board does not separate the stall bed from the manger. Instead, the brisket board separates the bed space from the lunge space. The recommended heights for brisket boards and manger walls differ, i.e., ≤ 4 inches (≤ 10.16 cm) for brisket boards (Anderson, 2016) and ≤ 8 inches (≤ 20.32 cm) for manger walls (Anderson, 2014).

Chain length. Chain length is a feature unique to tie-stall housing systems and is the element responsible for keeping the cow from leaving her stall at will (Anderson, 2014), thus ensuring that each animal remains within her assigned space. The basis of the current recommendation for chain length, based on observational studies, is to enable a cow to rest with her head turned back against her body, to groom herself, and to extend her head forward, all while maintaining her safety by limiting her risk of getting a leg caught in the chain (Anderson, 2014). The chain should also not interfere with the cow when she lies or when she rises (Graves et al., 2007). The resulting recommendation for chain length (tie-rail height-manger wall height) thus stipulates that the snap or tie should touch the top of the manger wall (Graves et al., 2007; Anderson, 2014; Valacta, 2014), making its length theoretically dependent upon two other stall parameters, manger wall height and tie-rail position, which are dependent upon cow size (Graves et al., 2007; Anderson, 2014; Valacta, 2014).

Stall base and bedding. Adding bedding to the stall base helps keep the cow clean and provides softness, traction, and thermal insulation for the cow (Anderson, 2016). On Canadian tie-stall dairy farms, the most common stall bases reported are rubber mats and mattresses, representing about 51% and 44% of tie-stalls, respectively, while straw is the most commonly reported bedding, utilized by around 92% of farms (Nash et al., 2016). Deep-bedded sand stalls are not typically utilized on tie-stall farms in Canada. On Canadian free-stall farms, the most prevalent stall bases reported are geotextile mattresses (56–60%), with rubber mats (8–11%), concrete (11–14%), and sand (11–12%) comprising almost the rest of the farms (Zaffino-Heyerhoff et al., 2014; Solano et al., 2015). There is less of a consensus in bedding material type, with shavings being the most commonly reported type (32–41%), followed by sawdust (24–30%), straw (17–20%), and sand (4%; Zaffino-Heyerhoff et al., 2014; Solano et al., 2015).

Electric trainers. Electric trainers are meant to train cows to step back upon defecating and urinating, so that manure and urine fall into the gutter and not on the surface of the stall. Recommendations for the position of electric trainers are based on observational studies. It is recommended to position the trainers at the chine of the cows, slightly further in front of the area where the back of the cow begins to curve when she defecates or urinates (Anderson, 2014). It is recommended for the trainer's height to be adjusted for each animal to be 2 inches (5.08 cm) above the chine during the training period and increased to 4 inches (10.16 cm) after that training period (Anderson, 2014).

3.1.2 What Do We Know About the Impact of Stall Configuration on Cow Welfare Outcome Measures?

Numerous research studies in Canada and abroad have attempted to assess the impact of stall configuration on various animal welfare outcomes (e.g., biological functioning, affective states, and naturalness): the majority have focused on health (hygiene, lameness, injuries), productivity, and behavioural responses (lying times as an indicator of comfort and preference).

When interpreting this section, it is important to note that while the current body of evidence suggests several different welfare outcomes can be improved through the modification of stall configuration and features, the relationships between individual features cannot be fully understood if these interrelated elements are evaluated separately, as one can compensate for another, and as it is their combination in the stall that yields an overall level of comfort for the cow. Further observational and experimental research is needed to build upon our current understanding.

Stall length. Longer stalls have been demonstrated to increase lying time (Tucker et al., 2004; Bouffard et al., 2017; McPherson & Vasseur, 2020a,b) and decrease injury (Kielland et al., 2009; Potterton et al., 2011; Nash et al., 2016; Bouffard et al., 2017; Jewell et al., 2019a) and lameness prevalence (Dippel et al., 2009; Rutherford et al., 2009) but are often not utilized by producers due to concerns about cleanliness (Bouffard et al., 2017). Longer stall length, or longer bed length in particular, was previously demonstrated to decrease the prevalence of injuries and lameness. Longer bed lengths are often anecdotally associated with dirtier stalls and therefore dirtier cows; however, relatively few studies have been conducted to investigate the relationship between stall or bed length and cleanliness experimentally (Ruud et al., 2011) or epidemiologically (Zurbrigg et al., 2005a; Bouffard et al., 2017). The limited research available shows that longer stalls lead to slightly dirtier cows and stalls (Zurbrigg et al., 2005a; Ruud et al., 2011; Bouffard et al., 2017), suggesting that management practices may need to be adapted when using longer stalls.

Stall width. Wider stalls are associated with longer lying times in tie-stalls (Bouffard et al., 2017) and in free-stalls (Tucker et al., 2004; Solano et al., 2016). Stalls of recommended width were associated with improved ease of movement (Plesch, 2011). A recent study conducted in tie-stalls reported that increasing stall width further beyond the current recommendation results in improved ability for cows to express natural lying postures without encroaching on the neighbouring stalls, in addition to significantly reducing the occurrence of contact with side dividers upon lying down (Boyer et al., 2020c). In tie-stalls, increasing width was associated with decreased risks for lameness (Bouffard et al., 2017), hock injuries (Nash et al., 2016), knee injuries (Nash et al., 2016), and neck injuries (Bouffard et al., 2017), although different studies published on the matter present contradicting results (Jewell et al., 2019a,b; Boyer et al., 2020a,c). In free-stalls, data tend towards the absence of a link between cubicle width and the risk for hock, knee, and neck injuries (Potterton et al., 2011; Barrientos et al., 2013; Chapinal et al., 2014; Jewell et al., 2019a), but the average stall width recorded in most of these studies falls below currently recommended dimensions. The portrait is the same for the link between lameness and stall width in free-stalls (Haskell et al., 2006; Chapinal et al., 2013, 2014; de Vries et al., 2015; Jewell et al., 2019b). Stall width has been linked in different studies with decreased cleanliness (Ruud et al., 2011; Bouffard et al., 2017), increased cleanliness (Lapointe, 2010; Ruud et al., 2011), or as having no significant impact on the cleanliness of cows (Zurbrigg et al., 2005a; Ruud et al., 2010; Plesch, 2011; van Gastelen et al., 2011; de Vries et al., 2015).

Position of the tie-rail and of the neck-rail. In most studies, it has been demonstrated that tie-rails, neck-rails, and feed-rails at mid-range heights increase the risk of neck and hock injuries (Zurbrigg et al., 2005b; Kielland et al., 2010; Potterton et al., 2011; Zaffino-Heyerhoff et al., 2014), except for a study on tie-stall barns by Bouffard et al. (2017), who reported an increase in the risk of neck injuries with when tie-rails met or exceeded the current recommendation for height. Conflicting results were also reported for the effect of neck-rail and tie-rail heights on lameness, lying behaviours, and cleanliness. For instance, increasing neck-rail height in free-stalls was reported to reduce the prevalence of lameness and had no detected effect on lying behaviours and cleanliness (Gaworski et al., 2003; Tucker et al., 2005; Solano et al., 2015). For tie-stalls, increasing tie-rail height to, or higher than, current recommendation increased the risk of lameness, reduced lying time and number of lying bouts, and increased the prevalence of clean udders (Zurbrigg et al., 2005b; Bouffard et al., 2017). These results suggest that increasing tie-rail and/or neck-rail height only increases comfort to a certain point, or that the height requirement for tie-rails in tie-stall barns needs to be different from the height requirement for neck-rails in free-stall barns. In tie-stall facilities, cows are attached to the tie-rail, which creates a different interaction between the cow and the rail than in free-stall facilities.

Results of the studies presented above indicate that increasing the forward position of tie-rails and neck-rails may decrease the incidence or prevalence of neck, hock, and knee injuries, sole lesions, digital dermatitis, and lameness, increase the number of lying bouts, and reduce cow and stall cleanliness. Only one study, by Nash et al. (2016), reported an increased probability of hock injuries with increasing tie-rail forward position. Recent data from an experimental study conducted in tie-stalls combining tie-rail height and forward position indicate that injuries to the neck appeared higher or lower on the neck depending on the position of the tie-rail, and that no matter the position of the bar, it remained a factor limiting the ability of cows to move within their stalls without hitting on the tie-rail or the side dividers (St John et al., 2020).

Height of the manger wall and of the brisket board. The impact of manger wall height on cow welfare has not been researched extensively, but manger wall height may work in conjunction with other stall components to define the space available to the cow. Only one experimental study exists looking at the impact of brisket boards in free-stall housed dairy cattle (Tucker et al., 2006), and currently only one recent experimental study has examined the impact of manger wall height. Lower, less restrictive manger walls and brisket boards have been reported to be associated with a decrease in lameness prevalence (Espejo & Endres, 2007), an increase in likelihood of dirty udders (Bouffard et al., 2017), and an increase in lying time (Tucker et al., 2006). Brisket boards have also been demonstrated to influence where larger cows lay down in the stall (Tucker et al., 2006). Reducing manger wall height has also been associated with a reduced ability to rise and lie down in cows, likely due to the fact that although longitudinal space was increased by the lower manger wall, the tie-rail position remained too restrictive for the cows to fully benefit from the increase in the space made available to them (McPherson & Vasseur, 2020b).

Chain length. Longer tie chains were associated with reduced risks of injuries to the hock and knee (Zurbrigg et al., 2005a; Nash et al., 2016; Bouffard et al., 2017), despite conflicting results between different sources (Lapointe, 2010; Jewell et al., 2019a). In the literature there are conflicting results regarding the impact of chain length on neck injuries, with longer chains (Bouffard et al., 2017) and shorter chains (Lapointe, 2010) both identified as aiding in reducing risks of injuries in different studies, while in other studies, no significant effect has been reported (Zurbrigg et al., 2005b; Jewell et al., 2019a; Boyer et al., 2020a,b). Lameness and lying time were not associated with chain length (Bouffard et al., 2017; Jewell et al., 2019b; Boyer et al., 2020a,b). Chains longer than currently recommended were reported to improve ease of movement at the stall, with shorter durations of intention movements before lying down and increased use of the stall environment associated with a chain longer than the current recommendation (Boyer et al., 2020b).

Stall base and bedding. Bedding depth appears to be the most influential material component of the stall bed, as it has the greatest ability to compensate for properties of the stall base type and/or of the bedding type, which may be detrimental to cow comfort (e.g., hard, abrasive; Villettaz-Robichaud et al., 2020). Increasing bedding depth in the stall increases lying time, and therefore cow comfort, regardless of the stall base type or bedding type (Tucker et al., 2009; Gomez & Cook, 2010; Solano et al., 2016). Hock injuries result from bedding abrasiveness (Potterton et al., 2011; Jewell et al., 2019a) and lack of compressibility (van Gastelen et al., 2011; Zaffino-Heyerhoff et al., 2014; Cook et al., 2016; Jewell et al., 2019a), thus the combination of bedding depth and stall base can play a large role in decreasing the likelihood of a cow developing hock injuries. There are no obvious bedding systems or stall bases that yield cleaner cows (Fulwider et al., 2007; Norring et al., 2008; de Vries et al., 2015; Cook et al., 2016), but bedding depth may increase cow cleanliness if the stall is managed properly (Plesch & Knierim, 2012). Increased bedding depth is also associated with reduced lameness prevalence on-farm (Chapinal et al., 2013; Ito et al., 2014; de Vries et al., 2015; Solano et al., 2015). Another key component to bedding is its quality, namely how soft and dry it is. Numerous studies suggest that cows and calves show a clear preference for dry lying surfaces and will spend much more time standing when only wet bedding is available (Fregonesi et al., 2007a; Camiloti et al., 2012; Chen et al., 2017; Schütz et al., 2019). These studies suggest that wet and soiled lying surfaces negatively impact the welfare of the animals by affecting the quantity and quality of rest (Schütz et al., 2019) and can result in poorer hygiene and affect health and production (Chen et al., 2017).

Electric trainers. The literature available regarding the impact of electric trainers in tie-stalls on cow welfare outcome measures is scarce. One epidemiological study on electric trainers reported increased levels of dirty udders and dirty hind limbs in herds utilizing electric trainers (Zurbrigg et al., 2005b), while, on the contrary, another study reported that cows were cleaner and stalls less contaminated when trainers were used (Bergsten & Pettersson, 1992). The latter study also reported that the prevalence of heel horn erosion decreased with trainers (Bergsten & Pettersson, 1992). However, a more recent study concluded that exposure to cow-trainers increased the incidence risk of clinical mastitis, ketosis, weak estrous, and culling (Hultgren, 2001). Increased levels of injuries were also reported in herds utilizing trainers compared to those without (Busato et al., 2000; Zurbrigg et al., 2005b). Improperly positioned trainers impair the ability of cows to access feed and to use the space in their stalls (Zurbrigg et al, 2005b). To our knowledge, no studies offer insight into the impact of electric trainer on pain or fear. However, there is science that clearly indicates that cattle find electric shock aversive (Pajor et al., 2003).

3.2 Spatial Allowance and Stocking Density

For every resource provided to animals, it is important to consider stocking rate (i.e., how this resource is shared among all animals that have access). For some resources, like lying stalls and feeder space, a substantial body of literature has examined the effects of changes in stocking rates; below we summarize key conclusions of two recent published reviews summarizing this literature (Krawczel & Lee, 2019; Weary, 2017).

Readers should also be aware that estimating the stocking rate can be difficult in practice. Although it may seem obvious, it is important to be clear that the resource provided is indeed functional for the animal. For example, free-stalls that are too small, in poor repair, have wet bedding, or are otherwise unsuitable must be excluded; thus calculations based, for example, on the total number of stalls in the barn, should be considered a potentially serious overestimate of stall availability per cow. This also applies to calculations for space: space must be suitable for the intended activity to be included in calculations of stocking density.

For those resources distributed in discrete cow-sized units, like free-stalls and head locks, stocking rate is typically calculated by simply dividing the number of animals by the number of units, typically multiplied by 100 to express as a percentage (for example, 120 cows sharing 100 stalls would be described as "over" stocking at 120%). When resources are distributed more continuously, like the length of the feed bunk or the circumference of the water trough, then the number of cows sharing the space can be divided by the space available (for example, 10 cows sharing an 8 m section of feed bunk would be said to be stocked at 0.8 m/cow).

Stocking at the lying stall. A consistent result across the literature is that various measures of lying behaviour, most notably lying time, are negatively affected when the availability of lying stalls is reduced (reviewed by Krawczel & Lee, 2019). For example, Winckler et al. (2015) showed that lying time was reduced by 1 h/d at 150% versus 100% stocking. These authors also reported that lying time increased by approximately 15 min/d at 75% versus 100% stocking capacity, suggesting that cows may experience some competition even when each cow is provided a stall. The slightly reduced lying times at 1 stall to 1 cow relative to understocking may be explained by cows avoiding certain stalls; for example, it is known that cows tend to avoid certain areas such as those further away from the feed alley (Gaworski et al., 2003). Understocking may also allow cows to better express social preferences (for example, for a subordinate cow to avoid lying beside a dominant cow), but this idea still requires study.

The effects on lying times persist across a range of stocking rates (Krawczel & Lee, 2019). For example, Fregonesi et al. (2007b) gradually reduced the number of stalls available to a group of cows to test the effects of even modest levels of overstocking. This gradual increase in stocking led to a gradual decline in lying, indicating that even modest overstocking may be problematic. Not surprisingly, a number of researchers have demonstrated that the effect of overstocking is greatest for socially subordinate cows (Krawczel & Lee, 2019), likely because dominant cows can simply displace subordinate cows from their stalls. This means that the effects of overstocking will be greatest on those cows least able to compete; this is likely to include lame and transition cows, including first lactation animals introduced into a pen of older cows (Proudfoot et al., 2018).

Stocking at the feed bunk. Although competition sometimes occurs at lying stalls, this is more typically observed at the feed bunk, and increased competition is consistently observed when feeding spaces per cow declines (reviewed by Krawczel & Lee, 2019). Again, the effects of this competition are greatest on more vulnerable cows (e.g., transition cows; Proudfoot at al., 2009). For this reason, current recommendations for transition dairy cows are to provide enough space to allow simultaneous feeding (≥ 76 cm/cow of feed bunk space) (DeVries, 2019).

Competitive behaviours are often observed at the feed bunk as cows attempt to access feed, especially fresh feed that cows are most motivated to consume (DeVries et al., 2004). One reason for this competition at the feed bunk is that free-stall barns are often overstocked in terms of feeding space. A series of studies has demonstrated that competition for feed increases rapidly as stocking density at the feed bunk increases (see Krawczel & Lee, 2019). For example, Huzzey et al. (2006) reported that cows were more likely to competitively displace one another from the feeder as feeding space per cow declined from 0.8, to 0.6, to 0.4, and then to 0.2 m/cow. As expected, this competition at the feeder was greatest when cows returned from milking to freshly delivered feed. At 0.8 m/cow, more that 80% of the cows in the pen were able to feed at the same time, but as the stocking increased the percentage of cows able to access the feeder at peak times declined to about 50% in the 0.4 m treatment, and about 30% in the 0.2 m treatment. Reduced space per cow resulted in reduced feeding times and increased the time cows spent standing idle around the feeding area, presumably waiting to access the feed. These changes in eating patterns, associated with reduced feeding space, have been associated with reduced production, particularly milk fat, in observational field studies of commercial herds (Deming et al., 2013; Sova et al., 2013; Woolpert et al., 2017).

As with lying stalls, good facility design and management must also be considered as these can also affect the ability of cows to access and use the feed bunk (DeVries, 2019). Some designs are particularly vulnerable to the effects of overstocking. For example, Huzzey et al. (2006) reported cows were more likely to competitively displace one another when accessing feed from a post-and-rail feed barrier versus from head locks; this is likely because cows are able to use their head as a weapon to displace their competitors from the feed.

Stocking for other resources and in different milking systems. Although this review has focused on stocking for lying and at the feeder, readers are reminded that, in addition to these obvious resources that are well researched, other under-researched resources (such as brushes; McConnachie et al., 2019) are also important to cows and should be considered separately in stocking calculations. Appropriate stocking densities in bedded pack systems also remains a gap in the current body of knowledge on this topic.

The literature reviewed here comes from barns using some type of parlour milking. Barns with automatic milking systems (AMS) will require new research. For example, milking is a powerful driver of attendance at the feeder, explaining why peak time at the feeder is normally just after milking (DeVries, 2019). In barns using parlour milking, this results in almost every cow wanting to feed at the same times of the day. Synchronicity driven by milking may be reduced in barns using AMS, but adequate feeder space is still important. A field study of AMS herds in Ontario reported a mean feeder space of 0.7 m/cow, and that reduced feed bunk space was associated with reduced lying time and reduced milk yield (Deming et al., 2013). More research on AMS systems is needed, as there is not currently a large enough body of evidence from which consistent conclusions can be drawn.

3.3 Air Quality and Temperature

3.3.1 Dairy Cows

High temperatures. The thermoneutral zone for dairy cows is the range of ambient temperatures at which an animal can maintain a constant body temperature with minimal energy expenditure (Kadzere et al., 2002). When the ambient temperature is above the thermoneutral zone, heat stress occurs because heat load, accumulated both metabolically and from the environment, is higher than the animal's ability to dissipate this heat (Bernabucci et al., 2010). Along with ambient temperature, relative humidity (RH) affects heat stress, so the temperature-humidity index (THI) is often used to assess the risk of heat stress in dairy cows (West, 2003).

A THI of 68 is typically accepted as the threshold for the onset of heat stress based on changes in dairy cow behaviour (Cook et al., 2007) or declines in milk yield (Zimbelman et al., 2009), although other studies have identified different thresholds for declines in milk production (e.g., mean THI > 60, Brügemann et al., 2012; maximum THI between 65–76, Bernabucci et al., 2014). Previous work has suggested that heat stress may best be characterized by summarizing THI over a number of days (2 d, West et al., 2003; 3 d, Bouraoui et al., 2002, Hill & Wall, 2017; 2–4 d, Spiers et al., 2004), but it is not yet clear how the measures should be best integrated to capture the net effect on the cow.

The difficulty with identifying the specific ambient conditions that lead to heat stress is that THI thresholds can vary based on cow characteristics and previous temperature acclimation (Kadzere et al., 2002). Heat tolerance can be affected by level of milk production (Ravagnolo & Misztal, 2000), breed (Pereira et al., 2014), coat length (Dikmen et al., 2008), and size (Busby & Loy, 1996). High-producing cows are the most susceptible to heat stress due to the increased energy demands of milk production (Kadzere et al., 2002).

Heat stress THI thresholds for dairy cows are higher in semiarid climates (ambient temperature ≥ 30°C at 25% RH) than hot, humid climates (ambient temperature ≥ 23°C at 75% RH) (Bohmanova et al., 2007). Additionally, cows in temperate climates have lower heat stress thresholds of approximately 18°C at 75% RH (Hammami et al., 2013). The THI thresholds may be lower in temperate climates because cattle are only able to acclimate to heat during acute heat stress events in the summer (Renaudeau et al., 2012).

In addition to environmental measures of heat stress, evaporative heat loss mechanisms in dairy cows, such as increased respiratory rate and panting (Blackshaw & Blackshaw, 1994), are outcome-based measures of heat stress. Respiratory rate is 60 breaths/min in dairy cows in more neutral conditions (19°C at 55% RH) and 89 breaths/min in heat stress conditions (29°C at 50%

RH; Spiers et al., 2004). Between a THI of 66 to 76, the respiratory rate of cows offered no form of cooling can range between 60 to 90 breaths/min, but the respiratory rate of cows offered shade can range much lower between 40 to 60 breaths/min (Kendall et al., 2007).

Physiological effects of heat stress include increased body temperature (Dikmen & Hansen, 2009), reduced milk yield (Bernabucci et al., 2014), decreased reproductive performance (e.g., lower conception rates, López-Gatius et al., 2005; decreased estrus, Sakatani et al., 2012), and increased respiratory rate (Beatty et al., 2006). Behavioural responses to heat stress, which occur before drops in productivity (Polsky & von Keyserlingk, 2017), include increased standing time with shorter lying bouts (Nordlund et al., 2019), decreased feed intake (West et al., 2003), changes in feed sorting (Miller-Cushon et al., 2019), decreased rumination (Soriani et al., 2013), seeking shade (Schütz et al., 2009), increased drinking behaviour (Cook et al., 2007; Ammer et al., 2018), and competition for cooling resources (e.g., shade, Schütz et al., 2010; proximity to the water trough, Vizzotto et al., 2015).

Methods to reduce heat stress. Evaporative cooling can be improved by wetting cows and increasing air flow (Renaudeau et al., 2012). Evaporative cooling is most effective when cows are thoroughly wetted (larger droplets are better than smaller droplets; Strickland et al., 1989) and provided with airflow (Gebremedhin & Wu, 2001), but wetting the resting area can increase the risk of mastitis (Nienaber & Hahn, 2007). Methods to reduce the negative effects of heat stress include shade, roof insulation, air cooling systems (e.g., foggers, misters, evaporative cooling pads), fans, sprinklers, conductive bedding, and water-cooled heat exchangers (e.g., waterbeds) (Fournel et al., 2017).

Shade and roof insulation. Shade reduces body temperature and respiratory rate (Kendall et al., 2007) and makes the area underneath the shade structure cooler (Kendall et al., 2007; Schütz et al., 2009). Dairy cows on pasture will spend more time underneath shade structures that block more solar radiation (Schütz et al., 2009). Lack of shade outdoors may affect the preference of dairy cows to be indoors during the day, when ambient temperatures are high, but outdoors at night (Legrand et al., 2009). Trees are effective at blocking solar radiation and reducing body temperature (Valtorta et al., 1997; Veissier et al., 2018). Barn orientation can impact solar radiation levels reaching cows, where barns with an east-west longitudinal axis allow less heat via solar radiation to reach stalls than barns with a north-south longitudinal axis (Angrecka & Herbut, 2016). Overhead insulation can reduce the temperature within a barn (Fuquay et al., 1979).

Air cooling systems, fans, and sprinklers. Air conditioning greatly reduces THI inside a barn during hot weather (Bucklin et al., 2009), but it may be cost-prohibitive (Collier et al., 2006). Misting of the area underneath a shade structure in an open dry lot reduces body temperature and respiration rate (Correa-Calderon et al., 2004). Foggers and misters do not work as well in humid environments because they add to humidity in the barn and can wet bedding and feed (Renaudeau et al., 2012). Evaporative cooling pads incorporated into ventilation systems have been reported to lower core body temperature of cows during the summer in a hot, humid climate (Smith et al., 2016).

Sprinklers at the feed bunk that spray the backs of cows lower body temperature (Chen et al., 2013, 2016), increase milk yield (Chen et al., 2016), and mitigate the usual drop in feed intake

(Chen et al., 2016) and feeding time (Chen et al., 2013) due to heat stress. A combination of shade and oscillating sprinklers fixed above the ground reduces respiratory rate more than either alone (Kendall et al., 2007). Providing fans in addition to sprinklers/misters lowers respiration rate (fans and sprinklers at the feedbunk and in the pre-milking holding pen Strickland et al., 1989; fans and sprinklers at the feedbunk, Turner et al., 1992) and rectal temperature (Turner et al., 1992), and increases milk production (Strickland et al., 1989; Turner et al., 1992; fans and misters in the pre-milking holding pen, Avendaño-Reyes et al., 2012). Dairy cows provided with fans and sprinklers also have greater feed intake (Strickland et al., 1989; fans and sprinklers at the middle of individual stalls, Karimi et al., 2015) and increased lying time (fans and sprinklers in the feeding area, Calegari et al., 2014; Karimi et al., 2015).

Conductive bedding and water-cooled heat exchangers. Bedding materials with high thermal conductance, which is the ability to conduct heat, help heat loss; sand has a higher heat flux, which is a measure of thermal energy flow rate, than straw, mattresses filled with water granules (Radoń et al., 2014), and dried manure (Ortiz et al., 2015). Providing cows access to a mechanically cooled waterbed reduced rectal temperature and respiratory rate and mitigated the decline in milk yield due to heat stress; however, this effect was only identified when the waterbed was installed on top of a sheet of plywood covering insulation, not if the waterbed was placed on top of concrete (as recommended by manufacturer) (Perano et al., 2015).

Low temperatures. Dairy cows tolerate colder temperatures better than warmer temperatures because of their high heat production (Nardone et al., 2006); estimates of lower critical values being as low as -16 to -37°C (Kadzere et al., 2002). Identifying temperature thresholds at which cold stress begins has received much less attention in the literature compared to thresholds for heat stress; the combination of low temperature and low temperature duration that causes cold stress has yet to be extensively studied. When the ambient temperature falls below -6.7°C (duration of low temperature not provided), milk production will start to decline (Angrecka & Herbut, 2015) and cold stressed dairy cows have increased feed intake (Brouček et al., 1991).

Air quality and ventilation. Air quality in a barn is influenced by ventilation and air flow (Ngwabie et al., 2009). Proper ventilation of dairy barns, either mechanical or natural, removes buildup of gases and air particles that are harmful to both human and animal health and removes heat and moisture (Teye & Hautala, 2007). Air pollutants cause respiratory disease (Mitloehner & Calvo, 2008), and lower ventilation rates in calf barns can increase airborne bacterial count in alleys (Lago et al., 2006).

Ventilation is impacted by barn design and size, type of ventilation system, stocking density of animals, weather conditions, and manure management system (Herbut & Angrecka, 2014), and can be difficult to assess; especially natural ventilation because it is irregular (Teye & Hautala, 2007) and more influenced by local weather than mechanical ventilation (Joo et al., 2015). The amount of natural ventilation in a barn depends on sidewall height, roof pitch, ridge vent opening, roof width, and barn orientation (Bewley et al., 2017). Different airspeeds exist at different locations in a barn (Fiedler et al., 2013). In winter, closing ridges and side walls to prevent cold can result in ventilation rates that are too low (Teye et al., 2008).

Ammonia is a harmful gas, with recommended concentration limits of 20 ppm in dairy buildings (CIGR, 1984) or 25 ppm for human health (based on a 8 h day / 40 h work week) (CCOHS, 2019). Ammonia emissions are greater when the air temperature is warmer (Ngwabie et al., 2014), during manure removal, and when cow activity is heightened, such as for milking (Ngwabie et al., 2009). Average ammonia readings in dairy barns are usually below these recommended limits. In naturally ventilated, loose housing dairy systems, mean monthly ammonia concentrations ranged between 3.2–7.3 ppm in a barn in Sweden (Ngwabie et al., 2009), 48 h mean ammonia concentrations ranged between 7–20 ppm in 6 barns in Alberta (Clark & McQuitty, 1987), and, in Ontario, the average ammonia concentrations in the spring and fall were 3.8 ppm and 2.2 ppm, respectively (Ngwabie et al., 2014). However, researchers have also reported ammonia concentrations that reached close to, or surpassed, recommended concentrations limits (e.g., a maximum reading in one study was 18 ppm [Ngwabie et al., 2009], and in another the hourly mean concentration reached 54 ppm [Clark & McQuitty, 1987]).

3.3.2 Dairy Calves

The thermoneutral zone for young calves (from birth to 3 weeks of age) is 15–25°C. The lower critical temperature can drop to -5 to -10°C for calves older than 3 weeks of age (NRC, 2001). Heat stressed, pre-weaned calves have decreased appetite, lower daily gains, and lower weaning weights (Broucek et al., 2009; López et al., 2018). They will also spend more time standing, feeding, and drinking, and less time ruminating and self-grooming (Tripon et al., 2014).

Care should be paid to temperature conditions inside calf hutches, which can far exceed ambient temperatures on hot days (Carter et al., 2014). Reflective insulation decreases the interior temperature of a calf hutch at high ambient temperatures and increases the interior temperature at low ambient temperatures (Carter et al., 2014). Supplemental shade over calf hutches has also been demonstrated to reduce interior temperature in calf hutches, thereby decreasing heat stress in calves (Coleman et al., 1996; Spain & Spiers, 1996). Elevating the back of hutches with a concrete block (7.9 inches in height) was demonstrated to reduce interior temperatures, carbon dioxide levels, and decrease heat stress in calves (Moore et al., 2012).

Cold stress increases calf mortality (Svensson et al., 2006), decreases absorption of immunoglobulins from colostrum (Olson et al., 1980), and increases respiratory disorders and feed intake (Nonnecke et al., 2009). Providing dry, deep bedding (allowing calves to nest in the bedding; Lago et al., 2006), heat lamps (Borderas et al., 2009), insulating coats (Rawson et al., 1989), and extra feed (NRC, 2001) can help calves cope with cold stress.

