Lameness and pain management on Irish dairy farms

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Abstract

Lameness is a major concern for animal welfare due to the associated pain, and has significant negative economic and environmental consequences. Irish dairying differs from most other systems, whereby cows are out to grass for the majority of the year and housed over the winter months; therefore, research from other system types can be hard to apply to Irish dairy farms. Reducing lameness on Irish dairy farms is vitally important, as the welfare-friendly credentials of Irish dairy products are key to positioning Ireland as a leading supplier of dairy products internationally. In order to reduce lameness, further work is required on the prevalence, causes and risk factors for lameness in Irish dairy cows. The Irish dairy industry would also benefit from knowing what lameness management practices are currently in place on Irish dairy farms. The aim of this thesis was to gain knowledge on lameness and pain management in an Irish pasture-based dairy system.

The first study (Papers 1-3) involved lameness scoring cows from 99 pasture-based dairy herds in Ireland during the grazing period, and from 85 of these herds during the housing period. At each visit, infrastructure measurements were taken (housing facilities, milking facilities and cow tracks) and a questionnaire was undertaken with the farmer to identify background information and farm management practices. Cow-level data was also collected (e.g. breed, parity and milk yield). For 98 of the farms visited during the grazing period and for 74 of the farms visited during the housing period, the hind hooves of up to a maximum of 20 lame cows were examined and hoof lesions were recorded. The second study (Paper 4) involved sending a questionnaire on attitudes to pain and the use of non-steroidal anti-inflammatory drugs (NSAIDs) on Irish dairy farms, to both dairy farmers and veterinarians that work with dairy cows in Ireland. Over 1000 questionnaires were returned by dairy farmers and 116 by veterinarians.

Paper 1 determined the most important cow-level and herd-level risk factors for lameness in Irish pasture-based dairy herds, based on both the grazing and housing period. Triangulation of elastic net regression and logistic regression using modified Bayesian information criterion, with bootstrapping, were used to obtain a robust set of risk factors. Cow-level risk factors included age and genetic predicted transmitting ability for lameness, and herd-level risk factors included herd and farm size, the distance cows had to turn at the milking parlour exit, stones in paddock gateways, and slats on the cow track near the collecting yard; farmer's perception of lameness and digital dermatitis in their herd was also associated with lameness outcomes.

Paper 2 reported the lameness prevalence during both the grazing and housing periods, and identified lameness management practices that are currently in place on Irish dairy farms. This paper also described current infrastructure and general farm management that may relate to lameness. The median herd lameness prevalence was 7.9% during grazing and 9.1% during housing. This study identified many potential areas of lameness management that could be improved upon on Irish farms; for example, only one farmer carried out lameness scoring, 6% routine trimming and 31% regular footbathing. The majority of farms also had rough (uneven, larger stones, bumps and holes are common, signs of wear or erosion) cow tracks present, and had less than 1.1 cubicles per cow in all pens.

Paper 3 identified the prevalence of hoof lesions in lame dairy cows, correlations between lesions, the lesions that were associated with more severe lameness, and risk factors for digital dermatitis. The most prevalent lesions were white line separation, sole haemorrhage and overgrown claws. Digit amputation, foul of the foot, sole ulcer, white line abscess and toe necrosis were associated with more severe lameness. Overgrown claws and penetration of a foreign body were more common during grazing than housing. The strongest correlation at herd-level was between toe necrosis and digital dermatitis, and between overgrown claws and corkscrew claws at cow-level. Cow track characteristics, as well as the farmer's perception of lameness and digital dermatitis in the herd were associated with digital dermatitis risk.

Paper 4 reported attitudes to pain and pain relief by dairy farmers and veterinarians in Ireland, and the use of NSAIDs for various dairy cow and calf conditions and procedures, including those related to lameness. This study showed that veterinarians and farmers are potentially becoming habituated to pain; they scored the conditions and procedures they saw most regularly as less painful than those less commonly seen. Higher pain scores were also associated with higher NSAID use; however, for some conditions and procedures NSAID use was low despite the pain score given. The cost of NSAIDs was also considered less of an issue to farmers than veterinarians thought.

This thesis provides valuable insights into dairy cow health and welfare, with a particular focus on lameness. Compared to other countries, a relatively low lameness prevalence was reported during both the grazing and housing period; however, approximately one in ten lame cows is still arguably too high. Farmers should strive for the lowest lameness prevalence possible for welfare and economic reasons. This thesis also showed that there are many areas of lameness management that could be improved upon. Knowledge gained from this thesis will provide guidance for future research and allow information to be disseminated to farmers and veterinarians, thus further decreasing lameness and improving pain management on Irish dairy farms.

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Declaration

Own Work

'The thesis must be the result of the candidate's own work. This requirement does not preclude a candidate obtaining limited assistance with the routine collection and/or processing of data under guidelines and instructions clearly devised by the candidate. When such help is obtained it should be with the prior approval of the supervisor who must be satisfied that the spirit of the 'own work' requirement is not breached'.

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'*Prior publications of papers arising from the research being undertaken will not adversely prejudice the assessment of the thesis by the Examiners*'.

Publications forming the basis of this thesis are listed in the next section

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Publications presented in this thesis

Paper 1

Browne, N., C. D. Hudson, R. E. Crossley, K. Sugrue, E. Kennedy, J. N. Huxley, and M. Conneely. 2022. Cow- and herd-level risk factors for lameness in partly housed pasture-based dairy cows. J. Dairy Sci. 105:1418-1431. https://doi.org/10.3168/jds.2021-20767.

Paper 2

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Paper 3

Browne, N., C. D. Hudson, R. E. Crossley, K. Sugrue, J. N. Huxley, and M. Conneely. 2022. Hoof lesions in partly-housed pasture-based dairy cows. J. Dairy Sci. 105:9038-9053. https://doi.org/10.3168/jds.2022-22010.

Paper 4

Browne, N., M. Conneely, and C. D. Hudson. 2022. Use of non-steroidal anti-inflammatory drugs and attitudes to pain in pasture-based dairy cows: a comparative study of farmers and veterinarians. Front. Vet. Sci. 9:912564. https://doi.org/10.3389/fvets.2022.912564.

Other publications

Crossley, R.E., **N. Browne**, and M. Conneely. 2019. 'How do we measure dairy cow welfare on-farm?' Moorepark open day 2019 - Irish dairying - growing sustainably. Teagasc, Co. Cork, Ireland, 3 July 2019, 172-173.

Conneely, M., R. E. Crossley, **N. Browne,** K. Sugrue, E. Kennedy, C. D. Hudson, and E. A. M. Bokkers. 2020. Assessing Irish dairy cow welfare. Vet. Irel. J. 10:670-673.

Crossley, R. E., E. A. M. Bokkers, **N. Browne**, K. Sugrue, E. Kennedy, I. J. M. de Boer, and M. Conneely. 2021. Assessing dairy cow welfare during the grazing and housing periods on spring-calving, pasture-based dairy farms. J. Anim. Sci. 99:skab093. https://doi.org/10.1093/jas/skab093.

Browne, N. and M. Conneely. 2021. 'Strategies to reduce lameness on your farm' Moorepark open day 2021 - Irish dairying - delivering sustainably. Teagasc, Co. Cork, Ireland, 14-16 September 2021, 158-159.

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Table of Contents

Chapter 1: Literature review

1.1 The dairy industry

1.1.1 Product demand and public perception

Increased demand for dairy produce has been led by human population growth, strengthening of the global economy and a rise in urbanization (Wright, 2005). The global population will reach eight billion in 2022, and this is predicted to reach over 9.7 billion by 2050 (United Nations, 2022). In 2020, a total of 906 million tonnes of milk were produced globally, with the majority of milk production coming from Asia (379 million tonnes) and the European Union (236 million tonnes; FAO, 2021).

There is growing awareness of the need to produce food sustainably, with producers facing the challenges of environmental, economic and social sustainability (Arvidsson Segerkvist et al., 2020). Farm animal welfare is becoming an increasingly important issue as consumers are taking more interest in how their food is produced (European Commission, 2016). Surveys have shown that consumers say they are willing to pay more for dairy products produced under conditions that provide good animal welfare (Ellis et al., 2009; Infascelli et al., 2021). Good animal welfare can increase marketing power; therefore, retailers and processors are also becoming more involved in what is happening on-farm in terms of animal welfare and sustainable practices. The use of farm assurance schemes, which typically go beyond animal welfare legislation, are becoming increasingly common worldwide (More et al., 2017; More et al., 2021). Additionally, due to the increased awareness of dairy production practices and pain in dairy cows (Wolf et al., 2016; Cardoso et al., 2017; Remnant et al., 2017), pain management may become an increasingly important topic within the dairy sector for improving dairy cow welfare. For example, in a US survey over two thirds of the public agreed that castration without pain relief should be banned (Wolf et al., 2016).

1.1.2 The dairy industry from an Irish perspective

Ireland operates a predominantly spring-calving, pasture-based dairy system, whereby cows are grazed for a large proportion of the year and housed over the winter (Dillon et al., 1995). This differs from some other pasture-based systems, such as New Zealand and parts of South America, where cows are grazed year-round. The average number of days at grass on Irish dairy farms in 2020 was 233 days (Teagasc, 2021); however, the proposed target to increase profitability is to extend the grazing season to over 300 days (Läpple et al., 2012). The majority of Irish dairy farms operate a spring-calving system to allow peak milk production to coincide with peak grass growth, reducing production costs (Dillon et al., 1995). Farmers aim to calve 90% of the herd within a six week period, with the remaining 10% calving within a 12 week period (Butler, 2014).

Because it is predominantly pasture-based, Ireland's dairy industry is generally perceived as being welfare-friendly (Sweeney et al., 2022), providing potential marketing advantages for Irish dairy produce both nationally and internationally. Access to pasture has been reported to reduce lameness (Hernandez-Mendo et al., 2007; Olmos et al., 2009a), hock lesions (Rutherford et al., 2008), mastitis (Barkema et al., 1999; Washburn et al., 2002) and metritis (Bruun et al., 2002) in comparison to housed systems. Access to pasture also allows cows to exhibit normal behaviours such as grazing (Arnott et al., 2016). However, it must be noted that cows in Ireland are still subjected to the housing environment for an average of 4.5 months each year (Teagasc, 2021).

There are also negative welfare aspects associated with pasture-based dairying. Cows at pasture can be exposed to extreme weather conditions. Rain can lead to muddy conditions, which can reduce cleanliness (Aubé et al., 2022) and lying time (Chen et al., 2017). Tucker et al. (2007) reported that cattle housed outdoors in winter conditions had shorter lying times, and also adapted their lying position to reduce surface area exposed to poor weather. Sun exposure, high temperatures and humidity can also result in heat stress and sun-burn in pasture-based dairy cows; providing shade can reduce this impact (Aubé et al., 2022; Veissier et al., 2018). Cows at pasture are also at higher exposure to parasites, toxic plants and diseases from neighbouring cattle and wild animals (Aubé et al., 2022). Olmos et al. (2009c) also reported that during the peripartum period cows at pasture had lower rumen fill compared to fully housed cows, indicating a negative energy balance and nutritional stress. Cows at pasture have also been reported in some cases to have lower body weight and body condition score (BCS) compared to housed cows (Roca-Fernández et al., 2013).Variation in grass quality and quantity across the year can also make it hard for farmers to control feed intake (Aubé et al., 2022). It is important that welfare assessments are adapted to adequately measure welfare at pasture within Ireland (Aubé et al., 2022).

In 2015, milk quotas in the European Union were abolished after 31 years, which led to a steady rise in dairy cow numbers and milk production in Ireland. From 2014 to 2020 there was an increase of over 27% in total dairy cow numbers in Ireland (CSO, 2020, 2021) and an increase of over 45% in domestic milk intake by Irish creameries and pasteurisers (CSO, 2022). The average herd size in Ireland also increased by 28% from 2014 to 2020; the average herd size in 2020 being 84 cows (Teagasc, 2021). Growing herd sizes in Ireland will likely lead to an increase in the size of grazing platforms, thus increasing the distance cows must walk between the milking parlour and pasture (Boyle et al., 2015). There is concern that a longer walking distance may lead to increased lameness, especially if cow tracks are not well maintained (Dewes, 1978; Chesterton et al., 1989; Boyle et al., 2015).

1.2 Bovine lameness

1.2.1 Defining lameness

Lameness in general is defined as the "inability to walk correctly because of physical injury to or weakness in the legs or feet" (Cambridge University Press, 2022). In terms of bovine lameness, it is often defined as impaired locomotion most frequently due to pain (Van Nuffel et al., 2015a; Oehm et al., 2019). However, there is some heterogeneity in the definition of lameness between studies (Oehm et al., 2019). Some studies have previously defined lameness as the presence of particular claw lesions or diseases, as opposed to looking at the animal's locomotive pattern (Alban, 1995; Alban et al., 1996).

Lameness is often defined using lameness scoring, whereby if a cow scores above a certain score the cow is classified as lame. There are, however, many different scoring systems used both commercially and in research (Schlageter-Tello et al., 2014). Details on a variety of commonly used lameness scoring systems are reported in Table 1.1. The Agriculture and Horticulture Development Board (AHDB) four-point scoring system is used throughout this thesis (AHDB, 2013) and is commonly used in both research and commercial settings. Further details of this scoring system based on the updated version can be viewed in Table 1.2 (AHDB Dairy, 2020). There are also discrepancies within certain scoring methods as to what lameness score (LS) categorises a cow as lame. For instance, using a five-point lameness scoring scale, cows that score ≥ 3 are generally classified as lame (Sprecher et al., 1997; Bach et al., 2007; Solano et al., 2015); however, in a different study cows were classified as lame if they scored ≥ 4 (Kovacs et al., 2015). Consistency in the defining of lameness and the scoring methods used is required to enable comparisons across studies and further aid the improvement of animal welfare (Oehm et al., 2019).

Table 1.1. Commonly used lameness scoring systems reported in literature

Scale	Points in scale	Scale (min – max)
AHDB Dairy (2020)	4	0 - 3
Sprecher et al. (1997)	5	1 - 5
Winckler and Willen (2001)	5	1 - 5
Flower and Weary (2006)	9	1 - 5
Manson and Leaver (1988)	9	1 - 5

Table 1.2. Description and suggested action for each lameness score from the Agriculture and Horticulture Development Board (AHDB) lameness scoring scale (AHDB Dairy, 2020)

Category	Score	Description	Suggested action
Good mobility	0	• Walks with even weight bearing and rhythm on all four feet, with a flat back • Long, fluid strides possible	• No action needed • Routine (preventative) foot trimming when/if required • Record mobility at next scoring session
Imperfect mobility	1	• Steps uneven (rhythm or weight bearing) or strides shortened; affected limb or limbs not immediately identifiable	• Could benefit from routine (preventative) foot trimming when/if required • Further observation recommended
Impaired mobility	2	• Uneven weight-bearing on a limb that is immediately identifiable and/or obviously shortened strides (usually an arch to the centre of the back)	• Lame and likely to benefit from treatment • Foot should be lifted to establish the cause of lameness before treatment • Should be attended to as soon as practically possible
Severity impaired mobility	3	• Unable to walk as fast as a brisk human pace (cannot keep up with the healthy herd) • Lame leg easy to identify – limping; may barely stand on lame leg/s; back arched when standing and walking • Very lame	• This cow is very lame and requires urgent attention, nursing and further professional advice • Examine as soon as possible • Cow will benefit from treatment • Cow should not be made to walk far and kept on a straw yard or at grass • In the most severe cases, culling may be the only possible solution

1.2.2 Lameness detection

As described above, lameness scoring, also known as mobility scoring, can be used to identify lame cows in a herd. Cows are usually watched walking for approximately six to ten strides on a flat, non-slip, concrete surface and given a LS (Archer et al., 2010). Regular lameness scoring allows lame cows to be detected and promptly treated; however, farmers must not become reliant on lameness scoring as their only detection method. Farmers should be checking for lameness on a daily basis, through general daily observations, and treating on diagnosis. Routine lameness scoring can also be used as a benchmarking tool for farmers to compare changes in lameness prevalence in their herd over time, and for comparing their lameness prevalence to other dairy farmers (Archer et al., 2010). There is currently little information available regarding how many Irish dairy farmers carry out lameness scoring on their farm.

Although lameness scoring is designed to reduce variation between scorers, the scoring method is still based on observation and is therefore subjective. As herd sizes increase, lameness scoring can take up a large amount of time (Schlageter-Tello et al., 2014). Cows are also stoic animals which can lead to them trying to hide pain during lameness scoring, potentially leading to lameness going undetected and an underestimation of the herd lameness prevalence. The use of automatic lameness detecting systems have also been researched and implemented on farms to remove the subjective nature of lameness scoring, save time and improve lameness management (Schlageter-Tello et al., 2014; O'Leary et al., 2020). Automated lameness detection methods include accelerometers, vision-based analysis and pressure plates. Accelerometers are individually attached to cows and can be used to measure behaviour and gait measurements in order to detect lameness (O'Leary et al., 2020). The first accelerometer commercially available for lameness detection and lameness scoring was created by Icerobotics (Edinburgh, UK). This system was developed using a traffic light system to allow the farmers to simply view the probability of a cow being lame. Van De Gucht et al. (2017) reported that farmers have shown a preference towards sensors that were attached to the cow (e.g. accelerometers). This may be due to farmers being more familiar with this kind of technology for oestrus detection (Van De Gucht et al., 2017).

Vision-based technology and pressure plates removes the need to attach individual monitors to cows. Vision-based technologies are relatively low cost, however, heavy cow traffic has been shown to effect the accuracy of some vision-based systems and therefore farm layout may need to be considered when installing this type of technology (Van Hertem et al., 2018). 'CattleEye' is a relatively new tool that uses a simple security camera and artificial intelligence to detect lame cows as they walk. This system has been validated by Liverpool University based on three dairy farms, and was found to be at least as good at detecting lameness as an expert human lameness scorer (Anagnostopoulos et al., 2021). Pressure plates require large amounts of space and are expensive, therefore, this technology is not widely adopted on farm. Van De Gucht et al. (2017) reported that costs could be reduced by 83%, compared to the original system studied (StepMetrix®, BouMatic, Madison, WI, USA), through reducing the mat length and resolution, without impacting accuracy. However, an increase in the overall sensor accuracy is still required. In terms of detecting painful lesions, Bicalho et al. (2007) reported that lameness scoring by an expert outperformed lameness detection using pressure plates.

Detection performance of the technology itself is seen as a major limitation to the implementation of automatic lameness systems on-farms (O'Leary et al., 2020). O'Leary et al. (2020) suggests that lameness detection systems should have > 90% sensitivity and > 99% specificity to be valuable to dairy farmers. Such accuracy must be achieved in order to effectively differentiate between lame and non-lame cows. Specificity needs to be high to prevent farmers getting frustrated at cows being identified as lame, and drafted for treatment, despite not being lame (Van Nuffell et al., 2015b; O'Leary et al., 2020). Therefore, reducing the number of false positive results is essential for the uptake and acceptance of a technology on farm. High sensitivity is also vital for ensuring lame cows are detected and can therefore get treated (O'Leary et al., 2020). It must also be considered that the specificity and sensitivity of the technology is in relation to a visual assessment of the cows, through the likes of lameness scoring (Afonso et al., 2020). Therefore, the technology is limited based on the detection of lameness by a human observer. Cost of the technology is also seen as a barrier to farmers (Van De Gucht et al., 2017).

Early detection of lameness is only of use if followed by prompt and effective treatment. Lameness scoring and automated lameness detection needs to be used as a tool to allow cows to be treated promptly once diagnosed as lame (Pedersen and Wilson, 2021). Based on the AHDB 0-3 mobility scoring scale, it is recommended that cows with a score two are treated within 48 hours and cows with a score three as soon as possible upon detection (Pedersen and Wilson, 2021). Compared to the farmer carrying out normal on-farm lameness practices, Groenevelt et al. (2014) and Leach et al. (2012) reported that lameness scoring every two weeks, followed by treatment of score two cows within 48 hours, increased the cure rate and reduced cases of severe lesions. Leach et al. (2012) also reported that for cows being treated based on the farmers normal lameness practices, there was an average of 65 days between cows being scored lame and treatment. Thomas et al. (2015, 2016) reported that treatment of chronically lame cows had lower recovery rates compared to treatment of acutely lame cows. This highlights the importance of prompt and effective treatment to aid recovery (Thomas et al., 2016). A therapeutic trim, block and three days of non-steroidal anti-inflammatory drugs (NSAIDs) has been deemed an effective treatment method for claw horn lesions (Thomas et al., 2015). More information on lameness and NSAIDs can be found in section 1.5.1.

1.2.3 Lameness prevalence

Lameness prevalence in housed dairy systems has been widely reported. In freestall-housed herds in North America, average lameness prevalence has been reported to be as high as 55% (von Keyserlingk et al., 2012). Average lameness prevalence has also been reported to be as low as 9.6% in predominantly housed cattle in the United States (Adams et al., 2017). However, it must be noted that 29% of farms in this study had pasture access for lactating cows for part of the summer, therefore not all herds were fully-housed throughout the year. In studies where all herds included in the study were considered fully-housed, average lameness prevalence has been reported to be as low as 21% (Sarjokari et al., 2013; Solano et al., 2015). Studies have commonly also shown very large variation in lameness prevalence between herds. For example, Solano et al. (2015) reported that lameness prevalence across 141 farms in Canada ranged from 0% to 69%.

Research has shown that lameness prevalence is generally lower in pasture-based systems compared to housed-systems. A summary of literature that reports lameness prevalence in pasture-based herds can be viewed in Table 1.3. Olmos et al. (2009a) reported that cows kept on pasture had a lower LS compared to cows kept on cubicles with no pasture access. Haskell et al. (2006) also report that lameness prevalence was 15% for seasonal grazing herds and 39% in zero-grazing herds in the United Kingdom, when scored during the winter housing period. Zero-grazed cattle on small-scale farms also had 2.9 times higher odds of lameness compared to those grazed at pasture (Gitau et al., 1996). Although Ireland has a predominantly pasture-based dairy system, cows still spend a significant proportion of time indoors. It is therefore important to also investigate lameness during this period. Currently, no studies in Ireland have reported the lameness prevalence during the winter housing period, or compared this to the lameness prevalence during the grazing period.

Access to pasture has also been shown to improve lameness in dairy cows that were housed. Access to pasture during the dry period reduced the odds of lameness by 48% in freestall housed cows (Chapinal et al., 2013a). Hernandez-Mendo et al. (2007) reported that LS improved for cows that were at pasture for a four week period, following housing. Lower prevalence toward the end of the grazing period compared to the beginning of the grazing period was also reported by O'Connor et al. (2020a), indicating time at pasture following housing improved lameness. In contrast, Randall et al. (2019) reported that the duration cows are housed did not significantly impact lameness prevalence in the UK, and Griffiths et al. (2018) reported that the amount of access to grazing was not associated with lameness prevalence in England and Wales. The herd-level prevalence in these studies were reported to be 30% (range: 7% to 61%; Randall et al., 2019) and 32% (range: 6% to 65%; Griffiths et al., 2018). Similarly, a recent meta-analysis estimated the pooled lameness prevalence in Britain to be 30% (Afonso et al., 2020). This paper reported that across studies the lameness incidence was higher in grazing systems compared to non-grazing systems.

Care must, however, be taken when comparing lameness prevalence across studies and systems. The meta-analysis of lameness detection and classification methods in Britain emphasised the diversity in the methods used to classify lameness in research (Afonso et al., 2020). In total 17 different lameness detection methods were found across 69 papers, including farm and vet records, various lameness scoring scales and an automated system. The lack of standardisation hinders the ability to compare lameness prevalence across studies, systems and countries, and identify changes in prevalence over time. Due to lameness scoring being subjective, lameness classification may also vary depending on the observers experience and training, making studies less comparable.

Table 1.3. Summary of lameness prevalences reported by different studies on pasture-based dairy farms

Grazing system/ study	Lameness prevalence (%)	Lameness prevalence range (%)	Scoring period	Number of farms	Country
Year-round					
Tadich et al. (2010)	28.7 (HL)	ns	Grazing	57	CHL
Fabian et al. (2014)	8.1 (HL)	1.2 – 36	Grazing	59	NZL
Ranjbar et al. (2016)	18.9 (HL)	5 – 44.5	Grazing	63	AUS
Moreira et al. (2018)	16 (CL)	n/a	Grazing	48	BRA
Beggs et al. (2019)	3.8 (HL)	0 – 11.4	Grazing	50	AUS
Seasonal					
Clarkson et al. (1996)	20.6 (HL)	2 – 53.9	Grazing/ Housing	37	GBR
Manske et al. (2002a)	3.7 (HL)	0 – 33	Housing	101	SWE
Haskell et al. (2006)	15 (HL)	ns	Housing	< 37[1]	GBR
Tadich et al. (2010)	33.2 (HL)	ns	Grazing/ Housing	34	CHL
Somers and O'Grady (2015)	12.4 (HL)	9 – 17	Grazing	10	IRL
O'Connor et al. (2020a)	11.0 (HL)	ns	Early grazing	68	IRL
	5.9 (HL)		Late grazing		
Frequent access					
Becker et al. (2014)	14.8 (CL)	n/a	Grazing/ Housing	52	CHE
Bran et al. (2018)[2]	31 (HL)	10 – 70	Grazing/ Housing (V1)	44	BRA
	35 (HL)	5 – 76	Grazing/ Housing (V2)		

HL = herd-level; CL = cow-level; ns = not stated; n/a = not applicable; AUS = Australia; BRA = Brazil; NZL = New Zealand; CHL = Chile; IRL = Ireland; GBR = Great Britain; SWE = Sweden; CHE = Switzerland; V = Visit

[1]Study included 37 farms; however, this included zero-grazing farms in addition to grazing farms. Study did not specify how many farms were in each group

[2]Minimum 16 hours pasture assess per day

1.2.4 Impacts of lameness

Lameness impacts all three pillars of sustainability: social, economic and environmental. Lameness impacts social sustainability through its effect on animal welfare, economic sustainability through its financial implications, and environmental sustainability through its impact on factors such as greenhouse gas emissions.

1.2.4.1 Welfare

Lameness is associated with pain and discomfort, which is a major animal welfare concern within the dairy industry. Based on the "five freedoms" of animal welfare, animals should have freedom from pain (Farm Animal Welfare Council, 1992). Lameness also leads to increased culling due to both pain and reduced productivity (Booth et al., 2004). Whilst decisions to cull a lame cow may be vital for the welfare of the animal, high levels of culling due to lameness within a herd is indicative of poor welfare.

Lameness can also induce stress in dairy cows, negatively impacting welfare. Higher cortisol levels have been reported in lame cows (Gellrich et al., 2015) and those with a sole ulcer (O'Driscoll et al., 2015); however, not all studies have reported consistent results. Fischer-Tenhagen et al. (2018) and Almeida et al. (2008) both reported no statistical difference in cortisol levels between lame and sound cows. Total esterase activity has also been reported to increase with stress and lameness in pigs (Tecles et al., 2017). In a pilot study, total esterase activity was also higher in lame dairy cows compared to non-lame cows (Contreras-Aguilar et al., 2020), potentially indicating stress.

Lameness can cause behavioural changes, altering the time budget in dairy cows. Lame cows have been reported to have reduced eating time (Bach et al., 2007; González et al., 2008; Palmer et al., 2012; Norring et al., 2014a; Thorup et al., 2016) and intake (Bach et al., 2007; Norring et al., 2014a), and increased feeding rates (González et al., 2008; Thorup et al., 2016). Lame cows also have lower activity levels (O'Callaghan, 2002), longer lying times (Cook et al., 2004; Walker et al., 2008b; Ito et al., 2010) and reduced oestrus behaviour than non-lame cows (Walker et al., 2008a).

1.2.4.2 Economics

Lameness has previously been reported as the third most costly health-related issue following mastitis and fertility (Bruijnis et al., 2010). The greatest costs related to the disease are generally losses in production, such as reproductive performance and milk yield (Willshire and Bell, 2009). Lameness has been reported to affect many aspects of reproductive performance including calving interval, calving to conception interval and the number of services per conception (Huxley, 2013). On Irish pasture-based dairy farms, it has been reported that impaired mobility (score of two on AHDB scoring system) and severely impaired mobility (score of three on AHDB scoring system) resulted in milk yield losses of up to 1.4% and 4.7%, respectively (O'Connor et al., 2020b). As well as these indirect costs, there are also the direct costs of lameness including treatment and labour costs, and costs associated with early culling and discarding of milk due to antibiotic use. For a typical UK dairy herd the average cost of lameness per case was reported to be £323 (Willshire and Bell, 2009). For specific hoof lesions, this ranged from £76 for digital dermatitis to £519 for a sole ulcer. It was reported that 82% of costs were due to reduced milk yield and fertility, and only 1% of cost were related to veterinary costs. Bruijnis et al. (2010) also reported that a clinical hoof disorder would cost an average of $95.

Using dynamic modelling, O'Connor (2020) looked at the economic impact of Irish herds with good mobility (95% cows had a score of 0; AHDB 0 – 3 lameness scoring score) compared to a herd with very poor mobility (90% herd had a score ≥ 1). It was reported that the annual net profit could be as much as €16,500 higher for herds with optimal mobility compared to very poor mobility. Approximately 50% of this reduction in net profit was due to lower milk yields, 31% due to increased cull rates and 20% due to treatment costs; however, reproductive performance was not specifically looked at in this model (O'Connor, 2020). Ettema et al. (2010) also reported that halving the disease risk of digital dermatitis, interdigital hyperplasia and claw horn diseases increased the gross profit margin by €24,840 to €38,820, depending on the reproductive performance of the herd.

1.2.4.3 Environmental

Based on life cycle assessments, it has been shown that increased lameness prevalence and severity may lead to increased global warming, acidification, eutrophication and depletion of fossil fuels by a maximum of seven to nine percent (Chen et al., 2016). Lameness severity was found to have more of an environmental impact than lameness prevalence (Chen et al., 2016). Mostert et al. (2018) also reported that greenhouse gas emissions increased by an average of 0.4%, 4.3% and 3.6% per case of digital dermatitis, white line disease and sole ulcers, respectively.

Lameness causes reduced survival rates in a herd due to culling (Booth et al., 2004), increasing the requirements for replacement heifers and lowering the herd age structure and productivity (Zhang et al., 2019; Lahart et al., 2021). This reduced age structure results in decreased efficiency and increased greenhouse gas emission per unit of production (Zhang et al., 2019; Lahart et al., 2021). This highlights that preventing lameness plays an important part in reducing the environmental impact within the dairy industry. Reducing lameness will also allow a more selective method of culling to occur (i.e. low yielding cows as opposed to lame cows), which will further improve efficiency and reduce emissions per unit of production (Lahart et al., 2021).

1.3 Causes of lameness

The main cause of lameness is hoof lesions; Shearer (1997) reported that 99% of lesions that caused lameness were related to the hoof, with over 90% occurring on the hind hooves. Less common causes of lameness include musculoskeletal and neurological disorders. Hoof lesions can generally be split into two categories based on their aetiology: 1) infectious lesions and 2) claw horn lesions. Diagnosis of hoof lesions is generally done via subjective observations, which can lead to a lack of standardisation across studies.

1.3.1 Infectious

Infectious lesions are caused by a diverse range of different micro-organisms (Santos et al., 2012; Wilson-Welder et al., 2015). These infectious lesions are believed to be passed from cow to cow via the environment. Weakening of the skin barrier, though mechanical damage and contact with wet environmental conditions, can allow for these micro-organisms to more easily penetrate the skin (Mülling et al., 2006). Infectious lesions can also be spread through contact with infected equipment such as a hoof knife; it is therefore essential that equipment is disinfected between both farms and cows (Gillespie et al., 2020). Infectious hoof lesions include digital dermatitis, heel erosion and foul of the foot. Heel erosion is also sometimes classified as a partly infectious lesion (Greenough, 2007; Chapinal et al., 2013b). Table 1.4 highlights alternative names for these infectious lesions; for example, in Ireland, digital dermatitis is commonly referred to as Mortellaro by farmers and veterinarians. Digital dermatitis was found to be the most prevalent infectious lesion type in a small-scale study in Ireland (Somers and O’Grady, 2015); therefore, digital dermatitis is described in more detail below.

Table 1.4. Alternative names for infectious hoof lesions in dairy cows

Lesion	Alternative names
Digital dermatitis	Mortellaro
	Hairy heel warts
	Digital warts
	Strawberry footrot
	Digital papillomatosis
Foul of the foot	Footrot
	Interdigital necrobacillosis
	Interdigital phlegmon
	Infectious pododermatitis
Heel erosion	Slurry heel
	Heel horn erosion
	Heel necrosis[1]

[1]Note that not all erosions are necrotic

1.3.1.1 Digital dermatitis

Infectious lesions are generally reported to be the most common lesion type in housed systems, with digital dermatitis being the most prevalent (Cramer et al., 2008; Solano et al., 2016). Digital dermatitis is commonly located on the skin above the heel bulb and can be categorised into various disease stages as originally described by Döpfer et al. (1997), and adapted by Berry et al. (2012; Table 1.5). Several different microorganisms have been associated with bovine digital dermatitis (Mamuad et al., 2020). Although digital dermatitis is polymicrobial, *Treponema* species are generally considered the main microorganisms involved (Mamuad et al., 2020). Solano et al. (2016) and Cramer et al. (2008) both reported digital dermatitis as the most common lesion type within a housed-system with the cow-level prevalence at 15% and 9.3%, respectively. As previously mentioned, within an Irish predominantly pasture-based system, digital dermatitis was found to be the most prevalent of the infectious lesions in lame dairy cows, but not the most common lesion overall; 28% of lame dairy cows were diagnosed with digital dermatitis (Somers and O'Grady, 2015). When comparing these studies it must be noted that the Irish study only included lame cows, whereas the fully-housed studies were both based on the entire herd, hence the much lower prevalences reported.

A study that looked at 224 pasture-based herds in Taranaki reported that digital dermatitis was present on 64% of farms, with a relatively low cow-level prevalence of 1.2% across all farms visited (Yang et al., 2017b). However, it was estimated that 46% of digital dermatitis cases were missed through identifying digital dermatitis in the milking parlour (Yang et al., 2017a). Yang et al. (2020) also predicted through dynamic modelling that digital dermatitis prevalence within New Zealand pasture-based herds will continue to increase going forward. Risk factors for digital dermatitis in New Zealand included buying in heifers, rearing heifers together from multiple farms, grazing heifers with cattle from other farms, and getting someone external to trim or treat lame cows (Yang et al., 2018, 2019a). Soil temperature and lower rainfall were also associated with digital dermatitis risk in the New Zealand pasture-based system (Yang et al., 2019b). There is, however, little information on risk factors for digital dermatitis in the Irish pasture-based system, this therefore warrants more in depth investigation.

Table 1.5. Disease stages for digital dermatitis as described by Berry et al. (2012), adapted from Döpfer et al. (1997)

Category	Stage	Description
M1	Subclinical	Small (<2 cm across) focal active state. Circumscribed lesion. Surface is moist, ragged, mottled red–grey with scattered small (~1 mm diameter) red foci
M2	Acute	Larger (>2 cm across) ulcerative active stage. Extensively mottled red–grey. Can be painful upon manipulation
M3	Healing	Typically seen within a few days after antibiotic treatment. The ulcerated surface is now transformed to a dry brown, firm rubbery scab. No pain on manipulation
M4	Chronic	Surface is raised by tan, brown, black, rubbery, irregular, proliferative hyperkeratotic growths that vary from papilliform to mass-like projections
M4.1	Chronic (reoccurring)	Chronic stage with small active painful M1 focus
M5	Healthy	No sign of pre-existing lesion. Normal skin

1.3.2 Claw horn lesions

There are a large number of different types of claw-horn lesions found in dairy cows. Unlike infectious lesions, these are not caused by micro-organisms and cannot be passed from cow to cow; however, it must be noted that these lesions can become infected due to exposure to bacteria. In predominantly pasture-based dairy cows, claw horn lesions are generally found to be more prevalent than infectious lesions (Becker et al., 2014; Somers and O'Grady, 2015; O'Connor et al., 2019). A small-scale study of ten farms within Ireland reported that sole haemorrhages were the most common lesion in lame dairy cows (63%), followed by white line lesions (53%; Somers and O'Grady, 2015). A study of Irish dairy cows with sub-optimal mobility (LS $\geq$ 1 on a 0-3 scale) reported that sole haemorrhages, overgrown claws and white line disease were the most common lesions found (O'Connor et al., 2019). However, this study only investigated five lesion types, and lesion identification took place on average 58 days post lameness scoring, and up to 258 days, therefore the LS of the cow at lesion identification may have altered since the initial lameness scoring event. A large-scale study is required that identifies hoof lesions within a short time frame following lameness scoring; this will enable the prevalence of all hoof lesions to be determined within Irish dairy herds. Further details on these three common lesion types are reviewed below and alternative names for various claw horn lesions are reported in Table 1.6.

Table 1.6. Alternative names for common claw horn lesions

Lesion	Alternative names
Sole haemorrhage	Sole bruising
Sole ulcer	Pododermatitis Circumscripta Rusterholz ulcer
Overgrown claw	Long toe Abnormal claw shape Corkscrew claw[1]
White line disease	White line separation White line lesion Widening of white line
Double sole	Under-run sole
Interdigital hyperplasia	Interdigital fibroma Interdigital growth Corn

[1] Note that not all overgrown claws are corkscrew claws

1.3.2.1 Sole haemorrhages

Sole haemorrhages are categorised as discoloration (yellow to red) of the sole of the hoof (ICAR, 2020), and predispose to sole ulcers (van Amstel and Shearer, 2006). Sole ulcers occur when the underlying corium is exposed through the sole horn (ICAR, 2020). Sole haemorrhages and ulcers are caused by compression and damage of cells in the corium between the distal phalanx and hoof capsule at the sole (Shearer and van Amstel, 2017). Weakening of the collagen tissue connecting the distal phalanx and the hoof capsule can lead to the distal phalanx dropping within the hoof capsule, causing damage (Shearer and van Amstel, 2017). It is speculated that this weakening is due to hormonal changes such as the production of relaxin around calving (Tarlton et al., 2002). Webster (2002) reported that sole haemorrhages increased after calving compared to four weeks prior to calving; with the severity of the lesions peaking at four weeks post calving. Alongside weakening of the collagen tissue, contusion of the corium as a result of the cow standing on hard surfaces for prolonged periods of time, particularly post-partum, can also contribute to lesion development (Eriksson et al., 2021). This is also exacerbated by claw overgrowth causing uneven weight-bearing across the claws (van Amstel and Shearer, 2006). Overgrown claws can also cause weight to shift back towards the palmar/plantar region of the hoof, leading to more pressure over the typical sole ulcer site (Mahendran and Bell, 2015). A thin digital cushion is also thought to play a role in the formation of sole ulcers, due to the reduced ability to dampen the pressure of the distal phalanx on the corium (Bicalho et al., 2009). A thin digital cushion is generally associated with a low BCS and increasing age; however, heifers and primiparous cows are also reported to have a thinner and less well developed digital cushion compared to multiparous cows (Räber et al., 2004; Bicalho et al., 2009).

1.3.2.2 Overgrown claw

Claw overgrowth results from excess net growth compared to net wear, and can lead to alterations in weight bearing across the hoof (Shearer et al., 2015). An increase in claw length can shift the weight-bearing forces to the heel of the hoof, which is a common location for sole haemorrhages and ulcers (Shearer et al., 2015). Manske et al. (2002a) reported a correlation of 0.41 between sole ulcers and abnormal claw shape (overgrowth), and a correlation of 0.20 between sole haemorrhages and abnormal claw shape. Access to pasture has also been shown to increase net growth compared to cows in confinement (Hahn et al., 1986), due to the less abrasive surfaces. Cows may benefit from functional trimming both to prevent lameness from overgrown claws, and also to prevent the formation of other claw-horn lesions as a result of claw overgrowth. Care must also be taken not to over-trim; over-trimming can result in thin soles which are associated with the formation of other lesion types (Sanders et al., 2009). Kofler et al. (1999) reported that over-trimming was the major cause of toe ulcers in 49% of cases (based on 53 cows). According to the AHDB it is recommended that the hoof is trimmed to 80 mm from where the claw goes hard to the tip of the claw (AHDB Dairy, 2017).

1.3.2.3 White line disease

The white line is a complex structure located where the hoof wall joins the sole (Mülling, 2002). The white line horn is weaker than that of the hoof sole and wall, and is therefore more prone to penetration and damage (Mülling, 2002). White line disease can refer to both haemorrhages and separation of the white line; however, for this review white line disease is referred to as separation of the white line, which may or may not have an abscess (ICAR, 2020). Once separation of the white line occurs, stones and debris can build up within the white line, potentially leading to more severe separation and infection (Mülling, 2002).

The aetiology of white line disease is not fully clear; however, there are various hypotheses. It is theorised that cows standing on hard flooring for prolonged periods of time can cause swelling and inflammation of the lamellae region of the hoof (Tarlton et al., 2002). This results in pressure being exerted laterally on the wall of the hoof, leading to white line disease. This may be further increased by metabolic changes within the hoof around calving, causing weakening of the suspensory apparatus in the hoof, and potentially damaging horn producing cells (Tarlton et al., 2002).

Mechanical and physical forces may also play a role in the formation of white line disease. As suggested by Shearer and van Amstel (2017), it is hypothesised that shearing forces on the hoof cause stress on the white line area. These forces may occur when a cow has to turn sharply on their hooves or when cows are physically pushed by each other, for example in the collecting yard. External physical forces, such as a cow walking on uneven and stony surface, are also thought to cause damage to the white line and to the epidermal cells that produce white line horn. Walking on an uneven surface may also alter weight-bearing across the hoof, causing pressure on the hoof wall and inflammation of the corium, leading to further separation of the white line.

1.4 Risk factors for lameness

Lameness is well known for being multi-factorial in nature, meaning a large variety of risk factors are associated with the condition. There is currently a lack of research on risk factors specifically pertaining to the hybrid system of housing and grazing, such as that in Ireland. There is also limited information on the practices used to control lameness and the infrastructure in place on Irish dairy farms; this information is required to give advice to farmers, veterinarians and agricultural advisors on how lameness management can be improved in Ireland. A recent systematic review of housed cattle identified 128 different risk factors for lameness from 53 publications (Oehm et al., 2019). Lameness risk factors can be broadly categorised as animal, environmental, management and nutritional factors; further details of these factors are described below.

1.4.1 Animal factors

There are a number of animal factors that influence lameness risk, including breed, genetics, age and parity, and production parameters. Cows may also be at increased risk of lesions and lameness due to weakening of the internal structures within the hoof around calving, further increasing the impact of external risk factors (Tarlton et al., 2002).