3.4 Exercise and Outdoor Access

Lack of outdoor access (i.e., access to an outdoor bedded pack, paddock, and/or to pasture), sometimes referred to as “zero-grazing,” has been identified as a welfare concern for commercial dairy production (Rushen et al., 2008). This is due to the fact that many studies reported higher rates of numerous health conditions (e.g., lameness, mastitis, metritis) among cows housed completely indoors when compared to farms that offer their cows partial or complete access to pasture (Wells et al., 1999; Washburn et al., 2002; Somers et al., 2003); though outdoor access has been shown to not universally result in positive welfare outcomes (Loberg et al., 2004; Chapinal et al., 2010).

Dairy cows are physiologically and behaviourally well adapted to pasture. While pasture conditions can vary widely depending on climate, management, use, stocking density, and other factors, optimal pasture conditions offer comfortable lying surfaces, a cushioned surface with good traction for walking, and room to walk and graze (Knaus, 2016). Outdoor access can also be provided in the form of a dry-lot/paddock or bedded pack; while these environments do not offer the opportunity to graze, they offer many of the other advantages of pasture. Researchers have also previously demonstrated that cows are motivated to access pasture (Charlton et al., 2013; Legrand et al., 2009). Importantly, access to the outdoors presents important challenges and opportunities for dairy cattle welfare. Evidence from large pasture-based dairies suggests that walking distances and waiting times to be milked are typically much higher than indoor systems, and this comes at the expense of lying time and grazing (Beggs et al., 2015, 2018a,b). Other challenges relate to cow hygiene and health (Loberg et al., 2004; Chapinal et al., 2010). One important opportunity outdoor access presents relates to the amount of exercise dairy cattle get, which has been linked to improved health and welfare outcomes (Krohn et al., 1992; Gustafson, 1993; Loberg et al., 2004; Davidson & Beede, 2009; Popescu et al., 2013; Black et al., 2017).

This section will review the scientific literature on the definition of exercise and the effects of outdoor access on dairy cattle health and welfare, with a specific focus on the benefits of exercise.[1]

3.4.1 Defining Exercise

There are substantial differences in what scientists consider within studies to be the provision of exercise to dairy cattle. Early studies explored associations between cows' locomotion activity and level of physical fitness, measured through aspects of her health and physiology (e.g., heart rate, blood plasma lactate concentrations). These studies ensured individual exercise through forced movement in controlled environments, such as a circular run (e.g., Anderson et al., 1979), on a treadmill (e.g., Davidson & Beede, 2009), or with a person walking each cow (Black et al., 2017). These studies have considered speed, distance, and parity when accounting for the effect of exercise on the cow, finding that moderate walking speeds of around 3.25 km/h (Blake et al., 1982; Davidson & Beede, 2009) for a minimum distance of 4 km (Davidson & Beede, 2009) up to 8 km/d (Blake et al., 1982) led to a significant improvement in physical fitness (greater distances walked, lower heart rate and plasma lactate after exercise). Moreover, pregnant cows reportedly have an even greater response to increased exercise provision (Davidson & Beede, 2009), indicating that this is a period in the cow's life where increasing the opportunity to move freely may have the most benefit to her physical fitness. Age has also been demonstrated to affect the

[1] This chapter has been drafted on Shepley's PhD Thesis (2020; literature review chapter, https://escholarship.mcgill.ca/concern/theses/kk91fr26r) from which two manuscripts have been submitted to peer-reviewed journals. The first one is: Shepley, E., J. Lensink, and E. Vasseur. 2020. A Cow in Motion: A review of the impact of housing systems on movement opportunity of dairy cows and implications on locomotor activity. Appl. Anim. Behav. Sci. 230:105026. The second is: Shepley E. (2020) A cow in motion: The impact of housing systems on movement opportunity of dairy cows and the implications on locomotor activity, behaviour, and welfare. PhD Thesis. Ste-Anne-de-Bellevue, QC: McGill University, Faculty of Agricultural and Environmental Sciences, Department of Animal Science.

exercise requirements of the animal to reach a more fit state, with older cows requiring more exercise (Anderson et al., 1979).

It is important to note, however, that these "forced exercise" studies may not offer a realistic understanding of the benefits of increased locomotor activity in a commercial dairy setting. The cow's environment may provide her with the opportunity to move, hindering or promoting increased locomotor activity through a range of movements that the cow can choose to perform (such as express opportunities to explore, socialize etc.) and based on the type of housing she is exposed to, the quality and characteristics that comprises her indoor housing, and the addition of outdoor access. Studies have investigated the impact of offering outdoor access as a means to offer exercise opportunity in dairy cattle (e.g., Krohn et al., 1992; Gustafson, 1993; Loberg et al., 2004; Popescu et al., 2013). A key takeaway from these studies is that locomotor activity increases among cows that are offered access to the outdoors, and that offering more space outdoors undoubtedly results in greater locomotor activity. A comparison of the total number of steps taken in different indoor housing systems, with or without outdoor access, provides insight on the potential level of locomotor activity that can be expected across common housing systems. For example, tie-stall systems yield the lowest step activity (748 steps/d; Shepley et al., 2019b) of all housing systems. This is considerably lower than in free-stall (2,353 steps/d, range 1,120–4,918; Platz et al., 2008; Brzozowska et al., 2014; Black & Krawczel, 2016; Shepley et al., 2019a), loose housing that provides outdoor access (1,989 steps/d, free-stall with pasture access, Eckelkamp et al., 2014; 2,374 steps/d, bedded-pack with pasture access, Borchers et al., 2017), and pasture (3,390 steps/d, 2,715–4,064; Dohme-Meier et al., 2014; Black & Krawczel, 2016). These quantitative values confirm that systems offering either more incentive to move (e.g., grazing on pasture, express oestrus behaviour or social activities) or more space to allow for movement can positively influence the level of locomotor activity performed by the cow.

3.4.2 Effects of Outdoor Access and Exercise on Cow Health and Welfare

Few studies have been focused specifically on assessing the impact of increased movement (i.e., cow's locomotion activity) on dairy cattle health and welfare. A somewhat larger body of evidence compares health and welfare outcomes between cows with and without access to the outdoors, which can include everything from access to an outdoor bedded pack or paddock to access to pasture. While these studies offer insight into the potential impacts of outdoor access, attributing the impact specifically to increased movement/exercise (as opposed to the additional and likely cumulative benefits of softer lying surface, better traction, reduced pathogen load) is difficult as these relationships are complex and factors studied are often confounded. The reported impacts of outdoor access in these studies should, therefore, be interpreted carefully, as there are a number of important differences between indoor and outdoor housing systems, with outdoor access offering more than just increased opportunity for movement.

Lameness. Providing outdoor access to dairy cows has been associated with a decreased prevalence of lameness (Regula et al., 2004; Bielfeldt et al., 2005; Olmos et al., 2009; Popescu et al., 2013; de Vries et al., 2015). Popescu et al. (2013) reported a higher mean percentage of lame cows in tie-stall housing without outdoor access when compared to those that received an average of 10.7 h/d for 182 d/y on pasture (22.2% versus 15.1%, respectively). Similar studies report a lower overall lameness prevalence by 3.5–5.0% in tie-stall cows with regular outdoor access and

5.5–8.0% in loose housed cows with regular outdoor access, when compared to cows housed solely in tie-stalls (Regula et al., 2004; Bielfeldt et al., 2005).

An improvement in gait among loose-housed cows provided with access to pasture has been demonstrated to occur in as little as 4 weeks (Hernandez-Mendo et al., 2007). Hernandez-Mendo et al. (2007) reported that gait significantly improved for cows kept on pasture, resulting in a shift in average gait score from "moderately lame" to "sound," while gait for cows kept solely in free-stall housing tended to either remain the same or worsen in this same span of time. Hernandez-Mendo et al. (2007) suggested these improvements could be caused by increased general exercise by the cows while on pasture but concluded that there is insufficient research in this area to be certain. They further hypothesized that the improvements could have been the result of changes in joint stiffness due to the improved walking/lying surface associated with pasture, compared to the more slippery concrete floors seen indoors that have been demonstrated to affect gait (van der Tol et al., 2005) and joint stiffness (Philips & Morris, 2001).

Hoof health. A number of studies have demonstrated that access to pasture improves hoof health in lactating dairy cattle (loose housing, Smits et al., 1992, Somers et al., 2003, Chapinal et al., 2010; tie-stall housing, Gustafson, 1993). Similar to lameness, hoof health benefits may be better associated with more comfortable footing on pasture rather than the increased ability to move around on pasture. Non-infectious hoof health issues were reported to be 11% lower for cows with access to pasture than for those kept indoors in a free-stall (Chapinal et al., 2010). However, outdoor access does not always result in benefits and may be dependent upon factors of the environment itself, such as cleanliness. Loberg et al. (2004) reported that infectious hoof issues, such as digital dermatitis, were reported to be 4 times more likely to occur in tie-stall cows provided more access to an outdoor exercise paddock than their indoor counterparts. Differences between the reported studies are likely due to the wide range of factors in indoor and outdoor housing systems that could impact hoof health. However, they suggest that the overall management and cleanliness of the outdoor environment is a key to realizing positive outcomes. With respect to exercise, increased movement is associated with increased blood flow to the feet and legs, which improves nutrient and oxygen transport to the horn-producing area and aids in maintaining overall hoof health (Bielfeldt et al., 2005, tie-stall and loose housing). Additionally, increasing movement opportunity by providing access to an outdoor paddock may benefit net claw growth (Loberg et al., 2004, tie-stall housing), thereby decreasing discomfort and foot issues from overgrown claws.

Injuries. Previous studies in which cows were provided with outdoor access report a reduction in injuries, particularly of the hock. Popescu et al. (2013) reported a 13.4% reduction in cows with outdoor access compared to those that were permanently tied in stalls with mattresses and limited straw or sawdust bedding. Other studies have reported that the prevalence and severity of hock lesions in cows kept in tie-stalls on mattresses can be reduced by daily exercise of a constant duration (Gustafson, 1993; average score of 3.7 in non-exercised versus 1.9 in exercised cows; where 0, no lesions observed; 1, bare pale areas; 2, bare red areas; 3, occurrence of serum or/and sore scabs; 4, open infected wounds) or by outdoor exercise for a minimum 50 hours in a four-week period (Keil et al., 2006), though the extent to which biologically meaningful reductions can be achieved on farms are dependent on a variety of farm- and cow-specific changes. Further research is needed to better understand the true effects of outdoor access alone.

Reproduction. Providing less restrictive housing environments has been demonstrated to improve physiological outcomes (e.g., uterine involution, Lamb et al., 1979; dystocia, Popescu et al., 2013) associated with pain and increased risk of disease and culling. Increased movement as a result of outdoor access for tie-stall cows has also been demonstrated to reduce the number of treatments for health-related issues post-calving, especially in the first 2 weeks of the new lactation (Gustafson, 1993).

Udder health. Cows provided outdoor access have been reported to have lower instances of clinical mastitis than cows permanently housed in tie-stalls (Popescu et al., 2013) and free-stalls (Washburn et al., 2002). When targeted during the dry period, loose-housed cows provided with as little as 2 weeks on pasture reduced the odds of clinical mastitis occurring in the first 30 days of the subsequent lactation (Green et al., 2010). Connections between outdoor access and rates of mastitis must be considered with caution as mastitis is associated with a variety of cow, environment, and pathogen-specific risk factors (Jamali et al., 2018).

Lying behaviour. In cross-farm studies, dairy cattle spend 8.5 to 9.5 h/d lying down in bedded packs (Endres & Barberg, 2007) and pasture (Sepúlveda-Varas et al., 2014; Beggs et al., 2018b). Lying bouts, however, have been reported to be higher on pasture than in free-stalls (15.3 bouts/d versus 12.2 bouts/d; Hernandez-Mendo et al., 2007). Fewer lying bouts have been associated with a lower ease of standing and lying down movements in more restrictive environments (Haley et al., 2000). The provision of outdoor access to tie-stall cows for 1 h/d in a study by Gustafson and Lund-Magnussen (1995) nearly halved the amount of time it took the cow to rise compared to cows that remained tethered throughout the study, even though stall conditions in both cases were the same. This same effect can be found on the time it takes the cow to lie down, with considerable differences reported between pasture (19 s), a bedded-pack (59 s), tie-stall cows with 1 h/d of outdoor access (118 s), and tie-stall only cows (123 s). Environments that restrict movement (through housing type [i.e., tie-stall] or improper/insufficient stall design) may lead to the deterioration of the cow's physical condition (Krohn et al., 1992), particularly with regard to joint health (Gustafson & Lund-Magnussen, 1995). Furthermore, environments that affect lying down and rising ability have been correlated with incidence of lameness and injury (Zambelis et al., 2019), which can negatively affect locomotor ability in the cow. Thus, the benefits of housing that offers greater movement opportunity are two-fold: they increase the odds of improving overall health and condition and also provide a comfortable environment in which the cow can move with increased ease. These benefits can be realized through a number of different housing strategies. To be successful, strategies involving access to the outdoors must ensure the outdoor environment is well managed to ensure dairy cattle must not walk and/or stand for lengthy periods (factors that may negatively affect welfare; Beggs et al., 2015; 2018a,b) that counteract the potential benefits listed above.

3.5 References

Ammer S., Lambertz C., von Soosten D., Zimmer K., Meyer U., Dänicke S. & Gauly M. (2018) Impact of diet composition and temperature–humidity index on water and dry matter intake of high-yielding dairy cows. *Journal of Animal Physiology and Animal Nutrition* 102(1):103–113.

Anderson M.J., Lamb R.C. & Walters J.L. (1979) Effects of prepartum exercise on feed intake and milk production of multiparous cows. *Journal of Dairy Science* 62:1420–1423.

Anderson N.G. (2014) *Confort des vaches - Dimensions des stalles de stabulation entravée*. Guelph ON: Ontario Ministry of Agriculture, Food and Rural Affairs.

Anderson N.G. (2016) *Dairy Cow Comfort - Free-Stall Dimensions*. Guelph ON: Ontario Ministry of Agriculture, Food and Rural Affairs.

Angrecka S. & Herbut P. (2015) Conditions for cold stress development in dairy cattle kept in free stall barns during severe frosts. *Czech Journal of Animal Science* 60(2):81–87.

Angrecka S. & Herbut P. (2016) Impact of barn orientation on insolation and temperature of stalls surface. *Annals of Animal Science* 16(3):887–896.

Avendaño-Reyes L., Hernández-Rivera J.A., Álvarez-Valenzuela F.D., Macías-Cruz U., Díaz-Molina R., Correa-Calderón A., Robinson P.H. & Fadel J.G. (2012) Physiological and productive responses of multiparous lactating Holstein cows exposed to short-term cooling during severe summer conditions in an arid region of Mexico. *International Journal of Biometeorology* 56(6):993–999.

Barrientos A.K., Chapinal N., Weary D.M., Galo E. & von Keyserlingk M.A.G. (2013) Herd-level risk factors for hock injuries in freestall-housed dairy cows in the northeastern United States and California. *Journal of Dairy Science* 96:3758–3765.

Beatty D.T., Barnes A., Taylor E., Pethick D., McCarthy M. & Maloney S.K. (2006) Physiological responses of *Bos taurus* and *Bos indicus* cattle to prolonged, continuous heat and humidity. *Journal of Animal Science* 84(4):972–985.

Beggs D.S., Jongman E.C., Hemsworth P.E. & Fisher A.D. (2015) A survey of Australian dairy farmers to investigate animal welfare risks associated with increasing scale of production. *Journal of Dairy Science* 98:5330-5338.

Beggs D.S., Jongman E.C., Hemsworth P.E. & Fisher A.D. (2018a) Short communication: Milking order consistency of dairy cows in large Australian herds. *Journal of Dairy Science* 101:603–608.

Beggs D.S., Jongman E.C., Hemsworth P.E. & Fisher A.D. (2018b) Implications of prolonged milking time on time budgets and lying behavior of cows in large pasture-based dairy herds. *Journal of Dairy Science* 101:10391–10397.

Bergsten C. & Pettersson B. (1992) The cleanliness of cows tied in stalls and the health of their hooves as influenced by the use of electric trainers. *Preventive Veterinary Medicine* 13(4):229–238.

Bernabucci U., Lacetera N., Baumgard L.H., Rhoads R.P., Ronchi B. & Nardone A. (2010) Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animals* 4(7):1167–1183.

Bernabucci U., Biffani S., Buggiotti L., Vitali A., Lacetera N. & Nardone A. (2014) The effects of heat stress in Italian Holstein dairy cattle. *Journal of Dairy Science* 97(1):471–486.

Bewley J.M., Robertson L.M. & Eckelkamp E.A. (2017) A 100-year review: Lactating dairy cattle housing management. *Journal of Dairy Science* 100(12):10418-10431.

Bielfeldt J.C., Badertscher R., Tölle K.-H. & Krieter J. (2005) Risk factors influencing lameness and claw disorders in dairy cows. *Livestock Production Science* 95:265–271.

Black R.A. & Krawczel P.D. (2016) A case study of behaviour and performance of confined or pastured cows during the dry period. *Animals* 6:41.

Black R.A., van Amstel S.R. & Krawczel P.D. (2017) Effect of prepartum exercise, pasture turnout, or total confinement on hoof health. *Journal of Dairy Science* 100:8338–8346.

Blackshaw J.K. & Blackshaw A.W. (1994) Heat stress in cattle and the effect of shade on production and behaviour: A review. *Australian Journal of Experimental Agriculture* 34(2):285–295.

Blake J.T., Olsen J.D., Walters J.L. & Lamb R.C. (1982) Attaining and measuring physical fitness in dairy cattle. *Journal of Dairy Science* 65:1544–1555.

Bohmanova J., Misztal I. & Cole J.B. (2007) Temperature–humidity indices as indicators of milk production losses due to heat stress. *Journal of Dairy Science* 90(4):1947–1956.

Borchers M.R., Chang Y.M., Proudfoot K.L., Wadsworth B.A., Stone A.E. & Bewley J.M. (2017) Machine-learning-based calving prediction from activity, lying, and ruminating behaviours in dairy cattle. *Journal of Dairy Science* 100:5664–5674.

Borderas F.T., de Passillé A.M.B. & Rushen J. (2009) Temperature preferences and feed level of the newborn dairy calf. *Applied Animal Behaviour Science* 120(1–2):56–61.

Bouffard V., de Passillé A.M., Rushen J., Vasseur E., Nash C.G.R., Haley D.B. & Pellerin D. (2017) Effect of following recommendations for tiestall configuration on neck and leg lesions, lameness, cleanliness, and lying time in dairy cows. *Journal of Dairy Science* 100:2935–2943. doi:10.3168/jds.2016-11842.

Bouraoui R., Lahmar M., Majdoub A., Djemali M. & Belyea R. (2002) The relationship of temperature-humidity index with milk production of dairy cows in a Mediterranean climate. *Animal Research* 51(6):479–491.

Boyer V. & Vasseur E. (2020a, *in press*) Graduate student literature review: The impact of chain length and stall width on common outcome measures of dairy cow welfare in stall-based housing systems. *Journal of Dairy Science* JDS.2020-19279.R2.

Boyer V., de Passillé A.M., Adam S. & Vasseur E. (2020b, *in press*). Making tie-stalls more comfortable: II. Increasing chain length to improve the ease of movement of dairy cows. *Journal of Dairy Science* JDS.2019-17666.R3.

Boyer V., Edwards E., Guiso M.F., Adam S., Krawczel P., de Passillé A.M. & Vasseur E. (2020c, *in press*). Making tie-stalls more comfortable: III. Providing additional lateral space to improve the resting capacity and the comfort of dairy cows. *Journal of Dairy Science* JDS.2019-17667.R3.

Brouček J., Letkovičová M. & Kovalčuj K. (1991) Estimation of cold stress effect on dairy cows. *International Journal of Biometeorology* 35(1):29–32.

Broucek J., Kisac P. & Uhrincat M. (2009) Effect of hot temperatures on the hematological parameters, health and performance of calves. *International Journal of Biometeorology* 53(2):201–208.

Brügemann K., Gernand E., König von Borstel U. & König S. (2012) Defining and evaluating heat stress thresholds in different dairy cow production systems. *Archives Animal Breeding* 55(1):13–24.

Brzozowska A., Łukaszewicza M., Sender G., Kolasińska D. & Oprządek J. (2014) Locomotor activity of dairy cows in relation to season and lactation. *Applied Animal Behaviour Science* 156: 6–11.

Bucklin R.A., Bray D.R., Martin J.G., Carlos L. & Carvalho V. (2009) Environmental temperatures in Florida dairy housing. *Applied Engineering in Agriculture* 25(5):727–735.

Busato A., Trachsel P. & Blum J.W. (2000) Frequency of traumatic cow injuries in relation to housing systems in Swiss organic dairy herds. *Journal of Veterinary Medicine Series A* 47:221–229. doi:10.1046/j.1439-0442.2000.00283.x.

Busby D. & Loy D. (1996) Heat stress in feedlot cattle: Producer survey results. Ames IA: Iowa State University.

Calegari F., Calamari L. & Frazzi E. (2014) Fan cooling of the resting area in a free stall dairy barn. *International Journal of Biometeorology* 58(6):1225–1236.

Camiloti T.V., Fregonesi J.A., von Keyserlingk M.A.G. & Weary D.M. (2012) Short communication: Effects of bedding quality on the lying behavior of dairy calves. *Journal of Dairy Science* 95:3380–3383.

Canadian Dairy Information Centre (CDIC) (2019) *Dairy Barns by Type in Canada*. Available at: https://www.dairyinfo.gc.ca/resources/prod/dairy/pdf/barn_types_e.pdf.

Carter B.H., Friend T.H., Garey S.M., Sawyer J.A., Alexander M.B. & Tomazewski M.A. (2014) Efficacy of reflective insulation in reducing heat stress on dairy calves housed in polyethylene calf hutches. *International Journal of Biometeorology* 58(1):51–59.

CCOHS (2019) *Ammonia*. Available at: https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/ammonia.html. Accessed November 13, 2019.

Ceballos A., Sanderson D., Rushen J. & Weary D.M. (2004) Improving stall design: Use of 3-D kinematics to measure space use by dairy cows when lying down. *Journal of Dairy Science* 87:2042–2050.

Chapinal N., Barrientos A.K., von Keyserlingk M.A.G., Galo E. & Weary D.M. (2013) Herd-level risk factors for lameness in freestall farms in the northeastern United States and California. *Journal of Dairy Science* 96:318–328. doi:10.3168/jds.2012-5940.

Chapinal N., Liang Y., Weary D.M., Wang Y. & von Keyserlingk M.A.G. (2014) Risk factors for lameness and hock injuries in Holstein herds in China. *Journal of Dairy Science* 97:4309–4316. doi:10.3168/jds.2014-8089.

Chapinal N., Goldhawk C., de Passillé A.M., von Keyserlingk M.A.G., Weary D.M. & Rushen J. (2010) Overnight access to pasture does not reduce milk production or feed intake in dairy cattle. *Livestock Science* 129:104–110.

Charlton G.L., Rutter S.M., East M. & Sinclair L.A. (2013) The motivation of dairy cows for access to pasture. *Journal of Dairy Science* 96:4387–4396.

Chen J.M., Schütz K.E. & Tucker C.B. (2013) Dairy cows use and prefer feed bunks fitted with sprinklers. *Journal of Dairy Science* 96(8):5035–5045.

Chen J.M., Schütz K.E. & Tucker C.B. (2016) Cooling cows efficiently with water spray: Behavioral, physiological, and production responses to sprinklers at the feed bunk. *Journal of Dairy Science* 99(6):4607–4618.

Chen J.M., Stull C.L., Ledgerwood D.N. & Tucket C.B. (2017) Muddy conditions reduce hygiene and lying time in dairy cattle and increased time spent on concrete. *Journal of Dairy Science* 100:2090–2103.

CIGR Working Group (1984) *Climatization of Animal Houses*. Aberdeen, Scotland: CIGR.

Clark P.C. & McQuitty J.B. (1987) Air quality in six Alberta commercial free-stall dairy barns. *Canadian Agricultural Engineering* 29(1):77–80.

Coleman, D.A., Moss B.R. & McCaskey T.A. (1996) Supplemental shade for dairy calves reared in commercial calf hutches in a southern climate. *Journal of Dairy Science* 79:2038–2043.

Collier R.J., Dahl G.E. & VanBaale M.J. (2006) Major advances with environmental effects on dairy cattle. *Journal of Dairy Science* 89(4):1244–1253.

Cook N.B., Mentink R.L., Bennett T.B. & Burgi K. (2007) The effect of heat stress and lameness on time budgets of lactating dairy cows. *Journal of Dairy Science* 90(4):1674–1682.

Cook N.B., Hess J.P., Foy M.R., Bennett T.B. & Brotzman R.L. (2016) Management characteristics, lameness, and body injuries of dairy cattle housed in high-performance dairy herds in Wisconsin. *Journal of Dairy Science* 99:5879–5891. doi:10.3168/jds.2016-10956.

Correa-Calderon A., Armstrong D., Ray D., DeNise S., Enns M. & Howison C. (2004) Thermoregulatory responses of Holstein and Brown Swiss heat-stressed dairy cows to two different cooling systems. *International Journal of Biometeorology* 48(3):142–148.

Davidson J.A. & Beede D.K. (2009) Exercise training of late-pregnant and nonpregnant dairy cows affects physical fitness and acid-base homeostasis. *Journal of Dairy Science* 92:548–562.

de Vries M., Bokkers E.A.M., van Reenen C.G., Engel B., van Schaik G., Dijstra T. & de Boer I.J.M. (2015) Housing and management factors associated with indicators of dairy cattle welfare. *Preventive Veterinary Medicine* 118:80–92.

Deming J.A., Bergeron R., Leslie K.E. & DeVries T.J. (2013) Associations of housing, management, milking activity, and standing and lying behavior of dairy cows milked in automatic systems. *Journal of Dairy Science* 96:344–351.

DeVries T.J. (2019) Feeding behavior, feed space, and bunk design and management for adult dairy cattle. *Veterinary Clinics of North America: Food Animal Practice* 35:61–76.

DeVries T.J., von Keyserlingk M.A.G. & Weary D.M. (2004) Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. *Journal of Dairy Science* 87:1432–1438.

Dikmen S., Alava E., Pontes E., Fear J.M., Dikmen B.Y., Olson T.A. & Hansen P.J. (2008) Differences in thermoregulatory ability between slick-haired and wild-type lactating Holstein cows in response to acute heat stress. *Journal of Dairy Science* 91(9):3395–3402.

Dikmen S. & Hansen P.J. (2009) Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? *Journal of Dairy Science* 92(1):109–116.

Dippel S., Dolezal M., Brenninkmeyer C., Brinkmann J., March S., Knierim U. & Winckler C. (2009) Risk factors for lameness in freestall-housed dairy cows across two breeds, farming systems, and countries. *Journal of Dairy Science* 92:5476–5486. doi:10.3168/jds.2009-2288.

Dohme-Meier F., Kaufmann L.D., Görs S., Junghans P., Metges C.C., van Dorland H.A., Bruckmaier R.M. & Münger A. (2014) Comparison of energy expenditure, eating pattern and physical activity of grazing and zero-grazing dairy cows at different time points during lactation. *Livestock Science* 162:86–96.

Eckelkamp E.A., Gravatte C.N., Coombs C.O. & Brewley J.M. (2014) Case study: Characterization of lying behavior in dairy cows transitioning from a freestall barn with pasture access to a compost bedded pack barn without pasture access. *Professional Animal Scientist* 30(1):109–113.

Endres M.I. & Barberg A.E. (2007) Behavior of dairy cows in an alternative bedded-pack housing system. *Journal of Dairy Science* 90:4192–4200.

Espejo L.A. & Endres M.I. (2007) Herd-level risk factors for lameness in high-producing Holstein cows housed in freestall barns. *Journal of Dairy Science* 90:306–314. doi:10.3168/jds.S0022-0302(07)72631-0.

Fiedler M., Berg W., Ammon C., Loebsin C., Sanftleben P., Samer M., von Bobrutzki K., Kiwan A. & Saha C.K. (2013) Air velocity measurements using ultrasonic anemometers in the animal zone of a naturally ventilated dairy barn. *Biosystems Engineering* 116(3):276–285.

Fournel S., Ouellet V. & Charbonneau É. (2017) Practices for alleviating heat stress of dairy cows in humid continental climates: A literature review. *Animals* 7(5):37.

Fregonesi J.A., Veira D.M, von Keyserlingk M.A.G. & Weary D.M. (2007a) Effects of bedding quality on lying behaviour of dairy cows. *Journal of Dairy Science* 90:5468–5472.

Fregonesi J.A., Tucker C.B. & Weary D.M. (2007b) Overstocking reduces lying time in dairy cows. *Journal of Dairy Science* 90:3349–3354.

Fulwider W.K., Grandin T., Garrick D.J., Engle T.E., Lamm W.D., Dalsted N.L. & Rollin B.E. (2007) Influence of free-stall base on tarsal joint lesions and hygiene in dairy cows. *Journal of Dairy Science* 90:3559–3566. doi:10.3168/jds.2006-793.

Fuquay J.W., Zook A.B., Daniel J.W., Brown W.H. & Poe W.E. (1979) Modifications in freestall housing for dairy cows during the summer. *Journal of Dairy Science* 62(4):577–583.

Gaworski M.A., Tucker C.B. & Weary D.M. (2003) Effects of two free-stall designs on dairy cattle behavior. *Fifth International Dairy Housing Conference: Conference Proceedings, January 29–31, 2003, Forth Worth, Texas.* St. Joseph MI: American Society of Agricultural Engineers, pp. 139–146.

Gebremedhin K.G. & Wu B. (2001) A model of evaporative cooling of wet skin surface and fur layer. *Journal of Thermal Biology* 26(6):537–545.

Gomez A. & Cook N.B. (2010) Time budgets of lactating dairy cattle in commercial freestall herds. *Journal of Dairy Science* 93:5772–5781. doi:10.3168/jds.2010-3436.

Graves R.E., McFarland D.F., Tyson J.T. & Wilson T.H. (2007) *Cow Tie Stall and Details*. PA: Penn State University Agricultural and Biological Engineering Cooperative Extension.

Green M.J., Medley G.F., Bradley A.J. & Browne W.J. (2010) Management interventions in dairy herds: Exploring within herd uncertainty using an integrated Bayesian model. *Veterinary Research* 41:22–31.

Gustafson G.M. (1993) Effects of daily exercise on the health of tied dairy cows. *Preventive Veterinary Medicine* 17:209–223.

Gustafson G.M. & Lund-Magnussen E. (1995) Effect of dairy exercise on the getting up and lying down behaviour of tied dairy cows. *Preventive Veterinary Medicine* 25:27–36.

Haley D.B., Rushen J. & de Passillé A.M. (2000) Behavioural indicators of cow comfort: Activity and resting behaviour of dairy cows in two types of housing. *Canadian Journal of Animal Science* 80:257–263.