The majority of studies agree that Holstein Friesians (HF) are at the highest risk of lameness (Barański et al., 2008; Barker et al., 2010). A study in England and Wales reported that lameness in purely HF herds was 37.8% compared to 15.5% when no HF were present in the herd (Barker et al., 2010). Barański et al. (2008) also reported that Jerseys (J) had a lower prevalence of lameness than HF (1.5% vs. 13.5%). In contrast, Ribeiro et al. (2013) reported that the risk of lameness was higher in J (8%) compared to both Holsteins (3.9%) and cross breeds (2.3%); however, this study only examined lameness prevalence in the first 30 days of lactation. Holstein Friesians partition more energy into the production of milk than body tissue (Yan et al., 2006); therefore, less energy may be invested into repairing the hooves, leading to more lameness in HF. It has also been established that a higher body weight can be a risk factor for hoof lesion prevalence (Wells et al., 1993); therefore, heavier breeds, such as HF, may be more at risk of lameness. Holstein Friesians also generally have a lower body condition than other breeds. A study in an Irish pasture-based system stated that HF had a lower BCS, compared to J, and HF x J, over the entire lactation (Prendiville et al., 2011). Lower body condition has been shown to increase the risk of lameness (Randall et al., 2015); therefore, breeds that tend to have a lower BCS could be more at risk of lameness. More information on BCS and lameness can be viewed in the section 1.4.4.

Although heritability for lameness is generally low, genetics can still be used to reduce lameness risk long-term. The quality of the phenotypic data used influences the heritability. Using poor quality records, increases noise, which leads to low heritability estimates (Berry et al., 2019). Ring et al. (2018) reported that heritability for hoof traits were higher than previously reported, partly due to more detailed data collection of phenotypic hoof health traits in this study. A larger number of records are also required, to achieve a certain level of accuracy, when heritability is lower (Berry et al., 2019). This ascertains that even for traits with low heritability, high accuracy is still achievable, and genetic gain can still be accomplished (Berry et al., 2019). This highlights the importance of gathering large amount of quality data on lameness across dairy farms. Genetic variability is also a key factor for achieving rapid genetic gain (Berry et al., 2019).

Selecting for good hoof health and mobility should be considered in breeding programs for improving lameness at cow-level (Ring et al., 2018). A recent publication reported the lameness advantage index in the UK was associated with the presence of solar haemorrhages, solar ulcers and lameness, indicating that genetic selection using this index could help reduce lameness and specific claw horn lesions (Barden et al., 2022). In Ireland, the Economic Breeding Index (EBI) provides information on the profitability of cows and bulls for breeding purposes (Berry et al., 2007). Olmos et al. (2009b) reported that cows with a higher EBI had a lower risk of becoming lame 200 days post-partum; however, this study only looked at animals from one farm. Under the EBI there is a health sub-index (accounting for 4% of the EBI) which includes Predicted Transmitting Ability (PTA) for lameness (Berry et al., 2007); a lower PTA indicates that the progeny are less likely to become lame. O'Connor et al. (2020a) reported that cows with a positive PTA for lameness had 2.33 times the odds of being lame compared to cows with a negative PTA, highlighting the importance of breeding for reduced lameness.

Older cows and those with a higher parity are at higher risk of lameness. Solano et al. (2015) reported that the odds of lameness was 1.6, 3.3, and 4 times higher, for cows with a parity of two, three, and greater than three, compared to primiparous cows. Haskell et al. (2006) also reported that mean lameness prevalence ranged from 10% to 33% for cows with a parity of one compared to a parity of five or greater, respectively. Digital cushion thickness is associated with lameness prevalence and risk of claw horn lesions (Räber et al., 2004; Bicalho et al., 2009; Newsome et al., 2017b). Studies have reported that primiparous cows have a thinner digital cushion than multiparous cows (Newsome et al., 2017a; Griffiths et al., 2020), with a reduction again in digital cushion thickness as cows age (Räber et al., 2004). As cows age they are also more likely to have had a previous lameness event, which is also a major risk factor for lameness (Randall et al., 2018). Older cows, as well as those with previous lameness events and specific claw horn lesions, also have increased amount of irreversible bone development on the distal phalanx (Newsome et al., 2016). Newsome et al. (2016) reported that cows that were lame at over half of the lameness scoring occasions in the year prior to culling had bone development of nearly 10 mm greater compared to those that were never lame, based on the claw with the most severe development. The prevention of first time lameness cases is key to reducing lameness over a cow's lifetime.

The relationship between lameness and milk production is complex and likely bi-directional. Ristevski et al. (2017) reported that the odds of clinical lameness for cows that produced more than 30.9 kg milk per day were 1.9 times higher than cows that produced less. Bicalho et al. (2008) reported that lame cows produced 3.02 kg more milk per day prior to lameness than the non-lame controls. It is theorised that high-producing cows may use more fat reserves for milk production, which may reduce the digital cushion thickness, thus increasing the risk of claw horn lesions (Green et al., 2002; Bicalho et al., 2009). It must also be considered that although lame cows may be producing more milk than non-lame cows prior to lameness, these cows may have started from a higher average yield; therefore, the yield drop may have still been substantial (Green et al., 2002).

1.4.2 Environmental factors

1.4.2.1 Grazing risk factors

Environmental risk factors vary depending on whether the cows are at pasture or housed. At pasture, cow track conditions are considered a major risk factor for lameness, with cows commonly walking between the paddock and milking parlour twice a day (Chesterton et al., 1989). Burow et al. (2014) reported that cows had lower odds of being severely lame if roadways were prepared with a material rather than unprepared (i.e. sand, grass or soil). Harris et al. (1988) also reported that broken sections on the cow tracks were associated with lameness. Wet conditions on cow tracks and at pasture were also reported to pose a risk for lameness. Ranjbar et al. (2016) reported that increased rainfall over a 30-day period prior to lameness scoring resulted in a higher prevalence of lame cows. These studies emphasise the importance of cow track maintenance and drainage for reducing lameness risk.

On pasture-based dairy farms, long walking distances are also thought to pose a risk for lameness; however, there are limited peer reviewed publications that report evidence of this assumption. A study in New Zealand reported that lameness peaked on one farm when cows were walking a longer distance of 5.3 miles per day; however, the distance walked and the lameness prevalence was estimated by the farmer and was not formally recorded (Dewes, 1978). In contrast, Burow et al. (2014) found no correlation between walking distance and lameness on 36 farms; however, there was a maximum walking distance of only 700 m. More studies, using longer track lengths, need to be carried out to determine if long walking distances are associated with lameness in pasture-based herds.

1.4.2.2 Housing risk factors

Overstocking and poor cow comfort has previously been associated with lameness in housed dairy cows (Endres, 2017). Providing optimal lying areas increases lying times, which are associated with reduced lameness prevalence (Endres, 2017). Fregonesi et al. (2007) looked at lying time associated with various cubicle stocking rates ranging from 100% to 150% overstocked; cows stocked at 100% lay down for 1.7 hours per day more than cows stocked at 150%. An Irish study also reported that housing heifers at a cubicle ratio of two cows to one cubicle, resulted in lower lying times and increased lameness and lesion severity (Leonard et al., 1996). It is currently recommended best practice that farmers provide 10% more cubicles than cows in the herd (Huxley et al., 2012; FAWAC, 2019).

Cubicles should be designed to provide good cow comfort, to encourage longer lying times and reduced standing time on hard concrete surfaces (Endres, 2017). Cubicle dimensions and lying surface material are both important factors to consider. Inadequate dimensions can inhibit the cow's ability to rise from lying down, discouraging cubicle use (Endres, 2017). Cubicle dimensions commonly measured and reported are shown in Figure 1.1. Dippel et al. (2009b) reported that lunge space impediments and a short diagonal length were risk factors for lameness. Haskell et al. (2006) also showed that a shorter lunge space was associated with lameness and hock swellings. A short cubicle width, relative to the size of the cow, also poses a risk for lameness (Sogstad et al., 2005). This is likely due to the reduced lying time associated with narrow cubicles (Tucker et al., 2004).

Comfortable lying surfaces are associated with reduced lameness (Rouha-Mülleder et al., 2009). Use of deep bedding, such as sand, has generally been reported to reduce lameness prevalence compared to mats or mattresses (Cook et al., 2004; Espejo et al., 2006; van Gastelen et al., 2011; Cook et al., 2016). Cook et al. (2004) reported that lameness prevalence was lower in sand cubicles (11%) compared to mattresses (24%). Espejo et al. (2006) reported similar, whereby lameness prevalence was 17% for sand cubicles and 28% for mattress cubicles. In addition to straw bedding ≥ 2 cm, Rouha-Mülleder et al. (2009) also found that the use of cow-comfort mats reduced lameness prevalence. This indicates that the type of mat or mattress used, and bedding thickness, may influence comfort and therefore lameness prevalence within the herd.

Hygiene within the housing environment is also an important environmental factor associated with lameness. Exposure to slurry can cause infectious lesions, such as digital dermatitis and heel erosion, to spread throughout a herd. Digital dermatitis has previously been associated with leg cleanliness, which is likely to be indicative of housing hygiene (Relun et al., 2013). Knappe-Poindecker et al. (2013) also found associations between claw cleanliness and both interdigital dermatitis and heel erosion. Slurry management is essential for preventing a build-up of slurry which may act as an infectious reservoir for bacteria (Klitgaard et al., 2017). Biosecurity and keeping a closed herd must also be considered to prevent digital dermatitis bacteria entering the herd.

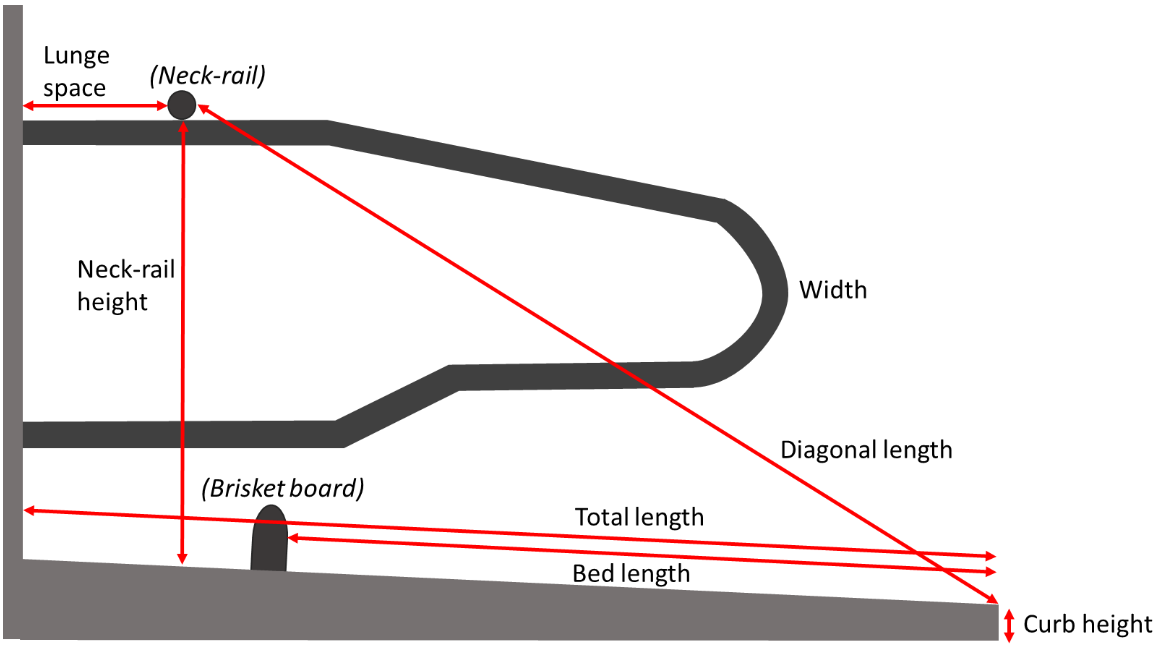

Figure 1.1. Cubicle dimension commonly measured

1.4.3 Management factors

A large variety of management practices influence lameness prevalence on-farm. A major risk factor for lameness is a history of lameness; therefore, prevention of lameness in the first instance is vital (Green et al., 2014; Randall et al., 2018). Wilson et al. (2021) reported that the digital cushion volume was reduced at culling for cows with a history of lameness. An increase in hoof lesion severity, in heifers, has also been reported to increase the risk for lameness in the future (Randall et al., 2016); therefore, detecting and effectively treating lesions promptly is key.

Routine hoof trimming is an important preventative practice for restoring hoof conformation, reducing imbalance across the medial and lateral claws. Manske et al. (2002b) reported that cows trimmed in the autumn had a lower risk of getting most non-infectious hoof lesions and of becoming lame in the spring. In the UK, trimming in early lactation was also associated with reduced lameness prevalence (Griffiths et al., 2018). Hernandez et al. (2007) demonstrated a decrease in lameness in late-lactation when the cows were trimmed in mid-lactation; however, the difference was not considered significant. The author stated the non-significant results were likely due to low statistical power due to a small number of farms participating in the study. In contrast, Barker et al. (2007) reported that routine trimming had a negative impact on lameness. It is hypothesised that this may be due to lame cows being left untreated until the next routine trim, resulting in slower diagnosis and treatment. Care not to over trim is also essential; Kofler (1999) revealed that over trimming was the likely cause of sole ulcers in 49% of cows. There is currently little peer reviewed evidence on the optimal timing and frequency of routine trimming. The majority of studies on routine trimming also took place on predominantly housed herds. As such, limited data is available on the benefit of routine hoof trimming in pasture-based systems.

Footbathing can provide an effecting way of controlling digital dermatitis within a herd. There is considerable variation in the frequency of foot bathing, the products and the concentrations used on farms (Cook et al., 2012). Commonly used footbathing solutions include formalin and copper sulphate (Cook et al., 2012). Both solutions have been shown to be effective; however, the products should be used with care due to health and environmental risks (Flis et al., 2006; Buesa, 2008). Randhawa et al. (2008) reported that formalin completely eliminated digital dermatitis and also significantly reduced heel erosion, solar ulcers and haemorrhages, white line lesions, double sole and overgrowth. Holzhauer et al. (2008) suggested weekly footbathing using 4% formalin was the optimal method for controlling digital dermatitis. Speijers et al. (2010) reported that weekly and fortnightly footbathing with 5% copper sulphate reduced the number of digital dermatitis cases compared to a 2% concentration, with weekly footbathing being more effective. Solano et al. (2017) also reported that using 5% copper sulphate solution reduced the presence of active digital dermatitis lesions by 8% and increased the number of cows with no digital dermatitis lesions by 9%. In contrast, Holzhauer et al. (2012) reported that copper sulphate did not cure lesions that were already present but was effective at preventing new digital dermatitis cases occurring. Footbath dimensions and the frequency the solution is changed must also be considered for optimising the footbathing routine (Cook et al., 2012).

Correct stockmanship behaviour is also an important management factor to consider for reducing lameness. Rushed handling causes sideways pushing between cows when walking along roadways, leading to lameness (Ranjbar et al., 2016). Cows will keep a lower head carriage when not forced to move at a faster pace to enable a safe footing to be chosen (Blowey and Dehghani Nazhvani, 2007). Chesterton et al. (1989) reported that being patient when moving cows on tracks had the biggest influence on reducing lameness. Clackson and Ward (1991) also showed that when cows were forced to walk at a faster pace by either the farmer on foot, a dog or a tractor, the number of new lameness cases was higher than for cows that could walk at their own pace.

Long periods of time away from pasture or housing have been associated with lameness in dairy cows. Cows should be managed to reduce the time they are held in the collecting yard before milking, to decrease the standing times on concrete flooring and increase lying times. Jewell et al. (2019) determined that cubicle-housed cows held for more than three hours in the collecting yard were more likely to become lame by odds of 2.11 compared to cows held in the collecting yard for a shorter period. Espejo and Endres (2007) reported the lameness prevalence when cows were held in the collecting yard for an average of 330 minutes compared to 160 min, increased lameness by 5.3%. In contrast to the above studies, Vokey et al. (2003) did not show that a difference in holding time influenced hoof health. However, lesion prevalence rather than lameness was recorded and the compared holding times were both relatively short (45 minutes vs. 90 minutes) in comparison.

1.4.4 Nutritional factors

The emphasis on nutrition and lameness has changed over the years. It was originally thought that there was a direct link between sub-acute ruminal acidosis (SARA) and laminitis (Nocek, 1997). Sub-acute ruminal acidosis occurs when the rumen pH becomes too acidic, commonly caused by high levels of concentrate in the diet (Plaizier et al., 2008). Acidosis was believed to cause weakening of the collagen fibres in the suspensory apparatus due to the release of ruminal toxins into the bloodstream activating matrix metalloproteinase enzymes. This would allow the distal phalanx to sink within the hoof capsule, ultimately leading to sole ulcers and white line lesions forming. In recent years this theory has mostly been disregarded (Mülling et al., 2006; Newsome et al., 2017b). Danscher et al. (2010) reported that the strength of the collagen fibres supporting the distal phalanx did not reduce in laminitic cattle after acute acidosis was induced by oligofructose. However, this study only looked at acute laminitis and the fibres were only examined for a short period (72 hours) after oligofructose overload.

In terms of nutrition, more recently research has focused on BCS and the impact on lameness. Previous studies found associations between a low BCS and lameness (Espejo et al., 2006; Solano et al., 2015; O'Connor et al., 2020a); it was thought that this may be because lameness reduced feed intake (Espejo et al., 2006). Although lameness may still result in reduced intake, an eight year longitudinal study revealed that a low BCS predisposes to lameness (Randall et al., 2015). The greatest risk of lameness was reported for cows with a BCS of less than two

(Randall et al., 2015). The digital cushion is located below the distal phalanx and digital cushion thickness is deemed to play a role in lameness risk. A low digital cushion volume has been associated with a low BCS, increasing the risk of claw horn lesions and lameness (Wilson et al., 2021).

Vitamin and mineral deficiencies are also potential risks for lameness. In particular, biotin supplementation has proven beneficial to hoof health and lameness prevention. Supplementation of biotin can be used to increase biotin levels in both serum samples (Midla et al., 1998; Higuchi et al., 2004) and milk samples (Fitzgerald et al., 2000). After eight months of supplementation, Fitzgerald et al. (2000) reported that lameness scores decreased and the need for antibiotics and hoof blocks was reduced (Fitzgerald et al., 2000). Many studies have shown that biotin is important for preventing claw horn lesions, particularly white line disease. Supplementation with 20 mg/day/cow of biotin has shown to reduce lameness from white line disease by approximately half (Hedges et al., 2001; Pötzsch et al., 2003).

1.4.5 Irish risk factor studies

Lameness risk factor studies have generally focused on more intensive systems where cows are housed for the entire year or for a large proportion of the year, or in extensive systems where cows are grazed throughout the entire year. There are a limited number of studies on risk factors for lameness in Irish dairy herds, or herds with a similar system of being predominantly grazed but also housed for a small proportion of the year. In the Irish system, cows are exposed to both grazing and housing risk factors. A small-scale study of ten Irish dairy farms determined cow-level risk factors for lameness, with risk factors including parity, BCS and BCS loss after calving (Somers et al., 2019). No herd-level risk factors were considered in this risk factor analysis. A larger risk factor study was carried out in Ireland which included both cow- and herd-level predictors (O’Connor et al., 2020a). Risk factors for lameness included using a footbath, holding the cows back following milking, lower BCS, positive PTA for lameness and days-in-milk > 120 days. Although this study included cow-level data and herd-level data collected from farmer surveys, no infrastructure measurements and observations were obtained on-farm for the risk factor analysis. This study also only focused on the period when cows were at grass; no lameness scoring took place between December and February when cows are generally housed full-time. A large scale study is required using cow-level data and data from both surveys and infrastructure measurements, from both the grazing and housing period, to determine the most important risk factors in this system type.

1.5 Risk factor analysis and novel machine learning methods

Various technical aspects of novel machine learning methods are reported and discussed in detail within Paper 1. This includes the use of triangulation of elastic net regression (Enet) and logistic regression using modified Bayesian information criterion (mBIC), with bootstrapping.

1.5.1 Animal health risk factor analysis using machine learning

The first study to use bootstrapped regularised regression to identify risk factors within animal health epidemiology was Lima et al. (2020). This study identified risk factors for lamb-derived revenue on sheep farms. Hyde et al. (2021) also used bootstrapped Enet to identify risk factors for daily live weight gain in calves. Grimm et al. (2019) and Schindhelm et al. (2017) both used Enet to determine performance and behavioural risk factors for lameness in dairy cows, however, in neither studies was bootstrapping implemented. Lewis et al. (2021) used triangulation of multiple models, with bootstrapping, to identify risk factors for lameness in sheep. It was determined that triangulation was a reliable method for identifying a small set of important variables for mitigating lameness in the national flock. On submission of this thesis, the use of multiple machine learning methods with bootstrapping, to carry out a risk factor analysis in dairy cows, had not previously been implemented to my knowledge.

1.6 Pain in dairy cows

Pain in dairy cows can be caused by various diseases, including those related to lameness, as well as from injuries and calving (Rushen et al., 2007a). Pain can also be caused by surgical procedures, such as left displaced abomasum surgery and surgical castration, and from non-surgical procedures such as calf disbudding and the treatment of a sole ulcer (Rushen et al., 2007a).

1.6.1 Pain and lameness research

Lameness is generally associated with pain; however, this can be hard to assess. Although not directly indicative of pain, studies have reported that lame cows had a lower nociceptive threshold than sound cows, demonstrating heightened sensitivity to a noxious stimuli (Whay et al., 1998; Laven et al., 2008). It has also been shown that the use of anaesthetic improved the LS and increased weight bearing on the lame leg, emphasising that lameness causes pain (Rushen et al., 2007b). Different lesion types have also been reported to be associated with more severe lameness and therefore more pain. O'Connor et al. (2019) identified that severe forms of white line disease and the presence of digital dermatitis increased the odds of a cow being more severely lame in a partly-housed, pasture-based system. Tadich et al. (2010) also reported that sole ulcers, double sole and interdigital hyperplasia were linked to a higher LS in lame cows.

There are conflicting results on the use of pain relief, specifically NSAIDs, as part of lameness treatment. Thomas et al. (2015) reported that providing NSAIDs in addition to a trim and block increased the cure-rate of lameness in newly lame cows, compared to cows that did not receive

NSAIDs (Thomas et al., 2015). However, this was not found to be the case in chronically lame cows (Thomas et al., 2016). Laven et al. (2008) reported no long-term benefit of providing NSAIDs for lameness in a pasture-based system, based on LS or nociceptive threshold. Whay et al. (2005) also reported that NSAIDs did not significantly improve LS compared to cows that received standard treatment; however, the nociceptive threshold did significantly increase in cows that received NSAIDs as opposed to a saline control on three, eight and 28 days post treatment. A recent study also reported that providing NSAIDs to heifers after their first calving and all subsequent calvings, in addition to providing NSAIDs as part of lameness treatment, reduced the odds of lameness and culling (Wilson et al., 2022). It was suggested that providing NSAIDs when the animal is in pain at calving and lameness may prevent acute pain progressing into chronic pain due to inflammation (Wilson et al., 2022).

1.6.2 Defining pain

The International Association for the Study of Pain (IASP) originally defined human pain as "An unpleasant sensory and emotional experience associated with, or resembling that associated with actual or potential tissue damage, or described in terms of such damage" (IASP subcommittee on taxonomy, 1979). This definition of pain focused on the ability to describe pain; therefore, discriminating against those who could not communicate verbally. However, the original definition of pain was updated in 2020 to "an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage". The notes section of the new definition also stated that "verbal description is only one of several behaviors to express pain; inability to communicate does not negate the possibility that a human or a nonhuman animal experiences pain" (Raja et al., 2020). This update makes the definition more applicable to animals who cannot verbally communicate the presence of pain. A specific animal-based definition of pain has also been proposed by Zimmermann (1986): "An aversive sensory and emotional experience which elicits protective motor actions, results in learned avoidance and may modify species specific traits of behaviour including social behaviour".

1.6.3 Physiology of pain

Pain is caused when nociceptors in nerve endings are stimulated by damaging or potentially damaging mechanical, thermal or chemical stimuli (Snider and McMahon, 1998). Pain acts as a mechanism to alert humans and animals of actual or potential tissue damage by generating a reflex away from the stimuli. Stimulation of nociceptors occurs through the release of chemical mediators, such as histamine, bradykinin, and prostaglandins, by damaged cells (Snider and McMahon, 1998). Nociceptive stimulation leads to impulses travelling down the sensory nerve to the dorsal horn of the spinal cord, and further onto the brainstem and hypothalamus (Todd, 2010; Yam et al., 2018). The impulse then travels to the sensory cortex where the somatic sensation is processed, playing a part in the conscious perception of pain (Bushnell et al., 1999). In addition to nociceptive pain, there is also neuropathic pain which results from lesions or disease of the somatosensory system (Jensen et al., 2011).

Sensitization is an increased sensitivity to pain (Coutaux et al., 2005). A heightened pain response compared to the normal threshold is called hyperalgesia, whereas a pain response that was triggered by something that would not usually be painful, is known as allodynia (Coutaux et al., 2005). Hyperalgesia has been reported in lame cows following the treatment of a lesion (Whay et al., 1998). Peripheral sensitization can occur following the release of inflammatory mediators due to tissue injury, resulting in reduced nociception thresholds and increased responsiveness within the peripheral nervous system (Wei et al., 2019). Generally peripheral sensitization is localized and the nociception threshold would return to normal levels once inflammation subsides (Kyranou and Puntillo, 2012). For example, following surgical castration of calves, heightened pain would be felt around an incision, but this would subside once inflammation decreases and the incision heals. Central sensitisation is believed to occur due to ongoing inflammation or damage to the peripheral nerve, leading to synaptic plasticity and increased responsiveness to pain in spinal nociceptors (Woolf, 1983, 2011). Unlike peripheral sensitization, central sensitisation results in prolonged and widespread pain (Woolf, 2011).

1.6.4 Signs of pain

Assessing pain is an important part of evaluating animal welfare; however, it can be challenging to measure pain in animals. Unlike human patients, animals do not have the ability to verbally communicate their pain levels. It is therefore the responsibility of farmer and veterinarian to recognise signs of pain. Cows are, however, stoical animals and may hide signs of pain. Visual signs of pain may only become apparent when the animal is in severe pain (Hudson et al., 2008). Typical signs of pain that farmers and veterinarians should look out for are specified in Table 1.7.

Table 1.7. Signs of pain in dairy cows that are identifiable by a farmer or veterinarian

Category	Descriptors
Change in posture	• Head positioned below height of withers (Gleerup et al., 2015) • Lateral recumbency (Hudson et al., 2008) • Arched back (Gleerup et al., 2015)
Change in facial expression	• Ears drooping or laid back (Hudson et al., 2008; Gleerup et al., 2015) • Strained/tense appearance (Gleerup et al., 2015) • Furrow above eyes and nostrils (Gleerup et al., 2015)
Obvious signs of stress	• Increased heart rate (Grøndahl-Nielsen et al., 1999; Hudson et al., 2008; Heinrich et al., 2009) • Pupil dilation (Hudson et al., 2008) • Increased respiration rate (Hudson et al., 2008; Heinrich et al., 2009) • Trembling (Hudson et al., 2008)
Change in normal behaviour	• Cow reluctant to move/reduced movement (Hudson et al., 2008; de Oliveira et al., 2014; Gleerup et al., 2015) • Shortened strides (de Oliveira et al., 2014) • Increased lying time (de Oliveira et al., 2014) • Reduced rumination (Grøndahl-Nielsen et al., 1999; Gleerup et al., 2015) • Decrease in feed intake/feeding behaviours - flank may be visually hollow (Hudson et al., 2008; Gleerup et al., 2015) • Reduction in grooming activity – may lead to poor coat condition (Hudson et al., 2008; Gleerup et al., 2015)
Specific pain related behaviours	• Bruxism (Hudson et al., 2008; Braun et al., 2018) • Vocalization (Watts and Stookey, 1999; Braun et al., 2018) • Kicking/stamping hooves (Grøndahl-Nielsen et al., 1999; Eicher et al., 2006; Hudson et al., 2008) • Ear twitching (Grøndahl-Nielsen et al., 1999; Hudson et al., 2008) • Tail pushed against base of udder (Mølgaard et al., 2012) • Perching in cubicles (Mølgaard et al., 2012) • Head shaking (Grøndahl-Nielsen et al., 1999; Mølgaard et al., 2012)
Interaction with environment	• Not attentive to surroundings (Hudson et al., 2008; Gleerup et al., 2015) • Decreased interaction with other cows (Hudson et al., 2008) • Lack of eye contact to human observer (Gleerup et al., 2015)

1.6.5 Perception of pain

Pain perception can be affected by various qualities of an individual. Previous studies have reported that female veterinarians and those that graduated more recently scored the pain of various procedures and conditions in dairy cows and calves more severe than male veterinarians and those who graduated less recently (Huxley and Whay, 2006; Laven et al., 2009; Remnant et al., 2017). Similar results were found in veterinary students, whereby male students and those who enrolled less recently gave lower pain scores (Kielland et al., 2009). More empathetic veterinarians have also been reported to score cattle pain higher (Norring et al., 2014b). The majority of studies that look at pain perception focus on veterinarians, rather than farmers. Studies in Denmark and Bavaria have compared pain scores given by both veterinarians and farmers (Thomsen et al., 2012; Tschoner et al., 2021). Bavarian farmers and veterinarians both gave similar pain scores to various procedures and conditions (Tschoner et al., 2021). Whereas, farmers and veterinarians in Denmark were shown to generally agree to which conditions were most painful; however, farmers tended to consider most conditions more painful than veterinarians (Thomsen et al., 2012). The study in Denmark, however, only looked at cow conditions, and the veterinary survey took place over two years prior to the survey with the farmers. A summary of the pain scores given by veterinarians (Huxley and Whay, 2006; Laven et al., 2009; Thomsen et al., 2012; Remnant et al., 2017; Tschoner et al., 2020) and farmers (Thomsen et al., 2012; Tschoner et al., 2021) for each cow condition and procedure, across different studies are shown in Table 1.8 and 1.9. Table 1.10 also reports pain scores given by veterinarians (Huxley and Whay, 2006; Laven et al., 2009; Remnant et al., 2017; Tschoner et al., 2020) and farmers (Tschoner et al., 2021) for calf conditions and procedures. Generally across studies cow surgical procedures seemed to have the highest median pain scores, and mastitis (clots in milk only), hock with hair loss and neck calluses received the lowest pain scores.

Table 1.8. Comparison of median pain scores, across different studies, by veterinarians and farmers for a range of conditions in cows

	Veterinarians					Farmers	
	UK (Remnant et al., 2017)	UK (Huxley and Whay, 2006)	New Zealand (Laven et al., 2009)	Denmark (Thomsen et al., 2012)	Bavaria[1] (Tschoner et al., 2020)	Denmark (Thomsen et al., 2012)	Bavaria[1] (Tschoner et al., 2021)
Distal limb/long bone fracture	9	ns	ns	ns	8	ns	8
Foul of the foot	ns	ns	5	8	ns	8	ns
Fracture of tuber coxae	8	7	8	8	ns	8	ns
Mastitis (serious/toxic)	7	7	8	9	7	9	7
White line with sub-sole abscess	ns	7	7	ns	ns	ns	ns
White line disease	7	ns	ns	ns	ns	ns	ns
Uveitis	6	6	ns	8	5	4	4
Digital dermatitis	6	6	ns	7	7	7	6
Swollen hock	5	5	6	5	ns	5	ns
Metritis	5	4	5	6	5	6	5
LDA	4	3	6	5	5	6	5
Mastitis (clots only)	4	3	3	2	1	3	3
Hock with hair loss	3	3	ns	ns	ns	ns	ns
Neck calluses	3	2	ns	3	3	4	3

ns = not stated; LDA = left displaced abomasum
[1]Only conditions from this study that were comparable to the other studies are reported in this table

Table 1.9. Comparison of median pain scores, across different studies, by veterinarians and farmers for a range of procedures in cows

	Veterinarians				Farmers
	UK (Remnant et al., 2017)	UK (Huxley and Whay, 2006)	New Zealand (Laven et al., 2009)	Bavaria[1] (Tschoner et al., 2020)	Bavaria[1] (Tschoner et al., 2021)
Digit amputation	10	10	10	9	9
Caesarean-section	9	9	9	9	9
LDA surgery	8	9	9	7	8
Dehorning	8	8	8	8	8
Dystocia	7	7	7	8	8
Treatment of sole ulcer	7	6	ns	7	7
Debriding digital dermatitis lesion	7	6	ns	ns	ns
Treatment of white line abscess	ns	ns	4	ns	ns

ns = not stated; LDA = left displaced abomasum
[1]Only procedures from this study that were comparable to the other studies are reported in this table

Table 1.10. Comparison of median pain scores across different studies, by veterinarians and farmers, for a range of procedures and conditions in calves

	Veterinarians				Farmers
	UK (Remnant et al., 2017)	UK (Huxley and Whay, 2006)	New Zealand (Laven et al., 2009)	Bavaria[1] (Tschoner et al., 2020)	Bavaria[1] (Tschoner et al., 2021)
Distal limb/long bone fracture	ns	8	9	8	8
Umbilical hernia surgery	8	8	8	9	8
Disbudding	7	7	8	8	7
Joint ill	7	7	8	7	6
Castration (Burdizzo)	7	7	6	9	8
Castration (surgical)	7	6	8	9	8
Pneumonia	7	6	6	6	7
Castration (rubber ring)	6	6	5	ns	ns
Umbilical abscess	6	5	5	ns	ns
Dystocia	5	4	4	5	5

ns = not stated; LDA = left displaced abomasum
[1]Only conditions and procedures from this study that were comparable to the other studies are reported in this table

1.6.6 Analgesia

Recognising pain is the first step to alleviating pain. Where possible, pain should be pre-empted and analgesia provided prior to pain occurring, with the aim of reducing or preventing hyperalgesia and allodynia (Hudson et al., 2008). There are various analgesics available for use in dairy cows including NSAIDs, α2 –agonists and local anaesthetic (Stock and Coetzee, 2015). Local anaesthetic and α2 –agonists are generally used during surgical procedures to provide short-term pain relief (Stock and Coetzee, 2015), and the degree of analgesic effect associated with α2 –agonists is not well understood. This review will focus on NSAIDs, which can provide longer acting pain relief to dairy cows. Generally NSAIDs last between 24 and 72 hours per single dose (Hudson et al., 2008), and some NSAIDs can be given every 24 hours for up to five days (HPRA, 2022). A table of NSAIDs authorised in Ireland by the Health Product Regulatory Authority (HPRA) as of February 2022 can be viewed in Table 1.11, along with details on milk and meat withdraw periods and indications for use for each NSAID (HPRA, 2022).

Table 1.11. Non-steroidal anti-inflammatory drugs (NSAIDs) authorised in Ireland by the Health Product Regulatory Authority (HPRA, 2022)

NSAID (active ingredient)	Administration	Milk withdrawal period (days)	Meat withdrawal period (days)	Indicated use
Carprofen	SC, IV	0	21	Respiratory disease Acute mastitis
Flunixin	IV	1 – 1.5	5 – 10	Respiratory disease Acute mastitis
	Topical	1.5	7	Respiratory disease Acute mastitis Interdigital phlegmon Interdigital dermatitis Digital dermatitis
Ketoprofen	IM, IV	0	1 – 4	Respiratory disease Acute mastitis Parturient paresis Udder oedema Lameness Musculoskeletal disorders
Meloxicam	SC, IV	5	15	Respiratory disease Acute mastitis Diarrhoea in youngstock
Tolfenamic acid	IM, IV	0 – 1	4 – 12	Respiratory disease Acute mastitis
Salicylic acid	Topical	0	0	Acute Mastitis Minor skin conditions
	Oral solution	n/a	1	Acute respiratory disease (calves only)

IV = intravenous; SC = subcutaneous, IM = intramuscular; n/a = not licensed for lactating cows
Summary of product information is constantly being updated, check HPRA website for the most up-to-date product information (https://www.hpra.ie)

1.6.6.1 How NSAIDs work

At the site of tissue injury the enzyme phospholipase A_2 is released and converts phospholipids in the cell membrane to arachidonic acid (Davies et al., 1984). Arachidonic acid is further converted to prostaglandin and thromboxane by cyclooxygenase-1 (COX-1) and to prostaglandin by cyclooxygenase-2 (COX-2), or alternatively to leukotrienes by lipoxygenase (Rao and Knaus, 2008). The enzyme COX-1 is expressed constantly and is mainly involved in 'housekeeping' roles including homeostasis, renal physiology and the secretion of gastric mucus (Crofford, 1997). On the other hand, COX-2 is inducible and mediates inflammation, pain and fever (Crofford, 1997). Non-steroidal anti-inflammatory drugs prevent the production of prostaglandin by inhibiting COX-1 and COX-2, therefore, decreasing inflammation, pain and fever (Rao and Knaus, 2008; Figure 1.2).

The ability of NSAIDs to inhibit COX-1 can potentially lead to negative side effects, including gastrointestinal complications and renal disease (Rao and Knaus, 2008; Harirforoosh et al., 2013). Few studies have looked at these side effects in cows. A small-scale study reported that a ten day course of ibuprofen in calves resulted in an increase in abomasal ulceration and interstitial nephritis compared a control group; however, these were not found to be statistically significant (Walsh et al., 2016). A larger sample size would be required to determine if NSAIDs had a significant effect. Using an NSAID that favours COX-2 selectivity over COX-1 may also help reduce negative symptoms (Hatt et al., 2018). An *in vitro* study reported that carprofen is preferential towards COX-2 inhibition in cattle (Miciletta et al., 2014). Previous studies have also reported that meloxicam strongly favours COX-2 inhibition in horses, dogs and cats (Brideau et al., 2001); however, information on selectivity for COX-2 in cattle is scarce.

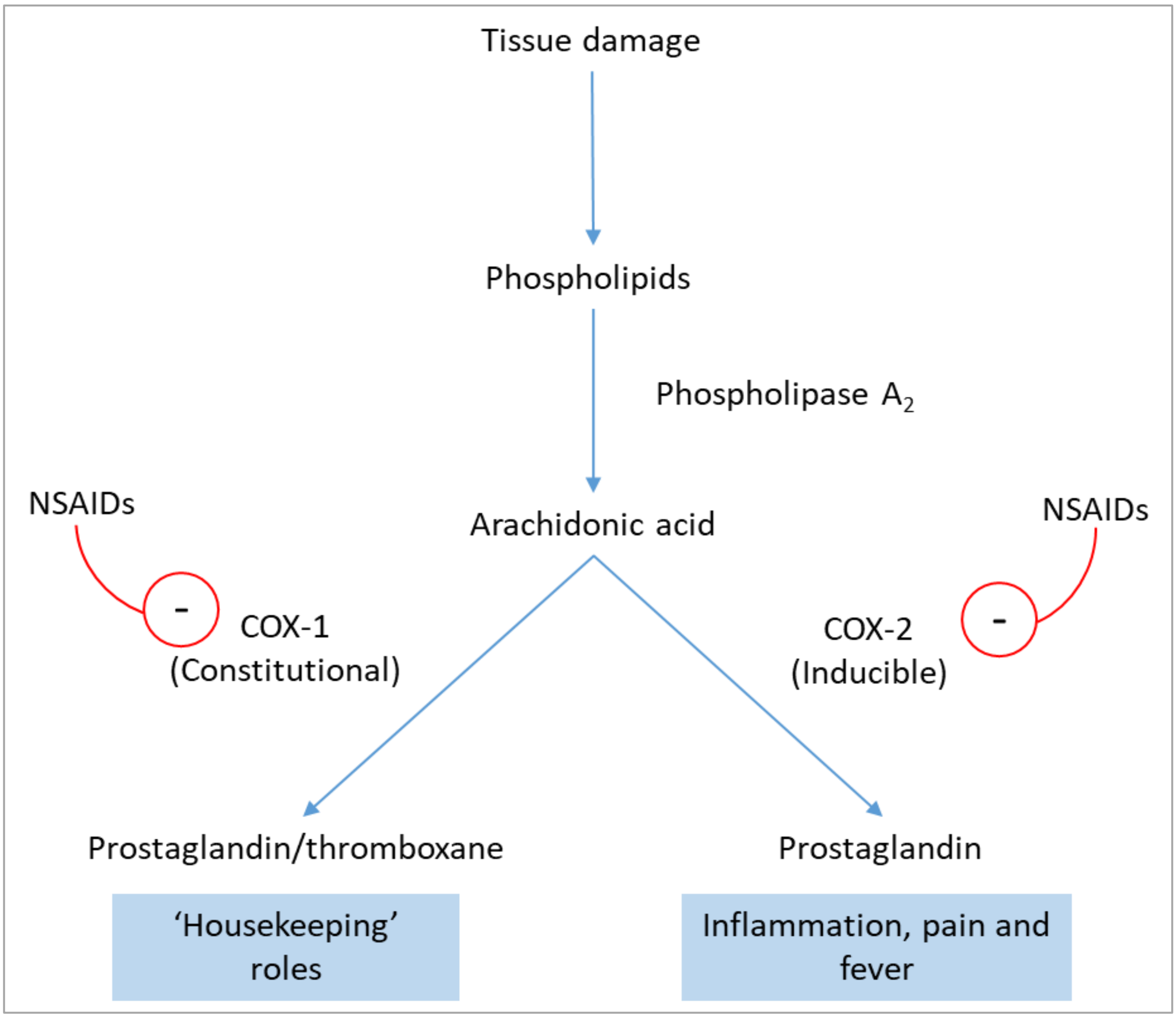

Figure 1.2. Cyclooxygenase (COX) pathway for the production of prostaglandin and thromboxane and the inhibition of COX-1 and COX-2 enzymes by non-steroidal anti-inflammatory drugs (NSAIDs)

1.6.6.2 Factors affecting NSAID use

Based on survey data, studies have found that NSAID use was higher when dairy cow and calf conditions or procedures were given a higher pain score by veterinarians (Huxley and Whay, 2006; Laven et al., 2009; Remnant et al., 2017). Remnant et al. (2017) reported that male veterinarians and those that graduated prior to 1990 were less likely to use NSAIDs, compared to female veterinarians and those who graduated later. Additionally calves received significantly less NSAIDs for procedures such as disbudding and castration, despite the relatively high pain score given by veterinarians. A common misconception is that younger animals feel less pain and do not require analgesia; however, there is no evidence that calves feel less pain than adult cows.

Despite dairy farmers also having a responsibility to detect and treat pain, there has been limited research of factors that affect willingness for NSAIDs to be given by farmers. A few studies have compared differences in analgesia use between veterinarians and farmers. Thomsen et al. (2012) reported that despite Danish veterinarians considering cow conditions less painful than dairy farmers, veterinarians were more likely to use analgesia. Becker et al. (2013) also reported that veterinarians were significantly more likely to consider NSAIDs in the treatment of sole ulcers and white line disease than farmers; this study only considered lameness-related procedures. There is also no research on the perception of pain and factors that affect NSAID use in dairy cow conditions and procedures, by farmers and veterinarians in Ireland. This information is important for increasing the use of NSAIDs in Irish dairy cows, thus improving recovery and animal welfare.