Hammami H., Bormann J., M'hamdi N., Montaldo H.H. & Gengler N. (2013) Evaluation of heat stress effects on production traits and somatic cell score of Holsteins in a temperate environment. *Journal of Dairy Science* 96(3):1844–1855.

Haskell M.J., Rennie L.J., Bowell V.A., Bell M.J. & Lawrence A.B. (2006) Housing system, milk production, and zero-grazing effects on lameness and leg injury in dairy cows. *Journal of Dairy Science* 89:4259–4266. doi:10.3168/jds.S0022-0302(06)72472-9.

Herbut P. & Angrecka S. (2014) Ammonia concentrations in a free-stall dairy barn. *Annals of Animal Science* 14(1):153–166.

Hernandez-Mendo O., von Keyserlingk M.A.G., Veria D.M. & Weary D.M. (2007) Effects of pasture on lameness in dairy cows. *Journal of Dairy Science* 90:1209–1214.

Hill D.L. & Wall E. (2017) Weather influences feed intake and feed efficiency in a temperate climate. *Journal of Dairy Science* 100(3):2240–2257.

Hultgren J. (2001) Observational and experimental studies of the influence of housing factors on the behaviour and health of dairy cows. PhD Thesis. Uppsala: Sveriges lantbruksuniv., Acta Universitatis Agriculturae Sueciae. *Veterinaria.*

Huzzey J.M., DeVries T.J., Valois P. & von Keyserlingk M.A.G. (2006) Stocking density and feed barrier design affect the feeding and social behavior of dairy cattle. *Journal of Dairy Science* 89:126–133.

Ito K., Chapinal N., Weary D.M. & von Keyserlingk M.A.G. (2014) Associations between herd-level factors and lying behavior of freestall-housed dairy cows. *Journal of Dairy Science* 97:2081–2089. doi:10.3168/jds.2013-6861.

Jamali H., Barkema H.W., Jacques M., Lavallee-Bourget E.M., Malouin F., Saini V., Stryhn H. & Dufour S. (2018) Invited review: Incidence, risk factors, and effects of clinical mastitis recurrence in dairy cows. *Journal of Dairy Science* 101:4729–4746.

Jewell M.T., Cameron M., Spears J., McKenna S.L., Cockram M.S., Sanchez J. & Keefe G.P. (2019a) Prevalence of hock, knee, and neck skin lesions and associated risk factors in dairy herds in the Maritime Provinces of Canada. *Journal of Dairy Science* 102:3376–3391. doi:10.3168/jds.2018-15080.

Jewell M.T., Cameron M., Spears J., McKenna S.L., Cockram M.S., Sanchez J. & Keefe G.P. (2019b) Prevalence of lameness and associated risk factors on dairy farms in the Maritime Provinces of Canada. *Journal of Dairy Science* 102:3392–3405. doi:10.3168/jds.2018-15349.

Joo H.S., Ndegwa P.M., Heber A.J., Ni J.Q., Bogan B.W., Ramirez-Dorronsoro J.C. & Cortus E. (2015) Greenhouse gas emissions from naturally ventilated freestall dairy barns. *Atmospheric Environment* 102:384–392.

Kadzere C.T., Murphy M.R., Silanikove N. & Maltz E. (2002) Heat stress in lactating dairy cows: A review. *Livestock Production Science* 77(1):59–91.

Karimi M.T., Ghorbani G.R., Kargar S. & Drackley J.K. (2015) Late-gestation heat stress abatement on performance and behavior of Holstein dairy cows. *Journal of Dairy Science* 98(10):6865–6875.

Keil N.M., Wiederkehr T.U., Friedli K. & Wechsler B. (2006) Effects of frequency and duration of outdoor exercise on the prevalence of hock lesions in tied Swiss dairy cows. *Preventive Veterinary Medicine* 74:142–153. doi:10.1016/j.prevetmed.2005.11.005.

Kielland C., Ruud L.E., Zanella A.J. & Osteras O. (2009) Prevalence and risk factors for skin lesions on legs of dairy cattle housed in freestalls in Norway. *Journal of Dairy Science* 92:5487–5496. doi:10.3168/jds.2009-2293.

Kielland C., Bøe K., Zanella A. & Østerås O. (2010) Risk factors for skin lesions on the necks of Norwegian dairy cows. Journal of Dairy Science 93:3979-3989. doi:10.3168/jds.2009-2909.

Kendall P.E., Verkerk G.A., Webster J.R. & Tucker C.B. (2007) Sprinklers and shade cool cows and reduce insect-avoidance behavior in pasture-based dairy systems. *Journal of Dairy Science* 90(8):3671–3680.

Knaus W. (2016) Perspectives on pasture versus indoor feeding of dairy cows. *Journal of the Science of Food and Agriculture* 96:9–17.

Krawczel P.D. & Lee A.R. (2019) Lying time and its importance to the dairy cow: Impact of stocking density and time budget stresses. *Veterinary Clinics of North America: Food Animal Practice* 35:47–60.

Krohn C.C., Munksgaard L. & Jonasen B. (1992) Behaviour of dairy cows kept in extensive (loose housing/pasture) or intensive (tie stall) environments I. Experimental procedure, facilities, time budgets – Diurnal and seasonal conditions. *Applied Animal Behaviour Science* 34:37–47.

Lago A., McGuirk S.M., Bennett T.B., Cook N.B. & Nordlund K.V. (2006) Calf respiratory disease and pen microenvironments in naturally ventilated calf barns in winter. *Journal of Dairy Science* 89(10):4014–4025.

Lamb R.C., Barker B.O., Anderson M.J. & Walters J.L. (1979) Effects of forced exercise on two-year-old Holstein heifers. *Journal of Dairy Science* 62:1791–1797.

Lapointe G.D. (2010) Vos vaches sont-elles "confortables"? *34e Symposium sur les Bovins Laitiers*. Drummondville QC: Centre de Référence en Agriculture et Agroalimentaire du Québec.

Legrand A.L., von Keyserlingk M.A.G. & Weary D.M. (2009) Preference and usage of pasture versus free-stall housing by lactating dairy cattle. *Journal of Dairy Science* 92:3651–3658.

Loberg J., Telezhenko E., Bergsten C. & Lidfors L. (2004) Behaviour and claw health in tied dairy cows with varying access to exercise in an outdoor paddock. *Applied Animal Behaviour Science* 89:1–16.

López E., Mellado M., Martínez A.M., Véliz F.G., García J.E., de Santiago A. & Carrillo E. (2018) Stress-related hormonal alterations, growth and pelleted starter intake in pre-weaning Holstein calves in response to thermal stress. *International Journal of Thermal Biology* 62(4):493–500.

López-Gatius F., López-Béjar M., Fenech M. & Hunter R.H.F. (2005) Ovulation failure and double ovulation in dairy cattle: risk factors and effects. *Theriogenology* 63(5):1298–1307.

McConnachie E., Hötzel M.J., Robbins J.A., Shriver A., Weary D.M. & von Keyserlingk M.A.G. (2019) Public attitudes towards genetically modified polled cattle. *PLoS ONE* 14:e0216542.

McPherson S.E. & Vasseur E. (2020a). Graduate Student Literature Review: The impact of bedding, stall length, and manger wall height on common outcome measures of dairy cow welfare in stall-based housing systems. *Journal of Dairy Science* 103:1–11. doi:10.3168/jds.2020-18332.

McPherson S.E. & Vasseur E. (2020b *in press*). Making tie-stalls more comfortable: IV. Increasing stall bed length and decreasing manger wall height to heal injuries and increase lying time in dairycows housed in deep bedded tie-stalls. *Journal of Dairy Science* JDS.2019-17668.R3.

Miller-Cushon E.K., Dayton A.M., Horvath K.C., Monteiro A.P.A., Weng X. & Tao S. (2019) Effects of acute and chronic heat stress on feed sorting behaviour of lactating dairy cows. *Animal* 13(9):2044–2051.

Mitloehner F.M. & Calvo M.S. (2008) Worker health and safety in concentrated animal feeding operations. *Journal of Agricultural Safety and Health* 14(2):163–187.

Moore D.A., Duprau J.L. & Wenz J.R. (2012) Short communication: Effects of dairy calf hutch elevation on heat reduction, carbon dioxide concentration, air circulation, and respiratory rates. *Journal of Dairy Science* 95:4050–4054.

Nardone A., Ronchi B., Lacetera N. & Bernabucci U. (2006) Climatic effects on productive traits in livestock. *Veterinary Research Communications* 30(Suppl 1):75–81.

Nash C.G.R., Kelton D.F., DeVries T.J., Vasseur E., Coe J., Heyerhoff J.C.Z., Bouffard V., Pellerin D., Rushen J., de Passillé A.M. & Haley D.B. (2016) Prevalence of and risk factors for hock and knee injuries on dairy cows in tiestall housing in Canada. *Journal of Dairy Science* 99:6494–6506. doi:10.3168/jds.2015-10676.

National Farm Animal Care Council & Dairy Farmers of Canada (NFACC-DFC) (2009) *Code of Practice for the Care and Handling of Dairy Cattle*. Lacombe AB: National Farm Animal Care Council.

Ngwabie N.M., Jeppsson K.H., Nimmermark S., Swensson C. & Gustafsson G. (2009) Multi location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally-ventilated barn for dairy cows. *Biosystems Engineering* 103(1):68–77.

Ngwabie N.M., Vanderzaag A., Jayasundara S. & Wagner-Riddle C. (2014) Measurements of emission factors from a naturally ventilated commercial barn for dairy cows in a cold climate. *Biosystems Engineering* 127:103–114.

Nienaber J.A. & Hahn G.L. (2007) Livestock production system management responses to thermal challenges. *International Journal of Biometeorology* 52(2):149–157.

Nonnecke B.J., Foote M.R., Miller B.L., Fowler M., Johnson T.E. & Horst R.L. (2009) Effects of chronic environmental cold on growth, health, and select metabolic and immunologic responses of preruminant calves. *Journal of Dairy Science* 92(12):6134–6143.

Nordlund K.V., Strassburg P., Bennett T.B., Oetzel G.R. & Cook N.B. (2019) Thermodynamics of standing and lying behavior in lactating dairy cows in freestall and parlor holding pens during conditions of heat stress. *Journal of Dairy Science* 102(7):6495–6507.

Norring M., Manninen E., de Passillé A.M., Rushen J., Munksgaard L. & Saloniemi H. (2008) Effects of sand and straw bedding on the lying behavior, cleanliness, and hoof and hock injuries of dairy cows. *Journal of Dairy Science* 91:570–576. doi:10.3168/jds.2007-0452.

NRC (2001) *Nutrient Requirements of Dairy Cattle*, 7th rev. ed. Washington DC: National Academy Press.

Olmos G., Boyle L., Hanlon A., Patton J., Murphy J.J. & Mee J.F. (2009) Hoof disorders, locomotion ability and lying times of cubicle-housed compared to pasture-based dairy cows. *Livestock Science* 125:199–207.

Olson D.P., Papasian C.J. & Ritter R.C. (1980) The effects of cold stress on neonatal calves. II. Absorption of colostral immunoglobulins. *Canadian Journal of Comparative Medicine* 44(1):19–23.

Ortiz X.A., Smith J.F., Rojano F., Choi C.Y., Bruer J., Steele T., Schuring N., Allen J. & Collier R.J. (2015) Evaluation of conductive cooling of lactating dairy cows under controlled environmental conditions. *Journal of Dairy Science* 98(3):1759–1771.

Pajor E.A., Rushen J. & de Passillé A.M.B. (2003) Dairy cattle's choice of handling treatments in a Y-maze. *Applied Animal Behaviour Science* 80:93–107.

Perano K.M., Usack J.G., Angenent L.T. & Gebremedhin K.G. (2015) Production and physiological responses of heat-stressed lactating dairy cattle to conductive cooling. *Journal of Dairy Science* 98(8):5252–5261.

Pereira A.M.F., Titto E.L., Infante P., Titto C.G., Geraldo A.M., Alves A., Leme T.M., Baccari F. & Almeida J.A. (2014) Evaporative heat loss in *Bos taurus*: Do different cattle breeds cope with heat stress in the same way? *Journal of Thermal Biology* 45:87–95.

Phillips C.J.C. & Morris I.D. (2001) The locomotion of dairy cows on floor surfaces with different frictional properties. *Journal of Dairy Science* 84(3):623–628.

Platz S., Ahrens F., Bendel J., Meyer H.H.D. & Erhard M.H. (2008) What happens with cow behavior when replacing concrete slatted floor by rubber coating: A case study. *Journal of Dairy Science* 91:999–1004.

Plesch G. (2011) Cleanliness versus cow comfort - An insolvable problem? PhD Thesis. Kassel, Germany: University of Kassel, Faculty of Organic Agriculture.

Plesch G. & Knierim U. (2012) Effects of housing and management conditions on teat cleanliness of dairy cows in cubicle systems taking into account body dimensions of the cows. *Animal* 6:1360–1368. doi:10.1017/S1751731112000031.

Polsky L. & von Keyserlingk M.A.G. (2017) Invited review: Effects of heat stress on dairy cattle welfare. *Journal of Dairy Science* 100(11):8645–8657.

Popescu S., Borda C., Diugan E.A., Spinu M., Groza I.S. & Sandru C.D. (2013) Dairy cows welfare quality in tie-stall housing system with or without access to exercise. *Acta Veterinaria Scandinavica* 55:43. doi:10.1186/1751-0147-55-43.

Potterton S.L., Green M.J., Harris J., Millar K.M., Whay H.R. & Huxley J.N. (2011) Risk factors associated with hair loss, ulceration, and swelling at the hock in freestall-housed UK dairy herds. *Journal of Dairy Science* 94:2952–2963. doi:10.3168/jds.2010-4084.

Proudfoot K.L., von Keyserlingk M.A.G., Veira D.M. & Weary D.M. (2009) Competition at the feed bunk changes the feeding, standing and social behavior of transition dairy cows. *Journal of Dairy Science* 92:3116–3123.

Proudfoot K.L., Weary D.M., LeBlanc S.J., Mamedova L.K. & von Keyserlingk M.A.G. (2018) Exposure to an unpredictable and competitive social environment affects behavior and health of transition dairy cows. *Journal of Dairy Science* 101:9309–9320.

Radoń J., Bieda W., Lendelová J. & Pogran Š. (2014) Computational model of heat exchange between dairy cow and bedding. *Computers and Electronics in Agriculture* 107:29–37.

Ravagnolo O. & Misztal I. (2000) Genetic component of heat stress in dairy cattle, parameter estimation. *Journal of Dairy Science* 83(9):2126–2130.

Rawson R.E., Dziuk H.E., Good A.L., Anderson J.F., Bates D.W. & Ruth G.R. (1989) Thermal insulation of young calves exposed to cold. *Canadian Journal of Veterinary Research* 53(3):275–278.

Regula G., Danuser J., Spycher B. & Wechsler B. (2004) Health and welfare of dairy cows in different husbandry systems in Switzerland. *Preventive Veterinary Medicine* 66:247–264.

Renaudeau D., Collin A., Yahav S., de Basilio V., Gourdine J.L. & Collier R.J. (2012) Adaptation to hot climate and strategies to alleviate heat stress in livestock production. *Animal* 6(5):707–728.

Rushen J., de Passillé A.M., von Keyserlingk M.A.G. & Weary D.M. (2008) *The Welfare of Cattle.* Dordrecht NL: Springer.

Rutherford K.M.D., Langford F.M., Jack M.C., Sherwood L., Lawrence A.B. & Haskell M.J. (2009) Lameness prevalence and risk factors in organic and non-organic dairy herds in the United Kingdom. *Veterinary Journal* 180:95–105. doi:10.1016/j.tvjl.2008.03.015.

Ruud L.E., Bøe K.E. & Østerås O. (2010) Risk factors for dirty dairy cows in Norwegian freestall systems. *Journal of Dairy Science* 93:5216–5224. doi:10.3168/jds.2010-3321.

Ruud L.E., Kielland C., Østerås O. & Bøe K.E. (2011) Free-stall cleanliness is affected by stall design. *Livestock Science* 135:265–273. doi:10.1016/j.livsci.2010.07.021.

Sakatani M., Balboula A.Z., Yamanaka K. & Takahashi M. (2012) Effect of summer heat environment on body temperature, estrous cycles and blood antioxidant levels in Japanese Black cow. *Animal Science Journal* 83(5):394–402.

Schütz K.E., Rogers A.R., Cox N.R. & Tucker C.B. (2009) Dairy cows prefer shade that offers greater protection against solar radiation in summer: Shade use, behaviour, and body temperature. *Applied Animal Behaviour Science* 116(1):28–34.

Schütz K.E., Rogers A.R., Poulouin Y.A., Cox N.R. & Tucker C.B. (2010) The amount of shade influences the behavior and physiology of dairy cattle. *Journal of Dairy Science* 93(1):125–133.

Schütz K.E., Cave V.M., Cox N.R., Huddart F.J. & Tucker C.B. (2019) Effects of 3 surface types on dairy cattle behavior, preference, and hygiene. *Journal of Dairy Science* 102:1530–1541.

Sepúlveda-Varas P., Weary D.M. & von Keyserlingk M.A.G. (2014) Lying behavior and postpartum health status in grazing dairy cows. *Journal of Dairy Science* 97:6334–6343.

Shepley E. (2020) A cow in motion: The impact of housing systems on movement opportunity of dairy cows and the implications on locomotor activity, behaviour, and welfare. PhD Thesis. Ste-Anne-de-Bellevue QC: McGill University, Faculty of Agricultural and Environmental Sciences, Department of Animal Science.

Shepley E., Lensink J.B., Leruste H. & Vasseur E. (2019a) The effect of free-stall versus strawyard housing and access to pasture on dairy cow locomotor activity and time budget. *Applied Animal Behaviour Science* 226:104928.

Shepley E., Obinu G., Bruneau T. & Vasseur E. (2019b) The effect of housing tie-stall dairy cows in loose-pens over the duration of an eight-week dry period on lying time, lying postures, and rising and lying-down ability. *Journal of Dairy Science* 102(7):6508–6517.

Shepley E., Lensink J. & Vasseur E. (2020) A cow in motion: A review of the impact of housing systems on movement opportunity of dairy cows and implications on locomotor activity. *Applied Animal Behaviour Science* 230:105026.

Smith, J.F., Bradford B.J., Harner J.P., Potts J.C., Allen J.D., Overton M.W., Ortiz X.A. & Collier R.J. (2016) Short communication: Effect of cross ventilation with or without evaporative pads on core body temperature and resting time of lactating cows. *Journal of Dairy Science* 99(2):1495–1500.

Smits M.J.C., Frankena K., Metz J.H.M. & Noordhuizen J.P.T.M. (1992) Prevalence of digital disorders in zero-grazing dairy cows. *Livestock Production Science* 32:231–244.

Solano L., Barkema H.W., Pajor E.A., Mason S., LeBlanc S.J., Heyerhoff J.C.Z., Nash C.G.R., Haley D.B., Vasseur E., Pellerin D., Rushen J., de Passille A.M. & Orsel K. (2015) Prevalence of lameness and associated risk factors in Canadian Holstein-Friesian cows housed in freestall barns. *Journal of Dairy Science* 98(10):6978–6991.

Solano L., Barkema H.W., Pajor E.A., Mason S., LeBlanc S.J., Nash C.G.R., Haley D.B., Pellerin D., Rushen J., de Passillé A.M., Vasseur E. & Orsel K. (2016) Associations between lying behavior and lameness in Canadian Holstein-Friesian cows housed in freestall barns. *Journal of Dairy Science* 99:2086–2101. doi:10.3168/jds.2015-10336.

Somers J.G.C.J., Frankena K., Noordhuizen-Stassen E.N. & Metz J.H.M. (2003) Prevalence of claw disorders in Dutch dairy cows exposed to several floor systems. *Journal of Dairy Science* 86:2082–2093.

Soriani, N., Panella G. & Calamari L. (2013) Rumination time during the summer season and its relationships with metabolic conditions and milk production. *Journal of Dairy Science* 96(8):5082–5094.

Sova A.D., LeBlanc S.J., McBride B.W. & DeVries T.J. (2013) Associations between herd-level feeding management practices, feed sorting, and milk production in freestall dairy farms. *Journal of Dairy Science* 96:4759–4770.

Spain J.N. & Spiers D.E. (1996) Effects of supplemental shade on thermoregulatory response of calves to heat challenge in a hutch environment. *Journal of Dairy Science* 79:639–646.

Spiers D.E., Spain J.N., Sampson J.D. & Rhoads R.P. (2004) Use of physiological parameters to predict milk yield and feed intake in heat-stressed dairy cows. *Journal of Thermal Biology* 29(7–8):759–764.

St John J., Rushen J., Adam S. & Vasseur E. (2020, *in press*). Making tie-stalls more comfortable: I. Adjusting tierail height and forward position to improve dairy cows' ability to rise and lie down. *Journal of Dairy Science* JDS.2019-17665.R3.

Strickland J.T., Bucklin R.A., Nordstedt R.A., Beede D.K. & Bray D.R. (1989) Sprinkler and fan cooling system for dairy cows in hot, humid climates. *American Society of Agricultural Engineers* 5(2):231–236.

Svensson C., Hultgren J. & Oltenacu P.A. (2006) Morbidity in 3-7-month-old dairy calves in south-western Sweden, and risk factors for diarrhoea and respiratory disease. *Preventive Veterinary Medicine* 74(2–3):162–179.

Teye F.K. & Hautala M. (2007) Measuring ventilation rates in dairy buildings. *International Journal of Ventilation* 6(3):247–256.

Teye F.K., Hautala M., Pastell M., Praks J., Veermäe I., Poikalainen V., Pajumägi A., Kivinen T. & Ahokas J. (2008) Microclimate and ventilation in Estonian and Finnish dairy buildings. *Energy and Buildings* 40(7):1194–1201.

Tripon I., Cziszter L.T., Bura M. & Sossidou E.N. (2014) Effects of seasonal and climate variations on calves' thermal comfort and behaviour. *International Journal of Biometeorology* 58(7):1471–1478.

Tucker C.B., Weary D.M. & Fraser D. (2004) Free-stall dimensions: Effects on preference and stall usage. *Journal of Dairy Science* 87:1208–1216. doi:10.3168/jds.S0022-0302(04)73271-3.

Tucker C.B., Weary D. M. & Fraser D. (2005) Influence of neck-rail placement on free-stall preference, use, and cleanliness. *Journal of Dairy Science* 88:2730–2737. doi:10.3168/jds.S0022-0302(05)72952-0.

Tucker C.B., Zdanowicz G. & Weary D.M. (2006) Brisket boards reduce freestall use. *Journal of Dairy Science* 89:2603–2607. doi:10.3168/jds.S0022-0302(06)72337-2.

Tucker C.B., Weary D.M., von Keyserlingk M.A.G. & Beauchemin K.A. (2009) Cow comfort in tie-stalls: Increased depth of shavings or straw bedding increases lying time. *Journal of Dairy Science* 92:2684–2690. doi:10.3168/jds.2008-1926.

Turner L.W., Chastain J.P., Hemken R.W., Gates R.S. & Crist W.L. (1992) Reducing heat stress in dairy cows through sprinkler and fan cooling. *American Society of Agricultural Engineers* 8(2):251–256.

Valacta (2014) *The Barn; A Source of Comfort: Practical Guide to Evaluating and Improving Comfort in the Barn*. Available at: http://www.valacta.com/EN/publications/Documents/Guide%20Confort_ANG_V3_Version%20finale_2015-02-02.pdf. Accessed July 24, 2018.

Valtorta S.E., Leva P.E. & Gallardo M.R. (1997) Evaluation of different shades to improve dairy cattle well-being in Argentina. *International Journal of Biometeorology* 41(2):65–67.

van der Tol P.P.J., Metz J.H.M., Noordhuizen-Stassen E.N., Back W., Braam C.R. & Weijs W.A. (2005) Frictional forces required for unrestrained locomotion in dairy cattle. *Journal of Dairy Science* 88:615–624.

van Gastelen S., Westerlaan B., Houwers D.J. & van Eerdenburg F.J.C.M. (2011) A study on cow comfort and risk for lameness and mastitis in relation to different types of bedding materials. *Journal of Dairy Science* 94:4878–4888. doi:10.3168/jds.2010-4019.

Vasseur E., Gibbons J., Rushen J., Pellerin D., Pajor E., Lefebvre D. & de Passillé A.M. (2015) An assessment tool to help producers improve cow comfort on their farms. *Journal of Dairy Science* 98:698–708. doi:10.3168/jds.2014-8224.

Veissier I., Van Iaer E., Palme R., Moons C.P.H., Ampe B., Sonck B., Andanson S. & Tuyttens F.A.M. (2018) Heat stress in cows at pasture and benefit of shade in a temperate climate region. *International Journal of Biometeorology* 62(4):585–595.

Villettaz Robichaud M., Pic A., Delgado H., Adam S., Lacroix R., Pellerin D. & Vasseur E. (2020) Short communication: Use of the Clegg hammer measure as an indicator of stall-surface compressibility in tiestall housing and its relationship with stall comfort. *Journal of Dairy Science* 103(1):871–876.

Vizzotto E.F., Fischer V., Thaler Neto A., Abreu A.S., Stumpf M.T., Werncke D., Schmidt F.A. & McManus C.M. (2015) Access to shade changes behavioral and physiological attributes of dairy cows during the hot season in the subtropics. *Animal* 9(9):1559–1566.

von Keyserlingk M.A.G., Barrientos A., Ito K., Galo E. & Weary D.M. (2012) Benchmarking cow comfort on North American freestall dairies: Lameness, leg injuries, lying time, facility design, and management for high-producing Holstein dairy cows. *Journal of Dairy Science* 95:7399–7408. doi:10.3168/jds.2012-5807.

Washburn S.P., White S.L., Green J.T. & Benson G.A. (2002) Reproduction, mastitis, and body condition of seasonally calved Holstein and Jersey cows in confinement or pasture systems. *Journal of Dairy Science* 85:105–111.

Weary D.M. (2017) Getting stocking density right for your cows. *Advances in Dairy Technology* 29:243–253.

Wells S.J., Garber L.P. & Wagner B.A. (1999) Papillomatous digital dermatitis and associated risk factors in US dairy herds. *Preventive Veterinary Medicine* 38:11–24.

West J.W. (2003) Effects of heat-stress on production in dairy cattle. *Journal of Dairy Science* 86(6):2131–2144.

West J.W., Mullinix B.G. & Bernard J.K. (2003) Effects of hot, humid weather on milk temperature, dry matter intake, and milk yield of lactating dairy cows. *Journal of Dairy Science* 86(1):232–242.

Winckler C., Tucker C.B. & Weary D.M. (2015) Effects of under- and overstocking freestalls on dairy cattle behaviour. *Applied Animal Behaviour Science* 170:14–19.

Woolpert M.E., Dann H.M., Cotanch K.W., Melilli C., Chase L.E., Grant R.J. & Barbano D.M. (2017) Management practices, physically effective fiber, and ether extract are related to bulk tank milk de novo fatty acid concentrations on Holstein dairy farms. *Journal of Dairy Science* 100:5097–5106.

Zaffino-Heyerhoff J.C., LeBlanc S.J., DeVries T.J., Nash C.G.R., Gibbons J., Orsel K., Barkema H.W., Solano L., Rushen J., de Passillé A.M. & Haley D.B. (2014) Prevalence of and factors associated with hock, knee, and neck injuries on dairy cows in freestall housing in Canada. *Journal of Dairy Science* 97:173–184. doi:10.3168/jds.2012-6367.

Zambelis A., Gagnon-Barbin M., St John J. & Vasseur E. (2019) Development of scoring systems for abnormal rising and lying down by dairy cattle, and their relationship with other welfare outcome measures. *Applied Animal Behaviour Science* 220:104858.

Zimbelman R.B., Rhoads R.P., Rhoads M.L., Duff G.C., Baumgard L.H. & Collier R.J. (2009) A re-evaluation of the impact of temperature humidity index (THI) and black globe humidity index (BGHI) on milk production in high producing dairy cows. *Proceedings of the Southwest Nutrition Management Conference, Tempe, Arizona, USA.*

Zurbrigg K., Kelton D., Anderson N. & Millman S. (2005a) Stall dimensions and the prevalence of lameness, injury, and cleanliness on 317 tie-stall dairy farms in Ontario. *Canadian Veterinary Journal* 46:902–909.

Zurbrigg K., Kelton D., Anderson N. & Millman S. (2005b) Tie-stall design and its relationship to lameness, injury, and cleanliness on 317 Ontario dairy farms. *Journal of Dairy Science* 88:3201–3210. doi:10.3168/jds.S0022-0302(05)73003-4.

4 Pain Control for Painful Conditions and Procedures

Conclusions:

1. **Assessing pain in animals is challenging and necessitates careful consideration of study design and outcome selection. Pre-emptive administration of pain control for painful procedures is preferred to post-procedure treatment, and in painful disease conditions therapy early in disease course is preferred to best mitigate the pain response.**
2. **A large body of evidence has demonstrated benefits of the use of local anesthesia and nonsteroidal anti-inflammatory drug (NSAID) analgesia for cautery disbudding. Trials examining caustic paste have repeatedly demonstrated benefit to local anesthetic and NSAID analgesic.**
3. **Use of xylazine sedation has produced beneficial effects in a 2019 trial, but more research is needed to determine the effects of this, particularly on alleviating the pain and stress of disbudding.**
4. **Dystocia is a painful condition for both cow and calf. Providing cows with NSAID analgesia post-calving may alleviate this pain, but more research is needed. Based on the available evidence, the use of flunixin meglumine is not recommended as it may increase the risk of retained placenta. This effect has not been seen in other NSAID therapies. Administering an NSAID to calves following a dystocia has produced mixed results, but it has shown some benefit and was not shown to produce any harmful effects.**
5. **There is a strong body of evidence supporting use of NSAID therapy for severe mastitis, to reduce inflammation and indicators of pain. Despite the fact that more research is warranted to determine the impact of NSAID treatment for pain in mild to moderate clinical mastitis, current evidence indicates that NSAID therapy is of benefit for all clinical categories.**
6. **While it is clear that metritis is painful for cattle, more research is needed to determine if NSAID therapy produces clinically relevant changes in behavioural and physiologic outcomes associated with pain, as previous work typically has focused on reproductive health outcomes alone.**
7. **Providing diarrheic calves with an adjunct NSAID treatment has been demonstrated to improve outcomes, which may in part be due to the analgesia effects of these drugs on gastrointestinal pain and discomfort.**
8. **While few studies have been repeated for a given surgical procedure, the overall evidence demonstrates a general benefit for the use of both local anesthesia and NSAID analgesia for surgical procedures in cattle, including minor procedures. Further research is needed to better determine the true efficacy and appropriate duration of therapy for individual procedures.**

4.1 Main Principles

Pain in cattle can occur due to tissue damage, nerve damage, or inflammation, and is frequently associated with hypersensitivity due to hyperalgesia (i.e., increased response to a painful stimulus) and allodynia (i.e., painful response to a stimulus that is not normally painful) (Coetzee, 2017). Pain may persist until the tissue is healed, but nerve damage may cause pain that is far longer lasting (Whay, 2016; Adcock & Tucker, 2018; Vidondo et al., 2019). The nature of pain (duration, intensity, and quality) can depend on factors including the amount of damage as well as previous and concurrent experiences with pain or stress, cognitive, social, and emotional modulators, and quality and duration of anesthetics or analgesics (Adcock & Tucker, 2018). It can be challenging to assess pain, and research questions may require a combination of behavioural and physiological measures (Mainau & Manteca, 2011). For many procedures or conditions, lack of obvious behavioural reaction clinically should not necessarily indicate a lack of perceived noxiousness (Stafford & Mellor, 2011; Mainau & Manteca, 2011). Therefore, consideration of appropriate outcomes in study design is essential to the conduct and interpretation of pain research in dairy cattle.