Cost is also an important factor to consider when looking at factors affecting NSAID use by veterinarians and farmers. Based on a UK study in 2005, over 65% of veterinarians agreed that ‘Farmers would like cattle to receive analgesia but cost is a major issue’ (Whay and Huxley, 2005); however, in a more recent study in the UK, this value decreased to 45% (Remnant et al., 2017). Although cost is still considered a major issue by many veterinarians, it is a positive that over a decade, cost seemed to become less of a barrier to NSAID use. Even lower agreement was found in Danish veterinarians and farmers, whereby 26% and 27%, respectively, agreed with the statement ‘I would like to use analgesics for cows more, but the price is a major issue’ (Thomsen et al., 2012). The cost benefit of NSAID use in regard to production parameters should be discussed to further educate farmers on the benefits of NSAIDs. For example, cows that received NSAIDs for the treatment of E-coli mastitis had significantly higher milk yields post-treatment, than cows that did not receive NSAIDs (Yeiser et al., 2012). There is also no information currently available that looks at how cost affects the use of NSAIDs on Irish dairy farms. This information is important for determining if farmers are willing to pay for NSAIDs and how this varies between specific conditions and procedures.

In the UK, over 20% of veterinarians agreed that ‘Analgesia may mask deterioration in the animals condition’ (Remnant et al., 2017) and in Denmark 37% and 40% of veterinarians and farmers (Thomsen et al., 2012), respectively, agreed with the statement. Thomsen et al. (2012) also reported that 16% of farmers disagreed that ‘Cows recover faster after the use of analgesics’. These misconceptions need to be discussed with practicing veterinarians and dairy farmers, to enable attitudes towards the use and benefits of analgesia to be changed. Based on a survey of UK dairy farmers, 62% agreed that ‘Farmers do not know enough about controlling pain’ and 53% agreed that ‘Veterinary surgeons do not discuss controlling pain in cattle with farmers enough’(Remnant et al., 2017). These statements emphasise the need for veterinarians to discuss the benefits analgesia with their clients, allowing farmers to understand and make informed choices on analgesic use within their herd.

1.6.6.3 Legislation of analgesic use in Ireland

Under EU law farmers must take all reasonable measures to ensure the welfare of their animals and prevent unnecessary pain, injury and suffering (Council Directive 98/58/EC). The Council of Europe recommendation concerning cattle, adopted by the standing committee of the European Convention for the Protection of Animals kept for Farming Purposes, must also be adhered to by EU states (Council of Europe, 1988). This recommendation stipulates that anaesthesia is required for procedures that are deemed likely to cause considerable pain, including disbudding and castration of calves. However, anaesthesia is not required in disbudding using chemical or thermal cauterization of calves under the age of four weeks (Council of Europe, 1988).

Current legislation on animal welfare and the use of analgesia in Ireland includes the Animal Health and Welfare Act (2013), together with the Animal Health and Welfare (Section 17) Regulations (2014) and the Animal Health and Welfare (Operations and Procedures) (No. 2) Regulations (2014). This legislation states that operations or procedures, with or without the use of an instrument, that interfere with sensitive tissue or bone structure require the appropriate administration anaesthetic or analgesic agents. Ear-tagging and freeze-branding are exempt and do not require anaesthesia. Some routine practices of calves also have exceptions to these rules, whereby anaesthetic is not required if the procedure is carried out within a particular timeframe from birth. These include:

- Castration using Burdizzo within six months of birth
- Castration using a rubber ring within eight days of birth.
- Disbudding using thermal cauterisation within 15 days of birth

There is currently no legislation in Ireland on the use of NSAIDs in dairy cows and calves; however, the Scientific Advisory Committee on Animal Health and Welfare made recommendations to the Department of Agriculture, Food and the Marine in 2015 (Scientific Advisory Committee on Animal Health and Welfare, 2015). It was recommended that cattle of all ages are provided NSAIDs for castration, disbudding and dehorning.

1.7 Conclusion

1.7.1 Summary

The overall aim of this thesis was to collect baseline data and evaluate lameness and pain management on Irish dairy farms. Lameness is a huge welfare issue within the dairy industry.

The welfare of dairy cows is becoming increasingly important as consumers are becoming more attentive to the welfare standards associated with the production of dairy produce. There is currently a lack of information on the lameness prevalence within Irish dairy herds, particularly for the period of time when cows are housed. There is also very limited research on current lameness control strategies, and farm infrastructure, that are in place on Irish dairy farms. There is also a need for a large-scale study to identify the causes of lameness, through hoof lesion identification. Determining the causes of lameness, the current lameness management practices in place and the main risks for lameness on Irish dairy herds will enable practices that reduce lameness prevalence to be implemented on-farm. There is also a lack of data on the perception of pain and use of NSAIDs by farmers and veterinarians within the dairy industry. Understanding attitudes to pain and pain management associated with lameness, as well as other conditions and procedures, on Irish dairy farms could also help minimise pain and thus improve dairy cow welfare.

1.7.2 Thesis aims

This thesis aims to:

1. Identify the most important cow-level and herd-level risk factors for lameness on Irish dairy farms based on both the grazing and housing period.
2. Determine the lameness prevalence during both the grazing and housing period, and evaluate infrastructure and management practices, with a focus on lameness, currently used on Irish dairy farms.
3. Establish the most common causes of lameness (hoof lesions) in Irish dairy cows, and determine how these lesions relate to each other and to lameness severity.

4. Determine attitudes to pain of Irish veterinarians and farmers and the use of analgesics for various dairy cow conditions and procedures, including those related to lameness.

Paper 1: Cow- and herd-level risk factors for lameness in partly housed pasture-based dairy cows

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CH, MC and EK supervised this study. All authors contributed to study design. NB, RC and KS were major contributors to data collection, including cow scoring, farmer questionnaires and on-farm measurements. NB analysed the data and drafted the manuscript, with the assistance of CH and MC. All authors read and approved the final manuscript.

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Cow- and herd-level risk factors for lameness in partly housed pasture-based dairy cows

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ABSTRACT

Lameness in dairy cows is a major animal welfare concern and has substantial economic impact through reduced production and fertility. Previous risk factor analyses have focused on housed systems, rather than those where cows were grazed for the majority of the year and housed only for the winter period. Therefore, the aim of this observational study was to identify a robust set of cow-level and herd-level risk factors for lameness in a pasture-based system, based on predictors from the housing and grazing periods. Ninety-nine farms were visited during the grazing period (April 2019–September 2019), and 85 farms were revisited during the housing period (October 2019–February 2020). At each visit, all lactating cows were scored for lameness (0 = good mobility, 1 = imperfect mobility, 2 = impaired mobility, 3 = severely impaired mobility), and potential herd-level risk factors were recorded through questionnaires and infrastructure measurements. Routine cow-level management data were also collected. Important risk factors for lameness were derived though triangulation of results from elastic net regression, and from logistic regression model selection using modified Bayesian information criterion. Both selection methods were implemented using bootstrapping. This novel approach has not previously been used in a cow-level or herd-level risk factor analysis in dairy cows, to the authors' knowledge. The binary outcome variable was lameness status, whereby cows with a lameness score of 0 or 1 were classed as non-lame and cows with a score of 2 or 3 were classed as lame. Cow-level risk factors for increased lameness prevalence were age and genetic predicted transmitting ability for lameness. Herd-level risk factors included farm and herd size, stones in paddock gateways, slats on cow tracks near the collecting yard, a sharper turn at the parlor exit, presence of digital dermatitis on the farm, and the farmers' perception of whether lameness was a problem on the farm. This large-scale study identified the most important associations between risk factors and lameness, based on the entire year (grazing and housing periods), providing a focus for future randomized clinical trials.
Key words: dairy cow, lameness, risk factor, pasture-based, machine-learning

INTRODUCTION

Lameness is a debilitating problem in the dairy sector, representing a major welfare challenge and negatively impacting the economic sustainability of the industry (Huxley, 2012). Lameness is a painful condition that can lead to behavioral changes in dairy cows, including increased lying and decreased feeding time (Galindo and Broom, 2002). Lameness is commonly considered to be one of the 3 most costly diseases in dairy herds (Bruijnis et al., 2010), with financial losses attributable to decreased milk production and fertility as well as treatment and culling.

Risk factor studies are critical to identifying associations between potential risk factors and lameness, thus creating an important foundation for future intervention studies. Risk factors for freestall-housed cows included increased time away from the pen, decreased cow comfort, tiestall brisket boards, and no routine trimming (Espejo and Endres, 2007). In a fully housed Canadian system, herd-level risk factors included small herd sizes, slippery flooring, and reduced lying surface comfort, whereas cow-level risk factors included high parity, low BCS, and the presence of hock injuries and overgrown claws (Solano et al., 2015). Additional risk factors for cows with no pasture access include feed rail and alley design and water trough design (Sarjokari et al., 2013).

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Risk factors associated with lameness for cows that are grazed year-round differ from those that are fully housed. In a large-scale study in New Zealand, cow track maintenance and stockman behavior when moving animals on cow tracks were the most prominent risk factors for lameness (Chesterton et al., 1989). In an Australian pasture-based system, risk factors included rainfall levels, collecting yard stocking rate and concrete smoothness, feed-pad stocking rate, and rough handling of cattle on cow tracks (Ranjbar et al., 2016). Lameness incidence in Brazil was greater for cows that were moved faster along the cow tracks, Holstein Friesian cows compared with Jersey cows, cows with hoof abnormalities, and cows with higher parity and lower BCS (Bran et al., 2018).

Many dairy production systems are neither fully housed nor involve year-round grazing. For example, Irish dairy farms are almost entirely spring calving and pasture based (Dillon et al., 1995); however, cows also spend approximately 4.5 mo/yr in housed facilities before calving (Dillon et al., 2019). Cows in these hybrid systems may therefore be exposed to risk factors for both systems, which may alter the relative importance of each factor. For cows in this system type, white line disease and sole hemorrhages have been reported as the most common causes of lameness (Somers and O'Grady, 2015). This is similar to cows in fully grazed systems, such as New Zealand, where noninfectious lesions were most prevalent (Chesterton et al., 2008). In contrast, cows in fully housed systems tended to have a higher prevalence of infectious lesions, such as digital dermatitis (Solano et al., 2016).

Only limited research has investigated risk factors for lameness in a part-grazed, part-housed system. Doherty et al. (2014) derived a list of potential risk factors from previous research and established how common they were in Irish herds. Somers et al. (2019) also reported cow-level risk factors as part of the same study and included higher parity, BCS loss postpartum, and lower BCS at calving. O'Connor et al. (2020) reported that herd-level factors included footbath use and holding cows in the collecting yard until milking was complete, with cow-level risk factors including stage of lactation (>120 DIM), PTA for lameness, and BCS. However, O'Connor et al. (2020) focused on the grazing period only and did not consider the housing period or evaluate directly measured farm infrastructural features as potential risk factors for lameness. Risk factors for lameness in England and Wales, where cows were out to pasture full-time in the summer, included routine trimming, use of automatic scrapers, passageway widths <3 m, and stall curb heights <15 cm (Barker et al., 2007). However, compared with the farms studied by Barker et al. (2007), Irish farms tend to be less intensive, with lower-yielding and smaller cows and a longer grazing season. Moreover, previous research involving part-grazed, part-housed systems was undertaken before or the year of the abolition of European Union milk quotas in 2015 (Barker et al., 2007; Somers et al., 2019; O'Connor et al., 2020). Therefore, opportunities have arisen for dairy farmers to undergo expansion since then (Ramsbottom et al., 2020), and potential risk factors may be altered as a result. In addition, sample sizes in these studies ranged from 10 to 49 herds; a larger-scale study would provide a more representative sample and allow a smaller effect size to be detected.

The aim of this study was to identify a robust set of the most important cow- and herd-level risk factors for lameness in a pasture-based system where cows are also housed for part of the year, using a large number of potential predictors from the grazing and housing periods. Identifying associations between risk factors and lameness will contribute to lameness prevention and deliver a focus for future intervention studies.

MATERIALS AND METHODS

Ethical approval was granted by the Teagasc Animal Ethics Committee (Cork, Ireland) before the commencement of the study (review number: TAEC202-2018). All animal measurements were carried out in compliance with the European Union (Protection of Animals Used for Scientific Purposes) Regulation 2012 (S.I. 543 no. of 2012) and the European Directive 2010/63/EU. The study involved 2 visits: one during the grazing period (April 2019–September 2019) and one during the housing period (October 2019–February 2020). The median difference between the 2 visits was 168 d [interquartile range (**IQR**) = 127–217], ranging from 65 to 262 d. This study was part of a larger study assessing dairy cow welfare in pasture-based systems (Crossley et al., 2021).

Farm Selection

Before recruitment of farms, selection criteria were determined to ensure that study farms represented the predominant dairy production system in Ireland; pasture based, nonorganic, and spring calving. Herds recruited had a target of $\geq$30 and $\leq$250 cows, which accounts for 95% of farms that meet the selection criteria described. Herds enrolled were registered with the Irish Cattle Breeding Federation (**ICBF**; Bandon, Co. Cork, Ireland); the database for all Irish-born dairy and beef cattle. Herds recruited were located within 2 h of Teagasc Moorepark for practicality reasons, and were within the main dairy farming counties of Ireland (Cork, Tipperary, Limerick, Kerry, Kilkenny, Waterford, and Wexford); 69% of all dairy cows in the country were located in these 7 counties (ICBF, 2018).

To determine the number of farms required to detect a risk factor for lameness, a simulation-based power study was performed. Multiple different scenarios were evaluated; 100 herds of 100 cows produced an estimated 93% power to detect a risk factor with a relative risk of 1.4, and 62% power to detect a risk factor with a relative risk of 1.25. A target of 100 farms was therefore deemed to be an adequate number of farms to visit.

From a list of herds provided by ICBF, 518 farms were randomly selected using SAS version 9.4 (SAS Institute Inc.), and farmers were contacted via letter or telephone to invite them to participate in the study. In total, 131 farmers responded (response rate of 25%), and 102 of these farmers were willing to participate and were deemed suitable for the study. All 102 herds were visited during the grazing period (99 farms included in statistical analysis), and 87 farms were revisited during the housing period (85 farms included in statistical analysis).

Data Collection

Details on farm management practices and facilities were collected via questionnaires and on-farm infrastructure measurements.

Farmer Questionnaire

A questionnaire was conducted with the farmer at both the first and second visit; questionnaires can be viewed as supplemental material (Browne, 2021). The questionnaire was split between the 2 visits to ensure it was not too time consuming for the farmer. Both questionnaires gathered information on the grazing and housing periods. The questionnaire at the first visit gathered information on farm background and management, cow track maintenance and grazing practices, milking practices, and lameness prevention (including routine trimming and foot bathing), detection, and treatment methods. The second questionnaire focused on housing characteristics and management, nutrition, producer demographics, and the farmers' perception of hoof health on the farm.

Infrastructure Measurements

Infrastructure measurements were taken via direct observation for the milking facilities, cow tracks, and housing facilities. Categorical scales used as part of the infrastructure measurements can be viewed as supplemental material (Browne, 2021).

Milking Facilities

Collecting yard stocking rate, presence of a slope, entrance widths, presence of a backing gate, and flooring type were recorded. The milking parlor type, size, and flooring were also recorded. At the parlor entrance and exit, the floor slipperiness (de Vries et al., 2015) and the presence of steps, slopes, sharp turns, narrow doors, and obstructions were noted. The flooring type at the parlor exit was recorded, as was the distance from the first milking unit to the end wall of the parlor, to determine the space cows had to turn after milking. The presence, type, and length of footbaths were also included in this section.

Cow Tracks

Due to time constraints, it was not possible to collect data on every cow track on each farm. Therefore, measurements were taken on the cow track in use on the day of the first visit; at the estimated halfway point between the collecting yard and the paddock, at the end point of the cow track, and at the paddock gateway. At all 3 locations the width, surface material, surface condition, presence of loose stones, and presence of a drainage ditch were recorded. The presence of loose stones was measured by placing a quadrat (0.5 m × 0.5 m), divided into 25 smaller squares, in the center of the cow track. The number of quadrat squares containing at least one loose stone was recorded. In addition, the cow track slope and camber (measured using a spirit level), the verge width, and the presence of deep wheel tracks, water erosion, and a clear channel in the road surface, suggesting a single-file path made by cows, were recorded at the end point and the halfway point.

Measurements were also taken in the segment between the collecting yard entrance and 50 m from the collecting yard along all cow tracks utilized; this was to obtain information on cow track characteristics in areas that were most regularly used by cows. At 50 m from the collecting yard, the cow track width, verge widths, and presence of loose stones were measured. The surface material, surface condition, and gradient of the steepest slope within the first 50-m segment from the collecting yard were also recorded, as well as the presence of a drainage ditch, visible slope, consistent width, sharp turns, and a single-file path made by cows.

Housing Facilities

The presence or absence of loose housing (straw yards and slatted pens) and stall housing on each farm was recorded. Housing measurements were taken in each pen that housed dairy cows. Loose housing and stall housing measurements included number of cows present at the time of the visit, accessible feed barrier length, passageway widths, flooring type, and presence of automatic scrapers and dead-ends. Lying area dimensions and the presence or absence of bedding were also noted for loose housing. For stall housing the number of stalls, overall stall condition (percentage of stalls in disrepair), and proportion of each stall type (e.g., cantilever) and direction (head-head, wall-facing, or passage-facing) were recorded. Bedding type, mat thickness, and stall hardness (McFarland and Graves, 1995) and cleanliness were also recorded for 5% of stalls (stalls randomly selected; minimum of 2 stalls). Additionally, presence of brisket board, curb height, total length, bed length, lunge space, diagonal length, neck rail height, and width were recorded for 5% of the 2 most common stall types (stalls randomly selected; minimum of 2 stalls per type).

Herd Lameness and Body Condition Scoring

All scorers undertook training with an experienced body condition scorer from Teagasc. Scorers also attended and passed a Register of Mobility Scorers-approved course in England, ensuring that lameness scoring was standardized and consistent. A total of 6 scorers were trained in body condition scoring and 4 scorers in lameness scoring. Using weighted kappa coefficients, inter- and intraobserver agreement scores were calculated for lameness scoring and body condition scoring. The mean lameness score (**LS**) interobserver agreement at the beginning of the first visit was 0.73 [standard deviation (SD) = 0.07], and the mean LS inter- and intraobserver agreements before the beginning of the second round of visits were 0.85 (SD = 0.06) and 0.77 (SD = 0.05), respectively. The mean BCS interobserver agreement at the beginning of the first visit was 0.74 (SD = 0.06), and the mean BCS inter- and intraobserver agreements before the second visit were 0.81 (SD = 0.06) and 0.87 (SD = 0.05), respectively.

Herd scoring was carried out after milking at each visit; cows were retained in a crush (chute) to enable tag number identification and body condition scoring. At both visits, the number of cows in the milking herd to assess for BCS was calculated based on herd size using the Welfare Quality sample size protocol (Welfare Quality Consortium, 2009). The cows were scored using a scale from 1 to 5, in 0.25 increments (Wildman et al., 1982), by one observer. All cows in the milking herd were subsequently individually scored for lameness as they left the crush, by a single observer using the Agricultural and Horticultural Development Board Dairy 4-point scale (Archer et al., 2010).

Herd Management Data

Cow-level data were provided by the ICBF for all herds enrolled in the study. Date of birth and date of first calving were classified into age at visit (yr) and age at first calving (mo), respectively. Days in milk on the day of the visit, calving interval (between 2018 and 2019 calving), and days until next calving were calculated based on calving dates provided. Based on the 2019 lactation, the parity, calving difficulty, whether the cow had twins or a single calf, average SCC, 305-d milk recording prediction, and dry-off date were provided for each cow. Breeds were classified into Holstein Friesians, other purebreds (excluding Holstein Friesians), and crossbreeds. Purebreds were defined as cows that were ≥87.5% of a single breed. The 2019 Economic Breeding Index, maintenance subindex, and health subindex values were extracted for each cow; explanations of these indices can be found in Berry et al. (2007). The lameness trait within the health subindex, in the form of a PTA, was also provided. In terms of lameness, a positive PTA indicates that the progeny are more likely to become lame than the base population (Berry et al., 2007).

Statistical Analysis

All data cleaning, pre-processing of data, descriptive statistics, and statistical modeling were executed in R software version 3.3.1 (R Core Team).

Data Cleaning

A total of 22,164 LS were recorded across 102 farms. Three farms, comprising 262 LS observations, were excluded from the data set due to robotic milking (1 farm) or once-a-day milking (2 farms). A further 1,694 LS observations were removed due to wrongly recorded tag numbers, accidental scoring of pre-calving heifers, and scoring of non-spring-calving cows.

Pre-Processing

Before statistical analysis, all housing predictors were weighted by the number of cows in each pen, to account for varying number of cows being subjected to the conditions of each pen. Continuous cow-level variables with missing values were split into quartiles, and an additional category was made for both continuous and categorical variables, to represent missing data points (<1% of data set). Nonparametric methods based on random forest algorithms were employed to impute missing values (3.2% of data set) from the surveys and on-farm measurements, using the missForest package (Stekhoven, 2013). Thirty-five predictors with near-zero variance were removed (Kuhn, 2020), leaving a final data set consisting of 197 predictors (cow-level predictors = 16; herd-level predictors = 181). These predictors can be viewed as supplemental material (Browne, 2021). Continuous predictors were subsequently centered and scaled (to SD units relative to overall mean). Each cow was assigned a lameness outcome at each visit: LS of 0 or 1 was classified as non-lame, and a score of 2 or 3 was classified as lame.

Variable Selection Models

Triangulation (Lawlor et al., 2017; Lima et al., 2021) of results from elastic net regression (**Enet**), a form of regularized logistic regression, and logistic regression using modified Bayesian information criterion (**mBIC**) was used to establish important risk factors for lameness. These methods were chosen due to the large number of predictors and the need to avoid overfitting. The outcome variable was lameness status (0 = not lame, 1 = lame); lameness scores from both the grazing and housing visits were included in the models. All covariates described previously were offered to each model.

Elastic Net Regression

Elastic net regression combines the ridge penalty (penalizing the sum of squared coefficients) with the lasso penalty (penalizing the sum of coefficients). The elastic net penalty term is shown in Equation [1]:

$$\lambda\left\{\sum_{j=1}^{P}\left[\frac{1}{2}(1-\alpha)\beta_j^2\alpha\beta j\right]\right\}, \quad [1]$$

where λ is a model tuning parameter providing coefficient penalization; α is the mixing parameter to determine the proportion penalty applied as ridge or lasso, where $\alpha = 0$ represents a full ridge model and $\alpha = 1$ represents a full lasso model; j represents a predictor variable and P represents the total number of predictors; β represents the sum of coefficients.

Elastic net regression was performed using the packages caret (Kuhn, 2020) and glmnet (Friedman et al., 2010). An Enet model was fitted using a large tuning grid of α values (α = 0, 0.2, 0.4, 0.6, 0.8, 1) and λ values (λ = 0.0001, 0.001, 0.003, 0.004, 0.01, 0.015, 0.02, 0.03, 0.04, 0.05, 0.1). Five-fold cross validation with 10 repeats was used to evaluate model performance and select the best-performing model based on accuracy.

Selection Using Modified Bayesian Information Criterion

Any predictors not correlated with the outcome variable (Pearson correlation test, $P > 0.3$) were removed, and stepwise logistic regression model selection based on minimizing mBIC was performed using the bigstep package (Szulc, 2019). The model was fitted to best balance the penalty term against a measure of model fit. The mBIC penalty term can be described as follows (Equation [2]):

$$-\frac{1}{2}k_i \log n - k_i \log\left(\frac{1-p}{p}\right), \quad [2]$$

where k_i represents the number of predictors in the ith model, n is the number of observations, and p represents the probability that a predictor, chosen at random, influences the outcome variable (lameness status).

Bootstrapping

Bootstrapping was used for both the Enet and mBIC model selection processes. One thousand bootstrap repeats were performed for each model type; this was deemed sufficient to obtain an accurate 95% bootstrap percentile confidence interval (Efron and Tibshirani, 1993). For each bootstrap repeat, the coefficient for each predictor was returned, and the mean of the nonzero coefficients and the 95% bootstrap confidence interval for each predictor was calculated. Coefficient means were subsequently unstandardized by dividing by the SD, and odds ratios (**OR**) calculated using these values.

Stability Selection and Model Triangulation

A stability value was calculated for each predictor for each model selection method (elastic net regression and selection based on mBIC), defined as the proportion of bootstrap repeats in which the coefficient for that predictor was nonzero. A nonzero coefficient implied that the predictor was selected in the model. A bootstrap P-value was also determined for each predictor based on the distribution of nonzero coefficients. The P-value was calculated as the proportion of coefficients on the minority side of zero.

Drawing on the principles of stability selection, for which it is known that variables with the highest stability values are least likely to be false positives (Lima et al., 2021; Meinshausen and Bühlmann, 2010), and triangulation, for which it is accepted that use of multiple analyses reduces bias in results (Lawlor et al., 2017), final model selection was based on high-stability variables that occurred in both model types. Predictor variables that had a bootstrap P-value of <0.05 and were ranked in the top 24 by stability (number of predictors that had a stability of >80% in the Enet model, a previously established technique: Lima et al., 2020) for each method were deemed likely to have important associations with lameness. The final subset of results was not found to be sensitive with the arbitrary choice of selecting predictors ranked in the top 24 by stability. An identical subset of predictors was found if selection was based on the top 30 predictors ranked by stability.

Potential Clustering Effect

The effect of accounting for clustering at herd level and cow level were evaluated by estimating parameters for random effects logistic regression models using Markov chain Monte Carlo via the brms package (Bürkner, 2017). One model included a random effect representing herd, and a second model included random effects terms at cow and herd level. A subset of covariates was included in the logistic regression models based on those selected in both the Enet and the mBIC models. Coefficients from each model were assessed to ensure that direction of association was the same as (and effect size similar to) the results from triangulation of the Enet and mBIC models.

RESULTS

Cow Characteristics and Lameness Prevalence

The median age across all cows scored was 5 yr (IQR 3–7) with a median parity of 3 (IQR 2–5). The median 305-d milk yield was 6,638 kg per cow (IQR 5,750–7,597) with a median calving interval of 369 d (IQR 354–388). The median BCS during the grazing visit and the housing visit were 3 (IQR 3–3.25) and 3.25 (IQR 3–3.5), respectively. Of all cows scored, 51% were Holstein Friesian, 28% were crossbreeds, and 21% were other purebreds. The final data set consisted of 20,208 LS recorded across 99 farms. Cow-level lameness prevalence (LS2 and LS3) was 9.3% during the grazing period and 8.9% during the housing period. Lameness prevalence across farms ranged from 0.9% to 31.4% during the grazing period and from 0% to 28.0% during the housing period.

Model Results

Figure 1 shows the stability and bootstrap P-value for each predictor in both Enet and mBIC models, illustrating variables selected in the triangulation process. Twenty-four predictors were selected in the final Enet and final mBIC models. Of these predictors, 11 were selected in both models and therefore represented a robust set of risk factors for lameness. Figure 2 shows the standardized mean coefficient and 95% confidence intervals for each predictor that was selected in both models (for comparison of effect size). Table 1 reports full results for predictors selected in both the Enet and mBIC models. Random effects logistic regression models suggested that accounting for the clustering effect of (1) herd and (2) cow nested within herd did not substantially influence the results from the Enet and mBIC models.

Cow-Level Risk Factors

Age had the largest standardized effect size of all cow- and herd-level predictors (based on the average of the standardized mean coefficients from the Enet and mBIC models); as age increased by 1 yr, the odds of a cow being lame increased by approximately 20% (Enet OR = 1.19; mBIC OR = 1.21; mean OR = 1.20). A positive lameness PTA increased the odds of lameness by approximately 37.5% (Enet OR = 1.14; mBIC OR = 1.61) compared with those with a negative PTA.

Herd-Level Risk Factors

Five herd-level factors were associated with an increased risk of lameness. In both the Enet and mBIC models, "farmers who considered lameness to be a problem in their herd" had the largest standardized effect size of all herd-level predictors. When farmers considered lameness to be a problem in their herd, odds of lameness increased by approximately 47% (Enet OR = 1.17; mBIC OR = 1.77) compared with when farmers did not consider lameness to be a problem. When ≥10% of the herd had been treated for lameness in the year before the study, the odds of lameness were increased by approximately 27% (Enet OR = 1.08; mBIC OR = 1.46) compared with those herds where <10% were treated. Additionally, when >5% of the herd had digital dermatitis during the current lactation, according to the farmer, the odds of lameness were increased by approximately 30% (Enet OR = 1.08; mBIC OR = 1.52) compared with a herd with ≤5%. A 10% increase in the proportion of slats in the first 50 m of cow tracks following the collecting yard increased the odds of lameness by approximately 6.5% (Enet OR = 1.04; mBIC OR = 1.09). Also, a 10% increase in the percentage of the gateway surface material that was stones increased the odds of lameness by approximately 7% (Enet OR = 1.03; mBIC OR = 1.11).

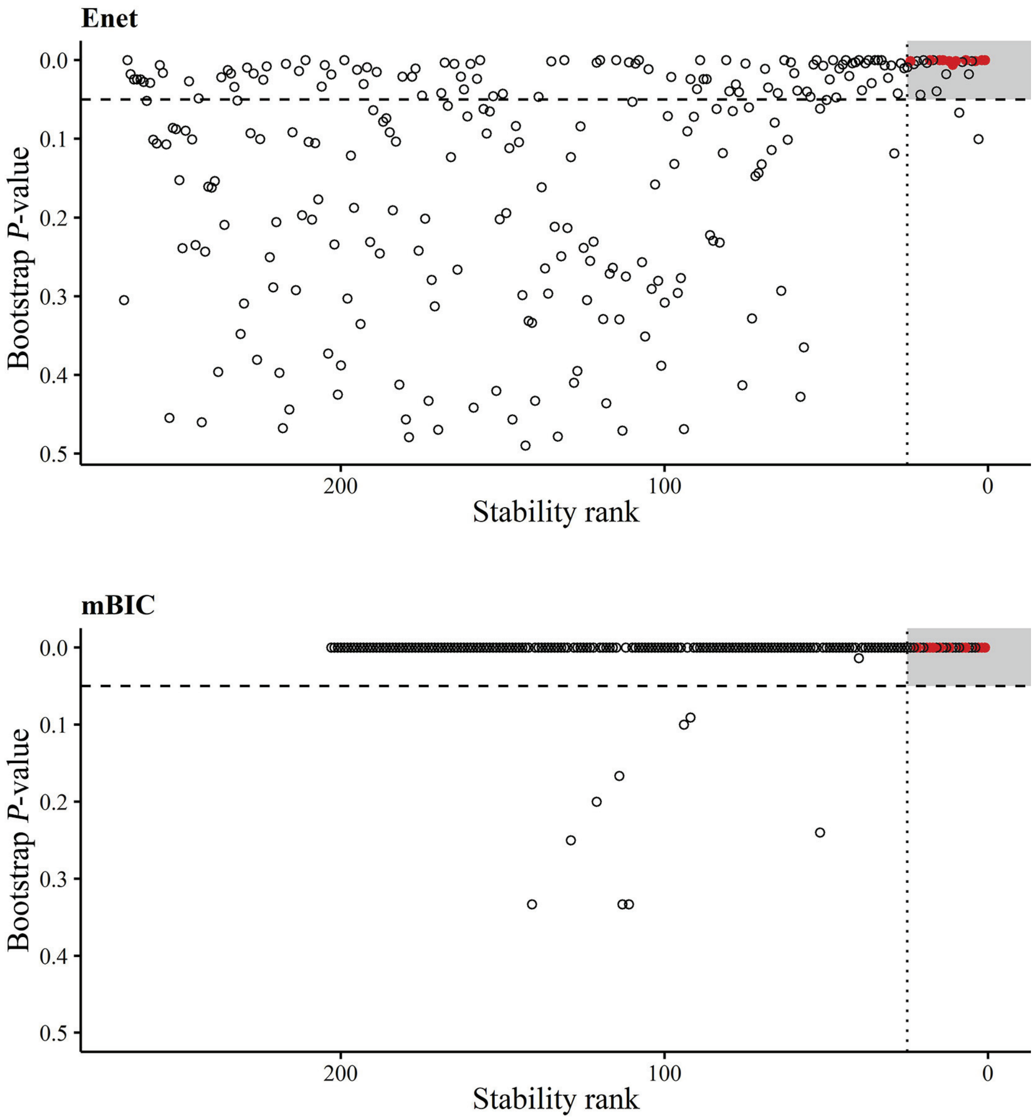

Figure 1. The stability rank and bootstrap P-values for each predictor in the elastic net regression model (Enet) and from the logistic regression model using modified Bayesian information criterion (mBIC), based on data from 99 spring-calving, pasture-based herds during the grazing period (April 2019–September 2019) and in 85 of these herds during the housing period (October 2019–February 2020). As indicated by the shaded area, predictors selected in each model had a P-value of <0.05 (dashed line) and were ranked in the top 24 by stability (dotted line). The red dots indicate the 11 predictors that were selected in both the Enet and mBIC models.

Four herd-level predictors reduced the risk of lameness. As herd size increased by 100 cows, the odds of lameness decreased by approximately 23% (Enet OR = 0.90; mBIC OR = 0.64). Similarly, as the grazing platform size increased by 100 ha, the odds of lameness decreased by approximately 45% (Enet OR = 0.74; mBIC OR = 0.36). Herds with no digital dermatitis cases during the current lactation, according to the farmer, had decreased odds of lameness of approximately 20.5% (Enet OR = 0.91; mBIC OR = 0.68) compared with a herd with >0% and ≤5%. Also, as the distance to turn after milking increased by 1 m, the odds of lameness decreased by approximately 8.5% (Enet OR = 0.97; mBIC OR = 0.86).

Predictors Selected in Individual Models but Excluded in Triangulation

A larger set of predictor variables were selected in one or the other of the individual models (Enet or mBIC), but not in both, and were therefore not reported in the previous triangulated results. Thirteen of the predictors that were selected in the final Enet model (within the top 24 ranked by stability) were not also selected in the final mBIC model. These predictors, which showed increased risk for lameness, included a higher proportion of cubicles of recommended width, higher proportion of cow track surface material measurements recorded as stones, and longer walking distance to the furthest paddock. Predictors that showed decreased risk for lameness included higher economic breeding index, genetic health and maintenance subindexes, greater days in milk, first-parity cows (i.e., no calving interval, compared with cows with a calving interval of 353 to 369 d), higher proportion of cubicles with thick mats, higher proportion of collecting yard that was grooved concrete, higher proportion of cow track measurements with a gradient >10%, higher proportion of cows tracks in the first 50 m from the collecting yard with a ditch, and higher proportion of cow tracks where the transition from concrete to other surface material was within 50 m of the collecting yard entrance.

Similarly, 13 of the predictors for lameness that were selected in the final mBIC model were not also selected in the final Enet model. Predictors that showed increased risk for lameness included high number of

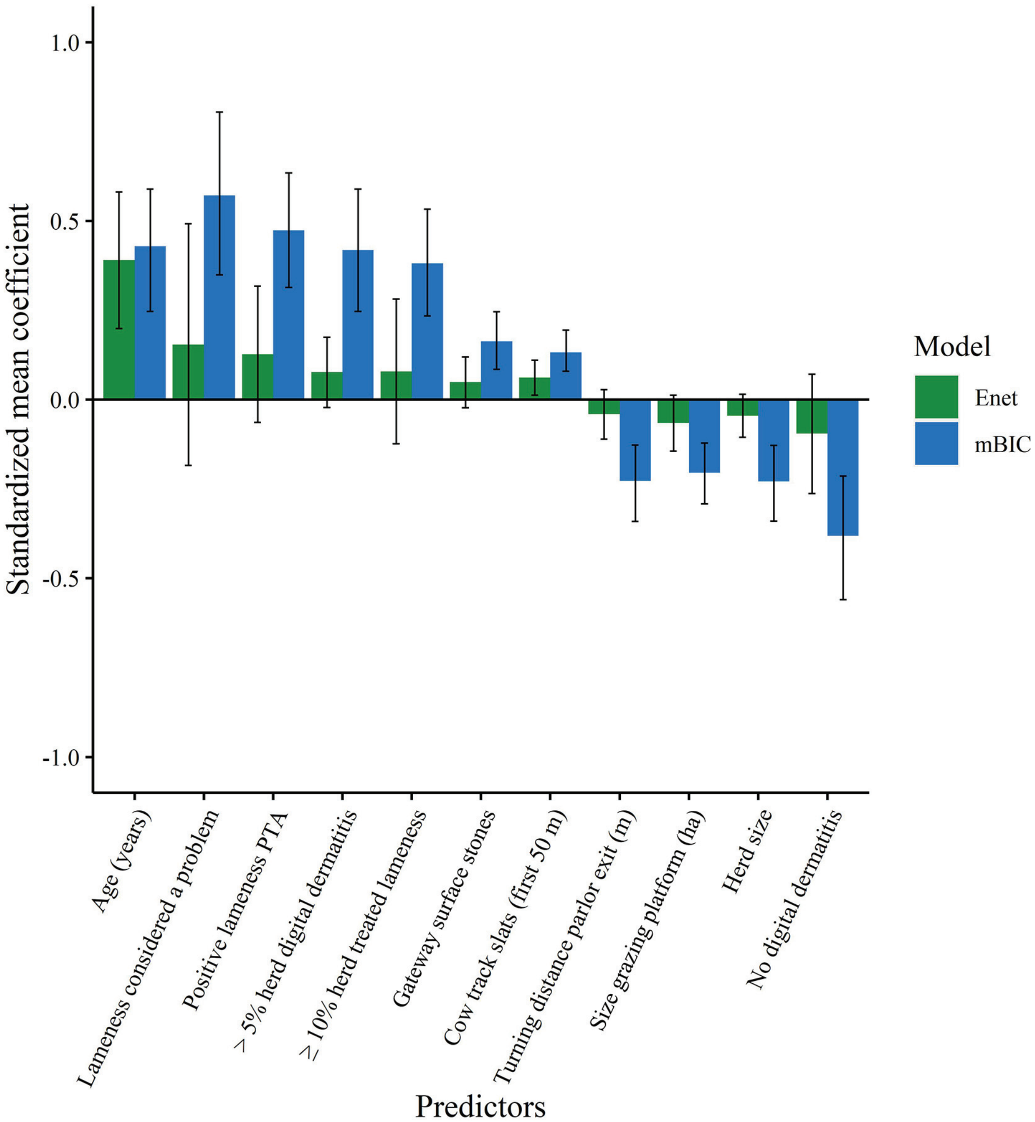

Figure 2. Standardized mean coefficients and 95% confidence intervals for the 11 predictors that were selected in both the final elastic net regression model (Enet) and from the logistic regression model using modified Bayesian information criterion (mBIC), ordered by the average standardized mean coefficients across both models. These risk factors were established from data collected on 99 spring-calving, pasture-based herds during the grazing period (April 2019–September 2019) and in 85 of these herds during the housing period (October 2019–February 2020).

Table 1. Results from the elastic net regression model (Enet) and from the logistic regression model using modified Bayesian information criterion (mBIC), ordered by mean stability rank across both models, to identify risk factors for lameness from 99 spring-calving, pasture-based herds during the grazing period (April 2019–September 2019) and in 85 of these herds during the housing period (October 2019–February 2020); the mean standardized coefficient and 95% CI, odds ratio, stability rank, and bootstrap *P*-value are shown for each predictor selected in both the Enet and mBIC models; the binary outcome is lameness status (0 = not lame, 1 = lame)

Predictor	Reference category (categorical predictors)	Mean standardized coefficient (lower 95% CI; upper 95% CI)		Odds ratio[1] (continuous predictor unit change)		Stability rank		Bootstrap *P*-value	
		Enet	mBIC	Enet	mBIC	Enet	mBIC	Enet	mBIC
Age (yr)		0.390 (0.136; 0.525)	0.429 (0.240; 0.578)	1.19 (1)	1.21 (1)	1	3	0.000	0.000
Lameness is considered a problem by the farmer	Lameness is not considered a problem by the farmer	0.154 (0.013; 0.689)	0.571 (0.361; 0.804)	1.17	1.77	7	1	0.000	0.000
Grazing platform size (ha)		−0.065 (−0.191; −0.016)	−0.205 (−0.297; −0.137)	0.74 (100)	0.36 (100)	2	8	0.000	0.000
Positive lameness PTA[2]	Negative lameness PTA	0.127 (0.012; 0.406)	0.474 (0.311; 0.638)	1.14	1.61	18	2	0.000	0.000
>5% herd had digital dermatitis[3]	>0% and ≤5% herd had digital dermatitis[3]	0.077 (0.009; 0.214)	0.418 (0.284; 0.624)	1.08	1.52	15	7	0.000	0.000
Proportion of slats in first 50 m of cow tracks		0.062 (0.014; 0.117)	0.132 (0.100; 0.202)	1.04 (0.1)	1.09 (0.1)	4	19	0.001	0.000
≥10% herd treated for lameness[4]	<10% herd treated for lameness[4]	0.079 (0.014; 0.440)	0.381 (0.260; 0.542)	1.08	1.46	12	12	0.001	0.000
Herd size		−0.045 (−0.128; −0.003)	−0.229 (−0.356; −0.143)	0.90 (100)	0.64 (100)	11	15	0.006	0.000
Distance to turn after milking (m)		−0.041 (−0.156; −0.003)	−0.227 (−0.343; −0.150)	0.97 (1)	0.86 (1)	10	17	0.001	0.000
No cases of digital dermatitis[3]	>0% and ≤5% herd had digital dermatitis[3]	−0.095 (−0.360; −0.007)	−0.381 (−0.583; −0.259)	0.91	0.68	14	22	0.000	0.000
Proportion of gateway surface stones		0.049 (0.005; 0.167)	0.163(0.104; 0.258)	1.03 (0.1)	1.11 (0.1)	24	18	0.001	0.000

[1]Odd ratios calculated from unstandardized means. For continuous predictors, a unit change of 0.1, 10, and 100, as well as the usual 1-unit change, was used to enable result interpretation.

[2]A positive lameness PTA indicates that the progeny are more likely to become lame than the base population (Berry et al., 2007).

[3]During the current lactation, according to the farmer.

[4]In the year before the study started (2018), according to the farmer.

stones in paddock gateway, dry cow cubicles cleaned once per day (compared with less than once per day), cows housed based on parity, cow tracks repaired less than once per 2 years (compared with once per year or more frequently), PTA of 0 for lameness (compared with negative PTA), mobility scoring visit carried out in May (compared with April), BCS <3 (compared with BCS 3), all cow track points measured as wide enough based on herd size (compared with farms with a combination of cow tracks measured that were wide and narrow), and herds that were routinely trimmed. Predictors that showed decreased risk for lameness included second-parity cows (compared with first-parity cows), third-parity cows (compared with first-parity cows), copper sulfate and formalin used in foot bathing routine (compared with copper sulfate only), and BCS >3.25 (compared with BCS 3).