Pain control is best used pre-emptively where possible, to reduce sensitization to subsequent stimuli that may amplify pain signaling (Coetzee, 2017). A multimodal approach using both local anesthesia to prevent acute pain, and a nonsteroidal anti-inflammatory drug (NSAID) to reduce inflammation has been generally demonstrated to reduce pain and distress following painful procedures or conditions in livestock (Coetzee, 2017). Labelled NSAID therapies for cattle in Canada are generally considered safe, with wide safety margins, and adverse reactions reported in trials examined in this section were negligible, with a notable exception covered in *Section 4.3: Dystocia (Cow and Calf)*. Therefore, in general, control of acute pain through local anesthesia and inflammatory pain through provision of NSAID analgesia is recommended for procedures or conditions known to cause acute pain and inflammation. Pre-emptive treatment for painful procedures is preferred, and in painful disease conditions therapy early in disease course is preferred to best mitigate the pain response.

4.2 Cautery and Caustic Paste Disbudding

Strong evidence exists to support the use of both a local anesthetic and NSAID for hot-iron disbudding, where use of both medications has repeatedly produced reductions in both behavioural and physiologic indicators of pain compared to either medication given alone or no pain control (Stafford & Mellor, 2011; Stock et al., 2013; Winder et al., 2018). A recent meta-analysis suggested heterogeneity of effect may be due in part to the variety of NSAIDs and dosages used; however, this could not be further explored (Winder et al., 2018).

Little work has explored the use of sedatives to reduce the stress response to disbudding. A recent study by Cuttance et al. (2019) showed benefit to the use of xylazine sedation on behavioural outcomes in the first day following disbudding; however, more work is needed to determine the effect of this treatment. Xylazine given alone has been shown to be ineffective at mitigating disbudding pain (Grøndahl-Nielsen et al., 1999; Stilwell et al., 2010). Sedation has also been shown to reduce handling stress (Grøndahl-Nielsen et al., 1999) but also can cause temperature depression in young calves, who do not thermoregulate as efficiently (Vasseur et al., 2014).

The nature, duration, and intensity of pain caused by a chemical burn can differ from that of a thermal burn (Bromberg et al., 1965), and therefore pain control specific to this method warrants specific further investigation. Additionally, caustic paste disbudding has been associated with reduced adoption of producer-use of pain control compared to cautery disbudding in both the United States (Adams et al., 2015) and Canada (Winder et al., 2016).

While there is less research examining pain control of calves disbudded with caustic paste compared to similar work in cautery, the current evidence supports the use of local anesthesia combined with NSAID analgesia as most efficacious. Use of local anesthetic alone produces an initial benefit (Morisse et al., 1995; Stilwell et al., 2009; Reedman et al., 2019), but combined use of both local anesthesia and NSAID analgesia results in substantially longer reductions in both behavioural and physiologic outcomes associated with pain (Stilwell et al., 2009; Winder et al., 2017; Yakan et al., 2018; Reedman et al., 2019). Method of administration of the local anesthetic may be important in caustic paste disbudding, as the former trials administered local anesthetic via a cornual nerve block, while another trial reported no benefit to giving local anesthetic administered via a ring block (Vickers et al., 2005). It is possible the local effects of the paste may interfere with local anesthesia given at the site, compared to desensitizing the nerve at some distance to the horn bud. An NSAID given without local anesthetic has been demonstrated to be insufficient to control the acute pain of caustic paste disbudding (Stilwell et al., 2008; Winder et al., 2017; Karlen et al., 2019), and the use of an opiate alone was similarly demonstrated to be ineffective (Braz et al., 2012).

4.3 Dystocia (Cow and Calf)

Dystocia is defined as a prolonged calving, which may occur with or without assisted extraction of the calf (Mee, 2008). It is clear this condition is painful; cattle experiencing dystocia show marked differences in behavioural and physiologic indicators of pain (Mainau & Manteca, 2011; Swartz et al., 2018). However, trials examining the impact of pain control treatment for dystocia are limited, as most studies have examined the impact of NSAID therapy for all cows at calving (Mainau & Manteca, 2011; Lavan et al., 2012). In one study by Newby et al. (2013a) specifically enrolling cows experiencing an assisted calving, it was reported that meloxicam-treated cows visited the feed bunk more in the first 24 h after injection, but no differences were reported in other outcomes; however, the treatment was given 24 h after calving, which may have resulted in less effect on inflammation. Trials administering NSAID therapy to all cows at or around calving have reported varied results. Mainau et al. (2014) reported no benefits to meloxicam administration, while two trials have identified increased risk of retained placenta with use of flunixin meglumine (Waelchli et al., 1999; Newby et al., 2017), and one reported a reduction in risk of retained placenta after ketoprofen administration (Richards et al., 2009). The current evidence indicates that NSAID therapy for all cows at calving is not warranted. However, treatment at calving specifically for cows experiencing dystocia may be recommended based on evidence that this condition is painful, although the efficacy of NSAID therapy for these animals merits much further research. Based on the potential for increased risk of retained placenta, flunixin meglumine should not be used for this purpose.

Dystocia is also a painful event for the calf (Mellor & Stafford, 2004). An incidental finding in a recent cohort study of 215 neonatal heifer calves in 3 commercial farms in Ontario was that 7% of calves had rib fractures (Dunn et al., 2018), meaning injuries to calves born from dystocia are likely underrecognized or undiagnosed. While trials examining the impact of NSAID therapy for calves born to dystocia are quite recent, results have been mixed. Some trials have reported no benefits for treatment of calves born to mild- to moderately-assisted calvings (Gladden et al., 2018) or assisted calvings (Pearson et al., 2019a), while others have demonstrated improvement in calf performance (Murray, 2014; Pearson et al., 2019b), behaviour (Murray, 2014; Gladden et al., 2019), and health (Murray, 2014). It should be recognized that calves born to dystocia experience pain and have potential for musculoskeletal injury. While current research is inconclusive as to the benefits of NSAID analgesia for these calves, treatment with NSAIDs in the above trials was not reported to be harmful and treatment may improve their welfare through mitigating pain and inflammation.

4.4 Mastitis

Although the exact definition within research studies may vary (Smith & Hillerton, 1999), clinical mastitis is generally categorized as mild, moderate, or severe (Wenz et al., 2006). Mild cases are defined as cows with visibly abnormal milk without notable swelling or heat in the udder; moderate cases are generally defined as abnormal milk with an abnormal quarter (heat, swelling, or pain), or with minimal signs of systemic illness; and severe cases are those with abnormal milk, with or without udder changes, but with signs of systemic illness such as fever, elevated heart or respiratory rate, dehydration, or decreased rumen function (Roberson, 2012).

Assessing pain associated with mastitis is challenging (Fitzpatrick et al., 2000); as an example, systemically ill animals typically lay more, but cattle with mastitis may lay less to reduce pressure on the udder (Siivonen et al., 2011; de Boyer des Roches et al., 2018). However, behavioural and physiologic indicators of pain have been demonstrated in all categories of clinical mastitis, indicating they are painful conditions (Milne, 2004; Milne et al., 2004; Leslie & Petersson-Wolfe, 2012; Peters et al., 2015). Increased signs of pain are observed with increasing clinical severity (Milne et al., 2004; Peters et al., 2015), and earlier in the course of disease for a given case (de Boyer des Roches et al., 2017).

While several trials have been conducted examining NSAID therapy for clinical mastitis (Francoz et al., 2017), fewer trials have examined outcomes associated with pain for mild and moderate clinical mastitis, or were designed to assess changes in pain related physiology or behaviour. There are clear benefits to providing NSAID therapy for severe mastitis, including reduced indicators of pain and inflammation and improved recovery (Leslie & Petersson-Wolfe, 2012; Fitzpatrick et al., 2013). Administration of NSAID therapy for mild to moderate cases has demonstrated improved recovery rates (Milne et al., 2004; McDougall et al., 2009, 2016) and reduced response to mechanical stimulation, indicating less sensitivity of the mammary gland (Milne, 2004). Despite the fact that more research is warranted to determine the impact of NSAID treatment for pain in mild to moderate clinical mastitis, current evidence indicates that NSAID therapy is of benefit for all clinical categories.

4.5 Metritis

Metritis is defined as an abnormally enlarged uterus and the presence of watery, fetid, red-brown vaginal discharge within 21 days post-partum, with or without pyrexia (i.e., fever) (Sheldon et al., 2006). This condition produces behavioural and physiologic changes in affected cattle

(Barragan et al., 2018; Lomb et al., 2018a) likely to stem from visceral inflammatory pain (Stojkov et al., 2015). While a larger body of research has examined efficacy of antibiotic protocols for treatment (Haimerl et al., 2017), examination of adjunct NSAID therapy is less common, and often these trials aim to measure reproductive performance and either do not assess pain-related outcomes (e.g., Pohl et al., 2016) or are not primarily designed to examine these outcomes. While some researchers have demonstrated treatment with an NSAID improved clinical resolution (Amiridis et al., 2001) and decreased haptoglobin (Jeremejeva et al., 2012), others have demonstrated little or no differences in inflammatory biomarkers (Drillich et al., 2007) or behaviour (Lomb et al., 2018a). While it is clear that this condition is painful for cattle, additional trials (designed to measure clinically relevant changes in behavioural and physiologic outcomes associated with pain) are required to determine the efficacy of NSAID therapy.

4.6 Neonatal Calf Diarrhea

Neonatal calf diarrhea is a major contributor to early life morbidity and mortality in dairy calves (Smith, 2009). Regardless of the cause of the diarrhea, appropriate fluid therapy and continued feeding of milk are critical to recovery (Constable, 2009; Smith, 2009). While the bulk of research into therapeutics has focused on fluid therapy and antibiotics (Meganck et al., 2014), few trials have been conducted to examine the impact of adjunct NSAID therapy. In these studies, it has been reported that adjunct NSAID therapy is of benefit, resulting in improved appetite (Philipp et al., 2003; Todd et al., 2010), general condition (Philipp et al., 2003), performance (Todd et al., 2010), and recovery (Barnett et al., 2003). An older experimental challenge model also showed reduction in clinical diarrhea (Roussel et al., 1988). Beneficial effects from these drugs may be a result of their analgesic, anti-inflammatory, antipyretic, or anti-secretory properties (Constable, 2009). Adjunct treatment with NSAID appears to improve outcomes for calves with undifferentiated calf diarrhea, which may in part be due to the analgesia effects of these drugs on gastrointestinal pain and discomfort.

4.7 Surgical/Post-Surgical

Dairy cattle may experience a range of surgical procedures, including but not limited to abomasal surgery, caesarean section, umbilical repair, and claw surgery. All surgical procedures involve tissue damage through cutting and manipulating tissue, causing acute pain via nociceptive signals from either skin, muscle, joints, bone, or internal organs (Walker et al., 2011). Additionally, inflammation occurring after tissue damage can further induce hyperalgesia and allodynia (Walker et al., 2011). Even small-scale subcutaneous procedures have produced post-operative pain (Frondelius et al., 2018). As a result, a combination of both pre- and post-operative analgesia is generally recommended. Local anesthetic is commonly used to desensitize tissue during veterinary surgical procedures, but post-operative analgesia is less common, and little research has examined analgesia for surgical procedures in dairy cattle (Walker et al., 2011). For example, a review on common surgical procedures discussed abomasal surgery without any mention of pain mitigation strategies (Aubry, 2005).

From the few clinical trials conducted, treatment with an NSAID in combination with local anesthetics appears to show benefit in a variety of surgical procedures, including caesarian section (Barrier et al., 2014), claw surgery (Heppelmann et al., 2009; Offinger et al., 2013), abomasal surgery (Newby et al., 2013b), rumen fistulation surgery (Newby et al., 2014), and small-scale subcutaneous surgery (Frondelius et al., 2018), similar to the procedure of supernumerary teat removal. It should be noted that the use of flunixin meglumine was associated with increased risk of retained placenta in cattle treated following caesarean section (Waelchli et al., 1999) but was not observed in a trial with meloxicam (Barrier et al., 2014). Based on additional trials showing elevated risk with flunixin meglumine treatment after calving (Newby et al., 2017), it is recommended that caution be exercised with the selection of NSAIDs when given at calving. Outside of treatment at calving, the literature shows general benefit for the use of both local anesthesia and NSAID analgesia for surgical procedures in cattle, although further research is needed to determine actual nature of efficacy and duration of therapy for individual procedures.

4.8 References

Adams A.E., Lombard J.E., Shivley C.S., Urie N.J., Roman-Muniz I.N., Fossler C.P. & Kopral C.A. (2015) Management practices that may impact dairy heifer welfare on U.S. dairy operations. *Proceedings of the Joint Annual Meeting of the American Dairy Science Association and the American Society of Animal Science*, Orlando, Florida, U.S.A.

Adcock S.J.J. & Tucker C.B. (2018) Painful procedures: When and what should we be measuring in cattle? In: Tucker, C.B. (ed.) *Advances in Cattle Welfare.* Cambridge MA: Woodhead Publishing, pp. 157–198.

Amiridis G.S., Leontides L., Tassos E., Kostoulas P. & Fthenakis G.C. (2001) Flunixin meglumine accelerates uterine involution and shortens the calving-to-first-oestrus interval in cows with puerperal metritis. *Journal of Veterinary Pharmacologic Therapy* 24:365–367.

Aubry P. (2005) Routine surgical procedures in dairy cattle under field conditions: Abomasal surgery, dehorning, and tail docking. *Veterinary Clinics of North America: Food Animal Practice* 21:55–72.

Barnett S.C., Sischo W.M., Moore D.A. & Reynolds J.P. (2003) Evaluation of flunixin meglumine as an adjunct treatment for diarrhea in dairy calves. *Journal of the American Veterinary Medical Association* 223:1329–1333.

Barragan A.A., Pineiro J.M., Schuenemann G.M., Rajala-Schultz P.J., Sanders D.E., Lakritz J. & Bas S. (2018) Assessment of daily activity patterns and biomarkers of pain, inflammation, and stress in lactating dairy cows diagnosed with clinical metritis. *Journal of Dairy Science* 101: 8248–8258.

Barrier A.C., Coombs T.M., Dwyer C.M., Haskell M.J. & Goby L. (2014) Administration of an NSAID (meloxicam) affects lying behaviour after caesarean section in beef cows. *Applied Animal Behaviour Science* 155:28–33. doi:10.1016/j.applanim.2014.02.015.

Braz N., Carreira M., Carolino N., Rodrigues T. & Stilwell G. (2012) Effect of rectal or intravenous tramadol on the incidence of pain-related behavior after disbudding calves with caustic paste. *Applied Animal Behavior Science* 136:20–25.

Bromberg B.E., Song I.C. & Walden R.H. (1965) Hydrotherapy of chemical burns. *Plastic Reconstructive Surgery* 35:85–95.

Coetzee J.F. (2017) Pharmacological approaches to pain management in cattle. *Journal of Animal Science* 95 (Suppl 2):1.

Constable P.D. (2009) Treatment of calf diarrhea: Antimicrobial and ancillary treatments. *Veterinary Clinics of North America: Food Animal Practice* 25:101–120.

Cuttance E.L., Mason W.A., Yang D.A., Laven R.A., McDermott J. & Inglis K. (2019) Effects of a topically applied anaesthetic on the behaviour, pain sensitivity, and weight gain of dairy calves following thermocautery disbudding with a local anaesthetic. *New Zealand Veterinary Journal* 67:295–305.

de Boyer des Roches A., Faure M., Lussert A., Herry V., Rainard P., Durand D. & Foucras G. (2017) Behavioural and patho-physiological response as possible signs of pain in dairy cows during Escherichia coli mastitis: A pilot study. *Journal of Dairy Science* 100:8385–8397.

de Boyer des Roches A., Lussert A., Faure M., Herry V., Rainard P., Durand D., Wemelsfelder F. & Foucras G. (2018) Dairy cows under experimentally-induced Escherichia coli mastitis show negative emotional states assessed through Qualitative Behaviour Assessment. *Applied Animal Behaviour Science* 206:1–11.

Drillich M., Voigt D., Forderung D. & Heuwieser W. (2007) Treatment of acute puerperal metritis with flunixin meglumine in addition to antibiotic treatment. *Journal of Dairy Science* 90:3758–3763.

Dunn T.R., Ollivett T.L., Renaud D.L., Leslie K.E., LeBlanc S.J., Duffield T.F. & Kelton D.F. (2018) The effect of lung consolidation, as determined by ultrasonography, on first-lactation milk production in Holstein dairy calves. *Journal of Dairy Science* 101:5404–5410.

Fitzpatrick J.L., Nolan A.M., Young F.J., Hogarth C., McDonald T.M., Weber A., Eckersall P.D. & Davison H.C. (2000) Objective measures of pain and inflammation in dairy cows with clinical mastitis. *Proceedings of the 9th International Symposium on Veterinary Epidemiology and Economics, August 6–11, 2000, Breckenridge, Colorado, USA.*

Fitzpatrick C.E., Chapinal N., Petersson-Wolfe C.S., DeVries T.J., Kelton D.F., Duffield T.F., & Leslie K.E. (2013) The effect of meloxicam on pain sensitivity, rumination time, and clinical signs in dairy cows with endotoxin-induced clinical mastitis. *Journal of Dairy Science* 96:2847–2856.

Francoz D., Wellemans V., Dupre J.P., Roy J.P., Labelle F., Lacasse P. & Dufour S. (2017) A systematic review and qualitative analysis of treatments other than conventional antimicrobials for clinical mastitis in dairy cows. *Journal of Dairy Science* 100:7511–7770.

Frondelius L., Hietaoja J., Pastell M., Hanninen L., Anttila P. & Mononen J. (2018) Influence of postoperative pain and use of NSAID on heart rate variability of dairy cows. *Journal of Dairy Research* 85:27–29.

Gladden N., McKeegan D., Viora L. & Ellis K.A. (2018) Postpartum ketoprofen treatment does not alter stress biomarkers in cows and calves experiencing assisted and unassisted parturition: A randomized controlled trial. *Veterinary Record* 183:414.

Gladden N., Ellis K., Martin J., Viora L., & McKeegan D. (2019) A single dose of ketoprofen in the immediate postpartum period has the potential to improve dairy calf welfare in the first 48 h of life. *Applied Animal Behavior Science* 212:19–29.

Grøndahl-Nielsen C., Simonsen, H.B., Damkjer Lund J. & Hesselholt M. (1999) Behavioural, endocrine and cardiac responses in young calves undergoing dehorning without and with use of sedation and analgesia. *The Veterinary Journal* 158:14–20.

Haimerl P., Arlt S., Borchardt S. & Heuwieser W. (2017) Antibiotic treatment of metritis in dairy cows - A meta-analysis. *Journal of Dairy Science* 100:3783–3795.

Heppelmann M., Kofler J., Meyer H., Rehage J. & Starke A. (2009) Advances in surgical treatment of septic arthritis of the distal interphalangeal joint in cattle: A review. *The Veterinary Journal* 182:162–175.

Jeremejeva J., Orro T., Waldmann A. & Kask K. (2012) Treatment of dairy cows with PGF2-alpha or NSAID, in combination of antibiotics, in cases of postpartum uterine inflammation. *Acta Veterinaria Scandinavica* 54:45–45.

Karlen K.J., Baier F.S., Odegard A.L., Baumann R.M., Coetzee J.F., Kehoe S. & Vogel K.D. (2019, *in press*) Efficacy of oral meloxicam as primary pain mitigation following caustic paste disbudding of three day old Holstein calves. *Translational Animal Science* Oct 2019 (corrected proof). doi:10.1093/tas/txz151.

Lavan R., Chambers P. & Stafford K. (2012) Using non-steroidal anti-inflammatory drugs around calving: maximizing comfort, productivity and fertility. *Veterinary Journal* 192:8–12.

Leslie K.E. & Petersson-Wolfe C.S. (2012) Assessment and management of pain in dairy cows with clinical mastitis. *Veterinary Clinics of North America: Food Animal Practice* 28:289–305.

Lomb J., Neave H.W., Weary D.M., LeBlanc S.J., Huzzey J.M. & von Keyserlingk M.A.G. (2018a) Changes in feeding social and lying behaviors in dairy cows with metritis following treatment with a nonsteroidal anti-inflammatory drug as adjunctive treatment to an antimicrobial. *Journal of Dairy Science* 101:4400–4411.

Mainau E. & Manteca X. (2011) Pain and discomfort caused by parturition in cows and sows. *Applied Animal Behavior Science* 135:241–251.

Mainau E., Vuevas A., Ruiz-de-la-Torre J.L., Abbeloos E. & Manteca X. (2014) Effect of meloxicam administration after calving on milk production, acute phase proteins, and behavior in dairy cows. *Journal of Veterinary Behavior* 9:357–63.

McDougall S., Bryan M.A. & Tiddy R.M. (2009) Effect of treatment with the nonsteroidal anti-inflammatory meloxicam on milk production, somatic cell count, probability of re-treatment, and culling of dairy cows with mild clinical mastitis. *Journal of Dairy Science* 92:4421–4431.

McDougall S., Abbeloos E., Piepers S., Rao A.S., Astiz S., van Werven T., Statham J. & Perez-Villalobos N. (2016) Addition of meloxicam to the treatment of clinical mastitis improved subsequent reproductive performance. *Journal of Dairy Science* 99:2026–2042.

Mee J.F. (2008) Prevalence and risk factors for dystocia in dairy cattle: A review. *The Veterinary Journal* 176:93–101.

Meganck V., Hoflack G. & Opsomer G. (2014) Advance in prevention and therapy of neonatal dairy calf diarrhoea: A systematic review with emphasis on colostrum management and fluid therapy. *Acta Veterinaria Scandinavica* 56. doi:10.1186/s13028-014-0075-x.

Mellor D.J. & Stafford K.J. (2004) Animal welfare implication of neonatal mortality and morbidity in farm animals. *The Veterinary Journal* 168:118–133.

Milne M.H. (2004) Characterisation of inflammation and pain thresholds to mechanical stimulation in dairy cows with clinical mastitis and the effect of treatment with meloxicam. PhD Thesis. Glasgow, Scotland: University of Glasgow.

Milne M.H., Nolan A.M., Cripps P.J., Friton G.M. & Fitzpatrick J.L. (2004) Preliminary results on the effects of meloxicam (Metacam) on hypersensitivity in dairy cows with clinical mastitis. *Proceedings of the World Buiatrics Congress*, Quebec City, Quebec, Canada.

Morisse J.P., Cotte J.P. & Huonnic D. (1995) Effect of dehorning on behavior and plasma cortisol responses in young calves. *Applied Animal Behavior Science* 43:239–247.

Murray C.F. (2014) Characteristics, risk factors and management programs for vitality of newborn dairy calves. PhD Thesis. Guelph ON: University of Guelph.

Newby N.C., Pearl D.L., LeBlanc S.J., Leslie K.E., von Keyserlingk M.A.G. & Duffield T.F. (2013a) Effects of meloxicam on milk production, behavior, and feed intake in dairy cows following assisted calving. *Journal of Dairy Science* 96:3682–3688.

Newby N.C., Pearl D.L., LeBlanc S.J., Leslie K.E., von Keyserlingk M.A.G. & Duffield T.F. (2013b) The effect of administering ketoprofen on the physiology and behavior of dairy cows following surgery to correct a left displaced abomasum. *Journal of Dairy Science* 96:1511–1520.

Newby N.C., Tucker C.B., Pearl D.L., LeBlanc S.J., Leslie K.E., von Keyserlingk M.A.G. & Duffield T.F. (2014) An investigation of the effects of ketoprofen following rumen fistulation surgery in lactating dairy cows. *Canadian Veterinary Journal* 55:442–448.

Newby N.C., Leslie K.E., Putnam-Dingwell H.D., Kelton D.F., Weary D.M., Neuder L., Millman S.T. & Duffield T.F. (2017) The effects of periparturient administration of flunixin meglumine on the health and production of dairy cattle. *Journal of Dairy Science* 100:582–587.

Offinger J., Herdtweck S., Rizk A., Starke A., Heppelmann M., Meyer H., JanBen S., Beyerbach M. & Rehage J. (2013) Postoperative analgesic efficacy of meloxicam in lame dairy cows undergoing resection of the distal interphalangeal joint. *Journal of Dairy Science* 96:866–876.

Pearson J.M., Pajor E., Campbell J.R., Levy M., Caulkett N.A. & Windeyer M.C. (2019a) A randomised controlled trial investigating the effects of administering a non-steroidal anti-inflammatory drug to beef calves assisted at birth and risk factors associated with passive immunity, health, and growth. *Veterinary Record Open* 6(1). doi:10.1136/vetreco-2019-000364.

Pearson J.M., Pajor E., Campbell J.R., Caulkett N.A. & Winder M.C. (2019b) Clinical impacts of administering a non-steroidal anti-inflammatory drug to beef calves after assisted calving on pain and inflammation, passive immunity, health, and growth. *Journal of Animal Science* 97:1996–2008.

Peters M.D.P., Silveira I.D.B. & Fisher V. (2015) Impact of subclinical and clinical mastitis on sensitivity to pain of dairy cows. *Animal* 9:2024–2028.

Philipp H., Schmidt H., During F. & Salamon E. (2003) Efficacy of meloxicam as adjunct to a basic therapy for the treatment of diarrhoea in calves. *Acta Veterinaria Scandinavica* 44(Suppl 1):95.

Pohl A., Bertulat S., Borchardt S., Burfeind O. & Heuwieser W. (2016) Randomized, controlled clinical trial on the efficacy of nonsteroidal anti-inflammatory drugs for the treatment of acute puerperal metritis in dairy cows. *Journal of Dairy Science* 99:8241–8249.

Reedman C.N., Duffield T.F., DeVries T.J., Lissemore K.D., Karrow N., Li Z. & Winder C.B. (2019) Efficacy of pain control for caustic paste disbudding. *Proceedings of the Annual Meeting of the American Dairy Science Society, Cincinnati, Ohio, USA*.

Richards B.D., Black D.H., Christley R.H., Royal M.D., Smith R.F. & Dobson H. (2009) Effects of the administration of ketoprofen at parturition on the milk yield and fertility of Holstein-Friesian cattle. *Veterinary Record* 165:102–106.

Roberson J.R. (2012) Treatment of clinical mastitis. *Veterinary Clinics of North America: Food Animal Practice* 28:271–288.

Roussel A.J., Sriranganathan N., Brown S.A. & Sweatt D. (1988) Effect of flunixin meglumine on Escherichia coli heat-stable enterotoxin-induced diarrhea in calves. *American Journal of Veterinary Research* 49:1431–1433.

Sheldon M., Lewis G.S., LeBlanc S.J. & Gilbert R.O. (2006) Defining postpartum uterine disease in cattle. *Journal of Dairy Science* 65:1516–1530.

Siivonen J., Taponen S., Hovinen M., Pastell M., Joop Lensick B., Pyorala S. & Hanninen L. (2011) Impact of acute clinical mastitis on cow behaviour. *Applied Animal Behaviour Science* 132:101–106.

Smith G.W. (2009) Treatment of calf diarrhea: Oral fluid therapy. *Veterinary Clinics of North America: Food Animal Practice* 25:55–72.

Smith K.L. & Hillerton J.E. (1999) What do we mean by mastitis, is there a need for a redefinition? *Proceedings of the 38th Annual Meeting of the National Mastitis Council, Arlington, Virgina, U.S.A.*

Stafford K.J. & Mellor D.J. (2011) Addressing the pain associated with disbudding and dehorning in cattle. *Applied Animal Behavior Science* 135:226–231.

Stilwell G., Lima M.S. & Broom D.M. (2008) Comparing plasma cortisol and behavior of calves dehorned with caustic paste after non-steroidal anti-inflammatory analgesia. *Livestock Science* 119:63–69.

Stilwell G., de Carvalho R.C., Lima M.S. & Broom D.M. (2009) Effect of caustic paste disbudding, using local anaesthesia with and without analgesia, on behavior and cortisol of calves. *Applied Animal Behavior Science* 116:35–44.

Stilwell G., Carvalho R.C., Carolino N., Lima M.S. & Broom D.M. (2010) Effect of hot-iron disbudding on behaviour and plasma cortisol of calves sedated with xylazine. *Research in Veterinary Science* 88:188–193.

Stock M.L., Baldridge S.L., Griffin D. & Coetzee J.F. (2013) Bovine dehorning: Assessing pain and providing analgesic management. *Veterinary Clinics of North America: Food Animal Practice* 29:103–133.

Stojkov J., von Keyserlingk M.A.G., Marchant-Forde J.N. & Weary D.M. (2015) Assessment of visceral pain associated with metritis in dairy cows. *Journal of Dairy Science* 98:5352–5361.

Swartz T.H., Schramm H.H., Bewley J.M., Wood C.M., Leslie K.E. & Petersson-Wolfe C.S. (2018) Meloxicam administration either prior to or after parturition: effects on behavior, health, and production in dairy cows. *Journal of Dairy Science* 101:10515–10167.

Todd C.G., Millman S.T., McKnight D.R., Duffield T.F. & Leslie K.E. (2010) Nonsteroidal anti-inflammatory drug therapy for neonatal calf diarrhea complex: Effects on calf performance. *Journal of Animal Science* 88:2019–2028.

Vasseur E., Rushen J. & de Passille A.M. (2014) Short communication: Calf body temperature following chemical disbudding with sedation: Effects of milk allowance and supplemental heat. *Journal of Dairy Science* 97:5185–5190.

Vickers K.J., Neil L., Kiehlbauch L.M. & Weary D.M. (2005) Calf response to caustic paste and hot-iron dehorning using sedation with and without local anesthetic. *Journal of Dairy Science* 88:1454–1459.