DISCUSSION

From a cohort of approximately 200 potential cow-level and herd-level predictors in the final model, 11 risk factors were deemed highly likely to have important associations with lameness in partly housed pasture-based dairy cows. To the authors' knowledge, this is the first time important lameness predictors have been found based on the entire year, in this particular system, and the first time this novel statistical approach (mBIC and Enet triangulation with bootstrapping) has been used to identify risk factors in dairy cows.

Cow-Level Risk Factors

In agreement with previous studies, the risk of lameness increased with age (Rowlands et al., 1985; Haskell et al., 2006). This may be explained by changes in the functional anatomy of the hoof with age, such as the degeneration of the digital cushion (Räber et al., 2004). Irreversible bone development on the distal phalanx has also been reported to increase with age, history of lameness, and previous cases of sole ulcers, sole hemorrhages, and white line disease (Newsome et al., 2017). Additionally, older cows are more likely to have a history of lameness, and previous lameness has been shown to be a major predictor of future lameness (Randall et al., 2018). In contrast to the current study, the study by Randall et al. (2018) had a longitudinal study design and therefore provides much stronger evidence for causality. However, the study included only 2 UK dairy farms and may not be comparable to Irish dairy farms, where all cows have prolonged pasture access and cows are generally lower yielding. Aging is inevitable; however, the effect of aging on lameness can be minimized through prevention of first-time lameness events, early detection of lameness, and effective treatment of lesions (Randall et al., 2018).

Cows with a positive lameness PTA exhibited a higher risk for lameness than cows with a negative PTA. Lameness PTA is a specific genetic index, in which a higher lameness PTA indicates the progeny will have a higher susceptibility to lameness (Berry et al., 2007). O'Connor et al. (2020) reported similar findings: a positive lameness PTA compared with a negative PTA increased the odds of lameness by 41%. Similarly, the current study showed an increased odds ratio of 44%. These results add support for the lameness PTA and emphasize that genetic selection is influential for reducing lameness at cow level. The choice of bulls used for breeding may be more important as a long-term lameness reduction strategy than previously realized.

Herd-Level Risk Factors

The results of this study provide no evidence that farm expansion increases the risk of lameness in a part-grazed, part-housed system. As reported previously, a larger herd reduced lameness risk (Dippel et al., 2009; Chapinal et al., 2013). Solano et al. (2015) reported that a herd size of more than 100 cows reduced the odds of lameness by one-third, compared with a herd size of less than 100. Despite cows walking longer distances on larger pasture-based farms (Beggs et al., 2019), improved management and facilities could explain the reduced lameness prevalence. In contrast, Alban (1995) reported that lameness was positively correlated with herd size, which may be explained through more cows per staff member (Sundrum, 2015) and poorer recognition of individual cows (Dippel et al., 2009) in larger herds. Other studies have also reported that herd size was not significant in relation to lameness (Espejo and Endres, 2007; Barker et al., 2010; Beggs et al., 2019). The varied results highlight the lack of clarity regarding the association between herd size and lameness, and the interplay with other factors that influence this relationship.

Lameness risk was reduced when cows had a longer distance to turn at the parlor exit. All parlors in this study were herringbone or parallel, meaning that cows exited the parlor in single file, usually making a 90- or 180-degree turn onto a passageway to return to their pasture or pen. Similarly, Barker et al. (2010) reported that sharp turns at the parlor entrance or exit increased the risk of lameness. Similarly to the current study, the cross-sectional study design used by Barker et al. (2010) does not prove a causative relationship between sharp turns and lameness; however, it can be used to establish causal hypotheses. One commonly posited theory is that shearing forces on the hoof when cows turn sharply can lead to white line disease, potentially explaining the negative correlation between turning distance and lameness prevalence. Sharp turns may also reduce cow flow, instigating crowding and pushing of cows at the parlor exit. Rubber matting has been proven to increase friction and compressibility, in turn reducing slipping and improving mobility (Rushen and de Passillé, 2006). Therefore, introducing rubber matting where sharp turns are present at the parlor exit may be beneficial in improving cow flow and reducing claw trauma. Randomized clinical trials proving the effectiveness of this intervention are currently lacking; further research in this area is required.

Slats in the first 50 m of cow track following the collecting yard increased the risk of lameness in this study. Slatted flooring has previously been linked to increased lameness prevalence (Dippel et al., 2009) and claw health problems (Burgstaller et al., 2016) in housed cattle; however, limited information exists on the implications of slats on cow tracks. Concrete slats are more slippery compared with solid concrete flooring (Rouha-Mülleder et al., 2009), leading to a reduced pace and shortened strides (Telezhenko and Bergsten, 2005). Slatted flooring also creates uneven weight distributions across the claws, predisposing to white line disease (Hinterhofer et al., 2006). Installing rubber matting over the slats could reduce slipperiness, hoof lesions, and overall lameness prevalence (Hultgren and Bergsten, 2001; Telezhenko and Bergsten, 2005).

Stones in the gateways to pasture also presented a risk for lameness. It is hypothesized that stones penetrate the hoof horn, causing separation of the white line, and subsequently lead to an infection of the dermal tissue in more severe cases. An uneven stony surface may also result in shearing forces on the hooves. Although this study provides no evidence for causality, the association identified between stones in gateways and lameness supports these theories. Gudaj et al. (2012) reported that cows required more blocks during trimming when stones were present on cow tracks. However, in contrast to the current study, all cows in the study by Gudaj et al. (2012) were Holstein Friesian, and only cows on 14 farms, out of 25 farms visited, had access to pasture. Gateways may be more high-risk areas due to cows pushing through a narrow entrance and being unable to avoid stones. Where finances are limited, it may be beneficial to prioritize maintenance of commonly used gateways, to ensure minimal stones are present, before general cow track maintenance.

Three of the risk factors identified are subjective impressions of the farmer: the presence of digital dermatitis in the herd, the percentage of the herd treated for lameness, and farmers who consider their herd to have a lameness problem. Although these results are not entirely unexpected, they indicate that farmers in this study acknowledge lameness as an issue and can therefore work toward eliminating the disease. This is in contrast to previous studies, which have generally shown that a low proportion of farmers perceive lameness to be a problem in their herd (Leach et al., 2010; Sadiq et al., 2019).

Based on predictors identified by both the final mBIC and the Enet model, no characteristics specifically linked to housing infrastructure and management were found to be important risk factors for lameness in a typical Irish dairy system. This emphasizes that the housing period did not seem to have a large influence on lameness, in contrast to the grazing period. Cows are only housed for approximately one-third of the year in Ireland; therefore, cows are exposed to the effects of grazing for a more prolonged period of time, and thus the grazing period appears to have the greatest influence on lameness development. However, although the grazing period was shown to have the greatest influence on lameness development, some housing features and management were selected in one or another of the Enet and mBIC models (although excluded by triangulation as not selected in both), such as cubicle mat thickness and frequency of cubicle cleaning for dry cows. Due to these variables not being selected in both the Enet and mBIC models via triangulation, it is less likely that these are generalizable for the target population; these predictors may have smaller effect sizes and may be very important on some farms and not in others.

Modeling Methods

The multifactorial nature of lameness and the need to construct a statistical model based on a large number of predictor variables would likely lead to problems with overfitting in simple regression models (Vatcheva et al., 2016); this is increasingly recognized as a potential feature in a large proportion of previous work across a range of disciplines. This is especially problematic where the sample size is small relative to the number of potential predictors; in this case, the sample of lameness scores was relatively large, but the vast majority of predictors varied only at farm level. To overcome this issue, regularized regression (Zou and Hastie, 2005) and selection using mBIC (Bogdan et al., 2008) have both been proposed for variable selection. As the ability to capture large amounts of data on-farm improves and data sets become wider, these methods will become increasingly important in statistical analysis. Using conventional methods such as stepwise selection based on Akaike's information criterion, a larger set of risk factors would likely have been identified that were false positives and likely to have inflated coefficients (Hastie et al., 2015; Lima et al., 2021). In this study, a relatively conservative analytical approach was chosen, to minimize the chances of reporting false-positive risk factors. The additional predictors included in one or the other of the 2 models represent a set of factors that can more speculatively be associated with the outcome, and it is worth noting that these would have been reported as significant predictors had a single modeling approach been chosen. The aim of this study was to identify a set of risk factors that are the most important in a pasture-based system and are most likely to be generalizable across a high proportion of similar farms.

Between-model variation was also accounted for through triangulation (Lawlor et al., 2017) of the Enet and mBIC models. Triangulation combines results from multiple statistical methods to obtain reliable results, because the bias from each model type is discounted (Lawlor et al., 2017; Lima et al., 2021). Elastic net regression has a tendency toward a higher false-positive rate and deflated coefficient values, whereas mBIC has a higher false-negative rate and inflated coefficient values (Lima et al., 2021), displaying opposing biases. The difference in effect size between the Enet and mBIC models observed for some predictors is therefore not unexpected, and it is likely that the true effect size lies in between the 2 estimates. These methods have allowed identification of a robust list of risk factors and direction of effect, and have given an indication of likely effect size.

Within-model variation was also accounted for through bootstrapping, a resampling technique for statistical inference (Dixon, 2002). Bootstrapping is beneficial to assess variable stability and coefficient distribution (Sauerbrei and Schumacher, 1992; Meinshausen and Bühlmann, 2010). To the best of the authors' knowledge, regularized regression and model selection using mBIC, with the use of bootstrapped selection stability, have not previously been used in a cow-level or herd-level risk factor analysis among dairy cows.

Study Limitations

This study may be susceptible to some bias due to farmers having the opportunity to choose whether to participate in the study. However, a selection criterion was established before recruiting participants, to ensure farms were representative of a typical Irish dairy farm. Additionally, several of the observations and measurements were slightly subjective, therefore leading to potential bias. This study has a cross-sectional design, and, as such, the associations found do not imply causation. This study design is valuable for assessing a large number of potential risk factors at once, without the logistical challenges of running multiple expensive randomized clinical trials. Lameness typically occurs after exposure to a risk factor; therefore, exposure to a risk factor during the end of the grazing period may result in lameness during the subsequent housing period, and, similarly, exposure to housing risk factors may result in lameness during the subsequent grazing period. This issue was acknowledged by including lameness scores and potential predictors from both the housing and grazing periods in the same model. This also allowed the most important risk factors, based on the entire year, to be identified. Findings from this study provide a base of knowledge and deliver a focus for future lameness intervention studies in Irish pasture-based systems.

CONCLUSIONS

Both cow-level and herd-level risk factors were associated with lameness in a part-grazed, part-housed system. Triangulation of bootstrapped regularized regression and logistic regression model selection based on modified Bayesian information criterion proved a robust way to identify a subset of important risk factors from a very large number of potential predictors. Cow-level risk factors included increased age and a positive PTA for lameness. Herd-level risk factors included smaller herd size and grazing platform, increased presence of digital dermatitis, presence of stones in gateways and slats on cow tracks, a tighter turn following milking, farmers who treated a higher proportion of their herd for lameness, and farmers who considered lameness to be a problem in their herd. Based on this study, farmers may benefit from a breeding program that places greater emphasis on lameness traits, taking measures to mitigate the effect of tight turns at the parlor exit and slats on the cow tracks, and removing stones from paddock gateways. Applying a package of measures across multiple herds in a randomized clinical-type trial, such as putting matting at the milking parlor exit and replacing slats on the cow tracks, might be useful for determining effective methods for decreasing lameness in Irish dairy cows.

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Paper 2: Lameness prevalence and management practices on Irish pasture-based dairy farms

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CH, MC and EK supervised this study. All authors contributed to study design. NB, RC and KS were major contributors to data collection, including cow scoring, farmer questionnaires and on-farm measurements. NB analysed the data and drafted the manuscript, with the assistance of CH and MC. All authors read and approved the final manuscript.

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Lameness prevalence and management practices on Irish pasture-based dairy farms

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Abstract

Background: Lameness is a painful disease, which negatively impacts dairy cow production and welfare. The aim of this observational study was to determine herd lameness prevalence, describe current lameness management practices and identify the presence of established risk factors for lameness on Irish pasture-based dairy farms. Farms were visited once during grazing (99 farms) and again during housing (85 farms). Lameness scoring was carried out at each visit (AHDB 0–3 scale); cows were classified as lame if they scored two or three. Farm management practices and infrastructure characteristics were evaluated via farmer questionnaires and direct measurements of farm infrastructure.

Results: Median herd-level lameness prevalence was 7.9% (interquartile range = 5.6 – 13.0) during grazing and 9.1% (interquartile range = 4.9 – 12.0) during housing; 10.9% of cows were lame at a single visit and 3.5% were lame at both visits (chronically lame or had a repeat episode of lameness). Fifty-seven percent of farmers were not familiar with lameness scoring and only one farm carried out lameness scoring. Only 22% of farmers kept records of lame cows detected, and 15% had a lameness herd health plan. Twenty-eight percent of farmers waited more than 48 h to treat a lame cow, and 21% waited for more than one cow to be identified as lame before treating. Six percent of farmers carried out routine trimming and 31% regularly footbathed (> 12 times per year). Twelve percent put severely lame cows in a closer paddock and 8% stated that they used pain relief to treat severely lame cows. Over 50% of farms had at least one cow track measurement that was classified as rough or very rough, and cow tracks were commonly narrow for the herd size. On 6% of farms, all cubicle beds were bare concrete (no matting or bedding) and on a further 6% of farms, there was a combination of cubicles with and without matting or bedding. On 56% of farms, all pens contained less than 1.1 cubicles per cow and on 28% of farms, a proportion of pens contained less than 1.1 cubicles per cow.

Conclusions: Overall, this study identified infrastructure and management practices which could be improved upon. The comparatively low lameness prevalence demonstrated, compared to fully housed systems, also highlights the benefits of a pasture-based system for animal welfare; however, there remains scope for improvement.

Keywords: Lameness, Dairy cow, Infrastructure, Management, Welfare

Background

Lameness is a result of pain [1, 2] and is, therefore, a major animal welfare issue and an on-going concern within the dairy industry. Lameness has a negative economic impact due to reduced milk yields [3, 4] and reproductive ability [5–7], increased culling rates and replacement costs [8–10], and increased treatment [11] and labour costs [12]. Economic costs also result from discarding milk due to antibiotic use [9, 10], reocurring lameness cases [9] and implementing lameness prevention methods [13]. Lameness also has a negative environmental impact due to increased greenhouse gas emissions [14, 15].

Reported lameness prevalence has generally been higher in housed systems and lower in pasture-based

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systems [16]. Average herd-level prevalence in pasture-based systems has been reported between 3.7% in Swedish dairy farms [17] and 35% in small-scale Brazilian dairy farms [18]. Whereas in housed systems, average herd-level prevalence has been reported between 9.6% and 55% [19, 20]. Access to pasture is thought to be beneficial to animal health and wellbeing, allowing cows more opportunity to exhibit normal behaviours [21]. Depending on conditions, pasture provides an optimal walking surface for improved mobility [22] and a soft surface and space for cows to transition between bouts of standing and lying [23].

In Irish pasture-based herds, where cows are generally out to pasture for the majority of the year and housed for approximately 4.5 months during the winter period [24], average herd-level lameness prevalence has ranged from 5.9% towards the end of the grazing period [25] to 14.6% during the breeding season [26]. Although lameness prevalence during the grazing period has previously been reported on Irish dairy farms, limited studies have examined the prevalence of lameness during both the grazing and housing periods, and the transition between the two. Lameness prevalence in Ireland has also only been reported prior to quota removal; therefore, prevalence may have altered since farmers have had the opportunity for farm expansion. Furthermore, no studies to date have reported how lameness status at cow-level changes between the housing and grazing periods in Irish systems. Determining if the same cows remain lame or are recurrently lame during both periods will help with understanding the dynamics of lameness in part-housed, part-grazed dairy cows.

Lameness prevention methods, as well as early detection and treatment, are fundamental to effective lameness control programs [27–30]. However, very limited information currently exists on current lameness control strategies in Ireland. O'Connor et al. [25] revealed that approximately half of farmers in Ireland footbathed at least once per year; however, no details were provided on the footbathing protocols used. Additionally, limited data exists regarding the use of routine hoof trimming to prevent lameness and the use of lameness scoring to detect lame cows. Identifying the strategies Irish dairy farmers use to control lameness will help pinpoint areas for improvement, and deliver a focus to farmers, advisors and veterinarians regarding the best strategies to reduce lameness prevalence in Ireland.

It is also essential to determine the current general management practices and infrastructure characteristics on Irish dairy farms. This information will provide details on where improvements are needed, and help to identify which areas may pose a risk of lameness. As part of a survey-based study, Boyle et al. [31] reported that there was a lack of investment in cow tracks, handling facilities and housing in Irish pasture-based dairy herds as farms expanded, with more investment directed towards milking facilities. Although a small amount of information is available on current farm infrastructure in Ireland [31], this information was based on farmer surveys, as opposed to direct measurements on farm by external observers.

The aims of this study were to determine the herd-level lameness prevalence during both grazing and housing periods on Irish pasture-based dairy farms, and evaluate cow-level changes in lameness status and lameness scores across visits. A further aim was to identify current management practices and infrastructure in place on Irish dairy farms. This study ultimately aims to deliver useful knowledge to the dairy industry regarding aspects of lameness management where improvement is needed, and to provide direction for future research.

Methods

This study was part of a larger project investigating welfare in pasture-based dairy herds [32, 33]. For full details of the methods used in this study, see Browne et al. [33].

In brief, herds were randomly selected from a list of dairy farms provided by the Irish Cattle Breeding Federation (ICBF; Bandon, Co. Cork, Ireland), who allowed Teagasc access to their data. Selection criteria included: herd size between 30 and 250 cows, located in the seven counties with the highest number of dairy cows, no further than two hours from Teagasc Moorepark and willingness to participate in the study. Based on a simulation-based power calculation, 100 farms was the target sample size.

One hundred and two (99 included in the analyses) Irish spring-calving, pasture-based dairy farms were visited between April and September 2019 during the grazing period, and 87 (85 included in the analyses) of these farms were revisited between October 2019 and February 2020 during the housing period. The main reason for the withdrawals at the housing visit was cows being close to calving. At each visit the entire milking herd was lameness scored using a four-point scale ranging from zero to three [34] and a proportion of each herd was body condition scored [35]. All scorers undertook training in lameness scoring and body condition scoring. Interobserver reliability, using weighted kappa coefficients, was carried out for lameness scoring and body condition scoring at the beginning of both the grazing visits and housing visits; all interobserver agreement were greater than 0.7. Hoof lesions were recorded for up to 20 cows identified as lame (lameness score [LS] 2 and LS3). This data is the subject of a separate publication (Browne et al., unpublished). Additional cow-level information (production data, calving data, breed and genetic profile) was also provided by the Irish Cattle Breeding Federation for each herd enrolled in the study.

A structured questionnaire was undertaken with the farmer at both the grazing visit and housing visit to identify farm characteristics and management practices, including methods for controlling lameness. Direct infrastructure measurements were also recorded on each farm in the milking parlour and collecting yard, in all pens used by dairy cows and on cow tracks. Cow track measurements were taken on the track in use on the day of the grazing visit; at the estimated half-way point between the collecting yard and paddock, the end-point of this track and the paddock gateway. Cow track measurements were also taken in the segment between the collecting yard entrance and fifty-metres along all tracks used by cows. The questionnaires, categorical scales used as part of the infrastructure measurements and further details on measurements taken are available to view as supplementary material [36].

Statistical analysis

All data were analysed using R software version 3.3.1 (R Core Team, Vienna, Austria). Three farms from the grazing period and two farms from the housing period were not included in the analyses due to operating an automatic milking system or milking once per day. These farms were excluded as they were not considered to be representative of typical Irish dairy farms. These farms were also managed differently, so some measurements would not have been possible (e.g. parlour and collecting yard measurements). The final dataset consisted of 11,213 lameness scores (LS) from 99 farms (grazing period) and 8,995 LS from 85 farms (housing period).

Cows were categorised into lame (LS2 and LS3) and non-lame (LS0 and LS1) at each visit. Herd-level lameness prevalence was calculated for both the grazing and housing periods, defined as the number of lame cows divided by the total number of cows scored in the herd. Similarly, herd-level prevalence of severely lame cows (LS3 only) was calculated. For farms visited during both periods, lameness prevalence between the grazing and housing periods was compared using a t-test (normally distributed data) or the Wilcoxon test (non-normally distributed data). The difference in the proportion of each LS between periods was also compared using this method.

Cows that were lameness scored during both the grazing and housing periods were classified into four categories; no lameness (not lame at grazing or housing), became lame (not lame at grazing but lame at housing), recovered (lame at grazing but not housing) and remained lame (lame at both grazing and housing). The unit change in LS between the grazing and housing periods was also calculated. Descriptive statistics were calculated to summarize herd-level data gathered from the farmer questionnaires (milking practices and lameness detection, prevention and treatment methods) and infrastructure measurements (winter housing, cow tracks and milking facilities).

Results

Farm and cow characteristics

The median farmer-reported herd size across the 99 farms was 116 cows (interquartile range [IQR] = 81 – 156), with a median increase in herd size of 21% (IQR = 0 – 35) in the last five years. The median grazing platform size was 40 hectares (IQR = 29 – 52), with a median stocking rate of 2.9 cows per hectare (IQR = 2.3 – 3.5) and a median grazing season length of 252 days (IQR = 238 – 274). The median parity of cows was 3 (IQR = 2 – 5), calving interval was 369 days (IQR = 354 – 388) and 305-day yield was 6638 kg per cow (IQR 5750 – 7597). Seventy-two percent of cows were purebreds (51% Holstein–Friesian) and 28% were crossbreeds. The median body condition score during the grazing and housing period was 3 (IQR 3 – 3.25) and 3.25 (IQR = 3 – 3.5), respectively.

Herd-level lameness prevalence

The distribution of LS across each farm is shown in Fig. 1. The median herd-level lameness prevalence (LS2 and LS3) was 7.9% (IQR = 5.6—13.0) during the grazing period and 9.1% (IQR = 4.9 – 12.0) during the housing period. The median herd-level prevalence of severely lame cows (LS3) was 0.7% (IQR = 0.0—1.9) during the grazing period and 0.8% (IQR = 0.0—2.0) during the housing period.

There was no significant difference ($P = 0.497$) in lameness prevalence between visits for farms that were visited during both the housing and grazing periods ($n = 85$). There was, however, a small but statistically significant difference ($P = 0.047$) between the proportion of cows scored LS0 during grazing (35.5%) and housing (38.8%). There was no significant difference in proportions of cows scored LS1 ($P = 0.085$), LS2 ($P = 0.179$) or LS3 ($P = 0.430$) between the grazing and housing periods.

Change in lameness status and lameness score

A total of 8,676 cows were scored at both the grazing and housing visits; of these, 1,243 cows (14.4%) were lame at a minimum of one visit (Table 1). Of those cows that were lame during the grazing visit (778 cows), 305 (38.9%) remained lame at the housing visit and 473 (61.1%) recovered from lameness. Of those cows that were LS3 at grazing (81 cows), 50 (62.7%) remained lame at housing, whereas for cows that were LS2 at grazing (697 cows), 255 (36.6%) remained lame at housing. Of all cows scored

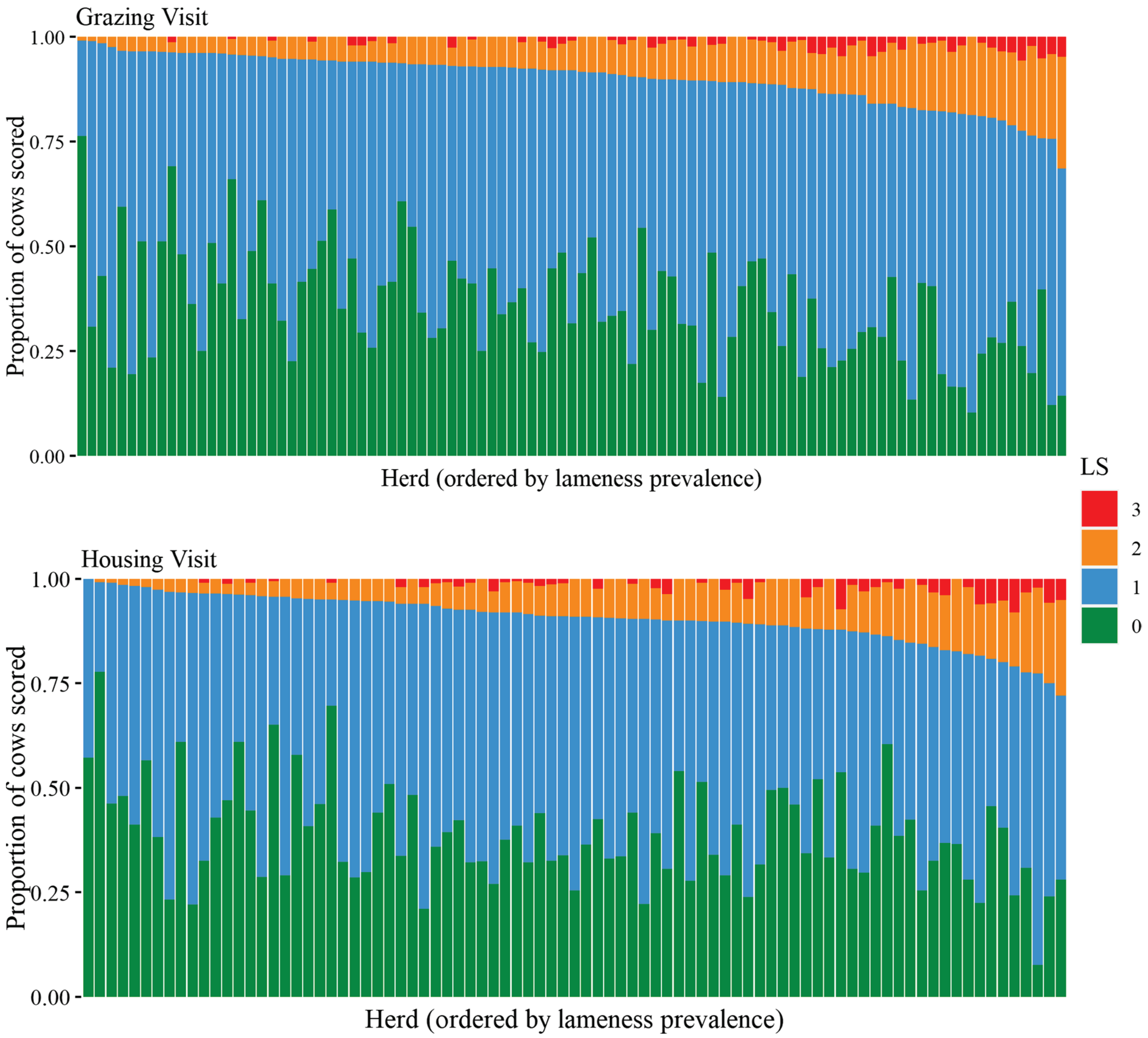

Fig. 1 Proportion of each lameness score, ordered by lameness prevalence (LS2 and LS3), across 99 spring-calving, pasture-based herds during the grazing period (April 2019 – September 2019) and in 85 of these herds during the housing period (October 2019 – February 2020). Each bar represents one farm

(8676 cows), 1651 (19%) had an increase in LS, 1799 (21.7%) had a reduction and 5226 (60.2%) had the same LS during both the grazing and housing period (Fig. 2).

Lameness detection methods

Forty-three percent of farmers said they were familiar with lameness scoring; however, only one farm carried out lameness scoring. That farm lameness scored three times per year using a 0–3 scoring system. Only one farm used technology to detect lameness, using a neck-based accelerometer. Ninety-nine percent of farmers said they detected lameness through visual inspection (i.e. watching cows as they walk, not through formal lameness scoring), with one farmer saying they used no methods to detect lameness in their herd. Twenty-two percent of farmers kept records of lame cows they detected.

Lameness prevention methods

Fifteen percent of farmers had a herd health plan that included lameness management protocols. Of these, 12% were created in conjunction with the farmer's veterinarian and 3% were created by only the farmer. Six percent of farmers routinely trimmed the whole herd; of these, one farm routinely trimmed twice per year and

Table 1 Change in lameness status for 8,676 cows from 85 spring-calving, pasture-based herds that were lameness scored during both the grazing (April 2019 – September 2019) and housing (October 2019 – February 2020) periods. Lameness was defined as LS2 and LS3 on the Agricultural and Horticultural Development Board four-point scale

Description[a]	Lame at grazing	Lame at housing	Frequency	%
No lameness	No	No	7433	85.7
Became lame	No	Yes	465	5.4
Recovered	Yes	No	473	5.5
Remained lame	Yes	Yes	305	3.5

[a] No lameness = not lame at grazing or housing; Became lame = not lame at grazing but lame at housing; Recovered = lame at grazing but not housing; Remained lame = lame at both grazing and housing

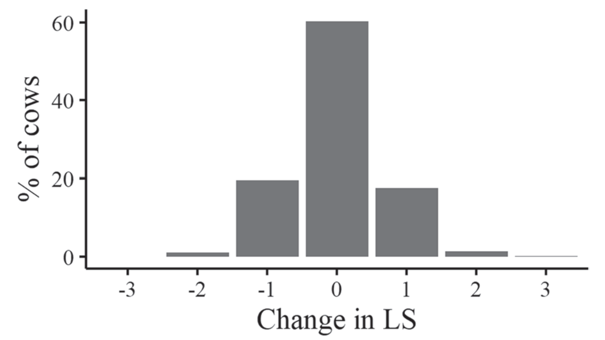

Fig. 2 Percentage of cows for each unit change in lameness score between the grazing and housing periods for 8,676 cows from 85 spring-calving, pasture-based herds that were lameness scored during both the grazing (April 2019 – September 2019) and housing (October 2019 – February 2020) periods. Zero represents cows that had the same lameness score during both the grazing and housing periods, a negative value represents a decrease in lameness score and a positive value represents an increase in lameness score

five farms trimmed once per year. Of those that routinely trimmed, half trimmed both the front and back hooves and half trimmed the back hooves only. Eighty-three percent of routine trimming was carried out by a professional hoof trimmer and 17% by the farmer.

Thirty-one percent of farmers used preventative footbathing regularly (> 12 times per year), 20% irregularly (≤ 12 times per year), 5% used footbathing only if required and 43% never used preventative footbathing (percentages may not total 100% due to rounding). Of farms that carried out footbathing, 67% used a single product in their footbath and 33% used a combination of different products in their footbathing routine. The most common product used was copper sulphate (54% of farms that footbathed), followed by formalin (35%) and an organic acid and tea-tree solution (33%). The footbath product was changed after a median of 228 cows (IQR = 168—325) across farms. Of farms that carried out footbathing, 6% cleaned the cows' hooves using a pre-wash footbath and 39% cleaned the cows' hooves with a hose prior to footbathing. Eighty percent of footbaths used were less than three metres in length.

Lameness treatment methods

According to the farmers, a median of 10% (IQR = 6—20) of each herd was treated for lameness in the last year. On 38% of farms, lameness treatment was completed by the farmer, 32% by a professional trimmer and 26% by a combination. Farmers would call a veterinary practitioner to treat a lame cow on 61% of farms; of these, 5% would request examination by a veterinary practitioner for all lame cows and 95% for severely lame cows, cows that do not recover or cows that could not be effectively treated by themselves or a trimmer.

Forty-nine percent of farmers aimed to treat cows within 24 h of detecting they were lame, 24% within 48 h, and 28% waited more than 48 h. Twenty-one percent of farmers waited for a number of cows to be lame before treating. On these farms, the median number of cows that needed to be lame before any were treated was 2.5 cows (IQR = 2.0 – 3.4). For a mildly lame cow, 4% of farmers said they would put the cow in a closer paddock and 1% would put the cow on once-a-day milking, whereas, for a severely lame cow, 12% of farmers would put the cow in a closer paddock and 4% would put the cow on once-a-day milking. Eleven percent provided antibiotics, 3% pain relief and 4% a form of unspecified medication to a mildly lame cow, whereas, for a severely lame cow, 23% provided antibiotics, 8% pain relief, and 8% a form of unspecified medication.

Nine percent of farmers used an antibiotic footbath as a treatment for digital dermatitis. One farmer who used erythromycin in the footbath was unaware it was an antibiotic. Of farms that used bandages as part of lameness treatment (91% of farms), only 21% removed the bandage within three days. Cows were always re-examined after treatment on 11% of farms, were re-examined only if still lame on 71% of farms, and never re-examined on 18% of farms.

Milking practices

The median distance cows walked on average from the paddocks to the collecting yard across all farms was 483 m (IQR = 300—600). The median distance to the furthest paddock from the collecting yard was 1000 m (IQR = 713—1200). Forty-four percent of farmers used a vehicle and 35% had a dog present when bringing cows in from the paddocks. Five percent used a backing gate to encourage cows into the parlour. The median holding time in the collecting yard for the last cow into milking was 80 min (IQR = 60—90). A quarter of farmers always held their cows after milking prior to returning to the paddock, 29% sometimes held their cows back, and on 46% of farms the cows always returned straight to their paddock.

The median space per cow in the collecting yard was 1.44 m^2 (IQR = 1.14 – 1.88). Twenty-nine percent of farms had less than 1.20 m^2 per cow (minimum recommended space per small cow; [37]) and 53% of farms had less than 1.5 m^2 per cow (minimum recommended space per large cow; [37]). Twenty-four percent of collecting yards were predominantly smooth concrete, 30% predominantly grooved concrete and 30% predominantly slats. At the parlour entrance, 36% of farms had a step, 30% a slope, 31% a 90-degree turn and 8% a 180-degree turn. At the parlour exit, 26% of farms had a step, 23% a slope, 89% a 90-degree turn and 30% a 180-degree turn. The median distance cows had to turn after milking (first milking unit to the back wall) was 2.49 m (IQR = 1.89 – 3.16). No farms used rubber matting at the milking parlour exit.

Cow tracks

Thirty-eight percent of farmers had added new cow tracks and 34% had renovated parts of their cow tracks in the last five years. Twenty-one percent of farmers aimed to repair their cow tracks at least once per year. Cow track widths and gradients are shown in Table 2 and track surface types in Table 3. Fifty-two percent of farms had at least one rough cow track and 9% had at least one very rough cow track in the first fifty metres following the collecting yard. Seventy-nine percent of farms had at least one cow track with a sharp turn, and 79% with an inconsistent width in the first fifty metres. Fifty-four percent of farms also had at least one cow track measurement recorded as rough and 5% very rough on the track in use on the day of the grazing visit.

Table 2 The median cow track and verge widths across 99 spring-calving, pasture-based farms. Measurements were taken fifty metres from the collecting yard on all cow tracks, and at the estimated half-way point between the collecting yard and pasture and the end-point of the cow track that was in use on the day of the grazing visit. The average gradient for the cow track in use and the gradient of the steepest slope within the first fifty metres are also reported

Cow track characteristic	Median (IQR)	
	First 50 m	Cow track in use
Average width (m)	4.31 (3.67 – 4.98)	3.68 (3.05 – 4.42)
Average verge width (m)	0.45 (0.26 – 0.61)	0.53 (0.40 – 0.67)
Average gradient (%)	n/a	4 (2 – 6)
Steepest gradient (%)	12 (7 – 17)	n/a

n/a not measured on-farm

Table 3 Percentage of farms with each surface material present within the first fifty metres of cow track following the collecting yard and on the cow track in use on the day of the grazing visit, from 99 spring-calving, pasture-based farms. For the cow track in use, surface material was recorded at the estimated half-way point between the collecting yard and the paddock and the end-point of this cow track

Cow track surface material	Farms (%)	
	First 50 m	Cow track in use
Subsoil	83	91
Concrete (smooth, grooved)	70	38
Concrete slats	26	1
Stones/gravel	19	18
Earthen (grass/soil)	7	42
Tarmac	5	1
Astro-turf	1	0

Paddock gateways

The median gateway width across farms, for the gateway in use on the day of the grazing visit, was 6.27 m (IQR = 5.06 – 7.96). Only nine percent of gateways were narrower than the cow track. Seventy-six percent of gateways had earth (grass/soil) as part of the gateway surface, 38% subsoil and 19% stones. Across farms, 46% of gateways measured were rough, and 8% very rough.

Winter housing

All farms used cubicle housing and 10% had additional loose housing (straw yards and slatted pens). Considering all housing types, 6% of farms had at least 0.6 m (recommended feeding space; [38]) available per cow at the feed barrier in all pens; in contrast, 58% of farms had less than 0.6 m available in all pens. Thirty-six percent had a combination of pens with and without 0.6 m per cow available at the feed barrier. Across farms, the median of the average feed space per cow across pens was 0.49 m (IQR = 0.40 – 0.60). Fifty-six percent of farms had dead-ends present in all pens, 5% had no dead-ends present in all pens and 39% had a combination of pens with and without dead-ends. Seventy-one percent of farms had grooved concrete present within the housing environment, 65% smooth concrete and 1% concrete flooring with rubber mats. In addition, 86% of farms had smooth concrete slats within the housing environment, 14% grooved concrete slats, and 5% slats with rubber matting.

For cubicle housing, 15% of farms had at least 1.1 cubicles per cow (recommended best practice; [39, 40]) in all pens, 56% of farms had less than 1.1 cubicles per cow in all pens and 28% had a combination of pens with and without 1.1 cubicles per cow. Across farms, the median of the average number of cubicles per cow across pens was one (IQR = 0.92 – 1.07). On 6% of farms cubicles had no mats or bedding present and cows were lying on concrete bases only; a further 6% of farms had a combination of cubicles with and without mats or bedding. The remaining 88% of farms had mats or bedding present on all cubicles. On 69% of farms, cubicles were in very good (< 5% in disrepair) or good (5–24% in disrepair) condition in all pens. On 5% of farms, cubicles were in poor (25–50% in disrepair) or bad (> 50% in disrepair) condition in all pens. On 14% of farms, there were a combination of pens with very good/good cubicle condition and poor/bad cubicle condition. Eight percent of farms had a brisket board present on all cubicles measured, 64% had no brisket board present on all cubicles measured, and 15% had a combination of cubicles with and without a brisket board. Fifty-nine percent of farms had a neckrail present on all cubicles measured, 3% had no neckrail present on all cubicles measured, and 23% had a combination of cubicles with and without a neckrail. Details on cubicle dimensions can be viewed in Table 4.

Table 4 Median cubicle dimensions across 85 spring-calving, pasture-based farms

Average cubicle dimensions (m)[a]	Median (IQR)
Curb height[b]	0.24 (0.22 – 0.25)
Width[c]	1.10 (1.07 – 1.12)
Neckrail height[d]	1.10 (1.06 – 1.12)
Diagonal length[e]	2.00 (1.96 – 2.05)
Bed length[f]	1.72 (1.68 – 1.87)
Lunge space[g] (wall facing cubicles)	0.59 (0.51 – 0.67)
Lunge space[g] (head to head cubicles)	0.54 (0.47 – 0.62)
Total length[h] (wall facing cubicles)	2.18 (2.12 – 2.26)
Total length[h] (head to head cubicles)	2.14 (2.09 – 2.25)

[a] A proportion of cubicles in each pen were measured (5% of the two most common cubicle types, with a minimum of two cubicles per type)

[b] From pen floor to upper surface of cubicle

[c] Between inner edges of cubicle partition at cubicle entrance

[d] Bottom of neckrail to surface of cubicle (only recorded if neckrail present)

[e] Back edge of cubicle to near-side of neckrail (only recorded if neckrail present)

[f] Back edge of cubicle to base of brisket board (only recorded if brisket board present)

[g] Front of neckrail to wall or mid-way between cubicles (only recorded if neckrail present)

[h] Back edge of cubicle to wall, or to midpoint between head-head cubicles

Discussion

The median herd-level lameness prevalence was 7.9% during the grazing period and 9.1% during the housing period; which was comparatively lower than that commonly reported in cattle in fully housed systems [19, 41, 42]. Average herd-level lameness prevalence in fully housed systems has previously been reported at 55% in the North-Eastern U.S. [19], 39% in the UK [41], 36% in Austria [42], 31% in California [19], 28% in British Columbia [19], 25% in Minnesota [43] and 21% in Québec, Ontario, and Alberta [44]. It is possible that the long grazing periods contributed to reduced lameness during the housed period. Access to pasture has been shown to reduce lameness prevalence [41] and risk of hoof disorders [45]. Lameness prevalence in the current study was lower than Somers et al. [26] who reported prevalence in Irish pasture-based systems to be 11.6% before and after breeding, with an escalation to 14.6% during breeding. The higher prevalence reported by Somers et al. [26] may be due to differences in farm location, management practices and lameness scoring time frame (February to August only). Lameness data was also only recorded on ten farms. O'Connor et al. [25] reported herd-level lameness prevalence in Ireland to be 11% early in the grazing season and 5.9% later in the grazing season. Ireland's pasture-based dairy system is considered to be beneficial for dairy cow welfare; maintaining this positive reputation provides a marketing advantage for Irish dairy produce. The lameness prevalence reported in this study compares well with other nations and could, therefore, strengthen the competitive and sustainable nature of Irish agriculture.

Although lameness prevalence in Irish pasture-based systems was shown to be comparatively low compared to fully housed systems, approximately forty percent of cows that were lame at grazing were also lame when scored at housing, which is clearly a welfare concern. However, as lameness scoring in this study occurred at two time points only, this may be due to reoccurring lameness as opposed to a single continuous lameness event. Scoring twice per year only may also miss the impact of seasonality on lameness. For example, it may be expected that lameness could peak towards the end of the housing period and into the start of the grazing period. A follow-up study monitoring the changes in lameness over a full lactation, through regular and frequent lameness scoring, would further help with understanding the dynamics of lameness in a pasture-based system.

It has been previously demonstrated in a longitudinal study that a history of lameness is a risk factor for a future case of lameness [46]. To prevent cows becoming chronically lame, early detection and treatment is vital [29, 30]. Only a single farm in this study performed lameness scoring to detect lame cows, and even more surprisingly, over half of farmers were not familiar with the concept of lameness scoring. In the UK, it is recommended that lameness scoring is carried out at least once per month, to enable early detection and allow producers to benchmark against other herds and within their own herd [34]. Good lameness detection on a daily basis by trained staff is also critical for detecting and treating lame cows promptly. Approximately a quarter of Irish dairy farmers waited over two days before treating a cow that was identified as lame. Twenty-one percent of farmers also waited for more than one cow to be identified as lame before treating. Given the relatively low lameness prevalence, this could lead to a very long period of time between detection and treatment, which could possibly explain the high number of reoccurring cases found in this study. These results suggest there is huge scope for improving lameness management on Irish dairy farms, through providing information and guidance on detection and early treatment of lameness.

Although early detection and treatment is vital for ensuring recovery of lame cows, lameness prevention strategies are critical to reduce lameness in the first instance. Routine trimming of the entire herd, as a method to prevent lameness, was uncommon on Irish pasture-based herds; six percent of farmers carried out this practice, which was lower than the fourteen percent of farmers that reported routine trimming in 2015 [47]. However, routine trimming may not be as important for cows in grazing herds due to wear on the hoof from walking long distances between the milking parlour and the paddocks; cows in this study were on average walking between 1200 and 2400 m per day. Routine trimming can also be a useful method for early detection of mild lesions and correcting overgrown claws, thereby preventing future lameness cases [48, 49]. Further research is required to determine if routine trimming in a pasture-based system is beneficial and economically viable.

Footbathing is another approach to help reduce lameness at herd-level, by treating and preventing the infectious disease digital dermatitis [50]. The presence of digital dermatitis in a herd (according to the farmer), has been found to be predictive of lameness [33]. Forty-four percent of farmers reported having digital dermatitis in their herd; however, only 31% of farmers footbath more than twelve times per year. Based on a meta-analysis, Jacobs et al. [51] reported that footbathing at least four times a week with 5% copper sulphate was the only protocol that showed a reduction in digital dermatitis compared to control groups (no footbath or water footbath). There are, however, limited guidelines on the optimum footbathing frequency and product for pasture-based herds; further research is required in this area. It must also be noted that the use of copper sulphate for footbathing is currently illegal under the EU biocide regulations [52]. O'Connor et al. [25] reported an association between footbathing and lameness in Irish pasture-based dairy herds; however, this is likely due to farmers deciding to footbath if they have a lameness problem in their herd. It is also recommended that the footbathing solution is changed after 100 to 300 cows [53]. This protocol was followed by the majority of farmers in this study; however, only twenty percent of footbaths were at least three metres long, which is the recommended length to allow for two immersions of each hind hoof [53].

A herd health plan should outline farm-specific management practices to help improve dairy cow health, whilst maintaining a productive herd. A herd-health plan should be continuously updated as management practices are implemented and the health of the herd reviewed [54]. A herd heath plan requires a team approach with the farmer and the farm's veterinarian. Only fifteen percent of farmers in this study had a herd-health plan which incorporated lameness protocols. As part of the Sustainable Dairy Assurance Scheme [55] in Ireland, farmers are only required to report in brief the months of the year they plan to check and treat lameness. In contrast, UK dairy farmers are required to have a detailed lameness herd health plan, reviewed by a veterinary professional, as part of the Red Tractor farm assurance scheme [56]. Keeping accurate records of detected lame cows is also an essential tool for monitoring individual cows and providing herd-level information [57]. Keeping records will help establish if a cow has a recurring or first-time lameness case, enable farmers to monitor problem cows and establish the main causes of disease. In this study, only one-fifth of farmers kept records of lame cows detected in their herd, which demonstrates that there is an urgent need for improved communication to farmers regarding the benefits of record keeping.

The use of antibiotics as a footbathing solution is not currently licensed in Ireland [58]; however, nine percent of farmers still reported using antibiotic footbaths as a treatment for digital dermatitis. Even more worryingly, one producer did not know that the product they were using was an antibiotic. Continued use of antibiotic footbaths presents a global health risk due to antimicrobial resistance [59]. Bell et al. [60] also reported that antibiotic footbaths only relieved digital dermatitis symptoms for a short duration. In the current study, farmers favoured injectable antibiotics over pain-relief to treat lameness; a very low proportion of dairy farmers in Ireland provided pain relief to severely lame cows. Implementing pain management will dramatically improve cow welfare and improve recovery rates; Thomas et al. [29] reported that a therapeutic trim followed by a block placed on the sound claw, in conjunction with non-steroidal anti-inflammatory drugs (NSAIDs), improved the cure rate of lameness by 16% compared to cows that only received a therapeutic trim. Kasiora et al. [61] also showed that freshly calved lame cows that were given a singular dose of ketoprofen produced 10.49 kg more milk per day than the control group. Lame cows also benefit from being in close proximity to the milking parlour to reduce the distance they have to walk; Thomsen et al. [62] reported that housing lame cows in a hospital pen improved recovery compared to lame cows housed with the entire herd. However, only twelve percent of farmers in this study put severely lame cows in a closer paddock. There is an immediate need to provide information to farmers regarding the appropriate treatments for lame cows, and especially the importance of pain-relief.

There are various views on the use of bandages for the treatment of hoof lesions. Klawitter et al. [63] reported that the use of topical treatment and applying a bandage to M2 digital dermatitis lesions for four weeks, changing the bandage on a weekly basis, increased the cure rate compared to lesions that only received the topical treatment. In contrast, a recent study reported that sole ulcers were less likely to heal following treatment when a bandage was applied [64]. However, a bandage may be beneficial for severe cases when the corium is considerably exposed or when the lesion is excessively bleeding [65]. A bandage can improve cleanliness and prolong contact with the topical treatment; however, leaving a bandage on for a significant length of time can lead to contamination from manure [63], preventing lesions from healing. In the current study, only twenty-one percent of farmers who used bandages removed the bandage within three days following application. Farmers who do not actively take responsibility to ensure bandages are removed promptly, should avoid having bandages applied to lame cow by either themselves or the hoof trimmer [65].

The milking routine can impact the risk of lameness in dairy cows; prolonged standing at milking can compromise the time budget by reducing lying times and feeding times [66], increase the risk of lameness, and negatively impact animal welfare [67, 68]. In this study, the median holding time for the last cow into milking was 80 min, which is comparable to a milking time of 83 min in Australian pasture-based systems for herd sizes of less than 150 cows. However, Beggs et al. [69] also reported that milking time increased to over 2.5 h in larger herds. If herd expansion continues, farmers must improve milking efficiency or consider having separate milking groups to prevent an increase in standing time on concrete collecting yards, which increases the risk of lameness [68]. A quarter of farmers in this study also held back their cows following every milking without access to cubicles or a lying area, instead of allowing them to return straight back to the paddock. This results in cows spending more time away from the paddock and standing on hard concrete surfaces for longer. An increase in the time cows spent away from their pen due to milking was previously associated with increased lameness prevalence [67]. It was speculated that this was due to the negative influence on lying time.

On the majority of farms in this study, cows were required to make a sharp turn at the parlour exit. The median distance available for cows to make a turn (first milking unit to back wall) was 2.49 m; which is only the approximate body length of a dairy cow. Previous risk factor analysis (as part of this same project) found that a shorter distance to turn at the parlour exit imposed a risk of lameness [33]. Sharp turns may reduce cow-flow and increase shearing forces on the hooves [70]. No farms in this study used rubber matting at the parlour exit, despite the high number of parlours with sharp turns. Rubber matting has been shown to reduce slipperiness and improve mobility [71], and may therefore be beneficial at the parlour exit, particularly if the distance available for cows to make a turn is short.

Well-designed and maintained cow tracks can be very beneficial in reducing the risk of lameness for dairy cows in a pasture-based system [72]. According to Irish government guidelines [73], the median cow track width recorded in this study (3.68 m; cow track in use on the day of the grazing visit) is suitable for a maximum herd size of 68 cows. However, the median herd size in this study was 116 cows. This provides evidence that on a large number of farms, cow tracks were too narrow and would benefit from widening to prevent pushing and overcrowding of cows. It is theorised that this pushing results in shearing forces on the hooves and prevents cows choosing their preferred hoof placement to avoid stones. The majority of farms also had at least one cow track of inconsistent width in close proximity to the collecting yard; this may lead to a bottleneck, reducing cow flow and posing a risk of lameness [74]. In contrast, on most farms the paddock gateway measured was at least the width of the track, which enhances cow-flow as cows enter the paddock.

Rough cow tracks are a major contributing factor to lameness. It is speculated that rough surfaces can cause shearing forces on the hooves and may lead to separation of the white line due to loose stones penetrating the sole of the hoof. Over half of farms in this study had at least one cow track measurement that was classified as rough or very rough. Harris et al. [75] stated that a fine track surface material with no broken sections would help minimise lameness incidence. On over half of farms in this study, the gateway measured was also rough or very rough. Recent findings have shown that a ten percent increase in the proportion of stones as the gateway surface material, increased the risk of lameness by seven percent [33]. This study demonstrated that improving cow track conditions on farms is likely very important to reduce lameness prevalence.

In a part-housed, part-grazed system, farmers may not prioritise investment in housing facilities because cows are only housed for a short period of time compared to a fully housed system. It was previously reported that there was no difference in investment in housing infrastructure between Irish dairy farmers who expanded and those that did not. Investment was primarily focused on milking facilities in expanding herds [31]. Although the majority of farmers in this study used bedding or matting on all cubicles, on 12% of farms, all or a proportion of cubicle beds were bare concrete. Also, only 15% of farms had at least ten percent more cubicles than cows in all pens; which is the recommended best practice for dairy herds [39]. Poor cow comfort and overstocking of cubicles can discourage lying behaviour [76, 77], which is a predisposing risk for lameness [78]. Farmers must be cautious of expanding their herd without increasing the space available in the housing environment.

Conclusion

This study found that the majority of farmers were not familiar with lameness scoring and did not lameness score their herd. Routine trimming and footbathing was also not regularly undertaken and cows were not treated promptly enough. The use of NSAIDs to treat lame cows and putting lame cows in a paddock close to the parlour were not common. Most farmers did not keep records of lame cows or have a lameness herd health plan. The majority of farms had rough and narrow cow tracks, a proportion of farms had bare concrete cubicles (no matting or bedding) and the majority of famers had less than 1.1 cubicles per cow. Irish dairy farmers appear to lack knowledge of the key practices and environment necessary to ensure low levels of lameness. There is an urgent need to provide farmers with more information and guidance on how to improve management and infrastructure to reduce lameness risk and improve dairy cow welfare.

Abbreviations

IQR: Interquartile range; LS: Lameness score; NSAIDs: Non-steroidal anti-inflammatory drugs.

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Authors' contributions

CH, MC and EK supervised this study. All authors contributed to study design. NB, RC and KS were major contributors to data collection, including cow scoring, farmer questionnaires and on-farm measurements. NB analysed the data and drafted the manuscript, with the assistance of CH and MC. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was granted ethical approval by the Teagasc Animal Ethics Committee (review number: TAEC202-2018).

Consent for publication

Not applicable.

Competing interests

The authors of this study declare that they have no competing interests.

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Publisher's Note

Paper 3: Hoof lesions in partly-housed pasture-based dairy cows

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CH and MC supervised this study. All authors contributed to study design. NB, RC and KS were major contributors to data collection, including cow scoring, farmer questionnaires and on-farm measurements. NB analysed the data and drafted the manuscript, with the assistance of CH and MC. All authors read and approved the final manuscript.

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Hoof lesions in partly housed pasture-based dairy cows

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ABSTRACT

Lameness is a symptom of a painful disorder affecting the limbs, which impacts dairy cow welfare and productivity. Lameness is primarily caused by hoof lesions. The prevalence of different lesion types can differ depending on environmental conditions and farm management practices. The aims of this observational study were to establish the cow-level and herd-level lesion prevalence during both housing and grazing periods in a partly housed, pasture-based system, establish the prevalence of lesions always associated with pain ("alarm" lesion), identify the lesions associated with a higher lameness score, determine relationships between lesions, and identify risk factors for digital dermatitis. On 98 farms during the grazing period and on 74 of the same farms during the housing period, every cow was lameness scored (0–3 lameness scoring scale), and the hind hooves of lame cows (score 2 and 3) were examined (maximum 20 cows per visit) and the prevalence of each lesion type recorded. To gather data on potential predictors for the risk factor analysis, a questionnaire with the farmer was conducted on lameness management practices and infrastructure measurements were taken at each visit. Cow-level data were also collected (e.g., parity, breed, milk yield, and so on). Noninfectious lesions were found to be more prevalent than infectious lesions in this system type. The most prevalent lesion types during both grazing and housing periods were white line separation, sole hemorrhages and overgrown claws; all remaining lesions had a cow-level prevalence of less than 15%. The cow-level prevalence of alarm lesions was 19% during the grazing period and 25% during the housing period; the most prevalent alarm lesion was sole ulcers during both periods. We found significantly more foreign bodies within the hoof sole (grazing = 14%, housing = 7%) and overgrown claws (grazing = 71%, housing = 55%) during the grazing period compared with the housing period. Cows with foul of the foot, sole ulcer, white line abscess, toe necrosis or an amputated claw had higher odds of being more severely lame, compared with mildly lame. The strongest correlation between lesions were between toe necrosis and digital dermatitis ($r = 0.40$), overgrown claws and corkscrew claws ($r = 0.33$), and interdigital hyperplasia and digital dermatitis ($r = 0.31$) at herd level. At the cow level, the strongest correlation was between overgrown claws and corkscrew claws ($r = 0.27$), and digital dermatitis and heel erosion ($r = 0.22$). The farmers' perception of the presence of digital dermatitis (and lameness) was significantly correlated with the actual presence of digital dermatitis recorded. Additional risk factors for the presence of digital dermatitis were cow track and verge width near the collecting yard, and stone presence on the cow tracks. Results from this study help further our understanding of the causes of lameness in partly housed, pasture-based dairy cows, and can be used to guide prevention and treatment protocols.
Key words: dairy cow, lameness, hoof lesions, pasture-based

INTRODUCTION

Lameness in dairy cattle is a global problem within the dairy industry resulting in financial, environmental, and animal welfare issues. Lameness is the result of a painful disorder (Coetzee et al., 2017), leading to reduced productivity (Green et al., 2002; Alawneh et al., 2011), increased risk of culling (Booth et al., 2004), and increased greenhouse gas emissions (Chen et al., 2016; Mostert et al., 2018). Bovine lameness is most commonly caused by the presence of hoof lesions (Murray et al., 1996).

Due to environmental differences, the prevalence of different lesion types varies between housed and pasture-based systems (Navarro et al., 2013; Somers and O'Grady, 2015; Solano et al., 2016). The majority of studies report that infectious lesions are the most common lesion type in fully housed dairy cows (Cramer

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et al., 2008; Solano et al., 2016). Digital dermatitis is thought to be spread mostly via slurry (Palmer and O'Connell, 2015), and housed systems tend to expose cows to this more compared with pasture-based systems (Somers and O'Grady, 2015).

There are only a limited number of publications on hoof lesion prevalence in partly housed, pasture-based dairy systems, such as those in Ireland, some in the United Kingdom, and some other regions of Europe, where cows are grazed for the majority of the year and housed for a few months over the winter period. This system is prominent in temperate areas, where grass can be used as the main feed source for most of the year, keeping concentrate input low (Dillon et al., 1995). In this system type, spring calving is common to allow peak milk production to coincide with maximum grass growth (Dillon et al., 1995). This system is uniquely different to the typical pasture-based system, such as that in New Zealand and Chile, where the majority of herds are grazed year-round; however, the partly housed, pasture-based dairy system may still be applicable to a proportion of dairy herds in these countries where cows are housed over the winter period. Interest in grass-fed dairy systems has increased worldwide as consumers are beginning to perceive this system type as more sustainable and animal welfare friendly than more intensive housed systems, providing marketing advantages globally (Moscovici Joubran et al., 2021). Currently, few dairying nations have the climate required to make out-wintering the entire year a sustainable option; therefore, this system of grazing cows for the majority of the year and housing cows for a few months over the winter period may become a sustainable option for dairy farmers around the world in the future.

A previous study reported that the most common lesion types in lame [lameness score (**LS**) 3, 4, or 5 on a 1–5 scale] partly housed, pasture-based dairy cows were white line disease (separation with or without abscess) and sole hemorrhages (Somers and O'Grady, 2015). However, this study had a relatively small sample size of 10 herds, which were part of a herd-health program; therefore, these results may not be representative of the general population of dairy cows in a partly housed, pasture-based system. Widening of the white line was also found to be common in Switzerland where cows had frequent pasture access (Becker et al., 2014). Navarro et al. (2013) also reported that white line separation was the most prevalent lesion type in lame cows (LS3 on a 1–5 scale) at pasture.

Although infectious lesions have historically been less commonly reported in pasture-based dairy systems than in housed systems, Browne et al. (2022a) reported that the presence of farmer-reported digital dermatitis in the herd increased the odds of lameness in part-housed, part-grazed dairy herds. Digital dermatitis has also been reported as the most prevalent of all infectious lesion types in a partly housed, pasture-based system (Somers and O'Grady, 2015). It would, therefore, be beneficial to determine the risk factors for digital dermatitis in partly housed, partly grazed dairy cows.

Lesion type can influence the ability of the cow to bear weight on the affected hoof, therefore altering the severity of lameness. A study on a single dairy farm in the United Kingdom reported that changes in gait, including a shortened stride, were greater in cows who had a sole ulcer compared with other lesion types (Blackie et al., 2013). Tadich et al. (2010) identified that sole ulcers, double sole, and interdigital hyperplasia were associated with a cow being more severely lame. In this study, cows were either grazed year-round or partially during the year.

Understanding the relationship between lesions can increase our understanding of the underlying causes of lameness and, therefore, improve treatment. Understanding lesion relationships will also help establish lesions with the same and similar causative mechanism, or lesions which have shared risk factors. In addition, it may also identify if a secondary lesion forms following a different lesion. Manske et al. (2002) reported that the strongest correlations at both cow and herd level were between heel erosion and digital dermatitis, between abnormal claw shape and sole ulcers, and between sole and white line hemorrhages. This study also demonstrated that most hoof lesions that affected one back hoof also affected the corresponding back hoof (Manske et al., 2020). To the best of our knowledge, no studies have looked at the relationship between lesion types in partly housed, pasture-based herds for both the grazing and housing seasons.

Investigating the hoof lesions present in partly housed, pasture-based dairy cows will increase our understanding of the etiology of the disease and provide direction to farmers, veterinarians, and advisors on where to focus lesion prevention and treatment in this unique system type. Therefore, the aims of this large-scale study were to (1) determine the cow-level and herd-level prevalence of each lesion type during both the grazing and housing periods in lame partly housed, pasture-based dairy cows, (2) establish the prevalence of lesions always associated with pain (alarm lesion), (3) identify which lesions were associated with a higher lameness score, (4) establish the relationship between lesions, and (5) identify the risk factors for digital dermatitis for lame cows in a partly housed, pasture-based dairy system.

MATERIALS AND METHODS

The Teagasc Animal Ethics Committee (Cork, Ireland) granted ethical approval prior to the start of the study (TAEC202-2018). Data for this study were collected as part of a larger investigation exploring dairy cow welfare and lameness in partly housed, pasture-based systems (Crossley et al., 2021; Browne et al., 2022a,b). A detailed description of the study method is provided by Browne et al. (2022a). In brief, 102 dairy farms in Ireland were visited during the 2019 grazing period (April 2019–September 2019), and 87 of these farms were revisited during the subsequent housing period (October 2019–February 2020). For farms visited during both periods, the median number of days between visits was 167 d [interquartile range (**IQR**) = 12–220]. The median herd size of all farms included in the analysis was 117 (IQR = 80–156). The median total distance cows walk between the collecting yard and pasture across all farms included in the analysis was 1,900 m/d (IQR = 1,200–2,400). All farms had cubicle (stall) housing, and a small proportion had additional loose housing. The majority of cubicles had a mat with no bedding present. The most common flooring type across farms was grooved concrete, smooth concrete, and smooth concrete slats.

At each visit, the entire milking herd was lameness scored using a 0 to 3 scale (AHDB, 2020a) and a proportion of the herd was body condition scored (1 to 5 scale, in 0.25 increments; AHDB, 2020b) based on the Welfare Quality sample size protocol (Welfare Quality Consortium, 2009). This ranged from 100% of the herd being scored for a herd size of 30 cows, to 28% of the herd being scored for a herd size of 250 cows. Training in body condition scoring and lameness scoring was carried out with all observers before farm visits starting. Interobserver reliability tests were carried out at the start of each visit period, ensuring consistency among scorers; additionally, all kappa coefficients were greater than 0.7. Infrastructure measurements (Browne et al., 2022a) were taken at the milking facilities (parlor and collecting yard), housing facilities (straw yards and cubicle housing), and cow tracks. Examples of cow track measurements taken were track width, verge width, and the presence of loose stones (measured by recording the number of the 25 squares within a quadrat that contained stones). Cow track measurements were taken within the first 50 m section from the collecting yard entrance for all cow tracks used by dairy cows, and on the cow track that was in use during the grazing visit at the half-way point between the collecting yard entrance and paddock entrance, end-point of the cow track, and paddock gateway. A questionnaire with the farmer was also completed at each visit (questions asked to the farmer by the researcher) to identify background information (e.g., herd size and distance cows walk between the collecting yard and pasture each day), farm management protocols and lameness prevention (e.g., proportion of farmers that footbath), detection, and treatment methods used; moreover, each questionnaire can also be viewed as supplementary material (Browne, 2021). Routinely recorded herd management data (e.g., breeding events and milk yields) were provided by the Irish Cattle Breeding Federation.

Hoof Examination

The hooves of up to a maximum of 20 lame cows (LS2 and LS3) were examined per visit. When more than 20 cows were scored as lame, random selection of cows was stratified by LS (e.g., if 15% of the herd had a LS2 and 5% of the herd had LS3, then 15 LS2 and 5 LS3 cows would be selected at random from the ID of cows in each category). A similar selection method was previously used by Tadich et al. (2010). Hoof trimming was performed by a professional hoof trimmer from the Farm Relief Service (Roscrea, Co. Tipperary, Ireland), and cows were examined by 1 trained observer per visit (from a pool of 5 observers in total) to diagnose and record lesions. All observers were trained in lesion identification at a hoof trimming course or by an observer who attended the hoof trimming course. Due to time constraints, only the hind hooves were examined; however, if the cow was noticeably lame on a front hoof during scoring, this hoof was treated as required (data not included in analysis).

During each hoof examination, the longest claw was measured from where the claw goes hard (distal limit of perioplic horn) to the tip of the toe to determine whether the hoof was overgrown, before any removal of horn. Claws with a dorsal wall length over 80 mm were classified as overgrown (AHDB, 2017). Next, a thin layer of horn was removed (~1 mm) to clean the hoof, as done in previous hoof health studies (Vanegas et al., 2006; O'Driscoll et al., 2008). This allowed lesions, such as mild white line separation, which may not be apparent after a full trim, to be identified. The trimmer subsequently trimmed the hoof using the 5-step Dutch hoof trimming method (Toussaint-Raven, 1985). The presence and number of each lesion type were recorded for each back hoof using a paper recording sheet. The majority of lesions were recorded after the cleaning of the hoof; however, if additional hoof lesions became apparent during the trimming process, these lesions were also recorded. A guide with photographs was used to ensure the 5 trained observers remained consistent when recording lesion types throughout the study; specifically, this included the infectious lesions digital dermatitis (meaning the lesion characteristic of the disease digital dermatitis), foul of the foot (interdigital phlegmon), and heel erosion, as well as the noninfectious lesions double sole, fissures (axial, horizontal, vertical), foreign body, hoof abscess, interdigital hyperplasia, sole hemorrhage, sole ulcer, toe necrosis, white line abscess, and white line separation. Claw deformations (overgrown claw and corkscrew claw) were also recorded, as well as the presence of digit amputation; for analysis, these were considered to be noninfectious lesions. The guide was created based on previous publications (Greenough and Vermunt, 1991; Döpfer et al., 1997; Leach et al., 1998; Berry et al., 2012) and from descriptions and images of lesions (for example, from the ICAR claw health atlas; ICAR, 2015).

Statistical Analysis

All statistical analysis was performed in R version 3.3.1 (R Core Team). Farms that were visited during both the grazing and housing period, as well as those only visited once during the grazing period, where in included in all analyses.

Cow-Level Lesion Prevalence

Descriptive analysis was first undertaken using the total number of each lesion type per lame cow. The presence or absence of each lesion type per lame cow was used for all further analyses. Cow-level lesion prevalence within lame cows was calculated for both the grazing and housing periods, defined as the number of lame cows with the lesion present divided by the total number of lame cows examined. Chi-squared (χ^2) tests for independence were used to compare cow-level lesion prevalence between grazing and housing, excluding lesions with a prevalence of less than 1%. The effect size was calculated using the phi coefficient (φ).

As adapted from Kofler et al. (2022), lesions always associated with pain were classified as "alarm" lesions, and in this study included foul of the foot, hoof abscess, M2 digital dermatitis (acute, ulcerative, and painful), sole ulcers, toe necrosis, and white line abscess. The cow-level prevalence of alarm lesions was calculated. The mean and maximum number of alarm lesions per cow, as well as the mean and maximum number of alarm lesion types per cow were also calculated.

Herd-Level Lesion Prevalence

The herd-level lesion prevalence within lame cows was calculated as the number of lame cows in the herd with each lesion present divided by the total number of lame cows examined in each herd, for both the grazing and housing visits. Proportion of herds affected was calculated for each lesion for both the grazing and housing visits as the number of herds with at least 1 affected lame cow with a particular lesion present divided by the number of herds examined.

Lesions Associated with a Higher Lameness Score

Logistic regression was performed at cow level with lameness severity as the binary outcome variable. The outcome of this model was impaired mobility (LS2) versus severely impaired mobility (LS3); specifically, LS2 was coded zero (negative outcome) and LS3 was coded one (positive outcome). The presence of each lesion type were the binary predictors. Predictors were checked for over-dispersion and multicollinearity. Farm was included in the model as a random effect. The final mixed effect logistic regression model was built via backward selection using Akaike information criterion.

The final parameter estimation was performed using the package 'brms' (Bürkner, 2017). Markov chain Monte Carlo (**MCMC**) methods were used to fit the model, and then the parameter estimate chains from the MCMC process were used to generate a predicted probability, with 95% confidence intervals, of each cow being scored a LS3 as opposed to a LS2. The MCMC method is a more reliable method of producing parameter estimates, compared with other methods such as maximum likelihood estimation (Browne and Draper, 2006). The probabilities were grouped into predicted risk deciles and compared with the observed proportion in the corresponding group. Model fit was judged acceptable where the observed proportion was situated within the predicted risk 95% confidence interval for each group. Odds ratios (**OR**) were calculated from model coefficient estimates, and full posterior predictions were used to assess model fit.

Relationship Between Lesions

Correlations between lesion types, using data from both the grazing and housing period, were analyzed at cow level using the phi coefficient (φ) and at herd level using Spearman's rank correlation coefficient. At cow level, binary scores were used, whereas the prevalence of each lesion was used at herd level. Correlation coefficients between lesions are displayed as a heat-map, whereby the magnitude of the coefficients is represented as colors.

Risk Factors for Digital Dermatitis at Herd Level

Factors included in the risk factor analysis included data from the Irish Cattle Breeding Federation (cow-level data), farmer questionnaires, and infrastructure measurements. To create a herd-level data set, dummy variables were created from all cow-level categorical predictors, such that each categorical variable was converted to multiple variables, each representing the proportion of cows in the herd which fell into each category of the original categorical variable. Further, both dummy and continuous cow-level predictors were averaged across farm. To account for situations where cows were housed in multiple different environments on the same farm, housing predictors were weighted by the number of cows present in each pen. Using the 'missForest' package (Stekhoven, 2013), missing herd-level data from both questionnaires and infrastructure measurements were imputed via random forest algorithms (3.7% of data set). Twenty-three predictors were subsequently removed from the data set due to near-zero variance; thus, the final data set consisted of 209 predictors. All continuous predictors were centered and scaled using the 'preProcess' function within the 'Caret' package (Kuhn, 2020). Digital dermatitis presence was included in the data set for each farm at each visit.

Important risk factors for digital dermatitis were determined though triangulation (Lawlor et al., 2016; Lima et al., 2021) of elastic net regression (**Enet**) and logistic regression using modified Bayesian information criterion (**mBIC**). The same method was previously used to establish important risk factors for lameness; additionally, a more detailed description and discussion of the method used can be found in Browne et al. (2022a). In the current analysis, the outcome variable took a binary form (0 = no lame cows in the herd had digital dermatitis, 1 = minimum of 1 lame cow in the herd had digital dermatitis). Covariates from cow-level data, questionnaires, and infrastructure measurements were offered to the model. Bootstrapping (1,000 repeats) was implemented for both the Enet and mBIC models.

Bootstrap P-values (proportion of coefficients from the bootstrap repeats on the minority side of zero) and stability values (proportion of coefficients from the bootstrap repeats that were nonzero) were calculated for each predictor. Predictors were selected in each model if $P < 0.05$ and the stability value was ranked in the top 11. Eleven is the number of predictors with a stability >80% in the Enet model, a method previously used by Lima et al. (2020) and Browne et al. (2022a). Predictors that were selected in both the final Enet and mBIC models were deemed to have important associations to digital dermatitis. Further details on triangulation of Enet and mBIC and the use of bootstrapping can be viewed in Browne et al. (2022a).

RESULTS

To ensure farms represented the typical Irish dairy system (spring-calving, pasture-based, and twice a day milking through a conventional parlor), we excluded 3 farms from the grazing visit and 2 farms from the housing visit due to once-a-day or robotic milking. Any non-lame cows, heifers, or non-spring-calving cows accidentally hoof scored were also removed from the data set. Lame cows (LS2 and LS3) were drafted for hoof scoring a median of 3 d following the lameness scoring visit (range: 0–11 d). Hoof examinations were not possible on 1 farm during the grazing visit (6 cows) and on 10 farms during the housing visit (110 cows); therefore, these farms were not included in the analysis. This was due to the farmer not wanting the hoof trimming visit to take place, or the scorer or hoof trimmer being unable to attend the visit due to unforeseen circumstances. One farm during the housing period had no lame cows; therefore, no hoof examination was required. An additional 35 cows during the grazing period and 130 cows during housing period were not hoof scored due to the farmer not wanting the cow examined, the cow refusing to enter the trimming crate (chute), or the cow not being drafted. The main reason for the farmer not wanting the cow examined was due to injury or the cow being heavily pregnant. The final data set consisted of hoof examinations from 941 lame cows on 98 farms during the grazing period, and hoof examinations from 631 lame cows on 74 farms during the housing period.

Cow-Level Lesion Prevalence

The mean number of lesions per lame cow was 5.5 during the grazing period and 4.9 during the housing period. The maximum number of lesions for a single lame cow was 16 and 14 for the grazing and housing periods, respectively. The mean number of lesion types per lame cow was 3.1 for the grazing period and 3.0 for the housing period. During both periods, the maximum number of different lesion types for a single lame cow was 8. Using the alarm lesion concept proposed by Kofler et al. (2022), there was a mean of 0.2 alarm lesions per lame cow during the grazing period and 0.3 during the housing period. The maximum number of alarm lesions for a single lame cow was 4 and 3 for the grazing and housing periods, respectively. The mean number of alarm lesion types per lame cow was 0.2 for the grazing period and 0.3 for the housing period. The maximum number of different alarm lesion types for a single lame cow was 2 during the grazing period and 3 during the housing period. During the grazing period, 1.6% of lame cows had no lesions present on either hind

Table 1. Cow-level lesion prevalence for 941 lame, spring-calving, partly housed, pasture-based cows (98 herds) during the grazing period (Apr. 2019–Sep. 2019) and for 631 lame cows (74 herds) during the housing period (Oct. 2019–Feb. 2020)[1]

	Cow-level prevalence[2] (%)				
Lesion	Grazing period	Housing period	χ^2	*P*-value	φ
Sole hemorrhage	79.9	76.9	2.099	0.147	0.037
White line separation	72.4	73.2	0.137	0.712	0.009
Overgrown	71.1	55.3	41.241	<0.001	0.162[a]
Corkscrew claw	14.6	9.8	7.654	0.006	0.070
Foreign body	14.3	7.0	20.352	<0.001	0.114[a]
Digital dermatitis	12.4	13.2	0.176	0.675	0.011
Heel erosion	12.3	13.8	0.716	0.397	0.021
Interdigital hyperplasia	11.2	8.1	3.998	0.046	0.050
Sole ulcer	9.6	12.7	3.798	0.051	0.049
Double sole	6.5	9.8	5.854	0.016	0.061
Toe necrosis	3.7	5.4	2.500	0.113	0.040
White line abscess	3.4	6.4	7.463	0.006	0.069
Axial fissure	1.9	4.4	8.500	0.004	0.073
Foul of the foot	0.9	0.8	NT[3]	NT	NT
Horizontal fissure	0.4	0.2	NT	NT	NT
Digit amputation	0.3	0.2	NT	NT	NT
Hoof abscess	0.1	0.6	NT	NT	NT
Vertical fissure	0.0	0.0	NT	NT	NT

[a] $P < 0.05$ and $\varphi \geq 0.1$ [i.e., minimum effect size of "small" (Cohen, 1992)].

[1] Chi-squared tests for independence (χ^2) were used to compare lesion prevalence during the grazing and housing periods; the effect size was also measured using the phi coefficient (φ). The association was not tested if the lesion prevalence was <1% at either visit.

[2] Number of cows with lesion present/total number of cows examined × 100.

[3] NT = not tested.

hoof and 8.3% had lesions present on one hind hoof only. Similarly, during the housing period 1.7% of lame cows had no lesions present on either hind hoof and 9.8% had lesions present on one hind hoof only.

Cow-level lesion prevalence within lame cows are reported in Table 1. Noninfectious lesions were found to be most prevalent; specifically, 97.2 and 96.8% of lame cows had at least 1 noninfectious lesion during the grazing and housing periods, respectively. In comparison, 21.6 and 23.6% of lame cows had at least 1 type of infectious lesion during the grazing and housing periods, respectively. The cow-level prevalence of alarm lesions in lame cows was 19 and 25% during the grazing and housing periods, respectively. The most prevalent alarm lesion was sole ulcer during both the grazing and housing period. The most prevalent noninfectious lesions were sole hemorrhages, white line separation, and overgrown claws; additionally, all other noninfectious lesions had a prevalence of <15%. The most prevalent infectious lesions were digital dermatitis and heel erosion (Table 1).

At cow level, we found a significant difference in lame cows, with an effect size of ≥0.1, between the prevalence of foreign bodies during grazing and housing ($P < 0.001$), and between the prevalence of overgrown claws during grazing and housing ($P < 0.001$). We also found a significant difference between visits for axial fissures ($P = 0.004$), corkscrew claws ($P = 0.006$), double soles ($P = 0.016$), interdigital hyperplasia ($P = 0.046$), and white line abscess ($P = 0.006$); however, these had an effect size <0.1.

Herd-Level Lesion Prevalence

Herd-level lesion prevalence within lame cows are reported in Table 2. Similar to cow level, the herd-level prevalence of sole hemorrhages, white line separation, and overgrown claw were the most prevalent noninfectious lesions, and digital dermatitis and heel erosion were the most common infectious lesions. Sole hemorrhages, white line separation, and overgrown claws were also present in the largest number of herds. Foul of the foot, digit amputation, horizontal fissures, and hoof abscesses were diagnosed in <10% of herds (Table 2).

Lesions Associated with a Higher Lameness Score

The lesions associated with a higher LS in lame cows (LS2 vs. LS3) are shown in Table 3. The odds of a cow being scored as LS3 as opposed to LS2 was 15.01 times higher for lame cows that had previously had a claw

Table 2. Herd-level lesion prevalence (mean, standard deviation, minimum, and maximum) for lame cows in 98 spring-calving, partly housed, pasture-based herds during the grazing period (Apr. 2019–Sep. 2019) and in 74 of these herds during the housing period (Oct. 2019–Feb. 2020)[1]

	Grazing period					Housing period				
	Herd-level prevalence[2] (%)				Herds affected[3] (%)	Herd-level prevalence (%)				Herds affected (%)
Lesion	Mean	SD	Min	Max		Mean	SD	Min	Max	
Sole hemorrhage	81.0	20.7	0.0	100.0	99.0	77.2	26.3	0.0	100.0	97.3
White line separation	72.3	22.0	25.0	100.0	100.0	73.0	26.3	0.0	100.0	97.3
Overgrown	71.5	22.8	0.0	100.0	98.0	52.4	24.2	0.0	100.0	91.9
Corkscrew claw	15.5	19.6	0.0	83.3	56.1	9.3	11.9	0.0	40.0	47.3
Foreign body	14.0	16.0	0.0	75.0	62.2	6.2	9.9	0.0	50.0	37.8
Heel erosion	11.7	19.5	0.0	85.7	37.8	12.8	20.0	0.0	85.7	44.6
Interdigital hyperplasia	11.7	15.4	0.0	75.0	53.1	8.9	16.7	0.0	100.0	37.8
Digital dermatitis	10.1	18.3	0.0	80.0	34.7	9.5	16.9	0.0	75.0	35.1
Sole ulcer	8.5	11.5	0.0	60.0	49.0	10.7	12.7	0.0	50.0	55.4
Double sole	4.8	7.7	0.0	33.3	36.7	9.4	12.3	0.0	50.0	47.3
Toe necrosis	3.6	9.5	0.0	50.0	19.4	4.2	10.0	0.0	62.5	24.3
White line abscess	3.3	8.0	0.0	50.0	23.5	6.8	15.2	0.0	100.0	28.4
Axial fissure	1.7	5.2	0.0	28.6	12.2	5.0	10.4	0.0	50.0	28.4
Digit amputation	0.7	4.2	0.0	33.3	3.1	0.3	2.3	0.0	20.0	1.4
Foul of the foot	0.6	2.5	0.0	14.3	7.1	0.6	2.4	0.0	14.3	5.4
Horizontal fissure	0.3	1.7	0.0	15.4	3.1	0.2	1.9	0.0	16.7	1.4
Hoof abscess	0.1	1.4	0.0	14.3	1.0	0.3	1.3	0.0	6.3	5.4
Vertical fissure	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[1]The percentage of herds affected by each lesion is also reported for each period.

[2]Number of cows with lesion on the farm/total number of cows examined on the farm × 100. Min = minimum; Max = maximum.

[3]Percentage of herds with at least one affected cow.

amputated. The odds of a cow being scored as LS3 compared with LS2 were 9.41, 4.70, 3.85, 2.03, and 1.68 times higher for cows with foul of the foot, white line abscess, sole ulcer, toe necrosis, or interdigital hyperplasia, respectively. However, the odds of a cow being scored as LS3 as opposed to LS2 was lower for cows with heel erosion (OR = 0.46).

Results from the full posterior prediction via MCMC, to indicate model fit, are shown in Figure 1. The mean observed outcome for each risk decile was within the 95% confidence interval of the predicted outcome, indicating good model fit.

Relationship Between Lesions

Correlations between cow- and herd-level lesion types are shown as a heat-map in Figure 2. At cow level, the strongest correlations were between overgrown claws and corkscrew claws, and between digital dermatitis and heel erosion. The strongest correlation at herd level

Table 3. Results from the multilevel logistic regression model to determine which lesions were associated with a higher lameness score in spring-calving, partly housed, pasture-based lame cows (i.e., lameness score of 3 rather than 2)[1]

Hoof lesion	Estimate	Lower 95% CI	Upper 95% CI	SE	Odds ratio	*P*-value
Intercept	−2.454	−2.809	−2.100	0.181		
Digit amputation	2.709	0.590	4.828	1.081	15.01	0.012*
Digital dermatitis	0.406	−0.103	0.915	0.260	1.50	0.118
Foul of the foot	2.243	1.031	3.454	0.618	9.41	0.000***
Heel erosion	−0.756	−1.360	−0.153	0.308	0.46	0.014*
Interdigital hyperplasia	0.520	0.019	1.020	0.255	1.68	0.042*
Overgrown	−0.344	−0.692	0.003	0.177	0.70	0.052
Sole ulcer	1.348	0.931	1.766	0.213	3.85	0.000***
Toe necrosis	0.712	0.032	1.392	0.347	2.03	0.040*
White line abscess	1.548	0.945	2.150	0.307	4.70	0.000***

[1]Scores from both the grazing period (98 herds; April 2019–September 2019) and the housing period (74 herds; October 2019–February 2020) were used in the analysis.

***Odds ratio is significantly different from 1 ($P < 0.001$).

*Odds ratio is significantly different from 1 ($P < 0.05$).

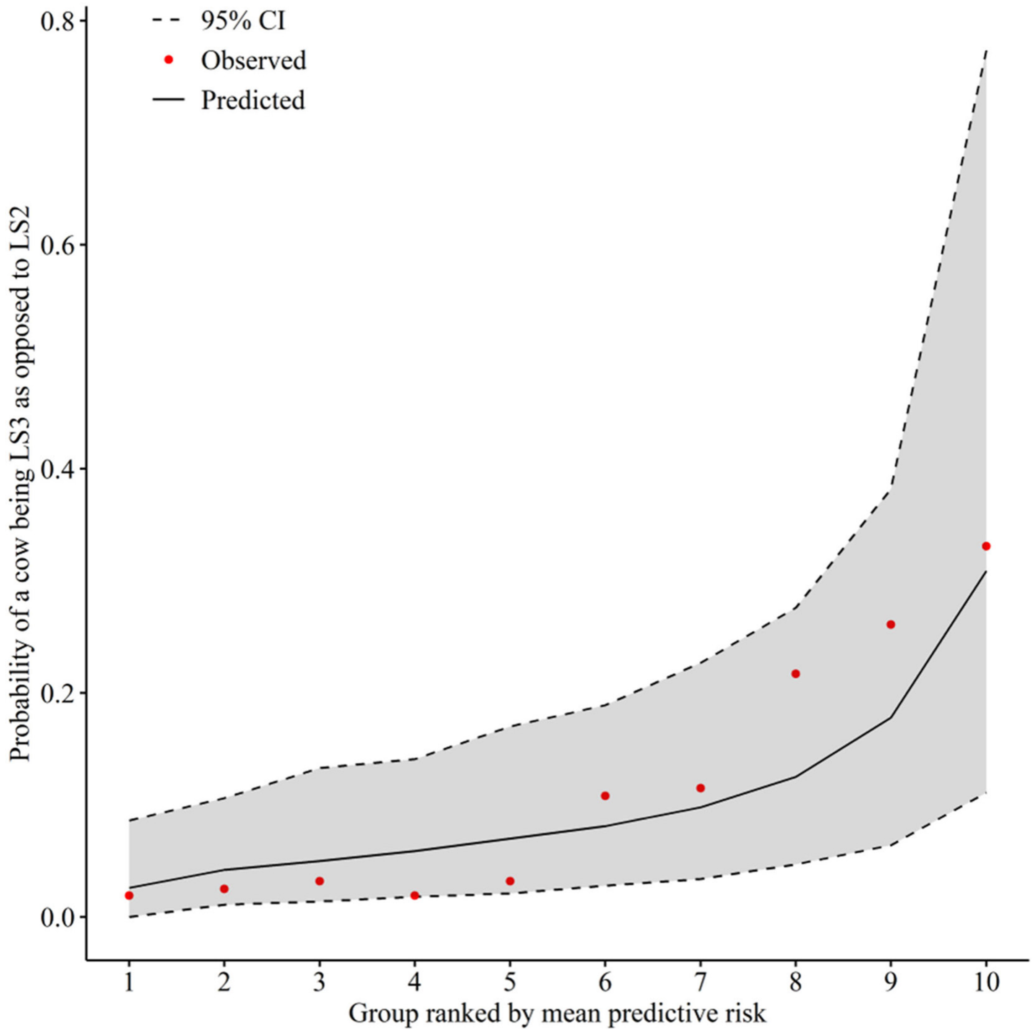

Figure 1. Predicted probability (and 95% CI) of a cow being scored a lameness score (LS) of 3 as opposed to a LS2 for each risk decile (groups ranked by mean predicted risk). Predicted probabilities were calculated via Markov chain Monte Carlo methods. Observed proportions of cows scoring a LS3 as opposed to a LS2 for each decile are also reported.

was between digital dermatitis and toe necrosis, followed by the correlation between overgrown claws and corkscrew claws, between interdigital hyperplasia and digital dermatitis, and between sole ulcers and digital dermatitis.