Vidondo B., Stettler S., Stojiljkovic A., Mogel H., Gaschen V., Spadavecchia C., Casoni D. & Stoffel M.H. (2019) Assessment of potential neuropathic changes in cattle after cautery disbudding. *Research in Veterinary Science* 126:9–16.

Waelchli R.O., Thun R. & Stocker H. (1999) Effect of flunixin meglumine on placental expulsion in dairy cattle after a caesarean. *The Veterinary Record* 144:702–703.

Walker K.A., Duffield T.F. & Weary D.M. (2011) Identifying and preventing pain during and after surgery in farm animals. *Applied Animal Behaviour Science* 134:259–265.

Wenz J.R., Garry F.B. & Barrington G.M. (2006) Comparison of disease severity scoring systems for dairy cattle with acute coliform mastitis. *Journal of the American Veterinary Medical Association* 229:259–262.

Whay H.R. (2016) Lameness and pain in dairy cows: does it hurt and does it matter? *Proceedings of the First Regional Conference on Cow Comfort and Lameness, Tehran, Iran*.

Winder C.B., LeBlanc S.J., Haley D.B., Lissemore K.D., Godkin M.A. & Duffield T.F. (2016) Practices for the disbudding and dehorning of dairy calves by veterinarians and dairy producers in Ontario, Canada. *Journal of Dairy Science* 99:10161–10173.

Winder C.B., LeBlanc S.J., Haley D.B., Lissemore K.D., Godkin M.A. & Duffield T.F. (2017) Clinical trial of local anesthetic protocols for acute pain associated with caustic paste disbudding in dairy calves. *Journal of Dairy Science* 100:6429–6441.

Winder C.B., Miltenburg C.L., Sargeant J.M., LeBlanc S.J., Haley D.B., Lissemore K.D., Godkin M.A. & Duffield T.F. (2018) Effects of local anesthetic or systemic analgesia on pain associated with cautery disbudding in dairy calves: A systematic review and meta-analysis. *Journal of Dairy Science* 101:5411–5427.

Yakan S., Duzguer V. & Aksoy O. (2018) Effects of flunixin meglumine on oxidant and antioxidant system after disbudding with caustic paste in calves. *Acta Scientiae Veterinariae* 46:1602–1611.

5 Lameness and Injuries

Conclusions:

1. **There is a relatively high prevalence of lameness on the average Canadian dairy farm, with Canadian estimates ranging from 15–29% of the average herd; global estimates suggest average prevalence between 13–55%.**
2. **Dairy farmers consistently underestimate the true level of lameness in their herds, with true prevalence 2–4 times higher than farmer estimates in free-stall and tie-stall facilities, respectively. Underestimates typically reflect cases of mild lameness in the herd.**
3. **Most of the epidemiological research has been focused on lameness and its relationship with hoof health. Infectious lesions are responsible for the largest proportion of lameness, with digital dermatitis and footrot being the primary infectious lesions of the hoof. Sole ulcers and white line disease are the most prominent non-infectious causes of lameness.**
4. **There is a relatively high prevalence of hock injuries on the average Canadian dairy farm, with Canadian estimates ranging from 27–47%; global estimates suggest average prevalence between 12–81%. Knee and neck injuries have been reported to be less common (with neck injuries significantly less common).**
5. **Numerous risk factors have been associated with the incidence of lameness, notably housing, management, and cow-level factors:**
    a. **Housing factors: deep bedding with organic material or sand, rubber flooring, and pasture access are consistently associated with lower levels of lameness, whereas the use of mats or mattresses are consistently associated with a higher level of lameness. Stall design and curb height are also important risk factors.**
    b. **Management factors: stalls contaminated with manure, infrequent preventative hoof trimming, longer standing times for milking, and high stocking densities are associated with higher levels of lameness.**
    c. **Cow-level factors: lower body condition score ($\leq$ 2.5), older parity (> 1st lactation), injured hocks, and longer days in milk are associated with a higher level of lameness, whereas higher milk production is associated with a lower amount of lameness.**
6. **Numerous risk factors have been associated with the incidence of hock injuries, notably housing, management, and cow-level factors:**
    a. **Housing factors: deep bedding, access to pasture, and the use of sand as bedding are associated with lower levels of hock injuries, whereas herringbone parlours, stalls with mattresses, and short length of stalls are associated with an increased level of hock injuries.**

   b. **Management factors: the most critical practice associated with lower prevalence is to ensure that stalls have sufficient bedding and are kept clean and dry.**
   c. **Cow-level factors: cows in a higher lactation and days in milk had a higher level of hock injuries, as did cows that were lame or had a low body condition score.**

7. **Key preventative approaches for lameness include routine preventative and corrective hoof trimming, improving cushioning and traction through access to pasture or adding rubber flooring, deep-bedded stalls, sand bedding, ensuring appropriate stocking densities, reduced holding times, and the frequent use of routine footbaths.**
   a. **Very little research has been conducted on hock, knee, and neck injury prevention and recovery.**
8. **Education and training are needed to consistently identify lame cows, particularly mild lameness. These mild cases are most likely to benefit from treatment and would benefit from early detection and treatment. Current manual visual assessment methods adequately detect varying levels of lameness but suffer from a number of limitations (time to conduct, subjectivity, consistency). Automated detection methods continue to emerge; however, more work is needed to validate and prove the accuracy and reliability of these methods long-term.**
9. **Early identification of lameness and therapeutic trimming has been demonstrated to be effective for non-infectious causes of lameness. More work is needed to understand the best strategy to mitigate pain caused by lameness; however, it seems that a combined therapeutic trim, hoof block, and nonsteroidal anti-inflammatory (NSAID) may be the best strategy, particularly for non-infectious lameness.**
10. **Numerous researchers have concluded that both extrinsic (e.g., time, money, space) and intrinsic (e.g., farmer attitude, perception, priorities, and mindset) barriers exist to addressing lameness and injuries on dairy farms.**
11. **There are many diverse stakeholders in lameness and injury management including the farmer, farm staff, veterinarian, hoof trimmer, nutritionist, and other advisors. Addressing dairy cattle lameness and injuries must, therefore, consider the people involved, as it is these people who are influencing and implementing on-farm decisions related to lameness prevention, treatment, and control.**

5.1 Assessment and Prevalence

Upon exploring the most recent literature on the prevalence of lameness on dairy farms within Canada, it is clear that a relatively high prevalence of lameness exists in the industry. Of the studies that have examined lameness prevalence, the majority use a 5-point scale for lameness (gait-score) detection in free-stalls (Table 1) (Flower & Weary, 2006) and in-stall lameness behaviours for detection of lameness in tie-stalls (Table 2) (Gibbons et al., 2014). A score of > 2 is considered lame within this 5-point scoring system used in free-stalls. For tie-stall lameness detection, if 2 or more of the behavioural indicators are present, the cow is considered to be lame. Although the two scoring systems are comparable when detecting cows that are a score of > 2 out of 5, the in-stall lameness scoring system could underestimate the level of lameness (Gibbons et al., 2014; Palacio et al., 2017). An additional consideration when using these scoring systems is the subjective nature that could impact their accuracy. It has been suggested that observers need to review a large number of cows to improve inter-observer reliability (Channon et al., 2009). Croyle et al. (2018) identified that using a 3-day training workshop, 3 weeks of experience, and video training led to substantial agreement among 18 lameness assessors evaluated. This suggests that through appropriate training a suitable level of agreement with respect to lameness scoring can be achieved.

Table 1 Numerical lameness (gait) scoring in walking dairy cows from Flower and Weary (2006)

Score	Description	Behavioural Criteria
1	Fluid and smooth movement	Flat back Steady head carriage Hind hooves land on or in front of the fore hooves Joints flex freely Symmetrical gait All legs bear weight equally
2	Imperfect locomotion but ability to move freely is not diminished	Flat or mildly arched back Steady head carriage Hind hooves do not track up perfectly Joints slightly stiff Slightly asymmetric gait All legs bear weight equally
3	Capable of locomotion but ability to move freely is compromised	Arched back Steady head carriage Hind hooves do not track up Asymmetric gait Slight limp can be discerned
4	Ability to move is obviously diminished	Obvious arched back Head bobs slightly Hind hooves do not track up Joints are stiff and strides are hesitant Asymmetric gait Reluctant to bear weight on at least one limb but still uses that limb in locomotion
5	Ability to move is severely restricted and must be vigorously encouraged to move	Extremely arched back Obvious head bob Poor tracking up with short strides Obvious joint stiffness characterized by lack of joint flexion with very hesitant and deliberate strides Asymmetric gait Inability to bear weight on one or more limbs

Table 2 In-stall lameness detection behaviours as described by Gibbons et al. (2014)

Behaviour	**Description**
Weight shift	Regular, repeated shifting of weight from one hoof to another, defined as lifting each hind hoof completely off the ground at least twice. The hoof has to be lifted and returned to the same location and does not include stepping forward or backward
Stand on edge	Cow places one or more hooves on the edge of the stall while standing stationary. This does not include times when both hind hooves were in the gutter or when the cow briefly placed her hoof on the edge during a movement or step
Uneven weight	Repeatedly resting one foot more than the other, indicated by the cow raising a part or the entire hoof off the ground. This does not include raising of the hoof to lick or during kicking
Uneven movement	Uneven weight bearing between feet when the cow is encouraged to move from side to side. This is demonstrated by a more rapid movement by one foot than the other or by an evident reluctance to bear weight on a particular foot

Based on the most recent studies utilizing the methods discussed above, it is estimated that the prevalence of lameness in Canada is between 15–29.2% (Bouffard et al., 2017; Solano et al., 2015; Jewell et al., 2019a; Croyle, 2019; von Keyserlingk et al., 2012; Nash et al., 2016; King et al., 2016). These estimates were completed on 736 farms across Canada using the validated lameness detection measures mentioned in Table 3.

Table 3 Prevalence estimates of lameness from Canadian studies

Study	Year of completion	Geography	Housing type	Point-Scoring Used	Number of herds assessed	Number of cows assessed	Mean (Range) prevalence of lameness	Mean (Range) prevalence of severe lameness
Solano et al., 2015	2011 to 2012	Ontario, Quebec, and Alberta	Free-stall	5	141	5,637	21% (0 to 69%	NR
Bouffard et al., 2017	2011 to 2012	Quebec, Ontario	Tie-stall	4	100	3,278	25% (NR)	NR
Jewell et al., 2019a	2015 to 2016	Nova Scotia, New Brunswick, and PEI	Free-stall	5	46	2,719	21% (0 to 31%)	NR
			Tie-stall	4	33	1,498	15% (0 to 52%)	NR
Croyle, 2019	2015	Across Canada	Free-stall and tie-stall	5 (free stall); 4 (tie-stall)	374	NR	29.2% (0 to 85%)	NR
von Keyserlingk et al., 2012	2007 to 2008	British Columbia	Free-stall	5	42	3,948	28% (NR)	7% (NR)
Westin et al., 2016a	2010 to 2012	Canada and USA	Free-stall (AMS)	5	36	1,378	15% (3 to 46%)	4% (NR)
Nash et al., 2016	2011	Canada	Tie-stall	4	100	3,868	24% (NR)	NR
King et al., 2016	2014 to 2015	Canada	Free-stall (AMS)	5	41	NR	26% (3 to 58%)	2% (0 to 12%)

NR = Not Reported

From the studies that have been completed, it is also clear that producers often underestimate the amount of lameness in their herds. In free-stall farms, it is estimated that the true prevalence of lameness is between 1.8–2.3 times greater than the producer-perceived level of lameness, whereas in tie-stalls the true prevalence of lameness is between 3.4–4.1 times greater than the producer-perceived level of lameness (Croyle, 2019; Cutler et al., 2017). The discrepancy in the identification of lameness is mostly seen in mild lameness cases (score of 3 out of 5) and could be due to many producers (42% of respondents in a survey of over 1,000 producers across Canada; National Dairy Study) never assessing cows for lameness other than casual observation (Croyle, 2019). However, it is likely that the largest reason for discrepancy is that producers may have substantially different definitions of what they classify as being lame when compared to researchers. To rectify this difference, further education and extension strategies are needed to provide producers with training surrounding identification of lameness.

Outside of Canada, many studies have been completed evaluating the prevalence of lameness. A range of prevalence of 13.2–54.8% has been reported (Cook et al., 2016; Foditsch et al., 2016; Thompson et al., 2019; Barker et al., 2010; Griffiths et al., 2018; von Keyserlingk et al., 2012) (Table 4). Although many studies used the methods discussed above, others, particularly in the United Kingdom, used a 4-point scale to identify lameness; cows were considered lame if they had a score > 1 using the 4-point scale.

Table 4 Prevalence estimates of lameness from studies completed outside of Canada *(continued on p. 65)*

Study	Year of completion	Geography	Housing type	Point-Scoring Used	Number of herds assessed	Number of cows assessed	Mean (Range) prevalence of lameness	Mean (Range) prevalence of severe lameness
Cook et al., 2016	2012	Wisconsin, USA	Free-stall	5	66	9,690	13.2% (3 to 36%)	3% (0 to 16%)
Foditsch et al., 2016	2012 to 2013	New York, USA	Free-stall	5	23	7,687	14% (0 to 24%)	NR
Thompson et al., 2019	2015	Brazil	Pasture-based	5	6	252	39% (26 to 61%)	NR
Barker et al., 2010	2006 to 2007	England and Wales	Free-stall, bedded pack, and grazing	4	205	NR	36.8% (0 to 79%)	5% (0 to 31%)
Griffiths et al., 2018	2015 to 2016	England and Wales	Combination of indoor housing and pasture	4	61	14,700	31.6% (6 to 65%)	NR
Kielland et al., 2009	2006 to 2007	Norway	Free-stall and grazing	5	232	2,335	17% (NR)	5% (NR)
Amory et al., 2006	2003 to 2004	Netherlands	Free-stall and grazing	3	36	1,450	17% (4 to 31%)	NR
Husfeldt et al., 2012	2009	Minnesota, USA	Free-stall	5	34	37,271	17% (NR)	5% (NR)
Rutherford et al., 2009	NR	United Kingdom	Free-stall, bedded pack, and grazing	4	80	12,100	17% (NR)	NR
Popescu et al., 2013	NR	Romania	Tie-stall	3	80	3,192	19% (NR)	NR

NR = Not Reported

Table 4 Prevalence estimates of lameness from studies completed outside of Canada (continued)

Study	**Year of completion**	**Geography**	**Housing type**	**Point-Scoring Used**	**Number of herds assessed**	**Number of cows assessed**	**Mean (Range) prevalence of lameness**	**Mean (Range) prevalence of severe lameness**
Cook, 2003	2000 to 2001	Wisconsin, USA	Free-stall and tie-stall	4	30	3,621	23% (7 to 52%)	3% (0 to 17%)
Sarjokari et al., 2013	2005	Finland	Free-stall and grazing	5	87	3,459	23% (NR)	6% (NR)
Huxley et al., 2004	2002 to 2003	United Kingdom	Free-stall and grazing	4	15	NR	24% (7 to 56%)	NR
Espejo et al., 2006	2004	Minnesota, USA	Free-stall	5	50	5,626	25% (2 to 62%)	6% (0 to 21%)
Popescu et al., 2014	NR	Romania	Tie-stall and bedded pack	4	60	2,624	27% (NR)	NR
Dippel et al., 2009a	2004 to 2005	Austria	Free-stall and grazing	5	30	832	31% (6 to 70%)	12% (NR)
Chapinal et al., 2014b	2012	China	Free-stall	5	34	NR	31% (7 to 51%)	10% (0 to 27%)
Dippel et al., 2009b	2004 to 2005	Germany and Austria	Free-stall and grazing	5	103	3,514	33% (0 to 81%)	16% (NR)
von Keyserlingk et al., 2012	2007 to 2008	California, USA	Free-stall	5	39	8,112	31% (0 to 70%)	4% (NR)
von Keyserlingk et al., 2012	2007 to 2008	North East, USA	Free-stall	5	40	6000	55% (12 to 80%)	8% (NR)

NR = Not Reported

Several Canadian studies have evaluated hoof lesions that may be responsible for causing lameness. Digital dermatitis, also known as strawberry footrot, remains a common cause of an infectious lesion present on 69.7–94% of herds and affecting 9.3–22.9% of cows (Cramer et al., 2008; Cartwright et al., 2017; Solano et al., 2016). Of the non-infectious, sole ulceration and white line disease remain prominent with 4.7–9.3% and 2–4% of the cows being affected, respectively. On a herd-level basis, between 70.4–92% of herds have sole ulceration present in their cows and 50–93% of herds have white line disease present.

Injuries. Similar to lameness, there are many different methods that have been used to detect hock injuries. The most commonly used method is a 4-point scale (Table 5), where a score of > 1 is considered to be a hock injury (Gibbons et al., 2012). The scale developed by Gibbons et al. (2012) is also commonly used for detecting knee (Table 6) and neck (Table 7) injuries. For knee and neck injuries, a score of > 1 is considered to be an injury.

Table 5 Hock scoring as described by Gibbons et al. (2012)

Score	Description
0	No swelling. No hair is missing. Thinning of hair or broken hair
1	No swelling or minor swelling (< 1 cm). Bald area on the hock
2	Medium swelling (1–2.5 cm) and/or lesion on bald area
3	Major swelling (> 2.5 cm). May have bald area/lesion

Table 6 Knee scoring as described by Gibbons et al. (2012)

Score	Description
0	No skin change
1	Hairless patch
2	Lesion/scab with or without medium swelling (< 2.5 cm). May have a hairless patch
3	Major swelling (> 2.5 cm) with or without lesion or hairless patch

Table 7 Neck scoring as described by Gibbons et al. (2012)

Score	Description
0	No swelling. No hair is missing. Some hair loss or broken hair
1	No swelling. Bald area is visible
2	Broken skin or scab and/or swelling. May have bald area

The prevalence of injuries has not been as well studied when compared to lameness. In Canada, the prevalence of hock injuries is estimated to be between 27–47%, whereas in other parts of the world it has been reported to range from 12.2–81.2% (Table 8). It is estimated that 14–43% of cows have knee injuries and 1–33% of cows have neck injuries in Canada.

One type of injury that is not commonly evaluated in the literature is tail injuries, which may cause a significant amount of pain and distress to dairy cattle. Estimates are sparse; however, Zurbrigg et al. (2005) estimated that of the 317 dairy farms visited in Ontario, most (62%) did not have any broken tails, but 5% of farms had a prevalence of more than 15% of their cows with broken tails. Beyond this, very little information is reported in the literature.

Table 8 Prevalence estimates of injuries from studies completed in Canada and worldwide

Study	Year of completion	Geography	Housing type	Method used	Number of herds assessed	Number of cows assessed	Mean (Range) prevalence of hock injuries	Mean (Range) prevalence of knee injuries	Mean (Range) prevalence of neck injuries
Ekman et al., 2018	2014 to 2015	Sweden	Free-stall	Mild hock injury (loss of hair) and severe hock injury (evident swelling or ulceration, with or without hair loss)	99	3,217	74% (68% mild [23 to 100%] and 6% severe [0 to 32%])	N/A	N/A
Zaffino-Heyerhoff et al., 2014	2011	Alberta and Ontario	Free-stall	Gibbons et al., 2012	90	2,304	47% (NR)	24% (NR)	9% (NR)
Jewell et al., 2019b	2015 to 2016	New Brunswick, Nova Scotia, PEI	Free-stall	Gibbons et al., 2012	40	3,129	39% (0 to 83%)	14% (0 to 60%)	1% (0 to 21%)
			Tie-stall	Gibbons et al., 2012	33	1,523	39% (12 to 75%)	17% (2 to 78%)	5% (0 to 31%)
Nash et al., 2016; Bouffard et al., 2017	2011	Ontario and Quebec	Tie-stall	Gibbons et al., 2012	100	3,868	56% (NR)	43% (NR)	33.4% (NR)
Cook et al., 2016	2012	Wisconsin, USA	Free-stall	Similar scales to Gibbons et al., 2012	66	9,690	12.2% (0 to 81%)	6.2% (0 to 35%)	2.0% (0 to 19%)
Croyle, 2019	2015	Across Canada	Free-stall and Tie-stall	Gibbons et al., 2012	374	N/A	27.0% (0 to 100%)	N/A	N/A
von Keyserlingk et al., 2012	2007 to 2008	British Columbia	Free-stall	Similar scales to Gibbons et al., 2012	42	3,948	42.3% (0 to 82%)	N/A	N/A
		California	Free-stall	Similar scales to Gibbons et al., 2012	39	8,112	56.2% (0 to 100%)	N/A	N/A
		North East USA	Free-stall	Similar scales to Gibbons et al., 2012	40	6000	81.2% (18 to 100%)	N/A	N/A

NR = Not reported

Similar to lameness, assessor training is necessary to increase the precision and accuracy of injury scoring to ensure that consistent and valid results are seen across farms (Lievens, 2001). Having a training program that includes classroom instruction and on-farm training with follow-up after some assessing experience has been demonstrated to produce substantial agreement between multiple assessors (Gibbons et al., 2012; Croyle et al., 2018).

5.2 Risk Factors from Epidemiological Studies (Lameness and Injuries)

Lameness. There have been many studies completed highlighting different management practices and demographic factors associated with lameness. It is clear from the literature that housing and its management is critical. Specifically, deep bedding with organic material or sand, rubber flooring, and pasture access are consistently associated with lower levels of lameness, whereas the use of mats or mattresses is consistently associated with a higher level of lameness. For "deep" bedding, the definition varied depending on the study evaluated. Some studies reported a dose-dependent relationship, where the deeper the bedding the lower the lameness (Croyle, 2019), while others quantified "deep" as $\geq$ 2 cm of bedding on top of the stall base (Solano et al., 2015). Additionally, stall design, specifically small stalls with large cows and curb height, were associated with lameness. Other factors were also identified and are described in Table 9. Management has also been identified as being an important factor to consider with respect to lameness. Specifically, stalls that were wet or had higher levels of fecal contamination, less preventative hoof trimming or preventative management practices, longer time away from the pen for milking, and higher stocking density were associated with higher lameness prevalence. For cow-level factors, lower body condition score ($\leq$ 2.5), older parity (> 1st lactation), injured hocks, and longer days in milk were associated with a higher prevalence, whereas higher milk production was associated with a lower amount of lameness.

Many epidemiological studies have also been conducted to identify factors that are associated with the development of infectious and non-infectious causes of lameness. If we evaluate the broad category of claw horn lesions, higher parity cows have been reported to be associated with a higher level of claw horn lesions, previous lameness, and tie-stall housing (Table 10). Many other factors have been identified individually for claw horn lesions, sole ulcers, white line disease, and heel horn erosion; however, these findings have not been replicated in multiple studies (Table 10).

Table 9 Factors associated with lameness

	Lower prevalence of lameness	Higher prevalence of lameness
Housing factors	Kept cows on pasture (Adams et al., 2017; Hernandez-Mendo et al., 2007; Olmos et al., 2009) Access to pasture (Chapinal et al., 2013; de Vries et al., 2015) Use of sand bedding (Adams et al., 2017; Chapinal et al., 2013; Cook, 2003; Salfer et al., 2018; Solano et al., 2015) Rubber flooring when compared to concrete (Bergsten et al., 2015; Chapinal et al., 2013) Use of deep bedding (Chapinal et al., 2013; de Vries et al., 2015; Dippel et al., 2009b; Griffiths et al., 2018; Jewell et al., 2019a; Rouha-Mulleder et al., 2009; Salfer et al., 2018; Solano et al., 2015; Croyle, 2019) Use of soft mattress when compared to concrete (de Vries et al., 2015) Distance of neck-rail from the rear curb (Chapinal et al., 2013) Neck-rail diagonal > 1.94 m (Rouha-Mulleder et al., 2009) Rubber flooring when compared to concrete (Bergsten et al., 2015; Chapinal et al., 2013)	Tie-stall without exercise (Bielfeldt et al., 2005) No access to pasture (de Vries et al., 2015) Zero-grazing farm (Haskell et al., 2006) Mats or mattresses when compared to sand (Dippel et al., 2009b; Salfer et al., 2018) Presence of head lunge impediments (Chapinal et al., 2013) Obstructed lunge space (Westin et al., 2016a) Neck-rail to curb diagonals too short (Dippel et al., 2009b) Concrete for lying area when compared to soft mats or mattresses (de Vries et al., 2015) Presence of damaged concrete (Barker et al., 2010) Presence of area behind the brisket board filled with concrete (Espejo & Endres, 2007) Brisket board height more than 15.24 cm (Espejo & Endres, 2007) Less than 2 cm groove spacing width (Griffiths et al., 2018) Small free-stalls and large cows (Haskell et al., 2006; Westin et al., 2016a) Narrower stalls, lower and less forward tie-rails (Bouffard et al., 2017) Curb height of stalls (King et al., 2016, 5 cm increase in curb height over 20.9 cm, increased risk of severe lameness; Rouha-Mulleder et al., 2009, lower prevalence of lameness when curb height < 0.22m) Slatted flooring (Rouha-Mulleder et al., 2009) Slippery floors (Solano et al., 2015) Narrow feed alley (Westin et al., 2016a)
Management factors	Larger operations (Adams et al., 2017) Lower herd size (Chapinal et al., 2013)	Higher stocking density (King et al., 2016; Rouha-Mulleder et al., 2009)

	Herd consisting of breeds other than Holsteins (Barker et al., 2010) Closed herd status (de Vries et al., 2015) Feet of all cows trimmed on a maintenance schedule once or twice annually (Espejo & Endres, 2007) Preventative hoof trimming in early lactation (Griffiths et al., 2018) Examining and picking up cows' feet within 48 hours of detecting lameness (Croyle, 2019) More frequent footbathing (at least once a week; Griffiths et al., 2018) More frequent scraping of manure alleys (King et al., 2016)	Not treating lame cows within 48 hours of detection (Barker et al., 2010) Increased percentage of stalls with fecal contamination (Chapinal et al., 2013) Wet stalls (Jewell et al., 2019a) Increased time away from the pen for milking (Espejo & Endres, 2007; Jewell et all., 2019a) Use of automatic scrapers (Barker et al., 2010)
Cow-level factors	Higher BCS (Foditsch et al., 2016) High milk yield in previous lactation (Foditsch et al., 2016) Higher milk production (Jewell et al., 2019a; Solano et al., 2015) First lactation (Jewell et al., 2019a; Solano et al., 2015)	Low BCS ($\leq$ 2.5) (Dippel et al., 2009b; Green et al., 2014; Jewell et al., 2019a; King et al., 2017; Lim et al., 2015; Solano et al., 2015; Westin et al., 2016b) Lame previously (Green et al., 2014) Larger width of cow (Jewell et al., 2019a) Higher DIM (Jewell et al., 2019a; Lim et al., 2015) Greater parity (King et al., 2017; Lim et al., 2015) Cows pushing each other or turning sharply to enter parlour (Barker et al., 2010) Incidence of claw horn disruption lesions in subsequent lactation (Foditsch et al., 2016) Overgrown claws (Solano et al., 2015) Sires predicted transmitting ability for strength (Foditsch et al., 2016) Injured hocks (Solano et al., 2015; Westin et al., 2016a,b; Croyle, 2019)

Table 10 Factors associated with the development of claw horn lesions

	Lower prevalence	**Higher prevalence**
Claw horn lesions	Use of rubber mats (Haggman & Juga, 2015) Use of a TMR (Haggman & Juga, 2015) Pasture access (Olmos et al., 2009)	Observed to be lame (Foditsch et al., 2016) Old cows (Foditsch et al., 2016; Haggman & Juga, 2015) Cows with claw horn lesions in previous lactation (Foditsch et al., 2016) High milk yield in previous lactation (Foditsch et al., 2016) Cows in early and mid-lactation (Haggman & Juga, 2015) Cows always kept indoors had higher odds of non-infectious claw disorders than cows with access to outdoors during summer, whereas cows with access to summer pasture and winter exercise yard were the most likely to have infectious claw disorders (Haggman & Juga, 2015)
Sole ulcers	Rubber flooring (Bergsten et al., 2015)	Tie-stall without exercise (Bielfeldt et al., 2005) Higher parity (Holzhauer et al., 2008) Parity of 4 or greater (Barker et al., 2009) Use of roads or concrete cow tracks between parlour and grazing (Barker et al., 2009) Higher DIM (Holzhauer et al., 2008) Use of lime on free-stalls (Barker et al., 2009) Housing in free-stalls with sparse bedding (Barker et al., 2009) Increased frequency of alley scraping (Cramer et al., 2009) Low BCS (Green et al., 2014) Lame previously (Green et al., 2014)
White line disease	Trimming heifers before calving (Cramer et al., 2009) Rubber flooring (Fjeldaas et al., 2011)	Tie-stall with exercise compared to tie-stalls with no exercise (Bielfeldt et al., 2005) Increasing parity (Barker et al., 2009) Increasing herd size (Barker et al., 2009) Cows at pasture by day and housed at night (Barker et al., 2009) Concrete yards or alleys (Barker et al., 2009) Year-round outdoor access in tie-stalls compared to seasonal and no access (Cramer et al., 2009) Low BCS (Green et al., 2014) Lame previously (Green et al., 2014)
Heel horn erosions	Housed on slatted concrete flooring (Haufe et al., 2012)	Tie-stall housing (Bielfeldt et al., 2005) Multiparous cows (Chapinal et al., 2010a) Increased DIM (Chapinal et al., 2010a)

Many factors have been reported to be associated with a higher prevalence of digital dermatitis within a dairy herd including higher level of dirty legs (Relun et al., 2013), solid grooved flooring compared to solid non-grooved concrete (Barker et al., 2009) and textured concrete flooring (Wells et al., 1999), higher moisture level in the environment (Rodriguez-Lainz et al., 1996; Read & Walker, 1998), introduction of new animals into the herd (Rodriguez-Lainz et al., 1996, 1999; Wells et al., 1999), first parity animals (Somers et al., 2005; Read & Walker, 1998; Rodriguez-Lainz et al., 1999) and improper disinfection of hoof trimming equipment (Wells et al., 1999). The inciting bacteria of digital dermatitis, *Treponema*, can survive for several hours after contact and specific disinfectants, such as sodium hypochlorite, Virkon, or FAM30, are necessary to kill the bacteria (Gillespie et al., 2020). Increased access to pasture (Somers et al., 2005, Read & Walker, 1998; Wells et al., 1999; Onyiro et al., 2008), slatted flooring (Fjeldaas et al., 2011; Somers et al., 2005), dry cows (Sommers et al., 2005; Holzhauer et al., 2006), and cows with a high antibody mediated immune response (Cartwright et al., 2017; Palmer & O'Connell, 2015) have each been associated with reduced digital dermatitis.