We found a correlation between having the infectious lesion digital dermatitis (r = 0.31) and heel erosion (r = 0.44), respectively, on 1 back hoof, and having the same lesion on the opposing back hoof. Similarly, weak correlations we detected between having the noninfectious lesions white line separation (r = 0.28), sole hemorrhages (r = 0.35), foreign bodies (r = 0.26), corkscrew claws (r = 0.29), and overgrown claws (r = 0.34) on 1 back hoof and having the same lesion on the opposing back hoof.

Risk Factors for Digital Dermatitis at Herd Level

Eleven predictors were selected in the final Enet and mBIC models (Table 4). Of these, 6 of the same predictors occurred in both model types, indicating that these are robust risk factors for digital dermatitis in lame cows. Three predictors were associated with an increased risk of digital dermatitis and 3 were associated with a decreased risk.

Cow track characteristics were risk factors for digital dermatitis. An increase in the proportion of cow tracks which were narrow (based on herd size; DAFM, 2021), and an increase in the proportion, which had small verges (≤0.5 m) at 50 m after the collecting yard, were associated with reduced risk of digital dermatitis. An

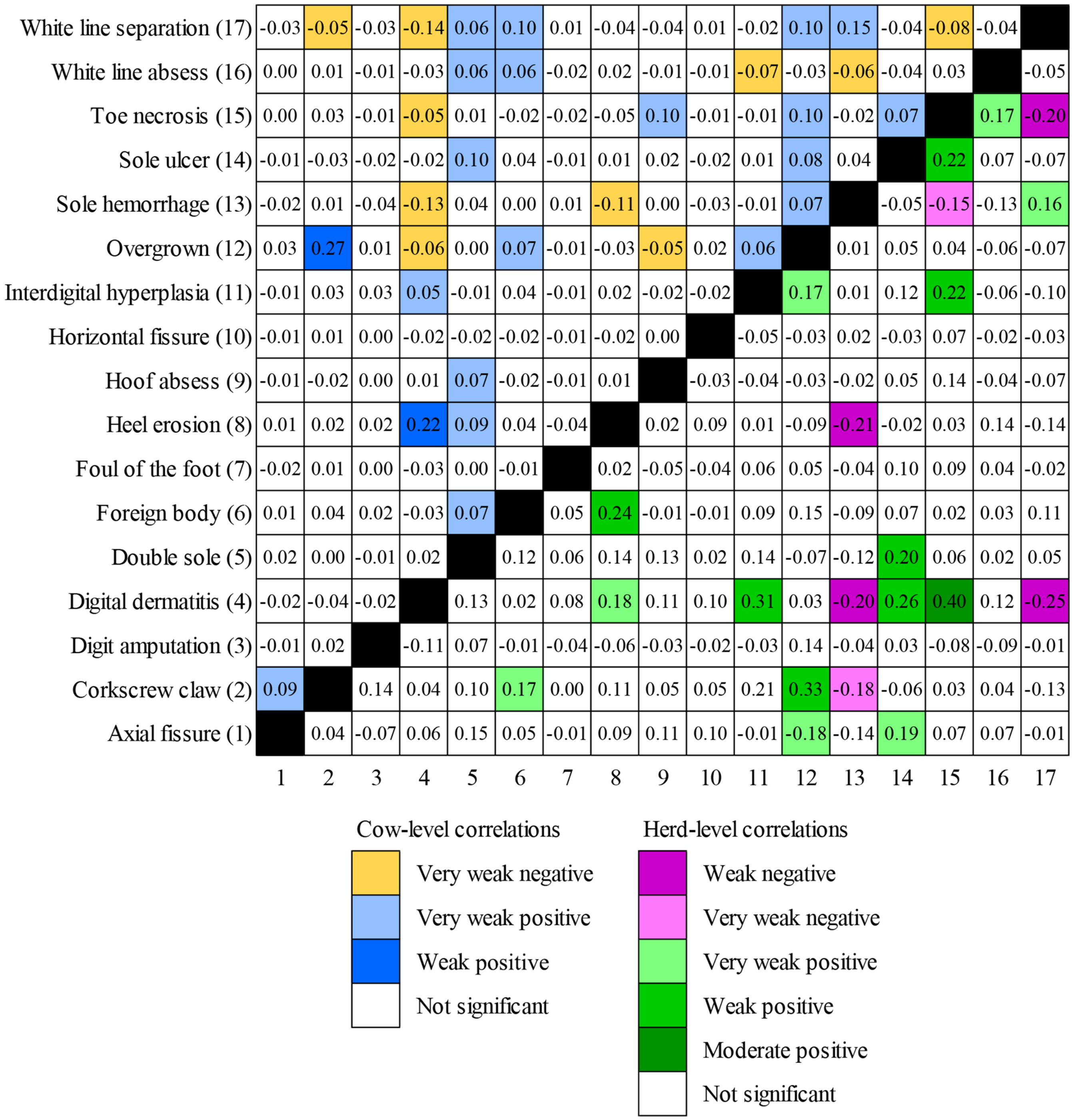

Figure 2. Correlation coefficient between lesions at cow level (binary scores; phi coefficient) and herd level (lesion prevalence; Spearman's coefficient) for lame cows in spring-calving, partly housed, pasture-based herds. Correlations between lesions with $P < 0.05$ are colored; white indicates that the correlation between lesions was not significant ($P \geq 0.05$). The color code enables visualization of correlation strength and direction: very weak (r = 0.01–0.19), weak (r = 0.20–0.39), and moderate (r = 0.40–0.59). Numbers on the x-axis refer to the lesions on the y-axis. Scores from both the grazing period (98 farms; April 2019–September 2019) and the housing period (74 farms; October 2019–February 2020) were used in the analysis.

Table 4. Risk factors for digital dermatitis at herd-level for lame cows in 98 spring-calving, partly housed, pasture-based herds during the grazing period (Apr. 2019–Sep. 2019), and in 74 of these herds during the housing period (Oct. 2019–Feb. 2020), using triangulation of elastic net regression (Enet), and logistic regression using modified Bayesian information criterion (mBIC)[1]

Predictor	Reference category (categorical predictors)	Mean standardized coefficient (lower 95% CI; upper 95% CI)		Odds ratio[2]		Stability rank		Bootstrap *P*-value	
		Enet	mBIC	Enet	mBIC	Enet	mBIC	Enet	mBIC
No cases of digital dermatitis, during the current lactation according to the farmer	>0% and ≤5% herd had digital dermatitis, during the current lactation according to the farmer	−1.851 (−4.509; −0.518)	−5.026 (−121.198; −2.804)	0.16	0.01	1	1	0.000	0.000
>5% herd had digital dermatitis, during the current lactation according to the farmer	>0% and ≤5% herd had digital dermatitis, during the current lactation according to the farmer	1.360 (0.167; 3.959)	4.810 (2.656; 183.145)	3.90	122.68	5	3	0.000	0.000
The proportion of cow tracks with a "medium" number of stones[3]		0.674 (0.091; 1.597)	1.528 (0.867; 47.683)	1.26	1.68	3	5	0.000	0.000
Proportion of small verges (≤0.5 m) at 50 m following the collecting yard		−0.483 (−1.374; −0.036)	−1.776 (−91.473; −1.079)	0.85	0.56	7	4	0.000	0.000
Lameness is considered a problem by the farmer	Lameness is not considered a problem by the farmer	0.877 (0.070; 2.573)	2.998 (1.835; 280.685)	2.40	20.04	6	7	0.000	0.000
Proportion of cow tracks that were narrow at 50 m following the collecting yard[4]		−0.609 (−1.501; −0.061)	−1.547 (−36.341; −0.909)	0.83	0.61	4	11	0.000	0.000

[1]Results are ordered by mean stability rank; the binary outcome is "digital dermatitis presence" (0 = digital dermatitis not recorded in the herd, 1 = digital dermatitis recorded in the herd).

[2]Odds ratios were calculated from unstandardized means; a unit change of 0.1 was used for continuous predictor.

[3]Nine to 17 quadrat squares out of 25 contain stones.

[4]Based on herd size (DAFM, 2021).

increase in the proportion of cow tracks with a "medium" number of stones (9 to 17 quadrat squares out of 25 contain stones; for method see Browne et al., 2022a) was associated with increased risk of digital dermatitis.

The recorded presence of digital dermatitis was also associated with farmer perception of digital dermatitis and lameness in the herd. Farms where more than 5% of the herd had digital dermatitis in the last year, according to the farmer, had lower odds of having digital dermatitis (compared with a herd >0 and ≤5%). However, where there were no cases of digital dermatitis in the last year, according to the farmer, the odds of digital dermatitis decreased (compared with a herd >0 and ≤5%). Farmers who considered their herd to have a lameness problem had higher odds of having digital dermatitis (compared with those that did not consider lameness to be a problem).

DISCUSSION

This large-scale study documents in detail hoof lesion types and relationships between lesions, compares lesion type with LS, and determines risks for digital dermatitis in lame cows, within an extensive partly housed, pasture-based dairy system.

Lesion Prevalence

Hoof lesions are the most common cause of lameness in dairy cows, so it is unsurprising that over 98% of lame cows examined in the current study had a minimum of 1 lesion on at least 1 hoof. However, only approximately 30% of lame cows were shown to have an alarm lesion present, which are always associated with pain (Kofler et al., 2022). It must also be noted that non-alarm lesions can still be painful and of concern, and should therefore not be ignored. Additionally, lameness may be caused by painful disorders located in the proximal limb. An average of 5.5 lesions were recorded per lame cow during the grazing period and 4.9 during the housing period, which is slightly higher than 3.4 lesions per lame cow reported previously in a similar partly housed, pasture-based system (Somers and O'Grady, 2015). Lame cows had an average of 3 different lesion types present, which indicates that a combination of lesions may have been responsible for lameness in individual cows, or that lameness is being caused by 1 lesion and that other lesions were observed but were not causing pain. Previous studies have reported that not all lesions will lead to lameness (Manske et al., 2002). In the present study, 1.6% of lame cows during grazing and 1.7% of lame cows during housing had no lesions present, demonstrating that a small number of lameness cases may be due to injury in places other than the hoof, that hoof problems may cause lameness without visible signs, or that lameness scoring may result in false positives.

Both the presence of a foreign body within the hoof sole (most commonly stones) and claw overgrowth in lame dairy cows were significantly more common during grazing, compared with housing. Penetration by a foreign body is likely more common during grazing due to cows stepping on stones when walking on tracks between the paddocks and the milking parlor, whereas in a housed environment, the presence of stones is less common. Overgrowth is caused when the claw growth rate is greater than the wear rate. Hahn et al. (1986) stated that both wear and growth rates where highest when cows where housed, compared with cows at pasture. Telezhenko et al. (2009) also reported that cattle housed on more abrasive surfaces have shown both increased growth rate and wear rate of the hoof, but also an overall lower net growth compared with cattle on less abrasive surfaces. Abrasive surfaces may also result in thin soles. Similarly, Chapinal et al. (2010) reported that net growth rate for cows with nighttime pasture access was also higher compared with fully housed cows. The higher prevalence of overgrown claws during the grazing period compared with the housing period in this study may suggest that net growth was highest when cows were at pasture.

In agreement with other partly housed, pasture-based studies, the most common hoof lesions in lame cows were sole hemorrhages and white line separation; however, the prevalence of these lesions were generally higher than in previous studies (Navarro et al., 2013; Somers and O'Grady, 2015). Somers and O'Grady (2015) reported that white line separation (with or without abscess) and sole hemorrhages were the most common lesion types in partly housed, pasture-based lame cows, with a prevalence of 52 and 63%, respectively. Somers and O'Grady (2015) also reported lower levels of overgrown claws (>80 mm) compared with the current study. The lower prevalence may be due to the 10 herds in the study participating in a herd-health program, which included lameness monitoring. In Swiss dairy herds (Becker et al., 2014), where cows gain frequent pasture access, cow-level prevalence of widened white line (81%) was similar to the prevalence of white line separation reported in the current study. The prevalence of white line disease (septic lesion) reported by Becker et al. (2014) was less than 5%, which is also similar to the prevalence of white line abscess reported in the current study.

Sole hemorrhages, white line separation, and overgrown claws were also found to affect the highest number of herds. It is proposed that walking on uneven and stony surfaces is a risk for white line disease (Archer et al., 2010); Chesterton et al. (1989) reported that poor maintenance of cow tracks was a risk for lameness. Cows in this study walked an average of approximately 2,000 m/d in total between milking and pasture, possibly explaining the high number of farms affected during grazing. This emphasizes how an important part of lameness prevention is maintaining cow tracks and ensuring they are stone free. Browne et al. (2022a) also reported that a high number of stones in paddock gateways was a risk for lameness. It is plausible that the high prevalence of white line separation observed during housing may be due to the time delay between injury to the hoof during the grazing period and manifestation of the lesion during the housing period; in fact, lesions can take at least 6 wk to become visible on the hoof sole (Ossent and Lischer, 1998). Long periods of time standing on concrete is also thought to pose a risk for claw horn lesions such as white line disease and sole hemorrhages (Bicalho and Oikonomou, 2013). In this study, 56% of dairy farms had less than 1.1 cubicles per cow in all pens, potentially leading to decreased lying time and increased standing time. Overstocking during housing has been reported to decrease time and thus increase lesion severity (Leonard et al., 1996). Somers and O'Grady (2015) reported similar findings in partly housed, pasture-based dairy cows: white line disease (separation with or without abscess) and sole hemorrhages were present on all farms visited. Based on the current study, farmers may benefit from routine trimming the entire herd to prevent overgrown claws. Routine trimming can also be a useful method for treating all undiagnosed lesions and for preventing hoof lesions forming, further reducing lameness incidence (Sadiq et al., 2020, 2021).

It is well known that infectious lesions are less common than noninfectious lesions in pasture-based systems (Somers and O'Grady, 2015). The cow-level prevalence of digital dermatitis in the current study was 12.4% during grazing and 13.2% during housing, which is comparably lower than Somers and O'Grady (2015), who reported a prevalence of 28% in lame partly housed, pasture-based dairy cows. The difference may be due to management differing on the 10 farms examined by Somers and O'Grady (2015), and due to hoof scoring only taking place over a 2-mo period. Similar to Somers and O'Grady (2015), Becker et al. (2014) reported a cow-level digital dermatitis prevalence of 29% in Swiss dairy cows within a similar system type. In contrast, infectious lesions are generally more common in housed systems (Cramer et al., 2008; Solano et al., 2016). Solano et al. (2016) reported that digital dermatitis was the most common lesion in housed Canadian cattle, with a cow-level prevalence of 15%. The prevalence reported by Solano et al. (2016) is similar to the prevalence found in the current study; however, their study collected data from all cows at routine trimming, as opposed to lame cows only, which suggests that digital dermatitis in partly housed, pasture-based herds was lower in comparison. Digital dermatitis was only recorded in 35% of herds in the current study; however, in housed systems, up to 94% of herds have digital dermatitis present (Solano et al., 2016). This emphasizes the extent of the problem in housed environments, where the buildup of manure is more common.

Lesions Associated with a Higher Lameness Score

Foul of the foot, white line abscess, sole ulcers, toe necrosis, interdigital hyperplasia, and digit amputation were associated with the highest odds of a cow being LS3 (severely impaired mobility) compared with being LS2 (impaired mobility), indicating that these lesions are associated with higher pain levels than other lesions identified. Previous publications have also identified lesions that elicit more severe pain (Tadich et al., 2010; Somers and O'Grady, 2015). Similar to the current study, Somers and O'Grady (2015) concluded that ulcers and white line disease led to higher pain in lame partly housed, pasture-based dairy cows; however, their study did not separate white line separation with white line abscess as we did is our study. Somers and O'Grady (2015) also reported that axial fissures and vertical fissures resulted in a higher LS. Farmers need to effectively detect and treat mild lesions early to prevent more severe lesions occurring (Groenevelt et al., 2014). For example, treating sole hemorrhages may prevent the more painful sole ulcer occurring, and avert the need for digit amputation. The use of nonsteroidal anti-inflammatory drugs, in conjunction with a trim and block, can contribute to higher cure rates and to improved animal welfare through reduced pain (Thomas et al., 2015). Ranjbar et al. (2021) reported that, in grazing cows that walked over 2,000 m/d, higher density blocks should be used to increase block longevity. In addition, farmers could consider focusing preventative efforts on the lesions found to be most painful.

Digit amputation is often used to treat deep infections within the hoof when less invasive treatment methods are unsuccessful. However, the success rate of digit amputation is relatively low; for example, Bicalho et al. (2006) reported that 45% of cows were culled within 60 d postsurgery. In addition, Starke et al. (2007) and Devaux et al. (2017) reported the mean survival rate postamputation to be 13.5 and 15 mo, respectively. The most common reason for culling following amputation is lameness (Starke et al., 2007). Effective prevention and treatment of lesions on the remaining claw is essential for increasing life span postamputation (Heppelmann et al., 2009). Most importantly, preventing severe lesions is key for eliminating the need for digit amputation in the first instance.

Relationship Between Lesions

In the present study, the strongest correlation between lesions at herd level was between toe necrosis and digital dermatitis in lame cows. Similarly, a previous study reported that digital dermatitis treponeme DNA was present in 84% of tissue samples taken from cows with nonhealing toe necrosis (Evans et al., 2011). In contrast, no DNA was present in healthy tissue samples from cows without toe necrosis (Evans et al., 2011). It has also been proposed that the reduced bone density and proliferation of the laminar corium in cows with toe necrosis may be due to the presence of the digital dermatitis treponemes (Blowey et al., 2013). It is generally believed that damaged necrotic tissue allows for digital dermatitis treponemes to enter the hoof, thus leading to the lesion becoming nonhealing (Kofler, 2017). However, it has also been theorized that digital dermatitis treponemes may cause damage at the coronary band, leading to the hoof wall splitting and allowing digital dermatitis treponemes to enter, predisposing to toe necrosis (Atkinson and Wright, 2013). The correlations found in this study do not enable a cause and effect relationship to be established. In either case, preventing digital dermatitis may prevent toe necrosis (Atkinson and Wright, 2013), or preventing claw horn lesions in general may prevent severe nonhealing cases of all digital dermatitis-associated lesions (Kofler, 2017).

This study also demonstrated an association between digital dermatitis and sole ulcers in lame cows. Similar to nonhealing toe necrosis, digital dermatitis treponeme DNA has previously been present in nonhealing sole ulcer tissue samples (Evans et al., 2011). However, unlike toe necrosis, it has not been speculated that digital dermatitis treponemes in sole ulcers cause changes in pedal bone pathology (Blowey et al., 2013), or that digital dermatitis may predispose to sole ulcers (Atkinson and Wright, 2013). As previously reported, digital dermatitis was also found to be associated with the infectious lesions, interdigital hyperplasia, and heel erosion (Manske et al., 2002; Holzhauer et al., 2006). Evans et al. (2011) demonstrated that digital dermatitis treponemes were not present in heel erosion tissue samples, indicating that the bacteria causing these lesions differ. It is speculated that the relationship between these infectious lesions are likely due to the bacteria associated with these lesions, all thriving in similar unhygienic environmental conditions.

Risk Factors for Digital Dermatitis at Herd Level

On farms where digital dermatitis was present in the herd within the last year, according to the farmer, there was an increased odds of digital dermatitis. Similarly, on farms where farmers stated they had no digital dermatitis in the herd, there was a reduced risk. This is unsurprising; however, it demonstrates that farmers were aware of the presence of digital dermatitis in their herd. The odds of digital dermatitis was also increased when the farmer considered themselves to have a lameness problem in their herd, which is indicative of the farmers' ability to perceive that digital dermatitis was a problem in their herd. However, despite 44% of farmers reporting that digital dermatitis was present in their herd in the last year, only 31% of farmers footbathed more than 12 times per year in this study (Browne et al., 2022b). Farmers should be encouraged to talk to their vet regarding optimal footbathing protocols and digital dermatitis treatment to reduce digital dermatitis in their herd.

Various cow track features influenced the risk of digital dermatitis. A higher proportion of cow tracks with small verges (<0.5 m), at 50 m following the collecting yard, reduced the odds of digital dermatitis. A small verge prevents cows from walking on the grass margin as opposed to the track, whereas large verges may result in cows walking and standing on the grass margins (Tuohy et al., 2017), creating muddy conditions that lead to increased digital dermatitis risk. A higher proportion of narrow cow tracks at the first 50 m following the collecting yard also reduced the risk of digital dermatitis. On farms where the majority of cow tracks were narrow, the most common surface type was subsoil within the first 50 m. Contrastingly, on farms where the majority of cow tracks were wide, concrete was the most common surface type within the first 50 m. It is possible that concrete allowed for manure to pool, thus increasing the risk of digital dermatitis (Blowey, 2006). A second theory is that farms with narrow cow tracks near the collecting yard may have been more likely to maintain and clean the area, preventing the buildup of manure. An increase in the proportion of cow tracks with a "medium" number of stones increased the risk of digital dermatitis. This may be linked to stones causing skin abrasions, allowing digital dermatitis treponemes to enter (Krull et al., 2016).

Some of the mBIC coefficients reported in this study are relatively large. Coefficients based on mBIC are generally somewhat inflated, whereas Enet coefficients are generally somewhat deflated (Lima et al., 2021). The range between these estimates is, therefore, a plausible range within which the true value is likely to lie. If conventional regression was used for this analysis, it is likely that these coefficients would be further inflated, and that more false-positive results would have been reported. In addition, the mBIC coefficients are largely inflated for risk factors that would be expect to have a strong relationship (e.g., proportion of herd with digital dermatitis according to the farmer); therefore, accurately quantifying the size of the relationship is of less interest.

Study Limitations

Farmers in this study had the choice of participation; therefore, some degree of selection bias may have occurred. Farmers that were more aware of lameness and hoof care may have been more willing to participate; however, those with a lameness problem may have also signed up to the study to get their lame cows identified and treated. Additional bias may have also occurred through subjective diagnosis of hoof lesions by different observers. To mitigate this effect, all observers were trained in lesion identification and a guide was created with photographs to refer to throughout the study. Ideally, both the hooves of non-lame cows as well as lame cows would have been examined; however, as resources and time were limiting factors in conducting this labor-intensive study, it was only viable to hoof score a maximum of 20 cows per farm. Therefore, it was decided that the most valuable information would be obtained by examining the hooves of a larger number of only lame cows per herd. The correlation between lesion types is an indication of a relationship; however, this does not imply causation. Similarly, in the risk factor analysis for digital dermatitis, the cause and effect cannot be depicted. Herd-level risk factor analysis was only carried out for digital dermatitis. This is because digital dermatitis is an infectious disease and spreads between cows, and it is generally present in some herds and absent in other herds. In contrast, the most prevalent noninfectious lesions were present on a very high proportion of farms, making herd-level risk factor analysis not possible.

CONCLUSIONS

This study identified that the noninfectious lesions white line separation, sole hemorrhages, and overgrown claws were the most prevalent lesions at both the cow and herd level. A low prevalence of infectious lesions was identified. All lesion types had a similar prevalence between grazing and housing, with the exception of foreign bodies within the hoof sole and overgrown claws, which had a higher prevalence during grazing. Cows had higher odds of being severely lame, compared with mildly lame, if they had an amputated claw, foul of the foot, white line abscess, sole ulcer, or toe necrosis. Toe necrosis and digital dermatitis had the strongest correlation of all lesion types, followed by overgrown claws and corkscrew claws, and interdigital dermatitis and digital dermatitis, all at herd level. The farmers' perception of digital dermatitis and lameness in the herd, as well as cow track characteristics, were identified as risk factors for digital dermatitis. Identifying the main causes of lameness in a partly housed, pasture-based system helps provide a focus for treating and preventing these lesion types.

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Paper 4: Use of non-steroidal anti-inflammatory drugs and attitudes to pain in pasture-based dairy cows: A comparative study of farmers and veterinarians

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CH and MC supervised this study. All authors contributed to study design. NB sent the surveys and input all data. NB analysed the data and drafted the manuscript, with the assistance of CH and MC. All authors read and approved the final manuscript.

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Use of Non-Steroidal Anti-Inflammatory Drugs and Attitudes to Pain in Pasture-Based Dairy Cows: A Comparative Study of Farmers and Veterinarians

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Pain is a significant welfare concern within the dairy industry. Recognizing and managing pain are important factors for safeguarding animal welfare. A questionnaire was sent via post to Irish dairy farmers and large animal veterinarians to assess attitudes to pain and the use of non-steroidal anti-inflammatory drugs (NSAIDs) in pasture-based dairy cows. The questionnaire could also be completed online. A total of 1,002 surveys were received from dairy farmers and 116 from livestock veterinarians. Veterinarians and farmers generally perceived the same conditions and procedures as the most painful. However, farmers scored surgical procedures significantly higher than veterinarians, and veterinarians scored lameness-related conditions, mastitis (clots in milk only) and hock hair loss significantly higher than farmers. Higher pain scores for conditions and procedures given by dairy farmers and veterinarians were associated with increased NSAID use. However, the use of NSAIDs was low, relative to the pain score, for Burdizzo castration (farmers and veterinarians), white line separation (farmers and veterinarians) and abscess (veterinarians), mastitis with clots in milk only (farmers) and calving with no assistance (farmers). Veterinarians who graduated less recently had significantly lower odds of using NSAIDs, and farmers that completed the survey online, had a larger herd size, completed education up to level four or five (as opposed to level three) and those who seemed to have less knowledge on analgesics, had significantly lower odds of using NSAIDs. Empathy was not found to be associated with NSAID use and no correlation was found between pain and empathy scores. Veterinarians perceived cost as more of a barrier than farmers did; therefore, NSAIDs should be offered more readily. For those working with dairy cows, there is a need to continue education on the benefits of analgesia, especially for conditions and procedures that have low NSAID use relative to pain score. The habituation of humans to pain in animals needs to be prevented to enable pain to be recognized and managed appropriately. Pain scores can be used as a benchmark for veterinarians and farmers to determine how their perception of pain compares to others, and see how this may influence their NSAID use.

Keywords: pain, dairy cow, veterinarian, NSAIDs, analgesia, farmer

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INTRODUCTION

Pain is a sensory and emotional experience which can have major impacts on dairy cow welfare. Under current EU legislation, farm animals are considered sentient beings (1), and are therefore recognized to suffer and feel pain. Freedom from pain is a key component of welfare (2); therefore, preventing and alleviating pain plays a vital role in safeguarding the welfare of cows and calves within the dairy industry. Pain in dairy cows can be caused by various diseases, injuries, parturition, and surgical and non-surgical procedures (3), as well as from routine management practices of calves such as disbudding and castration (4, 5). Pain is also a problem in terms of consumer perception and the supply chain; there is heightened pressure on the agricultural industry to produce food more ethically and sustainably (6, 7).

Pain must be recognized appropriately in order for it to be managed effectively. It is therefore important to understand what qualities and views of individuals lead to the recognition of pain in dairy cows. Although it is the shared responsibility of farmers and prescribing veterinarians to ensure pain is appropriately assessed and treated, the majority of studies focus only on veterinarians (8–11). There is also limited comparative work between the attitudes to pain between both veterinarians and farmers. Tschoner et al. (12) reported that there was no significant differences between pain scores of Bavarian veterinarians and farmers. In contrast, Thomsen et al. (13) reported that Danish dairy farmers gave higher pain scores compared to veterinarians. However, farmers in this study were part of a web-based panel and may therefore not be representative of the full population. Additionally, the farmer survey was undertaken over 2 years following the survey with the veterinarians. Further work is required to understand how attitudes to pain compare between veterinarians and farmers.

Non-steroidal anti-inflammatory drugs (NSAIDs) can be used to treat painful conditions such as mastitis (14), and to relieve post-operative pain in both cows and calves. Non-steroidal anti-inflammatory drugs are the only family of analgesics available for food producing animals in the European Union that provide long acting pain relief [24–72 h of pain relief per dose (15)]. In addition to improving the welfare of the dairy cow through reduced pain, NSAIDs can also accelerate recovery of lame cows (16) and improve productivity (17). Although the use of analgesia is generally increasing within the dairy sector, uptake was found to be low in the treatment of lameness within an Irish pasture-based dairy system (unpublished data), and other studies (8) have found evidence of scope to increase use further. The use of NSAIDs for different cattle procedures and conditions is generally higher if perceived more painful by a veterinarian (8, 9, 11). Using a multilevel model, Remnant et al. (8) also reported that NSAID use was higher in female veterinarians and for those that graduated in more recent decades, after accounting for the effect of pain score. However, to the authors' knowledge, no research to date has used multivariable statistics to determine factors that account for the use of NSAIDs by dairy farmers.

In Ireland, NSAIDs are classified as "prescription only" medicines; however, farmers can administer NSAIDs themselves to both cows and calves in line with the prescription obtained (18). Although the farm's veterinarian does not necessarily have to visit the farm in order to provide a prescription, they should have visited the farm within the last 12 months (19). The veterinarian can prescribe NSAIDs to both individual animals and to a group of animals (19). Based on a veterinary prescription, a small quantity of NSAIDs can also be kept on farms for future use, if deemed necessary by the veterinarian (20). In addition, as of June 2022 it will become mandatory for veterinarians to prescribe using the National Veterinary Prescribing System (NVPS) as opposed to using paper prescriptions, in line with new EU regulations to improve medicine availability and reduce the use of anti-microbials (21). This highlights that both the farmer and veterinarian have control and influence over NSAID use in dairy cows.

Empathy is a personality trait of clinical interest, particularly in the topic of pain recognition and management. However, no studies to date have researched empathy as a factor that may specifically affect NSAID use in dairy cows by either veterinarians or farmers. Empathy is measurable using assessments such as the Interpersonal Reactivity Index [IRI (22)]. Previous studies have found that empathy toward animals decreases with years of study in veterinary students, with female students maintaining higher empathy levels throughout the course of study compared to male students (23). Norring et al. (24) also reported that empathetic veterinarians scored the pain of various conditions and procedures higher than those with lower empathy scores.

The aim of this study was to assess attitudes to pain and use of analgesics in both dairy farmers and livestock veterinarians. A further aim was to identify factors associated with NSAID use in pasture-based dairy cows. The final aim was to establish the relationship between the pain score given to certain procedures and conditions and both NSAID use and empathy scores of farmers and veterinarians.

MATERIALS AND METHODS

The study took place from September 2021 to November 2021. Data were collected via two questionnaires, one directed at farmers and one directed at veterinarians in Ireland. Both questionnaires can be viewed as **Supplementary Material**. To allow for comparisons between studies, parts of each questionnaire were similar to those used previously in the UK (8, 9, 25), Europe (11, 13) and New Zealand (10). The study was approved by the School of Veterinary Medicine and Science Committee for Animal Research and Ethics (CARE) at the University of Nottingham (reference number: 3417 210812).

Farmer and Veterinarian Selection

Addresses of all veterinary practices registered with the Veterinary Council of Ireland (VCI) in July 2021 (768 practices) were retrieved from the VCI website (https://www.vci.ie). Each practice was checked to determine if the practice profile included large animal services, according to the VCI. For practices that did not have their profile accessible via the VCI, the veterinary practice's own website was checked. A total of 455 practices included large animal services. Each practice owner was sent the paper questionnaire via post, along with a cover letter asking the owner to distribute the questionnaire to veterinarians within the practice. Three surveys were returned undelivered by the postal service; therefore, a final subset of 452 surveys were received by veterinary practices.

A list of addresses were provided by the Irish Cattle Breeding Federation (ICBF) for farmers that had consented to allowing Teagasc access to their information in July 2021 (10,325 farmers). Due to financial and time constraints preventing us sending the survey to all farmers, a subset of 6,500 farmers were randomly selected and sent the paper questionnaire by post. Alongside each questionnaire and cover letter, a prepaid envelope to return the questionnaire were included. The cover letter stated the study aims, and that the study was anonymous, entirely voluntary, for research purposes and that results may be used in publications and conference presentations. Prior to survey distribution, both surveys were reviewed by three researchers outside of the research team. The farmer survey was also piloted on two dairy farmers and the veterinary survey on two veterinarians prior to sending out the survey. Postal surveys were sent to both veterinarians and farmers in September 2021.

An online version of each questionnaire was also produced on Microsoft Forms (Microsoft Corporation, Washington). The link to the corresponding questionnaire was also provided on the paper version, allowing the respondent the option to complete the questionnaire in his or her desired format. This also allowed for multiple veterinarians in a single practice to complete the questionnaire. The links were also posted on social media outputs to advertise the questionnaire to both veterinarians and farmers. Additionally, Veterinary Ireland (representative body for veterinary surgeons in Ireland) publicized the online veterinary survey via email to their members. The online veterinary survey was also advertised to delegates at the Cattle Association of Veterinary Ireland (CAVI) conference. The online surveys were closed and any remaining postal surveys were disregarded after 30th November 2021.

Questionnaire

The first section of the veterinarian questionnaire obtained demographic information including gender, date of birth, background prior to veterinary school (rural, urban, or a combination), location of veterinary school, year of graduation, postgraduate education, veterinary practice location, practice position and proportion of time spent treating cattle. The second section consisted of nine statements relating to the use of analgesics in dairy cows; veterinarians were asked if they agreed or disagreed with each statement. The third section asked for which procedures and conditions the respondent would provide NSAIDs and for what proportion of cases, and what they would consider an acceptable total cost for a course of pain relief for each procedure and condition. The fourth section asked veterinarians to rate the pain of 12 conditions and nine procedures that relate to cows or calves, when provided no pain relief, on a ten-point scale from one (no pain) to ten (worst imaginable pain). The fifth section consisted of questions to determine the veterinarians' empathy toward animals. As created by Norring et al. (24), this section included statements from the perspective taking (PT) and empathy concern (EC) subscale of the IRI (22), reworded to focus on empathy toward animals rather than humans. The PT subscale rates the respondent's ability to adopt the point of view of others, whereas the EC subscale rates the respondent's ability to feel sympathy and concern for others [IRI (22)]. Veterinarians were asked to score 14 statements on a five-point scale from zero (does not describe me well) to four (describes me very well). The final section related to lameness in dairy cows; questions pertained to the veterinarian's involvement with lameness on their clients' farms, education on lameness and pain management, views on current lameness management on dairy farms and lameness treatment (results from this section are not included in this paper).

The farmer questionnaire was similar to the veterinarian questionnaire described above. The first section obtained demographic information including gender, date of birth, highest level of education (26), background prior to farming, number of years full time farming, farm location and herd size. The second section (opinions on the use of analgesics) was identical to the veterinary survey, as was section four (pain assessment) and five (empathy assessment). The third section asked for which procedures and conditions the respondent would like a cow or calf under their care to receive pain relief that lasted $\geq$24 h, and what they would consider an acceptable total cost for a course of pain relief for each procedure and condition. The final section included questions relating to lameness in dairy cows, including the use of pain relief, veterinarian involvement and lameness management (results from this section are not included in this paper).

Statistical Analysis

Data from both the veterinarian and farmer paper questionnaires were input into Excel 2016 (Microsoft Corporation, Washington) and merged with data from the online version of the questionnaire. Data cleaning was undertaken to identify and correct errors within the dataset. All descriptive analysis and modeling was completed using R version 3.3.1 (R Core Team, Vienna, Austria).

Logistic regression models were used to assess the difference in agreement between veterinarians and farmers for the eight statements regarding opinions on analgesics. Statement agreement was the binary outcome variable (1 = respondent agrees; 0 = respondent disagrees). The model predictor was respondent group (veterinarian or farmer). For each statement, an additional logistic regression model was also built through backwards selection using a range of additional predictors (gender, age, background, farm or practice location, region, and empathy score). Predictors were removed one at a time (based on highest *P*-value) until all variables in the model had at least one significant category ($P < 0.05$). Multicollinearity was checked using variance inflation factor (27) and goodness of fit using the Hosmer-Lemeshow test (28).

Pain scores for each condition and procedure were compared between veterinarians and farmers using the Mann Whitney U test (Wilcoxon Rank Sum Test), and violin plots were produced to show data distribution. Using Spearman's rank correlation coefficient, the relationship between the percentage of farmers that would like NSAIDs used for each condition and procedure, and the median farmer pain scores was determined. The relationship between the percentage of veterinarians that use NSAIDs in ≥50% of cases for each condition and procedure [same threshold as used by Remnant et al. (8)], and the median veterinarian pain scores was also established. Separately for farmer and veterinarian respondents, the relationship between median pain scores across all conditions and procedures and empathy score at respondent level were also assessed using Spearman's rank correlation coefficient.

Mixed effects logistic regression was performed to model the effects of various predictors on the odds of a farmer wanting NSAIDs to be used. A second mixed effect logistic regression model was performed to model the effects of various predictors on the odds of whether veterinarians used NSAIDs in ≥50% cases. For both models, predictors included the condition and procedure, pain score for each condition and procedure, demographic information and statements regarding analgesia. Predictors were checked for non-zero variance, and were not included in the models if non-zero variance occurred. Data for modeling was structured such that each unit of data represented one procedure or condition for one respondent. A random effect term to reflect respondent was also included. The final models were selected via backwards selection based on significance; variables were kept in the model if at least one category had a P-value < 0.05. Multicollinearity was assessed using variance inflation factor (27) and model fit was checked using the Hosmer-Lemeshow test (28). Odds ratios were calculated based on coefficient estimates.

RESULTS

In total, 1,002 farmer surveys were received. Nine hundred and twenty five were completed due to the farmer receiving the survey via post (of these, 822 returned the paper version and 103 completed the online version instead), resulting in a response rate of 14% percent (925/6,500). The remaining 77 online survey responses were as a result of social media engagement; therefore, a response rate could not be calculated.

A total of 116 veterinarian surveys were received. One-hundred and two surveys were completed due to the practice receiving the postal survey (of these, 86 returned the paper version and 16 completed the survey online). This provided a response rate of 23% (102/452); however, multiple responses may have been from a single veterinary practice which would therefore lower this response rate. An additional 14 surveys were completed online due the survey being advertised via Veterinary Ireland, the CAVI conference and social media. Information in regards to the demographics of both farmer and veterinarian respondents can be found in **Table 1**.

TABLE 1 | Demographics of farmers (n = 1,002) and veterinarians (n = 116) that completed a survey on attitudes to pain and analgesic use in pasture-based dairy cows.

Demographics	Farmer	Veterinarian
Age (yrs)		
Median (IQR)	51 41–59	48 35–59
Gender (%)		
Female	5.0	21.7
Male	94.8	78.3
Other	0.2	0.0
Background (%)		
Rural	95.2	77.2
Rural & Urban	4.2	14.0
Urban	0.6	8.8
Veterinary school location (%)		
Ireland	n/a	82.6
Other	n/a	17.4
Graduation (yr)		
Median (IQR)	n/a	1994 (1983–2007)
Additional qualifications (%)		
None	n/a	60.2
Certificate	n/a	26.5
Diploma	n/a	5.3
Postgraduate	n/a	9.7
Highest level education (%)		
None	1.4	n/a
Level 3 (junior certificate)	22.8	n/a
Level 4 & 5 (leaving certificate)	44.7	n/a
Level 6 (higher/advanced certificate)	2.0	n/a
Level 7 & 8 (bachelor degree)	24.8	n/a
Level 9 & 10 (masters & doctorate)	4.4	n/a
Farm/veterinary practice location (%)		
Munster	57.9	46.3
Ulster	6.9	4.6
Leinster	30.5	25.5
Connacht	4.7	23.6
Position		
Partner/clinical lead	n/a	70.8
Employee	n/a	29.2
Proportion time treating cattle (%)		
Median (IQR)	n/a	65 (50–90)
Full time farming (yrs)		
Median (IQR)	31 (20–40)	n/a
Herd size (cows)		
Median (IQR)	110 (75–165)	n/a

For categorical variables the percentage of respondents in each category are reported and for continuous variables the median and interquartile range (IQR) are reported.

Opinions on Pain and Analgesics

Differences in the opinions on pain and analgesics between veterinarians and farmers can be viewed in **Table 2**. Significant differences between farmer and veterinarian agreement were found for four out of the seven statements. In addition to the difference found between veterinarians and farmers, it also appeared that the odds of a farmer and veterinarian agreeing with "Analgesics may mask deterioration in the animal's condition" was higher when the respondent's age was between 40 and 50, or >50, compared to <40, and when the respondent's empathy score was >40 compared to <30. For two of the statements where no difference was found between veterinarians and farmers, other factors were shown to affect agreement. The odds of a farmer and veterinarian agreeing with "Farmers do not know enough about controlling pain in cattle" was lower when the respondent's empathy score was between 31 and 40, and >40, compared to <30. The odds of a farmer and veterinarian agreeing with "Vets do not discuss controlling pain in cattle with farmers enough" was also lower when the respondent's age was between 40 and 50 compared to <40, and when the respondent's empathy score was >40 compared to <30.

NSAID Use and Cost

Table 3 reports the proportion of farmers that would like a cow to receive NSAIDs for a range of conditions and procedures, and the proportion of veterinarians that give NSAIDs for ≥50% of cases for a range of conditions and procedures. Surgical procedures, of both calves and cows, were the conditions or procedures for which the highest proportion of farmers (86–98%) stated that they would like NSAIDs used. For surgical procedures, the proportion of veterinarians that would give NSAIDs for ≥50% of cases ranged from 65 to 88%. The proportion of farmers that stated they would like NSAIDs used was generally higher than the proportion of veterinarians that stated they give NSAIDs for ≥50% of cases for all conditions, with the exception of mastitis.

The acceptable cost of a course of analgesia for each condition and procedure selected by both respondent groups is also reported in **Table 3**. For both veterinarians and farmers, calf procedures had the lowest acceptable cost for a course of analgesia; the highest proportion of respondents selected €0–5. Whereas, cow surgical procedures generally had the highest acceptable cost for both famers and veterinarians. For eight conditions and procedures, a proportion of farmers selected €0 as the acceptable cost, even though they stated they would like NSAIDs used for these conditions and procedures.

Pain Scores

Figure 1 shows distributions of pain scores, as given by farmers and veterinarians for each condition and procedure, using violin plots. The median of the mean pain score across all conditions and procedures was 6.2 (IQR = 5.4–6.9) for farmers, and 6.4 (IQR = 5.7–7.0) for veterinarians. Both veterinarians and farmers gave the highest median pain score to acute toxic *E-coli* mastitis and digit amputation, giving these a score of nine. Farmers also gave a cesarean section a median pain score of nine. Neither respondent groups had a median pain score of ten for any condition and procedure. The lowest median pain score was three, which was given for neck callouses by both veterinarians and farmers and for mastitis (clots in milk only) by farmers only. Veterinarians scored a swollen hock, mastitis (clots in milk only), digital dermatitis, white line separation (no abscess), white line abscess, and treatment of a sole ulcer significantly higher than farmers. Farmers scored a left displaced abomasum (LDA), LDA surgery and a cesarean section significantly higher than veterinarians.