Injuries. Similar to lameness, a significant number of studies have identified housing, management, and cow-level factors that are associated with hock injuries. Housing factors that were commonly associated with reduced hock injuries included deep bedding, access to pasture, and the use of sand as bedding; whereas, herringbone parlours, stalls with mattresses, and short length of stalls were associated with an increased level of hock injuries (Table 11). In terms of management, the most critical practice associated with lower prevalence was to ensure that stalls were kept clean and dry. Cows that were in a higher lactation and days in milk had a higher prevalence of hock injuries, as did cows that were lame or had a low body condition score.

Table 11 Factors associated with hock injuries

	Lower prevalence of hock injuries	Higher prevalence of hock injuries
Housing factors	Open/dry lot (Adams et al., 2017) Deep bedding (Barrientos et al., 2013; de Vries et al., 2015; van Gastelen et al., 2011) Use of sand as bedding (Barrientos et al., 2013; Zaffino-Heyerhoff et al., 2014; Jewell et al., 2019b; van Gastelen et al., 2011) Access to pasture in dry cow period (Barrientos et al., 2013) Soft mattress compared to rubber mats or concrete (de Vries et al., 2015; Ekman et al., 2018) Peat moss bedding when compared to sawdust and straw (Ekman et al., 2018) Appropriate stall width (Ekman et al., 2018) Use of straw or hay bedding (Jewell et al., 2019b; Keil et al., 2006) Manger wall height < 10 cm or > 20 cm (Jewell et al., 2019b) Chain length < 50 cm (Jewell et al., 2019b) Longer duration of outdoor access (Keil et al., 2006) (50 h min outside spent outdoors over 4-week period in tie-stall)	Use of automatic scrapers (Barrientos et al., 2013) Concrete for lying area when compared to soft mats or mattresses (de Vries et al., 2015) Herringbone parlours compared to tandem parlours (Ekman et al., 2018) and parallel parlours (Jewell et al., 2019b) Increasing stall gradient (Haskell et al., 2006) Use of sawdust for bedding when compared to sand (Barrientos et al., 2013) Stalls with mattresses when compared to concrete and sand (Zaffino-Heyerhoff et al., 2014; Jewell et al., 2019b; Nash et al., 2016; Salfer et al., 2018) Stall length < 165 cm (TS) or < 182 cm (FS) (Jewell et al., 2019b; Nash et al., 2016) High local pressure or friction on hard surfaces (Kester et al., 2014) Narrower stall width (Nash et al., 2016) Further forward tie-rail position (Nash et al., 2016) Shorter chain length (Nash et al., 2016) Presence of an electric trainer (Zurbrigg et al., 2005)
Management factors	Bedding dry matter ≥ 83.9% (Barrientos et al., 2013)	Increased percentage of stalls with fecal contamination (Barrientos et al., 2013) Increased stocking density (Barrientos et al., 2013) Poor bedding management (Barrientos et al., 2013) Cleaner cows (Ekman et al., 2018) Wet bedding (Jewell et al., 2019b)
Cow-level factors	First lactation cows (Jewell et al., 2019b) Presence of dirty flank (Jewell et al., 2019b)	Holsteins (Ekman et al., 2018) Higher DIM (Ekman et al., 2018; Zaffino-Heyerhoff et al., 2014; Jewell et al., 2019; Nash et al., 2016) Older cows (Ekman et al., 2018; Nash et al., 2016) Lame cows (Zaffino-Heyerhoff et al., 2014; Nash et al., 2016) Low BCS (Nash et al., 2016; Jewell et al., 2019b) Increased cow width (Nash et al., 2016)

Fewer studies were completed to determine risk factors that were associated with knee and neck injuries. For knee injuries, older cows were associated with a higher prevalence of injury (Table 12); whereas, for neck injuries, low neck-rails (< 140 cm in height) were associated with a higher prevalence of injury (Table 13).

Table 12 Factors associated with knee injuries

Lower prevalence of knee injuries	**Higher prevalence of knee injuries**
Rubber flooring when compared to concrete (Zaffino-Heyerhoff et al., 2014) Manger height 10 to 19 cm (Jewell et al., 2019b) Higher DIM (Nash et al., 2016) Higher BCS (Nash et al., 2016) Increased stall width (Nash et al., 2016)	Concrete stall bases compared to mattresses (Zaffino-Heyerhoff et al., 2014) Older cows (Zaffino-Heyerhoff et al., 2014; Jewell et al., 2019b) Slip or fall when moving into holding area (Zaffino-Heyerhoff et al., 2014) Stall width < 120 cm (Jewell et al., 2019b) Dirty flank (Jewell et al., 2019) Recycled construction bedding (Jewell et al., 2019b) Decreased chain length (Nash et al., 2016) Decreased bed length (Nash et al., 2016)

Table 13 Factors associated with neck injuries

Higher prevalence of neck injuries
Older cows (Zaffino-Heyerhoff et al., 2014; Jewell et al., 2019b)
Low feed/tie-rails (< 140 cm) (Zaffino-Heyerhoff et al., 2014; Zurbrigg et al., 2005) and higher tie-rail and less forward tie-rails (Bouffard et al., 2017)
Manger height < 10 cm in tie-stalls (Jewell et al., 2019b)
Tie-rail to curb distance < 180 cm or 200 to 209 cm (Jewell et al., 2019b)
Cow height 146 to 149 cm or > 153 cm (Jewell et al., 2019b)
Post and rail feed-rail (Jewell et al., 2019b)
Shorter chains (Bouffard et al., 2017)
Narrower stalls (Bouffard et al., 2017)

5.3 Prevention

Many of the risk factors associated with lameness mentioned above are important to consider when evaluating strategies to prevent lameness. Clearly, how cows are housed can have a significant impact on the prevalence of lameness, and making targeted changes in housing design can lead to reduced lameness. Morabito et al. (2017) reported that farmers that had increased bedding quantity, changed the stall base, and grooved crossover alleys had a lower prevalence of lameness and longer lying times than producers that made no changes. Hence, farmers should be encouraged to make positive changes to improve cow comfort within their herds, which will ultimately lead to a reduced level of lameness (Morabito et al., 2017).

One of the major strategies in the control of lameness is routine hoof trimming, aiming to maintain correct weight bearing and minimize and prevent lesion development (Manske et al., 2002); however, very few studies have been conducted to quantify the impact of hoof trimming on lameness score (Stoddard & Cramer, 2017). Additionally, it is difficult to interpret the studies that have been completed, as all the studies conducted included only lame cows (no controls/non-lame cows for comparison). Of the studies completed, mixed results have been reported, with one study demonstrating a positive effect of hoof trimming with improved gait of cows (Tanida et al., 2011); however, others identified that lameness score increased in the short period of time following hoof trimming (Chapinal et al., 2010b; Van Hertem et al., 2014). Other studies, however, have reported that hoof trimming reduces pressure on the claw and increased time to develop a case of lameness (van der Tol et al., 2004; Carvalho et al., 2006; Bryan et al., 2012). An increased frequency of hoof trimming has also been reported to be efficacious in reducing cases of lameness and horn-type lesions (Manske et al., 2002; Hernandez et al., 2007). Lastly, it is presumable that the type of method and quality of the trim may have an influence on lameness; however, further work is needed to explore these effects more specifically.

Claw horn disruption lesions (CHDL), such as sole ulcers and white line disease, can be prevented through improvements to housing systems to enhance cow comfort and through management strategies to reduce total standing time and increased resting time (Bicalho & Oikonomou, 2013). Concrete walking surfaces are clearly a major risk factor and allowing pasture access has been reported to have an impact in reducing CHDL (Hernandez-Mendo et al., 2007). Rubber flooring has been reported to have inconsistent effects with some studies identifying positive effects (Ouweltjes et al., 2011; Vanegas et al., 2006) and others finding negative effects (Fjeldaas et al., 2011; O'Driscoll et al., 2009; Vokey et al., 2001). It is likely that some of the benefit of improved cushioning and traction is neutralized by additional standing time and claw overgrowth (Bicalho & Oikonomou, 2013). Improved resting time achieved through deep-bedded stalls (Andreasen & Forkman, 2012), sand bedding, prevention of overcrowding, proper stall design, and reduced time standing waiting to be milked (Main et al., 2010) or held in headlocks are each thought to reduce the levels of CHDL (Bicalho & Oikonomou, 2013). Hence, ensuring that resting time is maximized can aid in preventing lesions of the claw. Genetic selection may also play a role in controlling CHDL with low to moderate heritability estimates being reported for specific foot lesions (Laursen et al., 2009; van der Linde et al., 2010; van der Waaij et al., 2005). Focusing on conformational traits, such as higher foot angle (Oikonomou et al., 2013), rear legs rear view (Boettcher et al., 1998), thurl width (Boettcher et al., 1998), and mammary composite traits (Onyiro et al., 2008) may also reduce CHDL.

Several control strategies have been recommended for digital dermatitis, including maintaining a clean, dry environment, individual topical treatment of affected cows, and footbathing (Laven & Logue, 2006; Nuss, 2006; Döpfer et al., 2012). Footbaths have been demonstrated to be effective in controlling digital dermatitis, with copper sulfate being effective in reducing the prevalence (Speijers et al., 2010; Solano et al., 2017; Fjeldaas et al., 2014). It is suggested that a 5% copper sulfate footbath could be completed at least weekly when the prevalence of digital dermatitis is high (Speijers et al., 2010). To maximize the effectiveness of the footbaths, it is important to get each foot submerged into the bath. The probability of each rear foot getting at least two immersions was 95% at a footbath length of 3.0 m and a significant increase in the frequency of three and four immersions per foot at a footbath length between 3.0 to 3.7 m long (Cook et al., 2012). This suggests that footbaths should be at least 3.0 m long to get ample submersion of the cows' feet.

With respect to injuries, very little research has been completed regarding preventative strategies to reduce the incidence of injuries. From the risk factors associated with the prevalence of injuries, it is clear that a variety of housing, management, and cow-level factors are involved. Based on previous studies, proper housing design and use of deep bedding appear to be the most consistently identified factors that can help to reduce the prevalence of injuries. To prevent tail injuries, it is necessary to prevent unnecessary force to a cow's tail. It is unlikely that accidently breaking a cow's tail can occur due to the substantial force needed to break the tail (Laven & Jermy, 2020). Hence, proper low-stress handling techniques, especially when moving cows into the parlour are needed to prevent the occurrence of tail injuries.

5.4 Early Identification and Treatment

Assessment. As described above, manual, visual lameness scoring methods are most commonly used to evaluate lameness, with 25 methods being described in the literature evaluating gait and posture (Schlageter-Tello et al., 2014). The main advantage of using these scoring systems is that they are non-invasive and can be easily applied under farm conditions (Whay, 2002). However, there are a number of limitations to these methods. Visual locomotion scoring may not be sensitive enough to detect small changes in gait and may not always express all traits of gait and posture described by the locomotion scoring (Engel et al., 2003; Tadich et al., 2010; Schlageter-Tello et al., 2014). These manual rating systems are also subjective, as evidenced by the large variation in agreement and reliability reported in the literature (Schlageter-Tello et al., 2014). However, training of the raters has been consistently demonstrated to reduce the subjectivity of the measure (Croyle et al., 2018; March et al., 2007). It is also suggested that raters continue to receive periodic training to avoid any change in how raters apply the definition of the measurement (Kazdin, 1977). Another important consideration, especially for dairy producers, is the time required to complete manual visual scoring. As manual scoring requires a significant time commitment, the use of this method could impede the ability of farmers to conduct the necessary lameness examinations to ensure prompt treatment (Schlageter-Tello et al., 2014).

Several automatic locomotion scoring systems have been described and used to evaluate lameness (Flower & Weary, 2009; Schlageter-Tello et al., 2014). While most technological approaches are still in the early days of development and commercialization, they offer important advantages over manual methods; namely, they may allow for more consistent assessment, cut the time needed to monitor for lameness, and may be able to detect lameness earlier than most people can.

Treatment. Very few studies have been completed regarding the appropriate treatment of lameness. Of the studies that have been completed, most of the literature evaluates the treatment of digital dermatitis (Potterton et al., 2012). The application of antibiotics (topical tetracycline, Cutler et al., 2013; oxytetracycline, Hernandez et al., 1999, Berry et al., 2012; lincomycin, Moore et al., 2001, Berry et al., 2012; and a copper-containing preparation, Hernandez et al., 1999) were reported to be effective in improving resolution of digital dermatitis. However, a recent meta-analysis identified that the effectiveness of these treatments remains unclear as the body of knowledge and current quality of evidence is low (Ariza et al., 2017).

The effect of intervening with therapeutic trimming for claw horn lesions has also been studied. Therapeutic trimming consists of the removal of all necrotic and loose or undermined horn to create an aerobic environment and minimize the possibility of abscess formation. This is followed by adjusting weight bearing on diseased or damaged claws (Shearer et al., 2013). Therapeutic trimming of cows identified with lameness leads to high recovery from lameness; however, recovery is dependent on the severity of the lameness, with severely lame cows being less likely to recover (Miguel-Pacheco et al., 2017). Another important consideration with therapy is whether the case is chronic or has been occurring for a long duration of time, as it is likely that the success of therapy will be lower. Given the high proportion of cows affected with chronic lameness (Randall et al., 2018), future research needs to be completed to determine the best methods to resolve chronic cases of lameness. Hence, early identification of lameness is critical to improve the outcome of the lameness case. Early intervention resulted in less severe foot lesions, reduced the prevalence of lameness, and cattle were less likely to be treated for subsequent lameness cases (Leach et al., 2012). However, on many farms, as mentioned previously, farmers may have difficulty in the early identification of lameness, with 40% of cows being treated for lameness by farmers more than 3 weeks after being identified as lame by researchers (Alawneh et al., 2012). Several researchers suggest that combining lameness scoring on a bi-weekly basis and appropriate treatment (i.e., therapeutic foot trimming) leads to higher cure rates of lameness and an increased number of sound cows (Groenevelt et al., 2014). In addition, when evaluating advanced methods of lameness treatment, the use of digit amputation as a therapy for lameness should be discouraged due to a slow return to productivity and higher culling risk when compared to arthrodesis surgery (Bicalho et al., 2006).

With respect to injuries, virtually no published studies have been completed on how to appropriately treat or manage cows with hock, neck, or knee injuries. Based on the previously presented risk factors, it is expected that improving the cushioning of cows' lying surface and bedding may aid in recovery. However, more research is needed to explore the recovery and remediation time associated with different treatment methods to manage injuries.

Pain management. Lameness is a painful condition that results in cows changing their gait due to pain resulting from infections and lesions that are primarily in their hooves (Whay et al., 1998; O'Callaghan et al., 2003). In addition to managing pain through corrective trimming and hoof blocks, the use of analgesics has been demonstrated to aid in recovery of lameness; however, a scant amount of controlled studies have been completed on this topic (Coetzee et al., 2017). The injection of a local anesthetic into the heel bulb of the affected lame limb led to improved weight bearing on the limb and reduced lameness score (Rushen et al., 2006); however, this is the single study that evaluated this technique, likely due to the practicality of its application. Multiple field trials have been conducted using the nonsteroidal anti-inflammatory drug (NSAID) ketoprofen. Following injection with ketoprofen, more even weight distribution was seen in all 4 limbs (Flower et al., 2008), and a reduced variation in weight distribution was reported (Chapinal et al., 2010c). A mild improvement in lameness score was also observed (Flower et al., 2008). Combining a corrective trim, hoof block, and injection with ketoprofen led to an improved cure of lameness 35 days after treatment compared to those solely receiving a corrective trim (Thomas et al., 2015). The use of another NSAID, flunixin meglumine, has also shown some benefit when provided to lame cows. In an induced lameness model, use of flunixin at the time of lameness induction and 12 hours later led to improved locomotion scores and more pressure placed on the affected foot (Schulz et al., 2011). More research is needed to understand the best strategy to mitigate pain caused by lameness; however, it seems that a combined therapeutic trim, hoof block, and NSAID may be the best strategy for the management of the first case of lameness. For cows with multiple cases of lameness, the evidence is less clear with respect to both treatment and pain management, and this should be a focus of future research. Another area of further work is to understand pain that occurs as a result of the process of therapeutic trimming, where the cow's legs are placed in potentially injury-inducing positions or cows are moved aggressively into the hoof trimming chute. Proper cattle movement and training on the use of hoof trimming chutes could mitigate some of the consequences of placing cows in a trim chute; however, more work is necessary to understand whether pain mitigation is necessary.

Hygromas, as a result of hock, neck, or knee injuries, are considered to be a painful condition where simple manipulation of the joint causes pain (Kester et al., 2014; Dyce et al., 2010; Aiello & Moses, 2010). However, similar to the treatment of injuries, very little evidence is available to suggest the impact of providing pain mitigation or the best strategy to reduce pain related to these injuries.

5.5 Farm-Level Barriers

As outlined above, the multifactorial nature of lameness (Solano et al., 2015; Cook et al., 2016) makes its prevention and control a challenge. However, simply understanding the root causes of lameness, and the necessary farm-specific changes that are required to reduce its occurrence, is only one aspect to its prevention and control. Reducing lameness in dairy herds requires farmers to adapt or change existing practices, which often requires investment and a change in behaviour. To improve the levels of lameness and injuries on Canadian dairy farms, it is therefore important to account for producers' attitudes and intention to take action (Bruijnis et al., 2013).

Numerous researchers have concluded that both extrinsic (e.g., time, money, space) and intrinsic (e.g., farmer attitude, perception, priorities, and mindset) barriers exist to addressing lameness on dairy farms. Among extrinsic factors, previous research suggests that producers view a shortage of time and labour as important barriers to lameness control (Leach et al., 2010a; 2013; Sadiq et al., 2019). Leach et al. (2010a) reported that time and skilled labour were important limiting factors for lameness control activities and that financial constraints prevented farmers taking action on advice in 30% of cases; similar findings were reported in Canada (Cutler et al., 2017). Sadiq et al. (2019) also highlighted that farmers' understanding of the implications of lameness on the farm business is limited. One strategy to address these barriers has been to try to understand the economic costs and returns of different interventions for lameness (Bruijnis et al., 2012; Dolecheck et al., 2019). Bruijnis et al. (2012) suggest that providing information about the correlation between welfare and economics could motivate producers to follow through with change. It can also support decisions on which measures to prioritize. On-farm assessment programs where producers are provided with feedback on animal-based measures may also help to motivate producers to improve lameness on their farms. Simply making producers aware of the scale of the problem on their farm was enough to motivate changes in management on their farm and improve the levels of both lameness and hock injuries (Chapinal et al., 2014a). Additional motivation for changes in facility design and management can be attained through providing reports to producers highlighting the prevalence of animal-based measures compared to other herds in the same region (Chapinal et al., 2014a). The use of these benchmarked reports has also been shown to be successful in motivating other on-farm changes, such as changing colostrum management (Sumner et al., 2018).

However, the provision of information and advice alone seldom produces lasting on-farm change (Sadiq et al., 2019). Though the extrinsic characteristics noted above (e.g., time, money, space) represent important barriers, there are also a number of important intrinsic barriers to lameness control. The decision to invest limited time and resources is ultimately determined by the level of importance and priority that one places on that issue (Bruijnis et al., 2012). Previous research suggests that incomplete detection, a high tolerance of lameness, lack of awareness of the welfare impact of lameness, and other herd health issues being given high priority are also important barriers to reducing lameness in dairy herds (Leach et al., 2010a, 2013; Sadiq et al., 2019).

Researchers have demonstrated that farmers substantially underestimate lameness in their herds when compared to researchers, veterinarians, and other on-farm advisors (Whay, 2002; Espejo & Endres, 2007; Šárová et al., 2011; Leach et al., 2010a, 2013). For example, the prevalence estimate from a study of 50 Minnesota free-stall herds was 3 times greater than the estimates given by herd managers (Espejo et al., 2006). Other studies comparing the level of self-assessed lameness by a farmer and independent researchers have demonstrated that farmers missed roughly two-thirds of lame cows (Cutler et al., 2017; Croyle et al., 2018). Croyle et al. (2019) suggested that this may be due to a phenomenon called "barn blindness," which they defined as a lack of perception of welfare problems in one's own barn. This underestimation of the true level of lameness on-farm may ultimately contribute to the belief that lameness is not a significant problem and is, therefore, not a priority. For example, in a survey of 222 U.K. dairy farms, Leach et al. (2010a) reported that 90% percent of farmers did not perceive lameness to be a major problem on their farm, although the average prevalence of lameness was 36%. They further described that for 62% of the sample farmers, lameness was not the top priority for efforts made to improve herd health. Given these attitudes, it would therefore not be surprising to see that these producers tend to prioritize other diseases on the farm (Leach et al., 2010b; Cutler et al., 2017). Bruijnis et al. (2013) demonstrated that most producers in their study of 152 Dutch dairy farmers were satisfied with the hoof health of their cows and were, thus, unlikely to take any related action to mitigate lameness in their herds. These researchers further reported that producers did not view subclinical foot disorders, where the cow was not visibly lame, as important with respect to animal welfare (Bruijnis et al., 2013).

Another important component contributing to how producers view lameness relates to their awareness of its impact on animal welfare. Researchers have suggested that lameness is not universally viewed by all farmers as a painful and economically impactful condition in dairy cattle. For example, Bruijnis et al. (2013) reported that 25% of producers surveyed thought that lame cows do not suffer pain. Further, Becker et al. (2013) reported that 52% of Swiss producers interviewed would not consult a veterinarian or provide pain management for common painful hoof health interventions. Although, it is notable that they reported that only 11% of farmers agreed with the statement that the cost of pain management was a major concern for farmers (compared to 47% of veterinarians and 33% hoof trimmers interviewed). These results suggest that while economic aspects impact decision-making, the producer's understanding of the condition and its impacts are most influential over their determination on whether to intervene or not. Several studies have demonstrated that producers consider pain and suffering and reduced performance by lame cows as motivating factors for making on-farm changes (Leach et al., 2010b; Croyle et al., 2019). Although, interestingly, Cutler et al. (2017) reported that producer perception of lameness as a painful condition and the economic costs of lameness were not related to success in controlling lameness on-farm. More work is needed to better understand the motivations and priorities of producers with respect to the prevention and control of lameness.

Advisors. There are many diverse stakeholders in lameness and injury management including the farmer, farm staff, veterinarian, hoof trimmer, nutritionist, and other farm advisors. Addressing dairy cattle lameness and injuries must, therefore, consider the people involved, as it is the people who are influencing and implementing on-farm decisions related to lameness prevention, treatment, and control. To date, no research has been conducted on how advisors play a role in the management of injuries; the remainder of this section reviews studies around how advisors play a role in lameness management.

Researchers have previously investigated the importance of involving advisors in lameness decisions, with a particular focus on the role of the veterinarian (Main et al., 2012; Whay et al., 2012; Leach et al., 2013; Croyle et al., 2019). This focus is primarily taken as veterinarians are in an ideal position to advise and motivate farmers to improve welfare-related practices (Lam et al., 2011). While evaluating the U.K.-based Healthy Feet project, Whay et al. (2012) reported that farmers implemented more changes likely to positively impact lameness when the ideas were generated with the direction of a veterinarian rather than on their own when told to generate a list. Main et al. (2012) concluded that the reduction of lameness observed over time by Whay et al. (2012) was greater on farms that were monitored and offered additional support (from veterinarians and/or other producers) compared to farms that only received monitoring. Further, Croyle et al. (2019) conducted a qualitative focus group study with Canadian producers and concluded that veterinarians were trusted and most commonly viewed as the most important partner in animal welfare. However, a Canadian study by Cutler et al. (2017) reported that only 8% of farmers surveyed called the veterinarian or hoof trimmer after they detected a lame cow.

Veterinarians represent one of many relevant advisors to the farmer, particularly when addressing a multifactorial disease such as lameness. Nutritionists, hoof trimmers, and other farm advisors also commonly work with farmers on the development and evaluation of health management programs. Hoof trimmers are a source of information and they work directly with the cows' hooves; however, little information exists about hoof trimmers and their impact on lameness decisions. Furthermore, nutritionists develop and monitor feeding programs on dairy farms. Depending on the farm, nutritionists may be involved more broadly in other areas of management impacting cattle dry matter intake, production, and welfare. In a recent review of dairy farmers' perceptions of and actions related to lameness, Sadiq et al. (2019) suggested that tensions between farm advisors can be an important barrier to change and that the lower-cost services of nutritionists and trimmers over veterinarians may result in less consideration being given to pain management of lame animals. Becker et al. (2013) compared the perceptions of Swiss farmers, hoof trimmers, and veterinarians and concluded that there was a lack of awareness among farmers and trimmers of the obligation to carry out painful therapeutic trimming under analgesia (a regulatory requirement in the country). Those researchers further reported that while the majority of veterinarians (79%) viewed local anaesthesia during the trimming of sole ulcers as reasonable, significantly fewer farmers (42%) and trimmers (47%) felt the same (Becker et al., 2013). In addition, research conducted in the United States found that veterinarians were more likely to provide a foot block when treating sole ulcers when compared to hoof trimmers; however, a low percentage of veterinarians (26%) recommended the use of analgesics for treatment of sole ulcer lesions (Kleinhenz et al., 2014).

Ultimately, advisors play an important role in guiding and influencing on-farm decision-making related to lameness. Farmers particularly value the pre-established relationship they have with these advisors, their expertise in dairy care/welfare, the opportunity for a fresh, outside perspective, the ability to compare and contrast with other clients' farms (a form of benchmarking), and the ability to advise and offer corrective recommendations (Croyle et al., 2019).

5.6 References

Adams A.E., Lombard J.E., Fossler C.P., Roman-Muniz I.N. & Kopral C.A. (2017) Associations between housing and management practices and the prevalence of lameness, hock lesions, and thin cows on US dairy operations. *Journal of Dairy Science* 100(3):2119-2136.

Aiello S.E. & Moses M.A. (2010) *The Merck Veterinary Manual, 10th ed.* Kenilworth NJ: Merck Sharp and Dohme Corp.

Alawneh J.I., Laven R.A. & Stevenson M. A. (2012) Interval between detection of lameness by locomotion scoring and treatment for lameness: A survival analysis. *Veterinary Journal* 193(3):622–625.Amory J.R., Kloosterman P., Barker Z.E., Wright J.L., Blowey R.W. & Green L.E. (2006) Risk factors for reduced locomotion in dairy cattle on nineteen farms in the Netherlands. *Journal of Dairy Science* 89:1509–1515.

Andreasen S.N. & Forkman B. (2012) The welfare of dairy cows is improved in relation to cleanliness and integument alterations on the hocks and lameness when sand is used as stall surface. *Journal of Dairy Science* 95:4961–4867.

Ariza J.M., Relun A., Bareille N. Oberle K. & Guatteo R. (2017) Effectiveness of collective treatments in the prevention and treatment of bovine digital dermatitis lesions: A systematic review. *Journal of Dairy Science* 100(9):7401–7418.

Barker Z.E., Amory J.R., Wright J.L., Mason S.A., Blowey, R.W. & Green, L.E. (2009) Risk factors for increased rates of sole ulcers, white line disease, and digital dermatitis in dairy cattle from twenty-seven farms in England and Wales. *Journal of Dairy Science* 92(5):1971–1978.

Barker Z.E., Leach K.A., Whay H.R., Bell N.J. & Main D.C.J. (2010) Assessment of lameness prevalence and associated risk factors in dairy herds in England and Wales. *Journal of Dairy Science* 93(3):932–941.

Barrientos A.K., Chapinal N., Weary D. M., Galo E. & von Keyserlingk M.A.G. (2013) Herd-level risk factors for hock injuries in freestall-housed dairy cows in the northeastern United States and California. *Journal of Dairy Science* 96(6):3758–3765.

Becker J., Reist M., Friedli K., Strabel D., Wuthrick M. & Steiner A. (2013) Current attitudes of bovine practitioners, claw-trimmers and farmers in Switzerland to pain and painful interventions in the feed in dairy cattle. *Veteterinary Journal* 196:467–476.

Bergsten C., Telezhenko E. & Ventorp M. (2015) Influence of soft or hard floors before and after first calving on dairy heifer locomotion, claw and leg health. *Animals* 5(3):662–686.

Berry S.L., Read D.H, Famula T.R, Mongini A. & Döpfer D. (2012) Long-term observations on the dynamics of bovine digital dermatitis lesions on a California dairy after topical treatment with lincomycin HCl. *Veterinary Journal* 193:654–658.

Bicalho R.C. & Oikonomou G. (2013) Control and prevention of lameness associated with claw lesions in dairy cows. *Livestock Science* 156(1–3):96–105.

Bicalho R.C., Cheong S.H., Warnick L.D., Nydam D.V. & Guard C.L. (2006) The effect of digital amputation or arthrodesis surgery on culling and milk production in holstein dairy cows. *Journal of Dairy Science* 89(7):2596–2602.

Bielfeldt J.C., Badertscher R., Tolle K.H. & Krieter, J. (2005) Risk factors influencing lameness and claw disorders in dairy cows. *Livestock Production Science* 95(3):265–271.

Boettcher P.J., Dekkers J.C., Warnick L.D., and Wells S.J. (1998) Genetic analysis of clinical lameness in dairy cattle. *Journal of Dairy Science* 81:1148–1156.

Bouffard V., de Passillé A.M., Rushen J., Vasseur A., Nash C.G.R., Haley D.B. & Pellerin B. (2017) Effect of following recommendations for tiestall configuration on neck and leg lesions, lameness, cleanliness, and lying time in dairy cows. *Journal of Dairy Science* 100:2935–2943.

Bruijnis M.R.N., Beerda B., Hogeveen H. & Stassen E.N. (2012) Food disorders in dairy cattle: Impact on cow and dairy farmer. *Animal Welfare* 21:33–40.

Bruijnis M., Hogeveen H., Garforth C. & Stassen E. (2013) Dairy farmers' attitudes and intentions towards improving dairy cow foot health. *Livestock Science* 155(1):103–113.

Bryan M., Tacoma H. & Hoekstra F. (2012) The effect of hindclaw height differential and subsequent trimming on lameness in large dairy cattle herds in Canterbury, New Zealand. *New Zealand Veterinary Journal* 60:349–355.

Cartwright S.L., Malchiodi F., Thompson-Crispi K., Miglior F. & Mallard B.A. (2017) Short communication: Prevalence of digital dermatitis in Canadian dairy cattle classified as high, average, or low antibody and cell-mediated immune responders. *Journal of Dairy Science* 100(10):8409–8413.

Carvalho V.R.C., Bucklin R.A, Shearer J.K. & Shearer L. (2006) Effects of trimming on dairy cattle hoof weight bearing and pressure distributions during the stance phase. *Transactions of the ASAE* 48:1653–1659.

Channon A.J., Walker A.M., Pfau T., Sheldon I.M. & Wilson A.M. (2009) Variability of Manson and Leaver locomotion scores assigned to dairy cows by different observers. *Veterinary Record* 164:388–92.