NSAID Use and Pain Scores

Figure 2 shows the percentage of farmers that would like NSAIDs used for each condition and procedure, plotted alongside median farmer pain scores for the same condition and procedure. This figure also shows the percentage of veterinarians that use NSAIDs in ≥50% of cases for each condition and procedure, alongside median veterinarian pain scores for the same condition and procedure. There was a correlation of 0.9 ($P < 0.05$) between the percentage of farmers that would like NSAIDs used and median farmer pain scores, and a correlation of 0.7 ($P < 0.05$) between the percentage of veterinarians that use NSAIDs in ≥50% of cases and median veterinarian pain scores.

Factors Associated With NSAID Use

Factors associated with NSAID use by veterinarians and farmers are shown in **Tables 4**, **5**, respectively. Conditions or procedures with pain scores >3 had higher odds of NSAID use by both veterinarians and farmers compared to conditions and procedures with pain scores ≤3. Different conditions and procedures were also associated with different levels of NSAID use by both veterinarians and farmers even after accounting for confounding factors such as the pain score for each of these conditions and procedures. Notable conditions and procedures that resulted in low NSAID use by veterinarians given the relatively high pain score included white line abscess, white line separation (no abscess) and castration of calves using Burdizzo. Conditions and procedures that resulted in low NSAID use by farmers given the relatively high pain score included white line separation (no abscess), mastitis (clots in milk only), calving with no assistance required and castration of calves using Burdizzo.

After accounting for condition and pain score, veterinarians that graduated more recently, and veterinarians that agreed that "Farmers are happy to pay the costs involved with giving analgesics to cattle" and "Farmers do not know enough about controlling pain in cattle" had higher odds of NSAID use. After accounting for condition and pain score, farmers who completed the paper survey (as opposed to the online survey), only completed education up to level three (as opposed to level four and five), had a smaller herd size, agreed that "Cattle recover faster if given analgesic drugs", "Farmers do not know enough about controlling pain in cattle" and "Vets do not discuss controlling pain in cattle with farmers enough," and disagreed that "Analgesics may mask deterioration in the animal's condition" had higher odds of NSAID use.

Empathy and Pain Scores

The median farmer empathy score was 38 (IQR = 31–44) and the median for the subscales empathetic concern and perspective taking were 21 (IQR = 18–25) and 17 (IQR = 13–20), respectively. The median veterinarian empathy score was 37 (IQR = 30–45) and the median for the subscales empathetic concern and perspective taking were 20 (IQR = 16–25) and 17 (IQR = 12–21), respectively. No significant correlation was found between median pain scores and empathy scores for either farmers or veterinarians.

DISCUSSION

Pain compromises animal welfare and can reduce dairy cow productivity. To enable pain to be alleviated, pain must firstly be recognized by both farmers and veterinarians. Farmers and veterinarians gave similar pain scores when averaged across all conditions and procedures. Contrastingly, Thomsen et al. (13) reported that Danish farmers generally scored pain as more severe compared to veterinarians. In the current study, farmers

TABLE 2 | The agreement of farmers and veterinarians with statements relating to analgesia and pain in cattle, in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows.

Statement	Veterinarian agreement (%)	Farmer agreement (%)	*P*-value	
Analgesics may mask deterioration in the animal's condition	25	38	0.006	**
Cattle benefit from receiving analgesic drugs as part of their treatment	98	90	0.012	*
Some pain is necessary to stop the animal becoming too active	15	18	0.371	
Cattle recover faster if given analgesic drugs	97	75	0.000	***
Drug side effects limit the usefulness of giving analgesics to cattle	10	12	0.397	
Farmers are happy to pay the costs involved with giving analgesics to cattle	63	75	0.006	**
Farmers would like cattle to receive analgesia but cost is a major issue	26	30	0.356	
Farmers do not know enough about controlling pain in cattle	70	63	0.133	
Vets do not discuss controlling pain in cattle with farmers enough	57	56	0.994	

*Statistical differences between the agreement of veterinarians and farmers are reported for each statement, based on logistic regression models (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).*

and veterinarians commonly perceived the same conditions and procedures as most painful; acute toxic *E-coli* mastitis and digit amputations were considered to be associated with the most severe pain. Similar findings have been reported previously, whereby digit amputation was reported as most severe by UK (8, 9) and New Zealand (10) veterinarians and E.coli mastitis by Danish veterinarians and farmers (13). Pain scores in this study can be used as a baseline for farmers and veterinarians to determine whether pain is being underestimated by themselves and to further assess whether they are appropriately treating this pain.

Differences in pain scores were, however, found between veterinarians and farmers for some conditions and procedures. Farmers scored LDA, LDA surgery and a cesarean section significantly higher than veterinarians. A possible explanation is that veterinarians see these procedures and conditions as routine, whereas for farmers these are rare and severe occurrences. In contrast, veterinarians gave significantly higher pain scores to lameness related conditions [digital dermatitis, white line separation (no abscess), white line abscess, and treatment of a sole ulcer], mastitis (clots in milk only) and hock hair loss compared to farmers. Becker et al. (29) also reported that the treatment of sole ulcer was scored significantly more painful by veterinarians than farmers. Similarly to the explanation above, it would be uncommon for veterinarians to be called out to farms for these conditions or procedures; they are often mild and treatable by the farmer, or a hoof trimmer may treat lameness related issues. Contrastingly, farmers would see these conditions and procedures on a day-to-day basis. This demonstrates that farmers and veterinarians can become habituated to the pain of certain conditions because of frequent exposure. It is important for cow welfare that efforts are made to prevent this "habituation" of pain.

Once pain is recognized, it can then be treated. Non-steroidal anti-inflammatory drugs block the release of prostaglandins, reducing inflammation, fever and pain (30). As opposed to anesthesia, which is generally used for short-term pain relief during surgical procedures, NSAIDs can provide longer-acting relief from pain. In agreement with previous studies, the higher the pain score for a particular condition or procedure, the more likely a veterinarian was to give NSAIDs (8, 9). Similarly, the recognition of more severe pain by dairy farmers was associated with an increased willingness for NSAIDs to be given. These associations also remained true when other factors, such as gender, were accounted for in multilevel models. This shows that both veterinarians and farmers are reasonably good at recognizing pain, and treat accordingly through the administration of NSAIDs.

Cow surgical procedures generally resulted in the highest NSAID use by both veterinarians and farmers. Despite this, the indicated NSAID use was still lower than that reported for the UK for these surgical procedures (8). It must be noted that these procedures will still be carried out under local anesthetic; however, local anesthesia alone does not offer the long-term post-operative pain relief that NSAIDs can provide. In contrast to cow surgical procedures, the use of NSAIDs by veterinarians for surgical castration of calves and disbudding was much higher in this study compared to the UK (8). However, the UK study was carried out 5 years prior to the current study, and it is expected that NSAID use in calves will have subsequently increased over this timeframe.

Some conditions and procedures seemed to have low NSAID use despite being assigned relatively high pain scores. Remnant et al. (8) also identified that the type of condition or procedure influenced NSAID use by veterinarians; however, no studies to date have used multilevel modeling to assess the willingness for NSAIDs to be given by dairy farmers. The use of NSAIDs in calves, despite the relatively high pain score, was low for castration using Burdizzo for both veterinarians and farmers. Similar was found for veterinarians in the UK; however, Remnant et al. (8) also identified disbudding to have low NSAID use relative to the pain perceived, whereas the current study showed a higher level of NSAID use for disbudding. Studies have shown that providing NSAIDs for calf castration has physiological and behavioral benefits (31, 32). The British Veterinary Association and Veterinary Ireland have both produced a position statement stating that they consider it best practice to provide NSAIDs for castration (33, 34); however, this study shows that more needs to be done to increase awareness on NSAID use and the benefits to calf welfare.

TABLE 3 | Proportion of farmers that would like a cow to receive NSAIDs for different conditions and procedures, and the proportion of veterinarians that give NSAIDs for ≥50% of cases for each condition and procedure, in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows.

Condition/procedure	Proportion farmers that would like a cow to receive NSAIDs for each condition/procedure (%)	Proportion veterinarians using NSAIDs for ≥50% of cases for each procedure/condition (%)	Proportion of respondents who selected the following as an acceptable cost for a course of analgesia for each procedure/condition (%)[a]									
			Farmers					Veterinarians				
			€0	€0–5	€5–15	€15–30	>€30	€0	€0–5	€5–15	€15–30	>€30
Disbudding (calf)	64	62	3	65	22	8	2	0	79	17	4	0
Burdizzo Castration (calf)	44	32	2	57	27	11	3	0	82	18	0	0
Surgical castration (calf)	86	65	2	42	36	14	7	0	67	29	4	0
Digit amputation	97	88	0	7	26	32	34	0	3	27	43	27
Sole ulcer treatment	80	75	0	21	46	26	7	0	10	45	41	3
Sole hemorrhage	63	54	1	24	47	23	6	0	16	52	31	2
White line abscess	74	64	0	23	46	23	8	0	13	46	34	7
White line (no abscess)	35	34	2	23	46	21	9	0	10	58	30	3
LDA surgery	91	72	1	11	30	26	32	0	9	46	39	6
Mastitis	26	42	1	27	38	23	10	0	21	37	38	4
Cesarean section	98	76	0	6	22	27	45	0	4	44	36	16
Dystocia	73	68	0	15	33	27	24	0	9	51	32	7
Calving (no assistance)	6	n/a	10	20	37	18	14	n/a	n/a	n/a	n/a	n/a

The acceptable cost selected for a course of analgesia for each condition and procedure is also reported. [a]Includes farmers that stated they would like a cow to receive NSAIDs for each condition/procedure and veterinarians that used NSAIDs for at least one case for each condition/procedure.

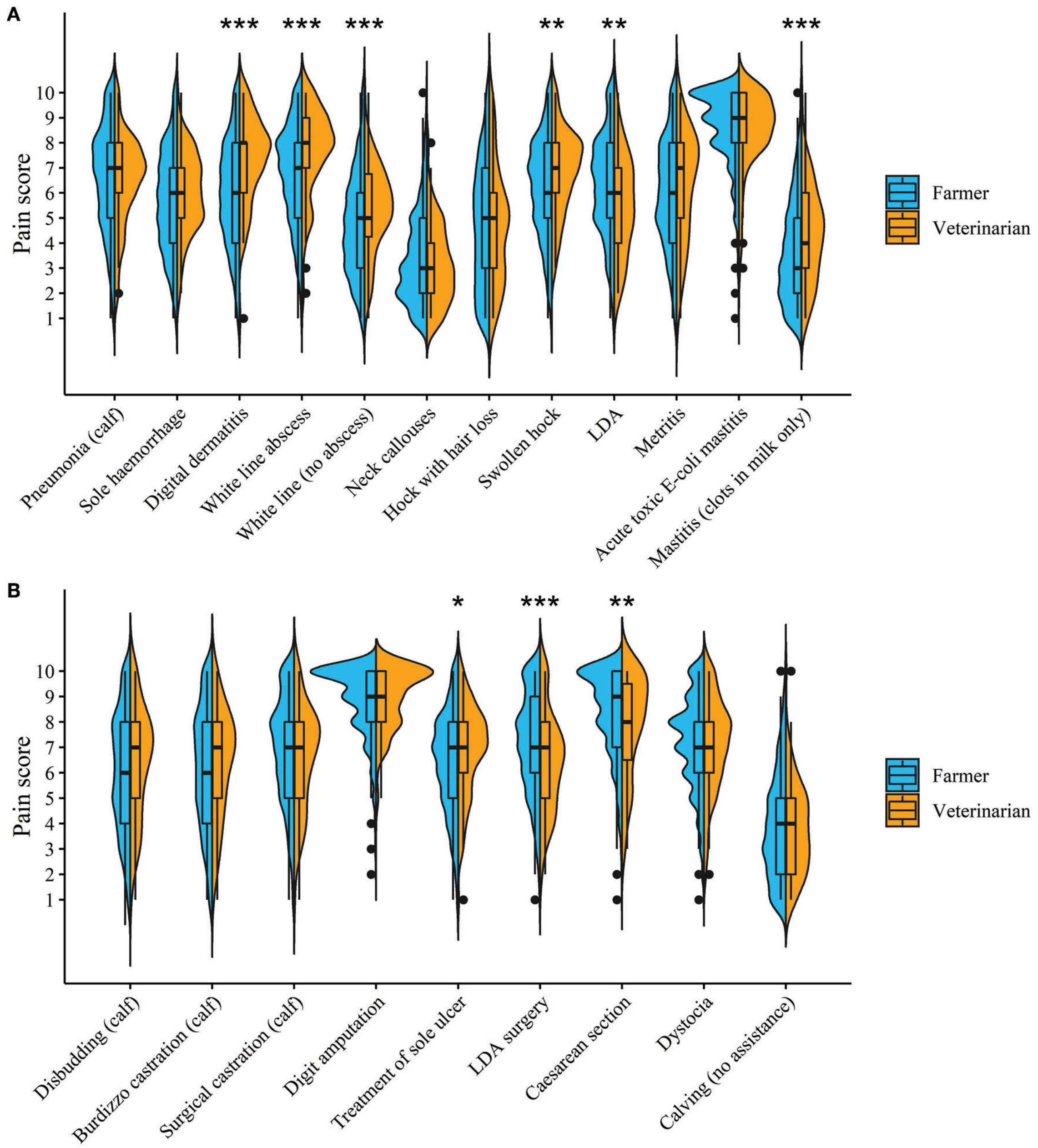

FIGURE 1 | Violin plots showing the distribution of pain scores for different conditions **(A)** and procedures **(B)** split for farmers and veterinarians, in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows. Overlaid boxplots show the median and interquartile range. Significant differences in pain scores between veterinarians and farmers are indicated (***$P < 0.001$, **$P < 0.01$, *$P < 0.05$).

Veterinarians were also significantly less likely to use NSAIDs, after accounting for the effect of pain score, for white line separation (no abscess) and white line abscess, and farmers were significantly less likely to want NSAIDs given for white line separation (no abscess) and mastitis (clots only). Mastitis and lameness are both common endemic diseases within the dairy industry, and while prevention is vital for controlling these diseases, appropriate treatment is equally important. Providing NSAIDs has been reported to reduce clinical signs of mastitis (35–37) and improve production measures (37, 38). In terms of lameness, Thomas et al. (16) reported that cure rates were improved if NSAIDs were provided on top of a therapeutic trim and block, in newly lame cows. However, a pasture-based study in New Zealand disagreed with these findings, showing no difference in locomotion score or nociceptive threshold between treatment groups (39). More studies are required to evaluate the benefits of NSAIDs for lameness in terms of cure rates, pain

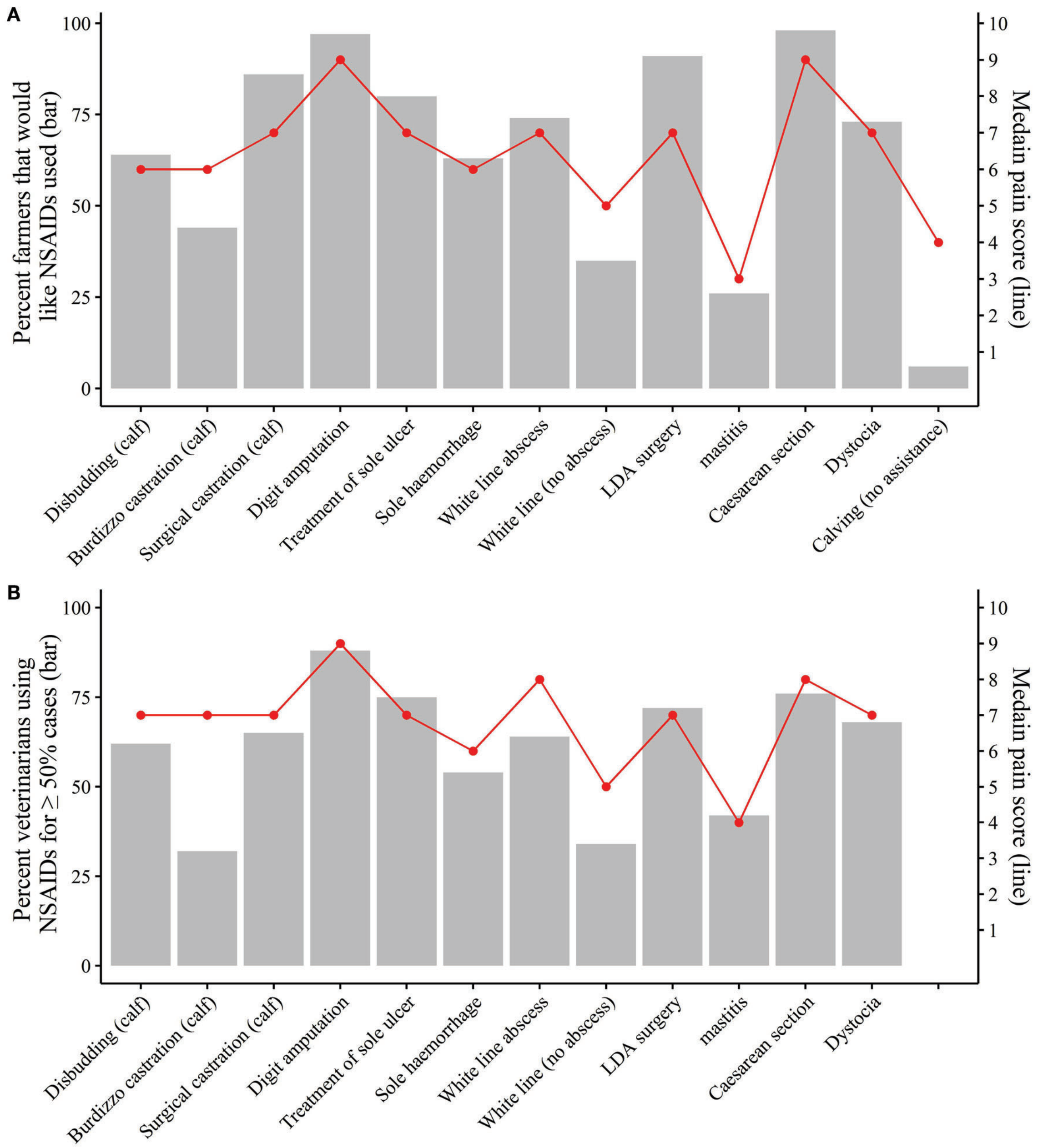

FIGURE 2 | Percentage of farmers that would like NSAIDs used for each condition and procedure (**A**; gray bars) and the percentage of veterinarians that use NSAIDs in ≥50% of cases for each condition and procedure (**B**; gray bars), in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows. Median pain scores are also shown across each condition and procedure for farmer (**A**; red line) and veterinarians (**B**; red line).

reduction and impact on production measures in different system types.

The biggest difference in the willingness of farmers to want NSAIDs given, relative to the pain score, was seen with calving (when no assistance was required). Despite a pain score of four, only 6% of farmers wanted NSAIDs given at calving. There is inconsistency in the reported effects of NSAIDs on cow welfare and performance at calving. Some studies have reported positive results of improved milk yield, reproductive performance and a reduction in uterine diseases (40, 41), whereas, other studies have shown no improvement in these factors (42). Additionally, Wilson et al. (43) reported reduced lameness and culling when heifers were given NSAIDs at their first and subsequent calvings; however, no effects where seen in cows that had already calved prior the commencement of the study. Despite the variation in results in terms of physiological benefits, it must also be considered that NSAIDs could improve cow welfare by reducing the pain during parturition (44, 45).

TABLE 4 | Results of a mixed effects logistic regression model that determined factors associated with NSAID use in dairy cows by veterinarians, in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows.

Predictor		Estimate	Odds ratio	*P*-value	
Condition					
	Dystocia	Reference			
	Cesarean	0.642	1.90 (1.90–5.21)	0.212	
	Treatment of sole ulcer	0.455	1.58 (1.58–3.84)	0.316	
	Sole hemorrhage	−0.681	0.51 (0.51–1.18)	0.113	
	White line abscess	−0.891	0.41 (0.41–0.99)	0.045	*
	White line (no abscess)	−1.932	0.14 (0.14–0.35)	0.000	***
	Digit amputation	2.105	8.21 (8.21–34.3)	0.004	**
	LDA surgery	1.318	3.73 (3.73–9.46)	0.005	**
	Mastitis	−0.664	0.51 (0.51–1.25)	0.139	
	Disbudding (calf)	−0.145	0.86 (0.86–2.04)	0.739	
	Surgical castration (calf)	0.124	1.13 (1.13–2.75)	0.784	
	Burdizzo castration (calf)	−2.403	0.09 (0.09–0.23)	0.000	***
Pain score					
	≤3	Reference			
	4	1.119	3.06 (3.06–7.10)	0.009	**
	5	1.571	4.81 (4.81–10.52)	0.000	***
	6	2.028	7.6 (7.60–16.78)	0.000	***
	7	2.284	9.81 (9.81–21.55)	0.000	***
	8	3.127	22.80 (22.80–52.83)	0.000	***
	9	4.267	71.29 (71.29–227.47)	0.000	***
	10	3.896	49.18 (49.18–160.94)	0.000	***
Graduation year					
	<1991	Reference			
	1991–2005	1.902	6.70 (6.70–16.8)	0.000	***
	2006–2021	2.595	13.40 (13.40–35.7)	0.000	***
Statement F[a]					
	Disagree	Reference			
	Agree	0.843	2.32 (2.32–5.10)	0.035	*
Statement H[b]					
	Disagree	Reference			
	Agree	0.961	2.61 (2.61–6.12)	0.027	*

*The binary outcome variable was whether the veterinarian used NSAIDs in ≥50% cases for each procedure and condition (1 = respondent used NSAIDs in more ≥50% cases, 0 = respondent did not use NSAIDs in more ≥50% cases). ***, **, * odds ratio is significantly different from 1 (P < 0.001, 0.01, 0.05) [a]Farmers are happy to pay the costs involved with giving analgesics to cattle [b]Farmers do not know enough about controlling pain in cattle.*

In addition to pain score and condition, year of graduation from veterinary school was also associated with NSAID use by veterinarians. Veterinarians graduating more recently had higher odds of giving NSAIDs, which is consistent with findings from previous studies (8). It is theorized that this may due to views on animal welfare and the perception of pain changing over the generations, or that veterinarian's sensitivity to pain may decrease with experience of treating painful conditions and carrying out procedures. As such, it is important that veterinarians continue professional development though courses and workshops relating to the recognition of pain to ensure pain perception is not desensitized over time.

Farmers that completed the survey via post had significantly higher odds of wanting NSAIDs used than those that completed the survey online. A possible theory is that completing the survey on paper and making the effort to post the survey, may demonstrate more commitment and an interest in the area of pain relief. Farmers that had completed education up to level three used more NSAID than those that completed education up to level four or five. There is no clear explanation as to why education to a higher level would seem to result in lower NSAID use; further research may be required to understand the reasons behind this finding.

Interestingly, herd size was associated with the odds of a farmer wanting NSAIDs used on their dairy cows. Farmers with larger herds had lower odds of NSAID use compared to those with smaller herd sizes. Farmers with smaller herds may be more aware and able to recognize the pain of individual cows. Those with larger herds may also be more mindful of profit margins and want to minimize the cost of NSAID use. Currently the

TABLE 5 | Mixed effects logistic regression model to determine factors associated with the use of NSAIDs in dairy cows by farmers, in a survey investigating attitudes to pain and analgesic use in pasture-based dairy cows.

		Estimate	Odds Ratio	*P*-value	
Condition					
	Dystocia	Reference			
	Cesarean	2.977	19.64 (11.48–33.79)	0.000	***
	Treatment of sole ulcer	0.859	2.36 (1.81–3.1)	0.000	***
	Sole hemorrhage	−0.053	0.95 (0.74–1.23)	0.680	
	White line abscess	0.215	1.24 (0.96–1.62)	0.103	
	White line (no abscess)	−1.294	0.27 (0.22–0.36)	0.000	***
	Digit amputation	2.533	12.59 (7.62–20.91)	0.000	***
	LDA surgery	2.153	8.61 (6.24–11.95)	0.000	***
	Mastitis	−1.519	0.22 (0.17–0.29)	0.000	***
	Disbudding (calf)	−0.146	0.86 (0.68–1.12)	0.250	
	Surgical castration (calf)	1.173	3.23 (2.44–4.31)	0.000	***
	Burdizzo castration (calf)	−1.451	0.23 (0.19–0.3)	0.000	***
	Calving (no assistance)	−3.940	0.02 (0.02–0.03)	0.000	***
Pain score					
	≤3	Reference			
	4	0.711	2.04 (1.64–2.56)	0.000	***
	5	1.346	3.84 (3.10–4.81)	0.000	***
	6	1.581	4.86 (3.90–6.12)	0.000	***
	7	2.013	7.48 (5.99–9.49)	0.000	***
	8	2.506	12.26 (9.59–15.80)	0.000	***
	9	3.098	22.14 (16.12–30.88)	0.000	***
	10	3.170	23.81 (16.78–34.13)	0.000	***
Survey format					
	Online	Reference			
	Paper	0.524	1.69 (1.30–2.23)	0.000	***
Education (highest level)					
	3	Reference			
	4 & 5	−0.429	0.65 (0.51–0.84)	0.001	***
	6	0.228	1.26 (0.56–2.83)	0.579	
	7 & 8	−0.166	0.85 (0.63–1.14)	0.271	
	9 & 10	−0.030	0.97 (0.58–1.65)	0.913	
	None	0.458	1.58 (0.66–3.82)	0.308	
Herd size (cows)					
	30–100	Reference			
	101–150	−0.292	0.75 (0.59–0.96)	0.018	*
	>150	−0.294	0.75 (0.58–0.96)	0.020	*
Statement A[a]					
	Disagree	Reference			
	Agree	−0.211	0.81 (0.66–1.00)	0.043	*
Statement D[b]					
	Disagree	Reference			
	Agree	0.660	1.94 (1.56–2.44)	0.000	***
Statement H[c]					
	Disagree	Reference			
	Agree	0.257	1.29 (1.05–1.62)	0.022	*
Statement I[d]					
	Disagree	Reference			
	Agree	0.262	1.3 (1.06–1.62)	0.016	*

*The binary outcome variable was whether farmers would like NSAIDs used for a cow under their care for each procedure and condition (1 = respondent wants NSAIDs used, 0 = respondent does not want NSAID used). ***, * odds ratio is significantly different from 1 (P < 0.001, 0.05) [a]Analgesics may mask deterioration in the animal's condition [b]Cattle recover faster if given analgesic drugs [c]Farmers do not know enough about controlling pain in cattle [d]Vets do not discuss controlling pain in cattle with farmers enough.*

majority of farmers believe that they are not educated enough on controlling pain and that veterinarians do not discuss controlling pain enough with farmers. Similar finding were found in UK farmers, whereby 62% of farmers did not feel educated enough on pain relief and 53% felt that veterinarians did not discuss the use of pain relief enough with farmers (25). This study also showed that knowledge on pain relief increased the willingness of farmers to use NSAIDs. Farmers should be educated on the benefits on NSAID use in terms of both welfare and profitability. A quarter of veterinarians also agreed with the statement "Analgesics may mask the determination in the animal's condition." This shows that veterinarians may also benefit from further education on pain relief within the dairy sector. This may also lead to improved knowledge transfer from veterinarians to farmers.

Empathy was not shown to affect NSAID use by either veterinarians or farmers in the multilevel model used. However, it appeared that empathy affected agreement with some statements regarding veterinarian and farmer opinions on analgesia and pain, of which some of these statements were shown to affect NSAID use in the multilevel model. Therefore, there does seem to be some link between empathy and NSAID use; however, it is unclear to what extent. The same was true for age of the respondent. There was also no correlation found between pain scores and empathy scores in this study, which contrasts to Norring et al. (24) where more empathetic veterinarians gave higher pain scores to bovine conditions and procedures. Comparing these studies, Irish veterinarians and farmers both showed lower empathy compared to Finnish veterinarians when using the same animal focused IRI (24). The difference in empathy scores may be due to gender differences between the two study populations. The majority of veterinarians in the Finnish study were female (91%), whereas, the majority of veterinarian (78%) and farmers (94%) in the current study were male. Previous work has reported that males are generally less empathetic than females, and therefore score lower on the IRI (46–48). The lower empathy score may also be due to cultural differences between countries.

With production costs rising (49) and tight profit margins, cost is also an important factor to consider when looking at NSAID use. Significantly more farmers than veterinarians agreed that "Farmers are happy to pay the costs involved with giving analgesics to cattle." This indicates that farmers are more willing to pay for NSAIDs than veterinarians perceive. Going forward, NSAIDs should be offered more readily by veterinarians when treating cattle. Compared to previous studies, the cost of NSAIDs seems to be less of a concern. Remnant et al. (8) reported that 45% of UK veterinarians agreed that "Farmers would like cows to receive analgesia but cost is a major issue," whereas in the current study only 25% of veterinarians agreed with this statement.

Calf procedures, including castration and disbudding, were given the lowest acceptable cost for a course of analgesia by both veterinarians and farmers. This may indicate that farmers are willing to pay more for pain relief of cows compared to calves. The lower acceptable cost may also be due to the smaller doses of pain relief required due to the reduced body weight of calves. The approximate cost of NSAIDs for disbudding and castration per calf is <€2, however, this price will vary depending on the NSAID brand and supplier, and the body weight of the calf. It must be noted that in Ireland disbudding of calves of up to 15 days, castration using Burdizzo up to 6 months and castration using a rubber ring up to 8 days can be performed by the farmer without the use of anesthetic (50, 51). Thermal cauterization is the only method of disbudding that is legal in Ireland (50, 51). There is also no legal requirements to use NSAIDs for disbudding and castration at any age currently in Ireland, however, it has been recommended (52). Some farmers also selected that €0 was an acceptable cost for a course of NSAIDs for some conditions and treatments, despite saying they wanted NSAIDs used. This indicates that a small number of farmers would like NSAIDs used but at no additional cost. This was particularly true for calving, where 10% of farmers wanted NSAIDs used but believed the acceptable cost to be zero.

It must be acknowledged that farmers and veterinarians had the choice to participate in this survey. Respondents may have chosen to participate due to an interest in pain relief management, equally respondents may have chosen to complete the survey to gain further insight into the use of pain relief in dairy cows. It is therefore hard to state definitely that the study population is fully representative; however, a large sample size was obtained, and as such, is as representative as possible. The response rate in this survey was 23% for veterinarians and 14% for farmers. The veterinary response rate in this study was higher than that in the study by Remnant et al. (8), however, lower than in other pain studies (9, 11, 39). The farmer response rate was similar to that of Huxley and Whay (25) and lower than that of Thomsen et al. (13). As with all voluntary surveys non-response bias must be considered when interpreting the results. Voluntary recruitment may lead to bias in prevalence reported estimates (53), such as pain scores in this study. However, sampling via voluntary surveys compared to mandatory sampling has been shown not to affect associations between variables in human health risk factor studies (53). If the same applies to this study, associations between various factors and NSAID use should not be affected by sampling bias. A high proportion of veterinary respondents in this study were also partners or clinical leads, therefore results may not be representative of all veterinarians in Ireland. Additionally, only 22% of veterinarian respondents were female; however, according to the VCI, 44% of veterinarians in Ireland are female (54). However, this statistic included both large and small animal veterinarians. It is therefore expected that a lower number of females specialize in large animal practice compared to small animal.

CONCLUSION

Farmers and veterinarians generally considered the same conditions and procedures as more severe; however, some differences in pain scores were seen for particular conditions and procedures. Lower pain scores were generally given by veterinarians for conditions and procedures which would be seen more regularly by veterinarians compared to farmers, and vice versa, highlighting potential habituation to pain. The recognition of pain was found to be an important attribute for increased NSAID use by both farmers and veterinarians. However, some conditions and procedures were shown to have low NSAID use relative to the pain score given. Pain scores should be used as a benchmark for veterinarians and farmers to determine their perception of pain and how this affects their NSAID use. Cost of analgesia did not seem to be as big a barrier to use for farmers as veterinarians perceived. NSAIDs should therefore be offered more readily prior to painful procedures and where the animal is experiencing a potentially painful condition. Education on the benefits of analgesia is vital for increasing NSAID use within the dairy industry and for improving animal welfare.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because data from this study contains potentially identifiable human information (gender, location, herd size etc.) for individual farmers and veterinarians. Requests to access the datasets should be directed to Natasha Browne, natasha.browne@hotmail.co.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the School of Veterinary Medicine and Science Committee for Animal Research and Ethics (CARE) at the University of Nottingham (reference number: 3417 210812). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MC received funding for the study. CH and MC supervised this study. NB sent the surveys and input all data. NB analyzed the data and drafted the manuscript and with the assistance of CH and MC. All authors contributed to study design, read, and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2022.912564/full#supplementary-material

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Chapter 2: General discussion

2.1 Overview and discussion of findings

A large-scale lameness study was carried out on 99 pasture-based dairy farms during the housing period, and on 85 of the same farms during the housing period (Papers 1 – 3). Paper 1 reported the most important risk factors for lameness in a pasture-based system, based on both the grazing and housing period (Paper 1). Elastic net regression and mBIC were used to enable a large number of potential predictors (from both questionnaires and on-farm measurements), to be included in the model, without overfitting occurring. Triangulation and bootstrapping ensured both between-model variation and within-model variation were accounted for, identifying a robust set of risk factors for lameness. In Paper 2, the herd-level lameness prevalence was reported for both the housing and grazing periods. This paper also identified current lameness management practices and infrastructure on Irish pasture-based dairy farms, highlighting the challenges around lameness control in these dairy herds. In Paper 3, a proportion of the lame cows identified in Paper 2 had their hind hooves examined and the prevalence of different lesion types were reported. Associations between different lesion types, associations between lesion type and lameness severity, and risk factors for digital dermatitis were also examined in this paper. Paper 4 presented the results of a questionnaire on attitudes to pain and NSAID use for various conditions and procedures (including those associated with lameness) in Irish pasture-based dairy cows, comparing the results of farmers with those of practicing veterinarians that work with dairy cows.

The lameness prevalence (LS2 and LS3 on a 0-3 scale) reported on Irish dairy farms in this study was 7.9% during grazing and 9.1% during housing. To compare, recent studies within the UK reported the lameness prevalence to be 30% (Randall et al., 2019) and 32% (Griffiths et al., 2018). The same lameness scoring system was used in all three studies, however, Randall et al. (2019) and Griffiths et al. (2018) both scored cows as they left the milking parlour, whereas in Paper 1 cows were scored one at a time as they left the crush. The experience of the scorer, and scorer subjectivity, must also be considered when comparing lameness prevalence across studies and systems. Irish farmers should still aim to achieve lower levels of lameness due to financial, ethical and environmental reasons. It was estimated that in Ireland a single lameness case costs an average of €300 (Ryan and O'Grady, 2004); therefore, reducing lameness even further will improve farm profits. It is also likely that the cost of lameness has further increased since 2004. Decreasing the herd lameness prevalence also reduces the number of animals in pain, thus improving animal welfare and the public perception of dairy farming. Lameness also increases culling and reduces survival within the herd, which has a role to play in environmental sustainability. The European Food Safety Authority (EFSA, 2009) states that a lameness prevalence of less than 2% is achievable on dairy farms, and that if lameness prevalence reaches close to 10% management is inadequate. This indicates that there is scope to further reduce lameness within the Irish pasture-based system.

Pasture-based systems are generally perceived by the consumer to benefit animal welfare (Sweeney et al., 2022). Despite this, few countries have the climate that allows cows to be out to pasture for the entire year. The typical Irish system of grazing cows for the majority of the year and housing for a short time over the winter period, therefore, may become a viable option for dairy farmers across the globe in the future, as consumer demand for higher-welfare methods of food production increases. Despite this, recent studies within the UK reported that time spent housed, as opposed to grazing, was not associated with lameness (Griffiths et al., 2018; Randall et al., 2019). Other aspects (e.g. cubicle bedding), in addition to lameness, must also be considered when examining the overall welfare status of the pasture-based system.

In the Irish pasture-based system, non-infectious lesions were the most common lesion type found in lame dairy cows; with white line separation, sole haemorrhages and overgrown claws as the most common lesion types (Paper 3). This is in contrast to fully housed systems, where infectious lesions are found to be most prevalent (Cramer et al., 2008; Solano et al., 2016). Identifying the most prevalent lesion types helps to pin point a focus for lameness prevention.

Age had the largest effect of all predictors on the risk of lameness in the Irish pasture-based system (Paper 1). A history of lameness has previously been reported to increase the risk of future lameness events (Randall et al., 2018). This is partly supported by the finding that 39% of cows that were lame during the grazing visit were also lame at the housing visit (Paper 2). However, lameness scoring in this study only took place at two time-points; therefore, it is unclear if cows were recurrently lame or lame for the entire period between grazing and housing. Although aging cannot be stopped, with the exception of culling, reducing first-time lameness events through prevention, and prompt and efficient detection and treatment may prove key to decreasing lameness risk. A balance is needed between increasing culling for welfare reasons, and minimising culling due to environmental and financial sustainability, ethics and public perception. Despite the benefits of effective prevention and treatment, only 15% of farmers had a herd health plan for lameness (Paper 2). Farmers may benefit from collaborating with their veterinarian to produce a tailored plan on the best ways to prevent and treat lameness, which will ultimately help to mitigate the effect of aging within the herd.

Genetic PTA for lameness also had a large impact on the risk of lameness within Irish dairy herds (Paper 1), which agrees with previous lameness research in Ireland (O’Connor et al., 2020a). This is an important finding that supports the use of genetic selection for reducing lameness long-term. To reduce the risk of lameness in a cow’s offspring and improve genetic potential, the farmer must select a bull with a lower PTA for lameness than the cow (ICBF, 2020). Improving the quantity and quality of lameness records across farms will further enable a reduction in lameness through genetic selection. However, currently only approximately one fifth of dairy farmers kept records of lame cows (Paper 2), which indicates huge scope for improvement. Recording of lameness events and hoof lesions would help improve genetic evaluation. Irish farmers can record lameness events through the Irish Cattle Breeding Federation.

Despite high average distances between the collecting yard and milking parlour (average total daily walking distance of nearly 2000 m; Paper 2), farms with a larger grazing platform and herd size had lower risk of lameness (Paper 1). This agrees with results from some previous studies (Dippel et al., 2009a; Solano et al., 2015), but is in contrast to others (Alban, 1995). Within grazed systems, there is worry that expansion may result in increased lameness due to the further distances cows would have to walk (Boyle et al., 2015); however, this study does not support this suggestion. It has previously been proposed that these larger farms in general have better management compared to the smaller farmer, thus reducing lameness (Dippel et al., 2009a). Therefore, farmers must not assume that increasing farm size, based on this study, will reduce lameness without considering the need to invest in infrastructure and improve lameness management protocols.

Slats on the cow tracks near the collecting yard entrance, stones in the paddock gateways and a tight turn at the milking parlour exit were all found to be risk factors for lameness (Paper 1). As reported in Paper 2, 26% of farms had slats present within the first 50 m following the collecting yard, 19% had stones as the surface material in the paddock gateways, and the median distance cows had to turn after milking was 2.5 m. These risk factors for lameness reported may increase shearing forces on the hooves and reduce cow flow, which can lead to white line separation. This may help explain the high prevalence of white line separation reported in Irish dairy herds (Paper 3). White line separation was reported on all farms in this study; Somers and O'Grady (2015) also reported that white line disease was present in all herds visited. The higher prevalence of foreign bodies within the hoof sole during the grazing period

(14% of lame cows), compared to the housing period (7% of lame cows), may also be indicative of stones on the cow tracks and gateways (Paper 3).

Factors associated with the farmer's perception of both lameness and digital dermatitis in their herd were also identified as risk factors for both lameness (Paper 1) and digital dermatitis (Paper 3). This identified that farmers in Ireland are particularly aware of lameness and digital dermatitis within their herds. In contrast, studies in other countries have found low lameness perception among farmers (Leach et al., 2010; Sadiq et al., 2019). Despite farmers in Ireland having this awareness, only 31% footbathed more than once per month (Paper 2), despite 44% of farmers reporting that they had digital dermatitis present in the herd within the last year. This indicated that although farmers are aware of the problem, they may not be preventing or treating accordingly. To compare, in a UK study of 61 herds, over 90% of farmers carried out routine footbathing (Griffiths et al., 2018). Footbathing may be lower in Ireland as it is considered more beneficial in fully housed herds where digital dermatitis prevalence is generally higher. It is plausible that if only pasture-based herds were surveyed within the UK, footbathing may be equally low.

In Paper 3, some cow track characteristics were also identified as risk factors for digital dermatitis; this included verge and track width at 50 m following the collecting yard and stone presence on the cow tracks. It is proposed that small verges decreased the risk for digital dermatitis due to cows having to walk on the track, whereas if the verge was larger cows would walk on the grass verge creating muddy conditions (Tuohy et al., 2017). The median verge width on farms was 0.45 m, which would be classified as small (Paper 2). Farms with more narrow roadways near the collecting yard (relative to the herd size) had reduced risk of digital dermatitis. This may be due to farmers being more likely to keep the area clean if the cow track is narrower; the median cow track width at 50 m following the collecting yard was 4.31 m (Paper 2). For the cow track nearest the collecting yard, the width should be 5.08 m for the average herd-size in this study (116 cows) according to Irish government specification (DAFM, 2021). Stone presence may also be associated with digital dermatitis due to skin trauma caused around the hoof, which allows bacteria to enter. Approximately 60% of farms had at least one cow track measurement that was rough or very rough (Paper 2). This indicates that poor quality roadways may be a factor leading to digital dermatitis in pasture-based dairy herds.

In Paper 3, associations were also reported between a cow having digital dermatitis and heel erosion at cow-level, and having digital dermatitis and interdigital hyperplasia, sole ulcer and toe necrosis at herd-level. This identifies that these lesions may have a similar causative mechanism or have similar risk factors to digital dermatitis; this is likely the case for the infectious lesion heel erosions. Digital dermatitis may also be a secondary lesion following a primary lesion; this is thought likely the case for the non-infectious lesions (Kofler, 2017). Preventing digital dermatitis through preventative management may, therefore, reduce the prevalence of the infectious lesions heel erosion, and prevent toe necrosis and sole ulcers becoming 'non-healing' due to digital dermatitis presence (Evans et al., 2011; Kofler, 2017).