Chapinal N., Baird L. G., Machado L.C.P., von Keyserlingk, M.A.G. & Weary D.M. (2010a) Short communication: Risk of severe heel erosion increased with parity and stage of lactation in freestall-housed dairy cows. *Journal of Dairy Science* 93(7):3070–3073.

Chapinal, N, de Passillé A.M. & Rushen J. (2010b) Correlated changes in behavioural indicators of lameness in dairy cows following hoof trimming. *Journal of Dairy Science* 93:5758–5763.

Chapinal N., de Passillé A.M., Rushen J. & Wagner S.A. (2010c) Effect of analgesia during hoof trimming on gait, weight distribution, and activity of dairy cattle. *Journal of Dairy Science* 93:3039–3046.

Chapinal N., Barrientos A. K., von Keyserlingk, M.A.G., Galo E. & Weary D.M. (2013) Herd-level risk factors for lameness in freestall farms in the northeastern United States and California. *Journal of Dairy Science* 96(1):318–328.

Chapinal N., Weary D.M., Collings L. & von Keyserlingk M.A.G. (2014a) Lameness and hock injuries improve on farms participating in an assessment program. *Veterinary Journal* 202(3):646–648.

Chapinal N., Liang Y., Weary D.M., Wang Y. & von Keyserlingk M.A.G. (2014b) Risk factors for lameness and hock injuries in Holstein herds in China. *Journal of Dairy Science* 97:4309–4316.

Coetzee J.F., Shearer J.K., Stock M.L., Kleinhenz M.D. & van Amstel S.R. (2017) An update on the assessment and management of pain associated with lameness in cattle. *Veterinary Clinics of North America: Food Animal Practice* 33(2):389–411.

Cook N.B. (2003) Prevalence of lameness among dairy cattle in Wisconsin as a function of housing type and stall surface. *Journal of the American Veterinary Medical Association* 223(9):1324–1328.

Cook N.B., Rieman J., Gomez A. & Burgi K. (2012) Observations in the design and use of footbaths for the control of infectious disease in dairy cattle. *Veterinary Journal* 193:669–673.

Cook N.B., Hess J.P., Foy M.R., Bennett T.B. & Brotzman, R.L. (2016) Management characteristics, lameness, and body injuries of dairy cattle housed in high-performance dairy herds in Wisconsin. *Journal of Dairy Science* 99(7):5879–5891.

Cramer G., Lissemore K.D., Guard C.L., Leslie K.E. & Kelton, D. F. (2008) Herd- and cow-level prevalence of foot lesions in Ontario dairy cattle. *Journal of Dairy Science* 91(10):3888–3895.

Cramer G., Lissemore K.D., Guard C.L., Leslie K.E. & Kelton, D.F. (2009) Herd-level risk factors for seven different foot lesions in Ontario Holstein cattle housed in tie stalls or free stalls. *Journal of Dairy Science* 92(4):1404–1411.

Croyle S.L. (2019) Steps towards understanding the consistently high prevalence of lameness and hock injuries on Canadian dairy farms. PhD Thesis. Guelph ON: University of Guelph.

Croyle S.L., Nash C.G.R., Bauman C., LeBlanc S.J., Haley D.K., Khosa D.K. & Kelton D.K. (2018) Training method for animal-based measures in dairy cattle welfare assessments. *Journal of Dairy Science* 101(10):9463–9471.

Croyle S.L., Belage E., Khosa D.K., LeBlanc S.J., Haley D.B. & Kelton, D.K. (2019) Dairy farmers' expectations and receptivity regarding animal welfare advice: A focus group study. *Journal of Dairy Science* 102(8):7385–7397.

Cutler J.H., Cramer G., Walter J.J., Millman S.T. & Kelton D.F. (2013) Randomized clinical trial of tetracycline hydrochloride bandage and paste treatments for resolution of lesions and pain associated with digital dermatitis in dairy cattle. *Journal of Dairy Science* 96:7550–7557.

Cutler J.H.H., Rushen J., de Passillé A.M., Gibbons J., Orsel K., Pajor E., Barkema H.W., Solano L., Pellerin D., Haley D. & Vasseur E. (2017) Producer estimates of prevalence and perceived importance of lameness in dairy herds with tiestalls, freestalls, and automated milking systems. *Journal of Dairy Science* 100(12):9871–9880. doi:10.3168/jds.2017-13008.

Dippel S., Dolezal M., Brenninkmeyer C., Brinkmann J., March S., Knierim U. & Winckler C. (2009a) Risk factors for lameness in cubicle housed Austrian Simmental dairy cows. *Preventive Veterinary Medicine* 90:102–112.

Dippel S., Dolezal M., Brenninkmeyer C., Brinkmann J., March S., Knierim U. & Winckler C. (2009b) Risk factors for lameness in freestall-housed dairy cows across two breeds, farming systems, and countries. *Journal of Dairy Science* 92(11):5476–5486.

Dolecheck K.A., Overton M.W., Mark T.B. & Bewley J.M. (2019) Use of a stochastic simulation model to estimate the cost per case of digital dermatitis, sole ulcer, and white line disease by parity group and incidence timing. *Journal of Dairy Science* 102(1):715–730.

Döpfer D., Holzhauer M. & Boven M.V. (2012) The dynamics of digital dermatitis in populations of dairy cattle: Model-based estimates of transition rates and implications for control. *Veterinary Journal* 193:648–653.

de Vries M., Bokkers E.A.M., van Reenen C.G., Engel B., van Schaik G., Dijkstra T. & de Boer, I.J.M. (2015) Housing and management factors associated with indicators of dairy cattle welfare. *Preventive Veterinary Medicine* 118(1):80–92.

Dyce K.M., Sack W.O. & Wensing C.J.G. (2010) *Textbook of Veterinary Anatomy, 4th ed*. Missouri: Saunders Elsevier.

Ekman L., Nyman A.K., Landin H. & Waller K.P. (2018) Hock lesions in dairy cows in freestall herds: A cross-sectional study of prevalence and risk factors. *Acta Veterinaria Scandinavica* 60.

Engel B., Bruin G., Andre G. & Buist W. (2003) Assessment of observer performance in a subjective scoring system: visual classification of the gait of cows. *Journal of Agricultural Science* 140:317–333.

Espejo L.A. & Endres, M.I. (2007) Herd-level risk factors for lameness in high-producing Holstein cows housed in freestall barns. *Journal of Dairy Science* 90(1):306–314.

Espejo L., Endres M.I. & Salfer J. (2006) Prevalence of lameness in high-producing Holstein cows housed in freestall barns in Minnesota. *Journal of Dairy Science* 89:3052–3058.

Fjeldaas T., Sogstad A.M. & Osteras O. (2011) Locomotion and claw disorders in Norwegian dairy cows housed in freestalls with slatted concrete, solid concrete, or solid rubber flooring in the alleys. *Journal of Dairy Science* 94(3):1243–1255.

Fjeldaas T., Knappe-Poindecker M., Bøe K.E. & Larssen R.B. (2014) Water footbath, automatic flushing, and disinfection to improve the health of bovine feet. *Journal of Dairy Science* 97:2835–2846.

Flower F.C. & Weary D.M. (2006) Effect of hoof pathologies on subjective assessments of dairy cow gait. *Journal of Dairy Science* 89(1):139–146.

Flower F.C. & Weary D.M. (2009). Gait assessment in dairy cattle. *Animal* 3:87–95.

Flower F.C., Sedlbauer M., Carter E., von Keyserlingk M.A.G., Sanderson D.J. & Weary D.W. (2008) Analgesics improve the gait of lame dairy cattle. *Journal of Dairy Science* 91:3010–3014.

Foditsch C., Oikonomou G., Machado V.S., Bicalho M. L., Ganda E. K., Lima S.F., Rossi R., Ribeiro B.L., Kussler A. & Bicalho R.C. (2016) Lameness prevalence and risk factors in large dairy farms in upstate New York: Model development for the prediction of claw horn disruption lesions. *PLoS One* 11(1):15.

Gibbons J., Vasseur E., Rushen J. & de Passillé A.M. (2012) A training programme to ensure high repeatability of injury scoring of dairy cows. *Animal Welfare* 21:379–388.

Gibbons J., Haley D.B., Cutler J.H., Nash C., Heyerhoff J.Z., Pellerin D., Adam S., Fournier A., de Passille A.M., Rushen J. & Vasseur E. (2014) Technical note: A comparison of 2 methods of assessing lameness prevalence in tiestall herds. *Journal of Dairy Science* 97(1):350–353.

Gillespie A., Carter S.D., Blowey R.W. & Evans N. (2020) Survival of bovine digital dermatitis treponemes on hoof knife blades and the effects of various disinfectants. *Veterinary Record* 186:67.

Green L.E., Huxley J.N., Banks C. & Green M.J. (2014) Temporal associations between low body condition, lameness and milk yield in a UK dairy herd. *Preventive Veterinary Medicine* 113(1):63–71.

Griffiths B.E., White D.G. & Oikonomou G. (2018) A cross-sectional study into the prevalence of dairy cattle lameness and associated herd-level risk factors in England and Wales. *Frontiers in Veterinary Science* 5.

Groenevelt M., Main D.C.J., Tisdall D., Knowles T.G. & Bell N.J. (2014) Measuring the response to therapeutic foot trimming in dairy cows with fortnightly lameness scoring. *Veterinary Journal* 201(3):283–288.

Haggman J. & Juga J. (2015) Effects of cow-level and herd-level factors on claw health in tied and loose-housed dairy herds in Finland. *Livestock Science* 181:200–209.

Haskell M.J., Rennie L.J., Bowell V.A., Bell M.J. & Lawrence A.B. (2006). Housing system, milk production, and zero-grazing effects on lameness and leg injury in dairy cows. *Journal of Dairy Science* 89(11):4259–4266.

Haufe H.C., Gygax L., Wechsler B., Stauffacher M. & Friedli K. (2012) Influence of floor surface and access to pasture on claw health in dairy cows kept in cubicle housing systems. *Preventive Veterinary Medicine* 105(1–2):85–92.

Hernandez J., Shearer J.K. & Elliot J.B. (1999) Comparison of topical application of oxytetracycline and four nonantibiotic solutions for treatment of papillomatous digital dermatitis in dairy cows. *Journal of the American Veterinary Medical Association* 214:688–690.

Hernandez J.A., Garbarino E.J., Shearer J.K., Risco C.A. & Thatcher W.W. (2007) Evaluation of the efficacy of prophylactic hoof health examination and trimming during midlactation in reducing the incidence of lameness during late lactation in dairy cows. *Journal of the American Veterinary Medical Association* 230:89–93.

Hernandez-Mendo O., von Keyserlingk M.A.G., Veira D.M. & Weary D.M. (2007) Effects of pasture on lameness in dairy cows. *Journal of Dairy Science* 90(3):1209–1214.

Holzhauer M., Hardenberg C., Bartels C.J. & Frankena K. (2006) Herd and cow level prevalence of digital dermatitis in the Netherlands and associated risk factors. *Journal of Dairy Science* 89:580–588.

Holzhauer, M., Hardenberg C. & Bartels C.J.M. (2008) Herd and cow-level prevalence of sole ulcers in the Netherlands and associated-risk factors. *Preventive Veterinary Medicine* 85(1–2):125–135.

Husfeldt A.W. & Endres M.I. (2012) Association between stall surface and some animal welfare measurements in freestall dairy herds using recycled manure solids for bedding. *Journal of Dairy Science* 95:5626–5634.

Huxley J.N., Burke J., Roderick S., Main D.C.J. & Whay H.R. (2004) Animal welfare assessment benchmarking as a tool for health and welfare planning in organic dairy herds. *Veterinary Record* 155:237–239.

Jewell M.T., Cameron M., Spears J., McKenna S.L., Cockram M.S., Sanchez J. & Keefe G.P. (2019a) Prevalence of lameness and associated risk factors on dairy farms in the Maritime provinces of Canada. *Journal of Dairy Science* 102(4):3392–3405.

Jewell M.T., Cameron M., Spears J., McKenna S.L., Cockram M.S., Sanchez J. & Keefe G.P. (2019b). Prevalence of hock, knee, and neck skin lesions and associated risk factors in dairy herds in the Maritime provinces of Canada. *Journal of Dairy Science* 102(4):3376–3391.

Kazdin A.E. (1977) Artifact, bias, and complexity of assessment: The ABCs of reliability. *Journal of Applied Behavior Analysis* 10:141–150.

Keil N.M., Wiederkehr T.U., Friedli K. & Wechsler B. (2006) Effects of frequency and duration of outdoor exercise: On the prevalence of hock lesions in tied Swiss dairy cows. *Preventive Veterinary Medicine* 74(2–3):142–153.

Kester E., Holzhauer M. & Frankena K. (2014) A descriptive review of the prevalence and risk factors of hock lesions in dairy cows. *Veterinary Journal* 202(2):222–228.

Kielland C., Ruud L.E., Zanella A.J. & Ostera O. (2009) Prevalence and risk factors for skin lesions on legs of dairy cattle housed in freestalls in Norway. *Journal of Dairy Science* 92:5487–5496.

King M.T.M., Pajor E.A., LeBlanc S.J. & DeVries T.J. (2016) Associations of herd-level housing, management, and lameness prevalence with productivity and cow behavior in herds with automated milking systems. *Journal of Dairy Science* 99(11):9069–9079.

King M.T.M., LeBlanc S.J., Pajor E.A. & DeVries T.J. (2017) Cow-level associations of lameness, behavior, and milk yield of cows milked in automated systems. *Journal of Dairy Science* 100(6):4818–4828.

Kleinhenz K.E., Plummer P.J., Danielson J., Burzette R.G., Gordon P.J., Coetzee J., Schleining J.A., Cooper V., Leuschen B., Krull A., Shearer L. & Shearer J.K.. (2014) Survey of veterinarians and hoof trimmers on methods applied to treat claw lesions in dairy cattle. *The Bovine Practitioner* 48:47–52.

Lam T.J., Jansen J., van den Borne B.H., Renes R.J. & Hogeveen H. (2011) What veterinarians need to know about communication to optimise their role as advisors on udder health in dairy herds. *New Zealand Veterinary Journal* 59:8–15.

Laursen M.V., Boelling D. & Mark T. (2009) Genetic parameters for claw and leg health, foot and leg conformation, and locomotion in Danish Holsteins. *Journal of Dairy Science* 92:1770–1777.

Laven R.A. & Logue D.N. (2006) Treatment strategies for digital dermatitis for the UK. *Veterinary Journal* 171:79–88.

Laven R.A. & Jermy M.C. (2020) Measuring the torque required to cause vertebral dislocation in cattle tails. *New Zealand Veterinary Journal* 68(2):107–111.

Leach K.A., Whay H.R., Maggs C.M., Barker Z.E., Paul E.S., Bell A.K. & Main D.C.J. (2010a) Working towards a reduction in cattle lameness: 1. Understanding barriers to lameness control on dairy farms. *Research in Veterinary Science* 89:318–323.

Leach K.A., Whay H.R., Maggs C.M., Barker Z.E., Paul E.S., Bell A.K. & Main D.C.J. (2010b) Working towards a reduction in cattle lameness: 2. Understanding dairy farmers' motivations. *Research in Veterinary Science* 89:311–317.

Leach K.A., Tisdall D.A., Bell N.J., Main D.C.J. & Green L.E. (2012) The effects of early treatment for hindlimb lameness in dairy cows on four commercial UK farms. *Veterinary Journal* 193(3):626–632.

Leach K.A., Paul E.S., Whay H.R., Barker Z.E., Maggs C.M., Sedgwick A.K. & Main D.C.J. (2013) Reducing lameness in dairy herds – Overcoming some barriers. *Research in Veterinary Science* 94:820–825.

Lievens F. (2001) Assessor training strategies and their effects on accuracy, interrater reliability, and discriminant validity. *Journal of Applied Psychology* 86:255–264.

Lim P.Y., Huxley J.N., Willshire J.A., Green M.J., Othman A.R. & Kaler J. (2015) Unravelling the temporal association between lameness and body condition score in dairy cattle using a multistate modelling approach. *Preventive Veterinary Medicine* 118(4):370–377.

Main D.C.J., Barker Z.E., Leach K.A., Bell N.J., Whay H.R. & Browne W.J. (2010). Sampling strategies for monitoring lameness in dairy cattle. *Journal of Dairy Science* 93:1970–1978.

Main D.C.J., Leach K.A., Barker Z.E., Sedgwick A.K., Maggs C.M., Bell N.J. & Whay H.R. (2012) Evaluating an intervention to reduce lameness in dairy cattle. *Journal of Dairy Science* 95:2946–2954.

Manske T., Hultgren J. & Bergsten C. (2002) Prevalence and interrelationships of hoof lesions and lameness in Swedish dairy cows. *Preventive Veterinary Medicine* 54:247–263.

March S., Brinkmann J. & Winkler C. (2007) Effect of training on the inter-observer reliability of lameness scoring in dairy cattle. *Animal Welfare* 16:131–133.

Miguel-Pacheco G.G., Thomas H.J., Huxley J.N., Newsome R.F. & Kaler J. (2017) Effect of claw horn lesion type and severity at the time of treatment on outcome of lameness in dairy cows. *Veterinary Journal* 225:16–22.

Moore D.A., Berry S.L. & Truscott M.L. (2001) Efficacy of a nonantimicrobial cream administered topically for treatment of digital dermatitis in dairy cattle. *Journal of the American Veterinary Medical Association* 219:1435–1438.

Morabito E., Barkema H.W., Pajor E.A., Solano L., Pellerin D. & Orsel K. (2017) Effects of changing freestall area on lameness, lying time, and leg injuries on dairy farms in Alberta, Canada. *Journal of Dairy Science* 100(8):6516–6526.

Nash C.G.R., Kelton D.F., DeVries T.J., Vasseur E., Coe J., Heyerhoff J.C.Z., Bouffard V., Pellerin D., Rushen J., de Passille A.M. & Haley D.B. (2016) Prevalence of and risk factors for hock and knee injuries on dairy cows in tiestall housing in Canada. *Journal of Dairy Science* 99(8):6494–6506.

Nuss K. (2006) Footbaths: The solution to digital dermatitis? *Veterinary Journal* 171:11–13.

O'Callaghan K.A., Cripps P.J., Downham D.Y. & Murray R.D. (2003). Subjective and objective assessment of pain and discomfort due to lameness in dairy cattle. *Animal Welfare* 12(4):605–610.

O'Driscoll K.K., Schutz M.M., Lossie A.C. & Eicher S.D. (2009) The effect of floor surface on dairy cow immune function and locomotion score. *Journal of Dairy Science* 92:4249–4261.

Oikonomou G., Cook N.B. & Bicalho R.C. (2013) Sires' predicted transmitting ability for conformation and yield traits and previous lactation incidence of foot lesions as risk factors for the incidence of foot lesions in Holstein cows. *Journal of Dairy Science* 96:3713–3722.

Olmos G., Boyle L., Hanlon A., Patton J., Murphy J.J. & Mee J.F. (2009) Hoof disorders, locomotion ability and lying times of cubicle-housed compared to pasture-based dairy cows. *Livestock Science* 125(2–3):199–207.

Onyiro O.M., Andrews L.J. & Brotherstone S. (2008) Genetic parameters for digital dermatitis and correlations with locomotion, production, fertility traits, and longevity in Holstein-Friesian dairy cows. *Journal of Dairy Science* 91:4037–4046.

Ouweltjes W., van der Werf J.T.N., Frankena K. & van Leeuwen J.L. (2011) Effects of flooring and restricted freestall access on behaviour and claw health of dairy heifers. *Journal of Dairy Science* 94:705–715.

Palacio S., Peignier L., Pachoud C., Nash C., Adam S., Bergeron R., Pellerin D., de Passille A. M., Rushen J., Haley D., DeVrie, T.J. & Vasseur E. (2017). Assessing lameness in tie-stalls using live stall lameness scoring. *Journal of Dairy Science* 100(8):6577–6582.

Palmer M.A. & O'Connell N.E. (2015) Digital dermatitis in dairy cows: A review of risk factors and potential sources of between-animal variation in susceptibility. *Animals* 5(3):512–535.

Popescu S., Borda C., Diugan E.A., Spinu M., Groza I.S. & Sandru C.D. (2013) Dairy cows welfare quality in tie-stall housing systems with or without access to exercise. *Acta Veterinaria Scandinavia* 55:43.

Popescu S., Borda C., Diugan E.A., Nicula M., Stefan R. & Sandru C.D. (2014) The effect of the housing system on the welfare quality of dairy cows. *Italian Journal of Animal Science* 13:2940.

Potterton S.L., Bell N.J., Whay H.R., Berry E.A., Atkinson O.C.D., Dean R.S., Main D.C.J. & Huxley J.N. (2012) A descriptive review of the peer and non-peer reviewed literature on the treatment and prevention of foot lameness in cattle published between 2000 and 2011. *Veterinary Journal* 193(3):612–616.

Randall L.V., Green M.J., Green L.E., Chagunda M.G.G., Mason C., Archer S.C. & Huxley J.N. (2018) The contribution of previous lameness events and body condition score to the occurrence of lameness in dairy herds: A study of 2 herds. *Journal of Dairy Science* 101(2):1311–1324.

Read D.H. & Walker R.L. (1998) Papillomatous digital dermatitis in California dairy cattle: Clinical and gross pathologic findings. *Journal of Veterinary Diagnostic Investigation* 10:67–76.

Relun A., Lehebel A., Bruggink M., Bareille N. & Guatteo R. (2013) Estimation of the relative impact of treatment and herd management practices on prevention of digital dermatitis in French dairy herds. *Preventive Veterinary Medicine* 110:558–562.

Rodriguez-Lainz A., Hird D.W. & Read D.H. (1996) Case-control study of papillomatous digital dermatitis in southern California dairy farms. *Preventive Veterinary Medicine* 71:11–21.

Rodriguez-Lainz A., Melendez-Retamal P., Hird D.W., Read D.H. & Walker R.L. (1999) Farm- and host-level risk factors for papillomatous digital dermatitis in Chilean dairy cattle. *Preventive Veterinary Medicine* 42:87–97.

Rouha-Mulleder C., Iben C., Wagner E., Laaha G., Troxler J. & Waiblinger S. (2009) Relative importance of factors influencing the prevalence of lameness in Austrian cubicle loose-housed dairy cows. *Preventive Veterinary Medicine* 92(1–2):123–133.

Rushen J., Pombourcq E. & de Passillé A.M. (2006) Validation of two measures of lameness in dairy cows. *Applied Animal Behavior Science* 106:173–177. Rutherford K.M.D., Langford F.M., Jack M.C., Sherwood L., Lawrence A.B. & Haskell M.J. (2009) Lameness prevalence and risk factors in organic and non-organic dairy herds in the United Kingdom. *Veterinary Journal* 180, 95:105. Sadiq M.B., Ramanoon S.Z., Mossadeq W.M.S., Mansor R. & Hussain S.S.S. (2019) Dairy farmers' perceptions of and actions in relation to lameness management. *Animals* 9:270.

Salfer J.A., Siewert J.M. & Endres M.I. (2018) Housing, management characteristics, and factors associated with lameness, hock lesion, and hygiene of lactating dairy cattle on Upper Midwest United States dairy farms using automatic milking systems. *Journal of Dairy Science* 101(9):8586–8594.

Sarjokari K., Kaustell K.O., Hurme T., Kivinen T., Peltoniemi O.A.T. Saloniemi H. & Rajala-Schultz P.J. (2013) Prevalence and risk factors for lameness in insulated freestall barns in Finland. *Livestock Science* 156:44–52.

Šárová R., Stěhulová I., Kratinová P., Firla P. & Špinka M. (2011) Farm managers underestimate lameness prevalence in Czech dairy herds. *Animal Welfare* 20:201–204.

Schulz K.L., Anderson D.E., Coetzee J.F., White B.J. & Miesner M.D. (2011) Effect of flunixin meglumine on the amelioration of lameness in dairy steers with amphotericin B induced transient synovitis-arthritis. *American Journal of Veterinary Research* 72:1431–1438.

Schlageter-Tello A., Bokkers E.A.M., Groot Koerkamp T.W.G., Van Hertem T., Viazzi S., Romanini C.E.B., Halachmi I., Bahr C., Berckmans D. & Lokhorst K. (2014) Manual and automatic locomotion scoring systems in dairy cows: A review. *Preventive Veterinary Medicine* 116:12–25.

Shearer J.K., Stock M.L., Van Amstel S.R. & Coetzee J.F. (2013) Assessment and management of pain associated with lameness in cattle. *Veterinary Clinics of North America: Food Animal Practice* 29:135–136.

Solano L., Barkema H.W., Pajor E.A., Mason S., LeBlanc S.J., Heyerhoff J.C.Z., Nash C.G.R., Haley D.B., Vasseur E., Pellerin D., Rushen J., de Passille A.M. & Orsel K. (2015) Prevalence of lameness and associated risk factors in Canadian Holstein-Friesian cows housed in freestall barns. *Journal of Dairy Science* 98(10):6978–6991.

Solano L., Barkema H.W., Mason S., Pajor E.A., LeBlanc S.J. & Orsel K. (2016) Prevalence and distribution of foot lesions in dairy cattle in Alberta, Canada. *Journal of Dairy Science* 99(8):6828–6841.

Solano L., Barkema H.W. & Orsel K. (2017) Effectiveness of a standardized footbath protocol for prevention of digital dermatitis. *Journal of Dairy Science* 100(2):1295–1307.

Somers J.G.C.J., Frankena K., Noordhuizen-Stassen E.N. & Metz J.H.M. (2005) Risk factors for digital dermatitis in dairy cows kept in cubicle houses in the Netherlands. *Preventive Veterinary Medicine* 71:11–21.

Speijers M.H.M., Baird L.G., Finney G.A., McBride J., Kilpatrick D.J., Logue, D.N & O'Connell N.E. (2010) Effectiveness of different footbath solutions in the treatment of digital dermatitis in dairy cows. *Journal of Dairy Science* 93:5782–5791.

Stoddard G.C. & Cramer G. (2017) A review of the relationship between hoof trimming and dairy cattle welfare. *Veterinary Clinics of North America: Food Animal Practice* 33:365–375.

Sumner C.L., von Keyserlingk M.A.G. & Weary D.M. (2018) How benchmarking promotes farmer and veterinarian cooperation to improve calf welfare. *Journal of Dairy Science* 103:702:713.

Tadich N., Flor E. & Green L. (2010) Associations between hoof lesions and locomotion score in 1098 unsound dairy cows. *Veterinary Journal* 184:60–65.

Tanida H., Koba Y., Rushen J. & de Passilé A.M. (2011) Use of three-dimensional acceleration sensing to assess dairy cow gait and the effects of hoof trimming. *Animal Science Journal* 82:792–800.

Thomas H.J., Miguel-Pacheco G.G., Bollard N.J., Archer S.C., Bell N.J., Mason C., Maxwell O.J.R., Remnant J.G., Sleeman P., Whay H.R. & Huxley J.N. (2015) Evaluation of treatments for claw horn lesions in dairy cows in a randomized controlled trial. *Journal of Dairy Science* 98:4477–4486.

Thompson A.J., Weary D.M., Bran J.A., Daros J.A., Hotzel M.J. & von Keyserlingk M.A.G. (2019) Lameness and lying behaviour in grazing dairy cows. *Journal of Dairy Science* 102(7):6373–6382.

van der Linde C., de Jong G., Koenen E.P. & Eding H. (2010) Claw health index for Dutch dairy cattle based on claw trimming and conformation data. *Journal of Dairy Science* 93:4883–4891.

van der Tol P.P., van der Beek S.S., Metz J.H., Noordhuizen-Stassen E.N., Back W., Braam C.R. & Weijs W.A. (2004) The effect of preventative trimming on weight bearing and force balance on the claws of dairy cattle. *Journal of Dairy Science* 87:1732–1738.

van der Waaij E.H., Holzhauer M., Ellen E., Kamphuis C. & de Jong G. (2005) Genetic parameters for claw disorders in Dutch dairy cattle and correlations with conformation traits. *Journal of Dairy Science* 88:3672–3678.

Vanegas J., Overton M., Berry S.L. & Sischo W.M. (2006) Effect of rubber flooring on claw health in lactating dairy cows housed in free-stall barns. *Journal of Dairy Science* 89:4251–4258.

van Gastelen S., Westerlaan B., Houwers D.J. & van Eerdenburg F. (2011) A study on cow comfort and risk for lameness and mastitis in relation to different types of bedding materials. *Journal of Dairy Science* 94(10):4878–4888.

Van Hertem T., Parmet Y., Steensels M., Maltz E., Antler A., Schlageter-Tello A.A., Lokhorst C., Romanini C.E.B., Viazzi S., Bahr C., Berckmans D. & Halachmi I. (2014) The effect of routine hoof trimming on locomotion score, ruminating time, activity, and milk yield in dairy cows. *Journal of Dairy Science* 97:4852–4863.

Vokey F.J., Guard C.L., Erb H.N. & Galton D.M. (2001) Effects of alley and stall surfaces on indices of claw and leg health in dairy cattle housed in a free-stall barn. *Journal of Dairy Science* 84:2686–2699.

von Keyserlingk M.A.G., Barrientos A., Ito K., Galo E. & Weary D.M. (2012) Benchmarking cow comfort on North American freestall dairies: Lameness, leg injuries, lying time, facility design, and management for high-producing Holstein dairy cows. *Journal of Dairy Science* 95:7399–7408. doi:10.3168/jds.2012-5807.

Wells S.J., Garber L.P. & Wagner B.A. (1999) Papillomatous digital dermatitis and associated risk factors in US dairy herds. *Preventive Veterinary Medicine* 38:11–24.

Westin R., Vaughan A., de Passille A.M., DeVries T.J., Pajor E.A., Pellerin D., Siegford J.M., Witaifi A., Vasseur E. & Rushen J. (2016a) Cow- and farm-level risk factors for lameness on dairy farms with automated milking systems. *Journal of Dairy Science* 99(5):3732–3743.

Westin R., Vaughan A., de Passillé A.M., DeVries T.J., Pajor E.A., Pellerin D., Siegford J.M, Vasseur E. & Rushen J. (2016b) Lying times of lactating cows on dairy farms with automatic milking systems and the relation to lameness, leg lesions and body condition score. *Journal of Dairy Science* 99:551–561.

Whay H. (2002) Locomotion scoring and lameness detection in dairy cattle. *In Practice* 24:444–449.

Whay H.R., Waterman A.E., Webster A.J.F. & O'Brien J.K. (1998) The influence of lesion type on the duration of hyperalgesia associated with hindlimb lameness in dairy cattle. *Veterinary Journal* 156:23–29.

Whay H.R., Barker Z.E., Leach K.A. & Main D.C.J. (2012) Promoting farmer engagement and activity in the control of dairy cattle lameness. *Veterinary Journal* 193(3):617–621.

Zaffino-Heyerhoff, J.C., LeBlanc S.J., DeVries T.J., Nash C.G., Gibbons J., Orsel K., Barkema H.W., Solano L., Rushen J., de Passillé A.M. & Haley D.B. (2014) Prevalence of and factors associated with hock, knee, and neck injuries on dairy cows in freestall housing in Canada *Journal of Dairy Science* 97(1):173–184.

Zurbrigg K., Kelton, D., Anderson N. & Millman S. (2005) Tie-stall design and its relationship to lameness, injury, and cleanliness on 317 Ontario dairy farms. *Journal of Dairy Science* 88(9):3201–3210.

6 End-of-Life Management

Conclusions:

1. **Compromised culled dairy cows arriving at auction and slaughter facilities in Canada and the United States (from Canada) are a potential high-risk animal welfare issue. The most common issues in culled dairy cows include low body condition score (BCS), lameness, udder engorgement, and illness.**
2. **Federal transport regulations require producers to modify their current approach to cull dairy cows with respect to the transport of lactating dairy cows to auction. Drying off cows, placing them in a comfortable environment, and feeding them for a few weeks prior to shipping may improve both cull cow value and dairy cow welfare.**
3. **Establishment of guidelines for prognosis of sick, lame, or down animals and pre-defined end-points for timely euthanasia helps minimize both poor fitness for transport decisions, and prolonged animal suffering.**
    a. **Likelihood of recovery is a key criterion, and euthanasia is generally warranted for cows with a poor prognosis, notably those with the following conditions: severe lameness, cancer eye, bloody gut, nonambulatory cattle, chronic diarrhea, unresponsive toxic (severe clinical) mastitis, and intractable rectal/vaginal or uterine prolapse**
4. **A clinical exam of downer cows helps determine cause and prognosis to aid in timely treatment and euthanasia decisions. Appropriate nursing care for downer cows greatly improves prognosis and includes:**
    a. **Frequent lifting or relief of the weight of the animal that causes ischemic necrosis to muscles and nerves in a humane manner and provision of shelter, a comfortable place to rest, food and water, and segregation from other cattle, among other requirements.**
    b. **Euthanasia is generally indicated in an animal that is recumbent for more than 24 hours. The longer the animal remains recumbent, the less likely they are to recover.**

6.1 Overview of End-of-Life Options

The management of cull dairy cows is an important welfare concern for consumers and dairy farmers throughout the world. Factors that influence culling decisions and longevity are complex and may include but are not limited to health, production, reproductive management, replacement management, and quota management. As all dairy cattle will eventually exit the herd, it is beneficial for farms to have clear protocols for the humane management of culling, including appropriate and timely decision-making surrounding euthanasia and determination of fitness for transport.

With the national lactating dairy herd just under 1 million dairy cows, approximately 350,000 to 400,000 dairy cows are removed from farms in Canada on an annual basis. The majority of these culled dairy cows are transported to auctions and then sold and transported to the U.S. for slaughter. The export of culled dairy cows to the U.S. is primarily due to a lack of slaughter capacity in Canada. This adds complexity to our marketing system, requiring animals to remain in the marketing system for a longer time, and increases welfare concerns for these vulnerable cows. In 2016, seventeen experts from key dairy cow and cull cow stakeholder groups were invited to participate in a two-day consultation meeting with the purpose of drafting a consensus statement and points of agreement on management of cull of dairy cows in Canada (Stojkov et al., 2018). The eight consensus points that were identified included: "(1) to assemble information on travel times and delays from farm to slaughter; (2) to increase awareness among producers and herd veterinarians of potential travel distances and delays; (3) to promote pro-active culling; (4) to improve the ability of personnel to assess animal condition before loading; (5) to identify local options for slaughter of cull dairy cows; (6) to investigate different management options such as emergency slaughter and mobile slaughter; (7) to ensure that all farms and auctions have, or can access, personnel trained and equipped for euthanasia; and (8) to promote cooperation among enforcement agencies and wider adoption of beneficial regulatory options" (Stojkov et al., 2018). These consensus statements highlight some of the major challenges with culling of cows from dairy farms in Canada. These issues will become even more important as federal transport regulations come into enforcement.

The decision-making around vulnerable cows on whether or not therapy is working, appropriate nursing care for down cows, and the provision of expedient euthanasia is an important topic for dairy cow management, as the longer an animal endures a severe condition the more likely there is to be pain and suffering. When a farm manager is faced with a decision to remove an animal from a herd, fitness for transport is also an extremely important consideration. If the animal is deemed to be unfit for transport, then the subsequent decision must be made about whether therapy is likely to improve cow health and ultimately fitness for transport or if euthanasia is the most humane approach. Determining prognosis and timely euthanasia is discussed in *Section 6.3: Prognosis and Decision-Making*.

6.2 Cull Cow Condition Prior to and During Transport and Marketing

Recent research has confirmed that many culled dairy cows are compromised at either auction or slaughter, indicating that there are issues with on-farm screening of cows for fitness for transport. The most common conditions noted in these studies relate to body condition, lameness, udder edema, injuries, and/or other signs of illness. One study conducted in Ontario evaluated dairy cull cows at three auctions over a sixteen-week study period and reported the prevalence of cows with a BCS ≤ 2.0 to be 27% and the prevalence of abnormal gait (equivalent of ≥ 3 out of 5) was 73% (Moorman et al., 2018). In addition, these cows were sold for a significantly lower price compared to cows with normal gait and BCS. More recently, Stojkov et al. (2020a) evaluated fitness for transport for culled dairy cows at livestock markets in British Columbia (B.C.). Cows were assessed at 137 livestock auction events at 2 livestock markets. In this population, 10% of cows were thin (BCS ≤ 2.0) and 7% were severely lame with a locomotion score of ≥ 4. In addition, 13% had engorged or inflamed udders and 6% had other quality defects, including abscesses, injuries, and signs of illness (Stojkov et al., 2020a). An interesting finding in this work was the influence of market demand for milk on the odds of poor fitness for transport. Cows that were culled during months with increased milk demand (based on milk fat quota) had a greater odds of being classified into a poor fitness for transport category. This suggests that producers may keep animals longer than they should in times of high market demand for milk. Similar to Moorman et al. (2018), Stojkov et al. (2020a) also reported that poor fitness for transport was associated with a substantially lower price at sale. A study in the U.S. also reported a high prevalence of thin (BCS ≤ 2.0) dairy cows (35%) and lame dairy cows (45%) at 10 auction markets in Idaho and California (Ahola et al., 2011). In Canada, Ontario is the only province that has a veterinary inspection system at salesyards that is administered by the provincial ministry of agriculture. Within this system, severely compromised animals are identified, euthanized at the salesyard, and the owner and/or trucker may be subject to investigation and fines related to the transport of compromised animals. Less severely compromised animals may be sold directly to a provincial slaughter facility. Animals identified as compromised through this system can be a function of poor decisions made on-farm regarding the cows' fitness to be transported, but also may be a function of the cows' time in the system itself. Stojkov et al. (2020b) also followed culled dairy cows through the slaughter system from farm to sale auction mart to slaughter facility. Cows culled, being shipped from 20 dairy farms in B.C., were followed for 11 months from farm to sale to slaughter to identify changes in their condition through the cull cow system. In this study, cows spent a mean of 82 ± 46 h in the system after leaving the farm and prior to slaughter. On the extreme, some cows were in the cull cow marketing and slaughter system as long as 16 days prior to being slaughtered. There were 2% of animals observed being sold on different days at 2 different auctions (Sojkov et al., 2020a). Further, the cows' condition deteriorated as she was in the system, with the odds of being classified as thin, having udder edema, or being compromised increasing significantly and substantially with the time since the cow left the farm (Stojkov et al., 2020b). For example, the BCS of cows changed from 3.1 to 2.7 over the average of 82 h in the system from farm to slaughter. This represents a loss of 0.4 of BCS points and since 1 BCS point is approximately equivalent to 80 kg of body weight (Schwager-Suter et al., 2001), this translates to a 32 kg loss in body weight. This weight loss most likely reflects a lack of feed and water while in the marketing system. The risk of udder swelling/edema did not increase between farm and auction but did increase between auction and slaughter. This likely reflects increased time in the cull cow system without being milked causing udder engorgement with time, as the majority of culled dairy cows are not dried off currently prior to shipment. Locomotion was unaffected throughout the system in this study. However, a Danish study evaluating the change in culled cows' condition from farm to slaughter, with a transport time of under 8 hours, reported increased risk of lameness, milk leakage, and wound occurrence at slaughter (Dahl-Pederson et al., 2018a). The transportation of pregnant animals also represents an important risk to the health and welfare of the dam and fetus (EFSA, 2017). Current Canadian regulations indicate that an animal is unfit for transport if it is in the last 10% of pregnancy or has given birth during the last 48 hours (CFIA, 2020). While no published Canadian data exist on prevalence of these animals arriving at slaughter, an expert panel for the European Food Safety Authority estimated that the median percentage of dairy cows slaughtered while pregnant was 13%; they further estimated that 3% were in the last third of gestation (EFSA, 2017).

Some limited research has been conducted to identify means to improve cull cow management in the dairy industry. A Danish study on fitness for transport that focused on lameness reported poor to moderate agreement in lameness scoring between and within producer, veterinarian, and trucker groups (Dahl-Pederson et al., 2018b), identifying issues with producers and truckers with respect to lameness recognition. The 2 Canadian studies previously mentioned also sought to examine producer behaviour around culling decisions. Stojkov et al. (2020b) provided half of participating farms information of compromised culled dairy cows (including transport duration data, cow condition data and prices at auction, information on identifying thin and lame cows, free veterinary support for improved decision-making for cull cows) partway through their study. This "treatment" of producers with information did not result in any difference in prevalence of compromised cattle shipped to auction between "informed" and "uninformed" groups. However, during this period, the overall prevalence of compromised culled dairy cows in the marketing system decreased (possibly as a result of changes in milk fat demand), and the percentage of cows on-farm that died and that were euthanized also decreased during this time indicating that, overall, cows were generally in better condition (Stojkov et al., 2020b). In a study conducted in Ontario, Moorman (2018) reported on provision of a cow checklist evaluation form delivered through participating veterinarians. The checklist included clinical data to consider in determining a cow's fitness for transport prior to loading. These included obtaining a rectal temperature, body condition score, locomotion score, udder measurement (CMT or other measure), date of last milking, date of last treatment (to assess risk of drug residue), and absence of other clinical problems. Both the veterinarians and the producers reported that the use of the form helped to raise awareness of proper evaluation of cull cows prior to shipping. Most producers indicated that the form was useful and that they would use it in their culling decisions if provided. Stojkov et al. (2020b) observed differences in the prevalence of compromised cattle within producers served by different veterinary clinics. They suggested that this might indicate differences between veterinary clinics in either their awareness of culled cow issues, or in their involvement in producer cull cow decision-making. However, as this study was limited to three veterinary clinics, more work is needed to explore this observation.

Based on all of the above data, efforts to reduce the prevalence of compromised culled dairy cows within the Canadian cull cow auction-slaughter system will need to involve producers, veterinarians, and truckers, among other dairy industry personnel. Current federal transport regulations highlight many of the issues that have been identified through research, including restrictions on transport of lactating dairy cows and increased restrictions around transport of cows with lameness and illness (Government of Canada, 2019).

6.3 Prognosis and Decision-Making

Decision-making for vulnerable dairy cows is not only important for determining fitness for transport but is also critical for determining prognosis and euthanasia, particularly if the animal is deemed to be unfit for transport. Although there are certainly welfare concerns for the transport of compromised animals, leaving animals on-farm without treatment or prolonged treatment of cows with a poor prognosis are also not desirable. Timely treatment and euthanasia are also critical components of proper care of vulnerable cattle. Manually applied blunt force trauma does not consistently result in irreversible loss of consciousness and death in cattle, including young calves, and is considered unacceptable by the American Veterinary Medical Association (AVMA, 2020), Humane Slaughter Association (HSA, 2007), and the American Association of Bovine Practitioners (AABP, 2019). Despite this clear guidance, recent Canadian studies report that manually applied blunt force is still used, in some cases as a primary method, to euthanize calves, and that blunt force is often used more commonly to euthanize male dairy calves (Roche et al., 2020). The use of improper methods and/or improper training for acceptable methods have both been demonstrated to be serious issues that lead to major animal welfare concerns (Shearer, 2018; Roche et al., 2020).

Aside from the provision of an efficient and effective method of euthanasia, timely euthanasia is also a critical component of dairy farm management (Walker et al., 2020). Timely euthanasia is often impeded by many factors that include but are not limited to proper training for personnel, provision of proper protocols, decisions for treatment, consideration around the cows' quality of life, influences of the human-animal bond (e.g., mental health and wellbeing), and financial impacts (Walker et al., 2020). Walker et al. (2020) pointed out that often a compromised cow at a slaughter facility that was determined to be unfit for slaughter and euthanized at either the auction or the slaughter facility should have been euthanized on the farm prior to transport and possibly much earlier than the day the decision was made to put the cow on the truck. As an example, Walker et al. (2020) provide a table with estimates of the number of cattle sold with severe conditions, reported through the National Animal Health Monitoring System (USDA, 2016) including cows with cancer eye, bloat, bloody gut, downers, and lameness that should have been euthanized on-farm prior to shipment. The total is over 300,000 cows and represents 3.5% of the total dairy cow population in the U.S. Similar data are not readily available for Canada; however, this highlights the importance of timely euthanasia and fitness for transport decisions. For an animal deemed to be unfit for transport, the decision to treat the animal versus euthanasia should be based not only on the likelihood of treatment success but also on several other factors including the ability to provide pain relief (if required) and quality of life considerations for the animal. Walker et al. (2020) identify three major considerations for timely euthanasia:

1. Development and dissemination of training resources and clear guidelines on timely euthanasia.
2. Planned and regular training sessions and staff discussions.
3. Measuring and tracking to help with objective assessment of procedures and accountability.

Walker et al. (2020) list severe lameness, cancer eye, bloat, bloody gut, nonambulatory cattle, chronic diarrhea, toxic mastitis (severe clinical mastitis), and intractable rectal/vaginal or uterine prolapse as examples of conditions that are unlikely to resolve with treatment and therefore timely euthanasia should be a strong consideration in cows with these conditions. These decisions are complex and are often cow- and farm-dependent, and often subjective, which is why numerous studies review and highlight the importance of developing detailed decision trees to provide more consistent and objective advice (Turner & Doonan, 2010; Wagner et al., 2010).

Lastly, an emerging area of research relates to the mental health and wellbeing of farm workers responsible for euthanasia. Though this is a new area of exploration, recent publications highlight the potential impact these practices may have on worker welfare, which may manifest in aversion or hesitancy to perform the procedure, ineffective execution, or as mental health challenges after performing the procedure (Shearer, 2018; Walker et al., 2020).

6.4 Nursing Care for Down Cows

A down or downer cow is one that has become nonambulatory and is no longer able to walk. Some definitions of downer cows specify being down in sternal recumbency for more than 24 hours with no evidence of systemic illness (Poulton et al., 2016a). Regardless of good management, it is common for an average herd to have at least one nonambulatory cow in a year (Green et al, 2008). Therefore, this is clearly an issue that every dairy producer should be prepared to manage. The duration of recumbency greatly influences the likelihood of recovery. As a benchmark, euthanasia should be considered in cows that are recumbent for greater than 24 hours (Green et al., 2008). Although there can be many reasons for a cow being down including infectious, metabolic, calving injury, traumatic injury, and neoplastic causes, cows that were presumably down for metabolic reasons (received calcium, phosphorus, or potassium while nonambulatory) were nearly 4 times more likely to recover than cows down for other reasons (not receiving those treatments; Green et al., 2008). Cows that were recumbent for more than 24 hours were reported to have their recovery influenced more by secondary damage from being down than by the original primary condition (Poulton et al., 2016a). This work suggests that early intervention and good nursing care may result in an increased likelihood of recovery (Poulton et al., 2016b; Green et al., 2008). Stull et al. (2007) suggest the two primary objectives in the treatment and care of downer cows are “to correct the primary cause of recumbency and to minimize secondary nerve and muscle damage.” Thus, if the primary cause of being down cannot be corrected, such as fracture, dislocation, or rupture of a tendon, then euthanasia should be an immediate decision. For downer cows with a working diagnosis that could involve a potential recovery, diligent management and nursing care are critically important factors in facilitating the success of treatment (Huxley, 2006). Part of the reason that increased duration of recumbency limits recovery is the development of muscle ischemia and nerve pressure damage from the weight and physical compression of being down (Huxley, 2006). This pressure causing muscle damage has been called compartmentalization and compression syndrome (Cox, 1988). Therefore, lifting down animals in part to relieve the pressure on muscles and nerves is an important component of down cow management. Compartment syndrome affected 36% of down cows based on serum creatinine kinase concentrations in an Australian study (Poulton et al., 2016a). Additionally, secondary femoral nerve damage was identified in 22% of downers (Poulton et al., 2016a). Huxley (2006) lists several methods of lifting cows including the use of slings, hoists (hip clamps or hip lifters), and floatation tanks. All methods must be used with adequate training and care to avoid injury to the cow or to the operators. Of these methods, the floatation tank is considered the best in terms of providing atraumatic lifting without pressure points, potentially providing a form of hydrotherapy to improve blood flow to damaged muscles (Stojkov et al., 2016). However, it is also the most expensive method. Floatation tanks can be used both diagnostically and therapeutically. Cows that do not respond to flotation (unable to stand or stand properly, failure to eat while being floated) typically have a very poor prognosis and euthanasia should be strongly considered (Burton et al., 2009; Stojkov et al., 2016). Additional nursing care should include relocation of the down animal to an appropriate location in a humane manner, frequent provision of feed and water, provision of a clean, dry, and comfortable lying environment, turning or lifting frequently, and segregation from other animals (Huxley, 2006; Stojkov et al., 2016). Additional considerations should include the administration of nonsteroidal anti-inflammatory drugs (NSAIDs) through consultation with the herd veterinarian to help with the management of pain and inflammation, and milking every 12 hours while being lifted or while in lateral recumbency to relieve udder pressure and reduce the risk of mastitis (Huxley, 2006). Cows should be turned or lifted every 3 hours or floated for a prolonged period of 6–8 hours (Huxley, 2006; Stojkov et al., 2016). The provision of appropriate nursing care cannot be over-emphasized. Stojkov et al. (2016) reported that cows that received good nursing care were more likely to recover following flotation therapy than cows that received poor nursing care. Nursing care for each cow was assessed through a survey of the farm manager and by on-site survey by the veterinarian (Stojkov et al., 2016). In that study, 64% of the cows receiving good nursing care and undergoing on average 1.7 flotations made a full recovery (Stojkov et al., 2016). By contrast only 1–9 cows from farms having poor nursing care recovered following an average of 1.7 flotations per cow. An Australian study also identified the association of high-quality nursing care with improved chance of recovery from recumbency (Poulton et al., 2016b). Cows receiving high quality nursing care had an improved chance of recovery from the primary condition and a reduced chance of secondary damage (Poulton et al., 2016b). The authors recommend that downer cows should either be provided appropriate nursing care or be immediately euthanized (Poulton et al., 2016b).

6.5 Linkage Between Dry-Off and Culling

Currently in Canada, most cows that are culled are sold in full milk to auction marts and then transported to slaughter facilities. In a pilot study with producers in Ontario, participating dairy producers were asked to fill out an evaluation form for each cow shipped over a period of three months. A total of 187 evaluation forms (85% of completed forms) were completed by 44 producers with the last milking date recorded as the same day the cows were shipped, indicating that the cows were not dried off prior to shipment (Moorman, 2018). In fact, only 33 forms (15% of completed forms) indicated a time of last milking that was prior to the same day of shipment (Moorman, 2018). Time in the cull cow system means that these cows are not milked for several days prior to slaughter. As an example, cows leaving dairy farms in B.C. spent on average 3.5 days in the system after leaving the farm and prior to slaughter (Stojkov et al, 2020b). However, 3% of cows were in the system between 8 and 16 days (Stojkov et al., 2020b). This is a marketing system with dairy cows being generally in close proximity to the auction and slaughter facilities. In other parts of Canada, there are likely to be many more cows with longer times in the marketing system than 3.5 days based on the conclusions from a Canadian cull cow consultation panel (Stojkov et al., 2018). The primary concern with cows in the marketing system without being dried off is that it likely creates udder swelling and edema, causing discomfort and pain and probably increases the risk of mastitis. In the work by Stojkov et al. (2020a), the prevalence of cows with engorged or inflamed udders was 13% out of 6,263 cull dairy cows observed at two B.C. auction marts. Additionally, the problem of udder engorgement was shown to be stable between the time from farm to auction but increased between auction to slaughter indicating that the longer the cow is in the system, the greater the risk of udder engorgement and inflammation. Further, cows in earlier stages of lactation and older cows (≥ parity 3) had a higher risk of udder swelling. A Danish study reported that the proportion of cows with milk leakage increased from 1% of cows at the farm prior to loading to 17% of cows by the time they arrived at slaughter (transport was direct from farm to slaughter with a mean time of only 187 minutes and only a few cows with more than 8 hours in transit) (Dahl-Pedersen et al., 2018a). In this study both early lactation (< 100 DIM) and transport distance (> 100 km) were associated with increased risk of milk leakage (Dahl-Pedersen et al, 2018a). Current federal transport regulations state that lactating animals cannot be transported unless they are milked at intervals sufficient to prevent mammary engorgement (Government of Canada, 2019). In most situations this effectively means that drying cows off prior to shipping would be required to comply with this regulation, unless cows are being shipped directly from farm to slaughter (with less than 12 hours from farm to slaughter). Dry off needs to be performed properly to mitigate the potential welfare concerns associated with abrupt cessation of milking, which include pain from udder engorgement, hunger, and unfulfilled motivation to be milked (Zobel et al., 2015). Although more work is needed to determine best methods for cessation of milking, one study has shown that intermittent milking over a five-day period reduced milk leakage and time anticipating milking (Zobel et al., 2013). Regardless of on-farm method, culled lactating animals not sent direct to slaughter are forced to undergo abrupt cessation of milking over multiple days spent in a marketing system prior to final processing. Thus, producers will need to dramatically change how they manage the shipment of lactating cull dairy cows in the very near future. One potential option for producers would be to dry cows off and then feed them to put body weight on. Studies conducted in both B.C. and Ontario have demonstrated that the price per kg obtained for culled dairy cows is significantly lower for thin cows (BCS ≤ 2.0) and for lame cows. Drying cows off, resting them in a comfortable pen, and feeding them to put weight on has the potential to both improve cow welfare and add value to cull dairy cows prior to shipment. The economics and impact of feeding cull dairy cows on carcass quality has been evaluated in other countries and has been shown to improve carcass quality, but is not always of economic benefit (Franco et al., 2009; Minchin et al., 2009; Maier et al., 2011). However, there has been no work published on this question yet in Canada and none of the existing research has investigated the impact of this strategy on improving dairy cull cow welfare.

6.6 References

Ahola J.K., Foster H.A., VanOverbeke D.L., Jensen K.S., Wilson R.L., Glaze J.B. Jr., Fife T.E., Gray C.W., Nash S.A., Panting R.R. & Rimbey N.R. (2011) Survey of quality defects in market beef and dairy cows and bulls sold through livestock markets in the Western United States: I. Incidence rates. *Journal of Animal Science* 89:1474–483.

American Association of Bovine Practitioners (AABP) (2019) *Guidelines for the Humane Euthanasia of Cattle*. Available at: www.aabp.org/Resources/AABP_Guidelines/EUTHANASIA-2019.pdf

American Veterinary Medical Association (AVMA) (2020) *AVMA Guidelines for the Euthanasia of Animals: 2020 Edition*. Available at: https://www.avma.org/sites/default/files/2020-01/2020-Euthanasia-Final-1-17-20.pdf.

Burton A.J., Nydam D.V., Ollivett T.L. & Divers T.J. (2009) Prognostic indicators for nonambulatory cattle treated by use of a flotation tank system in a referral hospital: 51 cases (1997–2008). *Journal of the American Veterinary Medical Association* 234:1177–1182.

Canadian Food Inspection Agency (CFIA) (2020) *Livestock Transport in Canada*. Available at: https://www.inspection.gc.ca/animal-health/humane-transport/livestock-transport-in-canada/eng/1363748532198/1363748620219.

Cox V.S. (1988) Nonsystemic causes of the downer cow syndrome. *Veterinary Clinics of North America: Food Animal Practice* 4:413–433.

Dahl-Pedersen K., Herskin M.S., Houe H. & Thomsen P.T. (2018a) Risk factors for deterioration of the clinical condition of cull dairy cows during transport to slaughter. *Frontiers in Veterinary Science* 5:1–8.

Dahl-Pedersen K., Herskin M.S., Houe H. & Thomsen P.T. (2018b) Lameness scoring and assessment of fitness for transport in dairy cows: Agreement among and between farmers, veterinarians and livestock drivers. *Research in Veterinary Science* 119:162–166.

European Food Safety Authority (EFSA) (2017) Animal welfare aspects in respect of the slaughter or killing of pregnant livestock animals (cattle, pigs, sheep, goats, horses). *Scientific Opinion* 15:4782.

Franco D., Bispo Esperanza E., Gonzalez L., Vazquez J.A. & Moreno T. (2009) Effect of finishing and ageing time on quality attributes of loin from the meat of Holstein-Fresian cull cows. *Meat Science* 83:484–491.

Government of Canada (2019) Part XII Transport of Animals. In *Health of Animals Regulations C.R.C., c. 296*. Available: www.laws-lois.justice.gc.ca/eng/regulations/C.R.C.%2C_c._296/page-15.html#h-548075

Green A.L., Lombard J.E., Garber L.P., Wagner B.A. & Hill G.W. (2008) Factors associated with occurrence and recovery of nonambulatory dairy cows in the United States. *Journal of Dairy Science* 91:2275–2283.

Humane Slaughter Association (HSA) (2007) *Humane Dispatch and Disposal of Infant Calves*. Technical note no. 2. Available at: http://www.hsa.org.uk/downloads/technical-notes/TN2-calves-human-dispatch-disposal-HSA.pdf.

Huxley J. (2006) Assessment and management of the recumbent cow. *In Practice* 28:176–184.

Maier G.U., Hoar B.R., Stull C.L., Kass P.H., Villanueva V. & Maas J. (2011) Effect of a nutritional reconditioning program for thin dairy cattle on body weight, carcass quality, and fecal pathogen shedding. *Journal of the American Medical Association* 239:1594–1602.

Minchin W., Buckley F., Kenny D.A., Monahan F.J., Shalloo L., O'Donovan M. (2009) Effect of grass silage and concentrate based finishing strategies on cull cow performance, carcass and meat quality characteristics. *Meat Science* 81:93–101.

Moorman A.K.G. (2018) Assessment of culled dairy cows on farms, and at livestock auction markets in Ontario. MSc Thesis. Guelph ON: University of Guelph.

Moorman A., Duffield T.F., Godkin A., Kelton D., Rau J. & Haley D.B (2018) Associations between the general condition of culled dairy cows and selling price at Ontario auction markets. *Journal of Dairy Science* 101:10580–10588.

Poulton P.J., Vizard A.L., Anderson G.A. & Pyman M.F. (2016a) Importance of secondary damage in downer cows. *Australian Veterinary Journal* 94:138–144.

Poulton P.J., Vizard A.L., Anderson G.A. & Pyman M.F. (2016b) High-quality care improves outcome in recumbent dairy cattle. *Australian Veterinary Journal* 94:173–180.

Roche S.M., Genore R., Renaud D.L., Shock D.A., Buaman C., Croyle S., Barkema H.W., Dubuc J., Keefe G.P. & Kelton D.F. (2020) Short communication: Describing mortality and euthanasia practices on Canadian dairy farms. *Journal of Dairy Science* 103:3599–3605.

Shearer J.K. (2018) Euthanasia of cattle: Practical considerations and applications. *Animals* 8:57.

Schwager-Suter R., Stricker C., Erdin D. & Kunz N. (2001) Quantification of changes in body weight and body condition scores during lactation by modelling individual energy balance and total net energy intake. *Animal Science* 72:325–334.

Stojkov J., Weary D.M. & von Keyserlingk M.A.G. (2016) Nonambulatory cows: Duration of recumbency and quality of nursing care affect outcome of flotation therapy. *Journal of Dairy Science* 99:2076–2085.

Stojkov J., Bowers G., Draper M., Duffield T., Duivenvoorden P., Groleau M., Haupstein D., Peters R., Pritchard J., Radom C., Sillett N., Skippon. W., Trépanier H. & Fraser D. (2018) Hot topic: Management of cull dairy cows: Consensus of an expert consultation in Canada. *Journal of Dairy Science* 101:11170–11174.

Stojkov J., von Keyserlingk M.A.G., Duffield T. & Fraser D. (2020a) Fitness for transport of cull dairy cows at livestock markets. *Journal of Dairy Science* 103: 2650–2661.

Stojkov J., von Keyserlingk M.A.G., Duffield T. & Fraser D. (2020b) Management of cull dairy cows: Culling decisions, duration of transport, and effect on cow condition. *Journal of Dairy Science* 103: 2636–2649.

Stull C.L., Payne M.A., Berry S.L. & Reynolds J.P. (2007) A review of the causes, prevention, and welfare of nonambulatory cows. *Journal of the American Veterinary Medical Association* 231:227–234.

Turner P.V. & Doonan G. (2010) Developing on-farm euthanasia plans. *Canadian Veterinary Journal* 51:1031–1034.

United States Department of Agriculture (USDA) (2016) *Dairy 2014 Dairy Cattle Management Practices in the United States, 2014*. Available at: https://www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy14/Dairy14_dr_PartI_1.pdf. Accessed: November 6, 2019.

Walker J.B., Roman-Muniz I.N. & Edwards-Callaway L.N. (2020) Timely euthanasia in the United States dairy industry-challenges and a path forward. *Animals* 71:1–17.

Wagner B.K., Cramer M.C., Fowler H.N., Varneli H.L., Dietsch A.M., Proudfoot K.L., Shearer J., Correa M. & Pairis-Garcia M.D. (2020) Determination of dairy cattle euthanasia criteria and analysis of barriers to humane euthanasia in the United States: The veterinarian perspective. *Animals* 10:1051.

Zobel G., Leslie K., Weary D.M. & von Keyserlingk M.A.G. (2013) Gradual cessation of milking reduces milk leakage and motivation to be milked in dairy cows at dry-off. *Journal of Dairy Science* 96: 5064–5071.

Zobel G., Weary D.M., Leslie K.E. & von Keyserlingk M.A.G. (2015) Invited review: Cessation of lactation: Effects on animal welfare. *Journal of Dairy Science* 98: 8263–8277.