A number of factors were not found to be associated with lameness in Paper 1. These included practices such as routine trimming and hoof trimming. Other infrastructure characteristics, such as those related to housing (e.g. bedding type, cubicle measurements), were also not found to be key risk factors for lameness within the pasture-based system. These may not have been identified in the risk factor analysis as the aim was not to identify as many risk factors as possible but rather to provide a robust set of risk factors. These factors may also not have been identified due to the low number of farms that implement some of these practices. In addition to risk factors identified within Paper 1, Paper 2 reports practices happening on farm that are also likely to be contributing to lameness. Paper 2 showed that many methods of lameness prevention, detection and treatment were not carried out on the majority of Irish pasture-based dairy farms. Only 6% of farms carried out routine hoof trimming, possibly explaining the high number of overgrown claws reported in this study (Paper 3). In contrast, Pedersen et al. (2022) reported that in a UK survey of 338 dairy farms, 82% carried out preventative trimming. This study also reported that farmers that housed their cows for longer tended to have higher odds of carrying out preventative trimming. The lower levels of routine trimming within Ireland could be due to the perception that pasture-based cows do not require preventative trimming, due to long walking distances wearing the hooves. Despite this, overgrown claws were reported to be more common during the grazing period (71% of lame cows), compared to the housing period (55% of lame cows). Furthermore, on over half of farms, all pens contained less than 1.1 cubicles per cow, and on 12% of farms, all or a proportion of cubicles had no matting or bedding (bare concrete only). Having ten percent more cubicles than cows is best practice (Huxley et al., 2012; FAWAC, 2019). A quarter of farmers also prevented cows from returning straight back to pasture following milking; cows were held back until milking was finished. These aspects increase the time cows spend standing on hard concrete flooring and decrease lying times (Gomez and Cook, 2010), which can increase lameness risk (Espejo and Endres, 2007; Jewell et al., 2019). These factors possibly indicate why a relatively high prevalence of sole haemorrhages were reported in Irish dairy herds (Paper 3).

Routine lameness scoring by the farmer was only carried out on one farm in the study (out of 99 farms). Lameness scoring is important to detect individual lame cows, to allow farmers to compare their lameness prevalence against other herds, and to see how their lameness prevalence changes over time (Archer et al., 2010). The use of pain relief to treat lame cows was also low on Irish dairy farms; only 8% of farmers used pain relief on severely lame cows. Additionally, nearly 30% of farmers waited over two days to treat a lame cow, and approximately one fifth of farmers reported waiting until multiple cows were lame before treating a single lame cow. Given the fairly low lameness prevalence in Irish herds, the waiting time could be prolonged between detection and treatment, decreasing the chance of recovery and causing a welfare concern. Thomas et al. (2015, 2016) reported that NSAIDs in conjunction with a trim and block maximised recovery in newly lame cows; however, the same response was not shown in chronically lame cows, highlighting the importance of prompt and effective treatment. All these factors highlight that there is huge scope for improvement in lameness management on Irish dairy farms.

The low use of pain relief in lame cows (Paper 2), was the basis for carrying out the study on attitudes to pain and the use of NSAIDs in pasture-based dairy cows, comparing both veterinarians and farmers (Paper 4). Paper 4 included conditions and procedures relating to lameness in dairy cows, as well as other conditions and procedures of cows and calves. This approach allowed results from this study to be compared to similar surveys on pain relief carried out in New Zealand (Laven et al., 2009), the UK (Huxley and Whay, 2006; Remnant et al., 2017) and across Europe (Thomsen et al., 2010; Thomsen et al., 2012). Including a range of procedures and conditions also allowed pain scores and NSAID use to be compared across those that are related to lameness and those that are not.

Digit amputation and acute toxic E-coli mastitis were given the highest pain scores, compared to other conditions and procedures, by both farmers and veterinarians (Paper 4). Digit amputation (Huxley and Whay, 2006; Laven et al., 2009; Remnant et al., 2017) and E-coli mastitis (Thomsen et al., 2012) were also reported as the most painful in previous studies. In Paper 3, digit amputation also had the highest odds of a cow being severely lame, compared to other hoof lesions. This indicates that farmers and veterinarians are aware of how painful the amputation procedure is, and that even after amputation the cow had high odds of remaining severely lame, or becoming severely lame again. Generally, veterinarians and farmers reported that the same conditions and procedures were the most painful (Paper 4); however, veterinarians were shown to score lameness-related conditions and procedures, mastitis (clots in milk only) and hock hair loss as more painful than farmers, and farmers scored cow surgical procedures more painful than veterinarians. It is theorised that this is due to farmers and veterinarians becoming 'habituated' to painful conditions and procedures they see on a regular basis. Continued education and the collaboration of veterinarians and farmers regarding when NSAIDs should be used, may improve the recovery and welfare of dairy cows. In addition, farmers seemed more willing to pay for NSAIDs than veterinarians perceived, which suggests there is further scope for discussion on NSAID use and that veterinarians should offer NSAIDs more regularly where required. Despite this, both farmers and veterinarians seemed less willing to accept the cost of analgesia for calf procedures (castration and disbudding), than cow conditions and procedures.

Multilevel modelling was carried out to identify factors that affect NSAID use by veterinarians and farmers. For both veterinarians and farmers, conditions and procedures with higher pain scores were associated with higher NSAID use (Paper 4). However, relative to pain score, castration with Burdizzo, white line separation and white line abscess were associated with lower NSAID use by veterinarians. Similarly, Remnant et al. (2017) reported low NSAID use for routine calf procedures, including castration with Burdizzo. Paper 3 reported that white line abscess resulted in higher odds of a cow scoring LS3 as opposed to LS2; despite this, use of NSAIDs was found to be low by veterinarians (Paper 4). Relative to pain score, castration with Burdizzo, white line separation, mastitis (clots in milk only) and calving with no assistance were associated with lower willingness for NSAIDs to be used by farmers (Paper 4). This emphasises that both farmers and veterinarians need further training on the benefits of analgesia, particularly for these conditions and procedures where NSAID use is low relative to the pain score given.

Paper 4 also determined that veterinarians that graduated more recently used more NSAIDs. This was also reported by Remnant et al. (2017) in a UK study on attitudes to pain. It is positive that attitudes towards pain relief may be changing; however, continued training may be required throughout a veterinarian's career to ensure NSAIDs continue to be used where required. Farmers that appeared to have increased knowledge of NSAIDs, also used more NSAIDs. This indicates that farmers would also benefit from training on the benefits of NSAID use.

Farmers with a larger herd were also associated with lower odds of using NSAIDs (Paper 4). Despite this, Paper 1 reported that larger herds were associated with lower odds of lameness. However, it must be acknowledged that Paper 4 included a range of conditions and procedures, and not just those related to lameness. In addition, lameness is multifactorial in nature; therefore, a large range of factors contribute to lameness risk. Farmers that completed the survey online (as opposed to the paper version) and completed education up to level four and five (as opposed to level three) were also associated with lower odds of NSAID use. Interestingly in this study, empathy was not directly associated with pain score or NSAID use, by either veterinarians or farmers; this is in contrast to Norring et al. (2014b) who reported an association between veterinary pain score and empathy score. Empathy was, however, associated with the response to some statements on the opinion of pain and pain relief in dairy cows, of which these statements were associated with NSAID use by farmers and veterinarians. This implies that empathy and NSAID use may be associated in some way.

2.2 Practical implications and direction for the dairy industry

Paper 1

- For a pasture-based herd in Ireland, the grazing period had greater influence on lameness risk, compared to the housing period. Farmers should focus on mitigating the impact of these grazing risk factors identified (e.g. slats on the roadway near the collecting yard, stones in paddock gateways and a sharp turning distance at the milking parlour exit). Despite this, farmers still need to maintain their housing infrastructure and management to ensure high levels of animal welfare.

- The results of the lameness risk factor analysis suggest that, in general, farmers who consider themselves to have a lameness problem are largely correct. This provides useful information to the dairy industry, and can be used in targeting messaging around lameness management.
- This paper provides support for using the PTA for lameness in dairy cow breeding programs. Farmers should be encouraged to use this sub-index as a long-term lameness prevention strategy.

Paper 2

- The low lameness prevalence reported during both the grazing and housing period, relative to other nations, provides scope for further advertising the benefits of a pasture-based dairy system in the selling of sustainable Irish dairy produce. Despite the lameness prevalence being relatively low, farmers should still aim to reduce it further to improve cow welfare, environmental sustainability and farm profitability.
- The median herd-level lameness prevalence reported can also be used by dairy farmers around Ireland as a benchmark for lameness in their own herd.
- This paper provides a thorough survey of lameness practices on Irish dairy farms, identifying where management practices and infrastructure could be improved (e.g. increasing number of farms that carry out lameness scoring). Advisors can also use information from this paper to determine where their farmers could make improvements. This paper also contains findings that may be relevant to agricultural policy makers, in order to improve animal welfare on Irish dairy farms.

Paper 3

- The most common hoof lesions reported were sole haemorrhages, white line separation, and overgrown claws in lame Irish pasture-based dairy cows during both the grazing and housing periods. Farmers and advisors should consider focusing lameness prevention methods on these lesion types.
- It is also vital to mitigate the risk of a cow developing the most painful lesions (foul of the foot, white line abscess, sole ulcers, toe necrosis, interdigital hyperplasia and digit amputation), as these have the most severe impact on welfare.

Paper 4

- Pain scores reported by both veterinarians and farmers can be used as a benchmark for other Irish dairy farmers and large animal veterinarians to identify how their perception of pain compares to others, and in turn see how this influences their use of NSAIDs.
- It was identified that farmers with more knowledge of pain relief had higher odds of wanting NSAIDs used. Training should be provided to farmers on the benefits of pain relief and thus increase usage and improve dairy cow welfare. In addition, farmers with a larger herd size used less NSAIDs, so there should be an imminent focus on educating farmers with larger herds.
- Veterinarians who graduated more recently used more NSAIDs. Routine training needs to be provided throughout a veterinarian's career to ensure the use of pain relief remains at the forefront of treatment decisions. It also needs to be emphasised to veterinarians that farmers are generally willing to pay for NSAIDs.
- Training in regards to the use of pain relief needs to emphasise the procedures and conditions that have low NSAID use, relative to the pain score, for both veterinarians and farmers. This includes castration with Burdizzo and white line separation for both

veterinarians and farmers, white line abscess for veterinarians, and mastitis (clots in milk only) and calving (non-assistance) for farmers.

- The results of this paper also suggest that veterinarians and farmers can become 'habituated' to pain in procedures and conditions they see on a more routine basis (e.g. surgical procedures for veterinarians, and lameness and mastitis for farmers). This suggests that training should be tailored differently between veterinarians and farmers with a focus on the pain associated with commonly seen procedures and conditions.

2.3 Limitations

Both studies (Papers 1-3 and Paper 4) are considered to have a cross-sectional study design. It must, therefore, be acknowledged that any associations in these papers do not imply causation. The direction of the effect cannot be determined. In the risk factor analysis (Papers 1 and 3), there were also differences observed in the effect size between the two models used (mBIC and Enet), therefore an exact value for the effect size could not be reported. It is, however, likely that the true effect size lies between the values reported in each of the models. Herd and cow were also not included as random effects in the risk factor analysis using Enet and mBIC, however, the potential effect of clustering was evaluated using logistic regression with cow and herd as random effects. There were also missing values within the datasets (Papers 1 and 3); therefore data was imputed prior to the risk factor analysis, which may introduce bias.

Both studies (Paper 1-3 and Paper 4) had potential for bias due to farmers or veterinarians choosing to participate in the study or return the questionnaire, leading to non-response bias. In Paper 4, a high proportion of veterinary leads and partners returned the questionnaire; therefore, the results may not be representative of all veterinarians in Ireland. There is also potential that respondents did not answer all the questions in the questionnaires truthfully, due to the respondent wanting to give more desirable or socially acceptable answers (Paper 1-3 and

Paper 4). For example, farmers may have stated that they use a footbath more frequently (Papers 1-3) or veterinarians may have overestimate their use of NSAIDs (Paper 4).

In Papers 1-3, some infrastructure observations were also subjective and therefore prone to bias, for example, cow track condition and cubicle hardness. Additionally, there may have been bias due to the subjective nature of lameness scoring (Papers 1-3) and the identification of hoof lesions across different observers (Paper 3). A limitation of Paper 2 is that scorer was not included in the model when comparing lameness prevalence between visits, however, within subsequent analysis (Appendix C) scorer was not shown to affect the odds of a cow being scored lame. Inter-observer reliability testing was also carried out for lameness scoring; however, it was not for the hoof lesion identification. Some aspects of the questionnaire in Paper 4 were also subjective; this included the pain scoring and the empathy scoring sections.

In Papers 1-3 lameness scoring only took place at two time-points; it was therefore not possible to identify if cows remained lame or were recurrently lame (Paper 2). Only scoring once during the grazing period and once during the housing period also did not take into account the impact of seasonality on lameness prevalence. Also, due to time constraints, only lame cows had their hooves examined for lesions; therefore no comparison can be made between hoof lesion in lame and sound cows (Paper 3). It is likely that the prevalence of more severe lesions would be higher using the approach used. If both lame and non-lame cows were examined, it is hypothesised that digital dermatitis and milder lesion may have had a higher prevalence. The front hooves of lame cows were also not examined in Paper 3, therefore, lameness may have been occurring as a result of lesions on the front hooves and these lesions were not identified. It is also possible that farmers improved their lameness management as a result of the first visit, influencing the results of the second visit (Papers 1-3). An additional limitation is that PTA reliabilities, which measures the degree of confidence, were not accounted for in the Enet and mBIC models within Paper 1.

2.4 Future Research

Intervention studies need to be carried out on specific risk factors that were identified in the risk factor analysis for lameness (Paper 1). For example, a tight turn at the milking parlour exit was identified as a risk factor for lameness. An intervention study could look at the impact of putting down rubber matting at the parlour exit to see if this mitigates the impact of the tight turn on lameness. Similarly, intervention studies could be carried out based on the risk factors for digital dermatitis identified in Paper 3. An alternative method would be to apply a variety of interventions concurrently on multiple farms, based on risk factors identified in Paper 1, to see how this might affect lameness prevalence in the herd. A similar approach was used in the UK for testing the implementation of a mastitis control program (Green et al., 2007). Based on the low level of footbathing and routine trimming (and high levels of overgrown claws; Paper 3) identified across Irish dairy farms (Paper 2), there may also be benefits to establishing the impact of these prevention methods in a pasture-based system through intervention studies. Similarly, few farmers used NSAIDs to treat lame cows and few farmers used a paddock close to the milking parlour to aid lameness recovery; intervention studies on these factors may be beneficial for a pasture-based system.

Due to the high number of cows that remained lame for long periods of time or were recurrently lame (Paper 2), there would be merit in exploring the dynamics of lameness in pasture-based systems in more detail. This would enable the duration of lameness to be established, as well as identifying the number of new cases, recovered cases, chronic cases and repeat cases throughout an entire season. A study on the prevalence of all hoof lesion types across both lame and non-lame dairy cows across multiple pasture-based dairy herds is also required. Comparing hoof lesions present in both lame and non-lame dairy cows that are managed under the same conditions, would enable painful and non-painful lesions to be identified and allow the identification of lesions that may be visible prior to lameness occurring. It would also be valuable to conduct a study to investigate how the provision of training days for veterinarians and farmers on pain and pain relief in dairy cows might affect the use of NSAIDs across Irish dairy herds. Training should include general benefits of pain relief but also focus on conditions and procedures that have low NSAID use relative to pain score.

2.5 Conclusion

This thesis presents a volume of information on lameness and pain management in Irish pasture-based dairy cows. Data was collected on lameness prevalence, specific hoof lesions and potential risk factors for lameness. This thesis also examined attitudes to pain and NSAID use for a range of dairy cow conditions and procedures, comparing results for both veterinarians and farmers. Results from this thesis provides a base for future studies in the area of lameness and pain management, specifically for a pasture-based dairy system. Knowledge generated will also allow advice to be provided to dairy farmers, veterinarians and advisors on strategies to reduce lameness in pasture-based dairy cows and improve NSAID use within the herd, thus further improving animal welfare and increasing the competitiveness and sustainability of the Irish dairy sector.

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Appendix A: Papers 1-3 combined supplementary material

Producer invitation to participate in research trial

Teagasc
Agriculture and Food Development Authority

Animal and Grassland Research & Innovation Centre
Moorepark
Fermoy
Co. Cork

29/03/2019

RE: Invitation to participate in a Teagasc research trial

Dear Herd Owner,

Ireland's unique pasture-based production system has a long-standing reputation for sustainable and welfare-friendly practices that allow farmers to provide a superior quality product to the market. In order to maintain this image and continue research into the advantages of the Irish dairy industry, it is imperative that we have a clear picture of dairy cow management practices, lameness prevalence and hoof lesion types within the country. Teagasc, in conjunction with the University of Nottingham, and Wageningen University & Research, will be conducting a study with the aim of collecting such data from a cross-section of Irish dairy farms such as yours.

This study will commence in April 2019 and run until February 2020. Each farm that is enrolled in the study will be visited twice; once during the grazing season (sometime between April and August 2019) and once during housing (sometime between October 2019 and February 2020). Each farm visit will be conducted by a team from Teagasc Moorepark, as well as a professional hoof trimmer.

Each visit will consist of:

1) A questionnaire regarding farm and cow management practices
2) Infrastructure and facility measurements (including housing, milking parlour and roadways)
3) Cow measurements and observations (including body condition scoring and mobility scoring to identify lame cows)

From ICBF records, your farm has been identified as a potential candidate for inclusion in this study, and we would like to offer you the opportunity to take part. Benefits from participation in this study include:

- Herd report outlining:
  - Mobility scores of all cows (carried out by a qualified scorer)
  - Herd-level body condition scores
  - A benchmark of your farm scores compared to other participating farms in the study (anonymously)

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Teagasc

Agriculture and Food Development Authority

- Teagasc will provide free hoof trimming for up to 20 cows identified as lame
    - Trimming will be carried out by a professional hoof trimmer on the day of the visit
    - Any trimming products required will be provided free of charge

Places are limited, and eligible farms will be enrolled on a first-come, first-served basis, so if you would like to take part in the study, please reply as soon as possible to a member of the research team by email or phone at cowcare.study@teagasc.ie or 0873308428. We may follow up with a phone call in the near future.

We thank you for taking the time to read this letter and would be very grateful for your participation in this study.

Sincerely,

Dr. Muireann Conneely (Principal Investigator)

Robin Crossley (PhD. Candidate)

Natasha Browne (PhD. Candidate)

Katie Sugrue (Research Technologist)

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Questionnaire and infrastructure measurements

At each visit, the questionnaire was conducted with the farmer by one member of the research team (out of a pool of five people). Each of the four team members were familiar with the survey and had practiced the questionnaire with pilot farmers prior to the study starting. Similarly, the infrastructure measurements were carried out by the research team. The team consisted of seven people who were trained to carry out the measurements. Whilst one team member conducted the questionnaire, two team members carried out the cow track measurements. Following completion of the survey and cow track measurements, measurements of the milking parlour, collecting yard, and the housing facilities were taken by the team. On some farms, placements students accompanied members of the research team to help take measurements. The questionnaire and measurement recording forms can be viewed below.

Lameness in pasture-based dairy cows (supplementary material): Farmer questionnaire

Questionnaire 1 – Grazing visit

Farm: Date: Interviewer:

Respondent:

Background

1. What is the size of your grazing platform this year (Ha/Ac)?
____

2. How many people work on your farm (including family members)?
   i. Full time ____
   ii. Part time ____________ # Days/week _______________________

3. Have you expanded your farm in the last 5 years?
   ☐ Yes
   ☐ No

   i. If yes, please specify how:

Increased milking cow numbers	Increased grazing area (Ha/Ac)

   ii. If yes, please tick all that apply:

	New build	Renovated
Roadways	☐	☐

4. Are you planning to expand in the next 5 years?
   ☐ Yes - How? ____
   ☐ No
   ☐ Don't know/ maybe

5. Current number of milking cows? ___________________________________

6. Do you ever buy/bring in new stock (tick all that applies)?
   - ☐ None
   - ☐ Heifers
   - ☐ Cows
   - ☐ Bulls
   - ☐ Calves
   - ☐ Other – Specify____

7. On what date are cows:

	Date
Turned out to pasture **full time this year (2019)**	
Housed **full-time last year (2018)**	

Milking

8. In general, how many times do you milk per day?
   - ☐ 1x/day
   - ☐ 2x/day
   - ☐ 3x/day
   - ☐ Other

   i. Does this ever change?
   - ☐ Yes – specify ____
   - ☐ No

9.

How are cows brought to the collecting yard?	How are cows brought into the parlour from the collecting yard?	How do cows exit the parlour?
☐ On-foot ☐ Motorised vehicle ☐ Other – specify ______________	☐ On their own ☐ Herd them always ☐ Herd when required ☐ Backing gate ☐ Other – specify _______________	☐ On their own ☐ Voice ☐ Physical ☐ Other – specify ______________

10. Is a dog present when moving the cows to/from the parlour?
   - ☐ Yes
   - ☐ No

11. How long are cows held in the collecting yard before milking?

Minimum time (mins)	Maximum time (mins)

12. During grazing, are cows held after milking?
    - ☐ Yes, every day – How long? ____
    - ☐ Yes, some days – How long? ______________________________________
    - ☐ No

Grazing and roadways

13. Do you have any cows that graze in a separate group?
    - ☐ No
    - ☐ Lame cows
    - ☐ Sick cows
    - ☐ Other – Specify____

14. Is the total walking distance ever a factor when deciding the order to graze paddocks? (e.g. do you alternate close and far paddocks)
    - ☐ Yes -When? ____
    - ☐ No ____

15. How often are the following repaired/maintained?

Roadways	Paddock entrances/gateways
☐ Once/year ☐ Twice/year ☐ Once/2 year ☐ Never ☐ Other – specify ___________________________	☐ Once/year ☐ Twice/year ☐ Once/2 year ☐ Never ☐ Other – specify ___________________________

16. What is the distance between the paddocks and the parlour?

Closest paddock	Furthest paddock	Generally

17. Is the furthest paddock part of your regular grazing rotation?

    ____

18. What materials are used in your main (most used) roadways?
    a. Surface ____
    b. Base ____

19. Are the roadways used by farm machinery or only animals?
    ☐ Cows only
    ☐ Cows and Machinery
    ☐ Combination – Specify _______________________________________

20. Do the cows ever have to cross a road?
    ☐ Yes
        i. How many times? ____________________________________
    ☐ No

21. Are there any over/underpasses on your cow roadways?
    ☐ Yes
    ☐ No

Lameness prevention

22. Do you have a herd health plan document?
    ☐ Yes
        i. Created by yourself only ☐
        ii. Created with vet input/review ☐
    ☐ No (***If no go to 24***)

23. Does your herd health plan include lameness protocols (e.g. footbathing)
    ☐ Yes
    ☐ No

Foot bathing

24. Do you use a footbath? (***If no, go to 29***)
    ☐ Never
    ☐ If required
    ☐ Yes – How often? _______________________________________
        Product used? _______________________________________

25. Do you ever use antibiotics in a footbath?
    ☐ Yes – How often? _______________________________________
        Reason? ____
    ☐ No

26. After how many cows would you change the footbath?

____

27. Do you clean the cows feet prior to using a disinfectant-containing footbath?
   - ☐ No
   - ☐ Using a hose
   - ☐ Using a footbath containing water
   - ☐ Other – specify ___________________________

28. Did you receive advice on your foot bathing method, if so, by who?
   - ☐ No
   - ☐ Vet
   - ☐ Foot trimmer
   - ☐ Teagasc advisor
   - ☐ Other – specify ___________________________

Routine herd trimming

29. Have you/ staff received hoof trimming training
   - ☐ No
   - ☐ From experienced staff members
   - ☐ Course – specify ___________________________
   - ☐ Other – specify ___________________________

30. Do all the cows, whether lame or not, undergo routine hoof examinations/ trimming in the year? (***If no, go to 34***)
   - ☐ Yes – How often? ___________________________
   - ☐ No

31. When do routine herd hoof examination/ trimming take place?
   - ☐ At drying off
   - ☐ Early lactation
   - ☐ Mid-lactation
   - ☐ Other – specify ___________________________

32. Are both the front and back feet examined/trimmed at the routine hoof examination?
   - ☐ Yes, both
   - ☐ Back only
   - ☐ Sometimes – specify ___________________________

33. Who performs the routine hoof trimming/examination?
- ☐ Myself
- ☐ Farm staff
- ☐ Foot trimmer
- ☐ Vet

Lameness detection

34. What methods are used to detect cows that are lame or have impaired mobility?

____
____
____

35. Who detects lameness/ impaired mobility?
- ☐ Myself
- ☐ Farm staff
- ☐ Foot trimmer
- ☐ Vet
- ☐ Other – specify ____

36. Are you familiar with mobility scoring?
- ☐ Yes
- ☐ No

37. Do you perform mobility scoring:

Yes *	**No**	**Frequency**	**System** (e.g. 0-3 MS scale)	**Training received - Y/N, how?** (e.g. shadow or course)	**Who scores?**
☐	☐				

** Scoring using a formal scoring scale.*

38. Do you keep specific lameness records?
- ☐ If medicated
- ☐ If trimmed
- ☐ If seen lame
- ☐ No

Lameness treatment

39. Approximately, how many cows were treated for lameness in 2018?

____

40. How quickly after identifying a lame cow do you treat her?
    - ☐ < 12 hrs.
    - ☐ <24 hrs.
    - ☐ < 48 hrs.
    - ☐ Within a week
    - ☐ Other – specify ____

41. Who treats lame cows?
    - ☐ Myself
    - ☐ Farm staff
    - ☐ Foot trimmer
    - ☐ Vet

42. Do you wait for a number of cows to be lame before treating?
    - ☐ Yes – How many? ____
    - ☐ No

43. Under what circumstances do you call a vet out to treat a lame cow?

____
____
____

44. Under what circumstances do you call a foot trimmer to treat a lame cow?

____
____
____

45. How do you treat a mildly lame cow?

____
____
____

46. How do you treat a severely lame cow?

____
____
____

47. Do you re-examine the foot after the initial treatment?

- ☐ Yes
- ☐ No
- ☐ Only if still lame

48. If a bandage is applied as part of a treatment, do you remove the bandage?

- ☐ No
- ☐ Yes – after how many days? ____
- ☐ Never needed to bandage

Lameness in pasture-based dairy cows (supplementary material): Farmer questionnaire

Questionnaire 2 – Housing visit

Farm: Date: Interviewer:

Respondent:

Updates

1. Have you made changes to any of the following management procedures **since our last visit** (if yes, please specify how):

Mobility Scoring	☐ Yes ☐ No	
BCS	☐ Yes ☐ No	
Footbathing	☐ Yes ☐ No	
Foot Trimming	☐ Yes ☐ No	
Other		

2. Have you started to use any new facilities since our last visit?
   - ☐ Yes – What/when? ____
   - ☐ No

Housing

3. On what date were the cows housed full time this year (2019)________________

4. Are your cows kept in more than one group during housing? (*If no, go to number 7*)
   - ☐ Yes
   - ☐ No

5. During housing, how are cows grouped?
   - ☐ Calving date
   - ☐ BCS
   - ☐ Parity/lactation
   - ☐ Other – Specify____

6. Do assigned groups change during the housing period (e.g. based on BCS)?
   - ☐ Yes - How/when? ______________________________
   - ☐ No

7. When are heifers first introduced to the main herd?

   ____

8. How were heifers housed previously?
   - ☐ Slats
   - ☐ Cubicles
   - ☐ Other – Specify ______________________________

9. What do you use to clean the passageways and how often?

	Select	Frequency (in 24hr period)
Automatic scraper	☐	
Robot	☐	
Tractor with scraper	☐	
Manual	☐	
Other	☐	
None	☐	

10. How often are the cubicles :

Cleaned?	Re-bedded/Limed?
☐ Once/day	☐ Once/day
☐ Twice/day	☐ Twice/day
☐ Other______________	☐ Other______________
☐ Never	☐ Never

Nutrition

11. During the 2019 lactation, how much was provided of:

	Total	Is this typical (Y/N)?	If 'No', what is typical?
Concentrate (kg per cow)		☐ Yes ☐ No	
Minerals		☐ Yes ☐ No	

12. What are cows fed when housed (including minerals)?

	Feed type & Approx. amount *(kg/cow if possible)*
Dry Cows	
Milking Cows	
Other groups	

13. How many times/day are cows delivered fresh feed?
    - ☐ Once/day
    - ☐ Twice/day
    - ☐ Once every 2 days
    - ☐ Other ____

14. How often do you push-in feed?
    - ☐ Once/day
    - ☐ Twice/day
    - ☐ Other ____

Other

15. In the current lactation (calving to dry off, 2019) approximately how many cases of mortellaro (digital dermatitis) have you had in your milking herd? ____________

Producer Demographics *(if more than one full-time farmer involved, include both)*

16. In what year were you born?
    - ☐ _______________
    - ☐ Prefer not to say

17. How long have you been farming full time (years)?

    ____

18. Have you attended any type of agricultural education program (e.g. Green Cert)?
    - ☐ Yes – Specify ____
    - ☐ No

19. Do you participate in a Knowledge Transfer program?
    - ☐ Yes
    - ☐ No

Lameness perception

20. Do you think lameness is a problem on your farm?
    - ☐ Yes
    - ☐ No
    - ☐ Other – Specify ____

21. Do you think the number of lame cows or cows with impaired mobility has increased or decreased over the past 2 years?
    - ☐ Increased
    - ☐ Decreased
    - ☐ Stayed the same

Visit 1 - Collecting yard & parlour

Farm Number	
Date	
Observer	

Farm Diagram

Section 1 - Collecting Yard & Parlour

Shape: Square/ Rectangle ☐ Round ☐ **Obvious Slope** Yes - up ☐ Yes - down ☐ No ☐

Dimensions (m):	**Length**	**Width (mid-point)**	**Height (centre)**	**OR**	**Diameter**
Yard entrance width (m):					

Is the yard covered? Yes ☐ No ☐ Partly ☐ % Covered ________

Backing Gate: Yes ☐ No ☐

Brushes:	Yes ☐ #: ____	No ☐	Stationary ☐	Rotating ☐

Yard Flooring Type:	Smooth concrete ☐	grooved concrete ☐	Slats ☐	Rubber ☐	Slatted rubber ☐
% of area:					

Collecting yard photo ☐

Total # milking units: _______ **Double-up style?** Yes ☐ No ☐

Parlour style		**Cow divisions (tick all that apply)**		**Flooring**		
				Type		**% area**
Side-by-side	☐	Open/none	☐	Smooth concrete	☐	
Herring-bone (zig-zag manger/ rail)	☐	Head partition	☐	grooved concrete	☐	
Rotary (inside facing)	☐	headlocks	☐	Slats	☐	
Rotary (outside facing)	☐	Sequential Bailing	☐	Rubber	☐	
Robotic	☐	Rapid-Exit	☐	Slatted rubber	☐	

Parlour Photo ☐

Floor slipperiness at parlour entrance:
☐ slippery, little to no grip, easy spinning
☐ Somewhat slippery, some grip but can still slide or spin
☐ Not slippery, good grip on abrasive surface, can't slide or spin

Does parlour entrance or exit have:	Step up/down	Slope	Turns?	→ 90° turns	→ 180° turns	Doors (Human size)	Obstruct-ions	Lighting*
Entrance	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	
Exit	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	

*Bright = can easily read a newspaper from the centre of the pen.
Dim = Can read, with minimal strain, in the centre of the pen.
Dark = Very difficult/impossible to read from centre of the pen.

Distance from milking unit to end (m):__________

Flooring Type at exit:	Smooth concrete ☐	grooved concrete ☐	Slats ☐	Rubber ☐	Slatted rubber ☐
% of area:					

Floor slipperiness at exit:

☐ slippery, no grip, easy spinning

☐ Somewhat slippery, some grip but can still slide or spin

☐ Not slippery, good grip on abrasive surface, can't slide or spin

Exit Photo ☐

Foot bath:	None ☐	Permanent ☐	Temporary ☐	Step-up ☐	Step-down ☐
Footbath photo ☐	Length _______	Width ______	Height/ depth ______		

Visit 1 - Sheds (booklet per pen)

Farm Number	
Date	
Observer	
Shed #	

Diagram (if needed)

Visit 1 - Sheds (booklet per shed)

Section 2 - Shed Features (all housing types)

Housing Type: Cubicles ☐ Loose ☐ **Covered?** Yes ☐ No ☐ Partly ☐ _____% covered

Cow area dimensions (m): Length: _________ Width: ________

Is area separated by feed alley? No ☐ Yes ☐ Width (m): _______

Roof height : At centre/peak: _______ At outer edge 1: _____ At outer edge 2: _______

 # Open sides (at least 50% open): long sides _______ short side _______

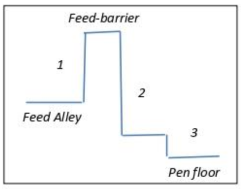
Width (m)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Feed passages							
Passages							
Cross-over alleys							

Does feed alley act as cross-over? Yes ☐ No ☐

Height of feed surface above pen floor: Outside *(1)* ________ Inside *(2)* ________

Is there a step up on the pen side? Yes ☐ *(3)* Height: ______ No ☐

Total Feedface length (m): ________



Auto Scrapers: Yes ☐ No ☐

Scraper type (all that apply):	Cable ☐	Track ☐	Above surface ☐	Recessed ☐	Robot ☐

Flooring Type:	Smooth concrete ☐	grooved concrete ☐	Slats ☐	Rubber ☐	Slatted rubber ☐
% of area:					

Brushes:	Yes ☐ #: ____	No ☐	Stationary ☐	Rotating ☐

Section 3 - Cubicles features (cubicle housing only)

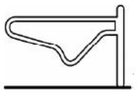
 # rows (single line of cubicles): ___________

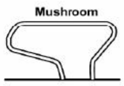
Number of cubicles: Head-to-head: ___________ Facing wall: _________ Open Facing: ________

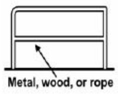
Cubicle base: Concrete ☐ Wood ☐ Sand ☐ Soil ☐
Other: ___________

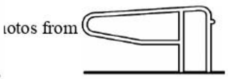
Partition Type: Cantilever ☐ Mushroom ☐ Front & Rear fixed (Newton Rigg) ☐ Double Front-fixed ☐

Count #: ____ Count #: ____ Count #: ____ Count #: ____









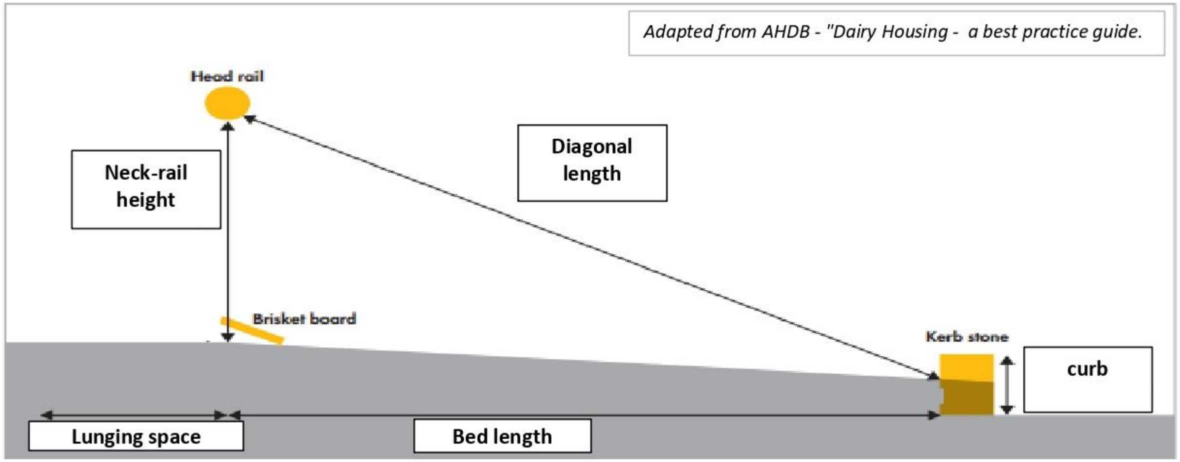
Flexible: Yes ☐ No ☐

Cubicle condition:
Very Good ☐ <5% in disrepair (e.g broken cubicles, torn mats etc.)
Good ☐ <25% in disrepair
Poor ☐ 25-50% in disrepair
Bad ☐ > 50% in disrepair

 # cubicles to measure *(minimum 2 of each design)*:

Most common	total # head-head/ open facing	
		x 0.05 =
	total # wall facing cubicles	
		x 0.05 =

2nd most common	total # head-head/ open facing	
		x 0.05 =
	total # wall facing cubicles	
		x 0.05 =



Curb Height: From pen floor to upper surface of cubicle

Total length: Back edge of cubicle to wall, or to midpoint between head-head cubicles

Lunge Space: Front of neckrail to wall or mid-way between cubicles

Bed Length: Back edge of cubicle to base of brisket board (if applicable)

Diagonal Length: Back edge of cubicle to near-side of neckrail

Neckrail height: Bottom of neckrail to surface of cubicle

Width: Between inner edges of cubicle partitions at cubicle entrance

Cubicle Dimensions (m)										
Cubicle	Cubicle Type		Brisket Board (Y/N)	Curb Height	Total Length	Lunge space	Bed Length	Diagonal length	Neckrail height	Width
	Style	Direction								
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										

Visit 1 - Farm level

Farm Number	
Date	
Observer	

Section 4 - Roadway Measurements				
Roadway leading to collecting yard: *Within 50m of the collecting yard entrance. Complete as many as needed				
	1	**2**	**3**	**4**
Width (m) -(excl. verge)				
Verge Width (m) - roadway edge to fenceline	|	|	|	|
Drainage Ditch	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
Surface Material:				
Smooth concrete	________ %	________ %	________ %	________ %
grooved concrete	________ %	________ %	________ %	________ %
Slats	________ %	________ %	________ %	________ %
Subsoil	________ %	________ %	________ %	________ %
Other	________ %	________ %	________ %	________ %
Surface condition*				
Visible slope				
Level	☐	☐	☐	☐
Upwards	☐	☐	☐	☐
Downwards	☐	☐	☐	☐
Steepest slope				
Does pathway have:				
consistent width	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
sharp turns (~90 °)	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
obvious cow track	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
Loose stones**				
Transition to collecting yard/milking platform				
Within 50m?	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
Transition material				
Photo (each side of 50m)	☐ ☐	☐ ☐	☐ ☐	☐ ☐
***Surface Condition = Very Smooth, Smooth, Rough, Very Rough** ****Loose stones = Record the number of quadrat squares containing loose stones > 0.5cm**				

Roadway to Paddock:

*Measured along pathway from parlour to paddock in use at time of visit

Roadway	**Gateway**	**End point**	**Half-way point**
Width (m)			
Verge Width (m) - roadway edge to fenceline			
Drainage Ditch	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
Surface Material:			
Smooth concrete	________ %	________ %	________ %
grooved concrete	________ %	________ %	________ %
Subsoil	________ %	________ %	________ %
Earthen (e.g soil/grass)	________ %	________ %	________ %
Other	________ %	________ %	________ %
*Surface condition**			
Slope Camber (% across)**			
Slope Camber (% up/down)			
Deep wheel tracks		Yes ☐ No ☐	Yes ☐ No ☐
Obvious cow path		Yes ☐ No ☐	Yes ☐ No ☐
Obvious signs of erosion		Yes ☐ No ☐	Yes ☐ No ☐
Loose stones**			
Photo	☐	☐	☐

***Surface Condition = Very Smooth, Smooth, Rough, Very Rough**

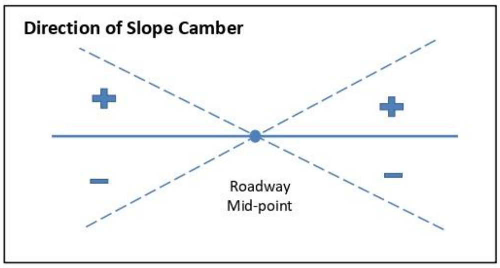
Very Smooth: *Even surface. Well maintained with no broken or damage surface, no large rocks or signs of erosion*

Smooth: *Mostly even surface, no broken sections. Occasional holes or bumps etc. May have signs of machinery use or erosion.*

Rough: *Somewhat uneven, larger stones, bumps and holes are common. Signs of wear or erosion.*

Very Rough *: Extremely bumpy and uneven, with coarse and broken surface. Many large, protruding rocks, holes etc.*

** Slope Camber - Measured from the mid-point of the roadway



**** Loose stones = Record the number of quandrat squares containing loose stones > 0.5cm**

Visit 2 - Pen Level (booklet per pen)

Farm #		
Date	**Start Time:**	**End Time:**
Observer		
Shed #		
Pen #		

Outdoor weather condition: ☐ Sunny ☐ Partly cloudy ☐ Overcast ☐ Raining

Section 5 - Cubicle features (cubicle housing only)

Cows # _________ **# Cubicles** _______ **Sample number - (5% rounded up)** _______

Access to extra outdoor area? e.g paddock/yard Yes ☐ No ☐ **Dead-ends:** Yes ☐ #:_______ No ☐

Passageway Slipperiness			
Floor Type	Slippery	Somewhat	Not
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐

Light level *(under centre of each roof line)*					*Former Shed #*
Point	**Bright**	**Dim**	**Dark**	**Light on?**	
1	☐	☐	☐	Yes ☐ No ☐	
2	☐	☐	☐	Yes ☐ No ☐	
3	☐	☐	☐	Yes ☐ No ☐	
4	☐	☐	☐	Yes ☐ No ☐	
5	☐	☐	☐	Yes ☐ No ☐	

Slippery: no grip, easy spinning

Somewhat slippery: some grip but can still slide or spin

Not slippery: good grip on abbrasive surface, can't slide or spin

Bright: Can comfortably read a newspaper from the centre of the pen.

Dim: Can read, with minimal strain, in the centre of the pen.

Dark: Difficult to read from centre of the pen.

Photo taken? ☐ Why?/ Of what?____

Select every 20th cubicle until sample target is reached. *Count end cubicles but don't measure (skip to next). Don't disturb cows lying in cubicles (skip to next)*

Cubicle Hardness (5% of cubicles)				Surface material	Bedding Type	Mat thickness (cm)	% Bedding Coverage			Cleanliness (C, P, D)		Bedding Depth *(if >1cm)*		Former Shed #
Cubicle	**Hard**	**Medium**	**Soft**				**Full**	**Part**	**Min**	**Top 1/2**	**Bot 1/2**	**Top 1/3**	**Bot 1/3**	
1	☐	☐	☐											
2	☐	☐	☐											
3	☐	☐	☐											
4	☐	☐	☐											
5	☐	☐	☐											
6	☐	☐	☐											
7	☐	☐	☐											
8	☐	☐	☐											
9	☐	☐	☐											
10	☐	☐	☐											
11	☐	☐	☐											
12	☐	☐	☐											
13	☐	☐	☐											
14	☐	☐	☐											
15	☐	☐	☐											

Cubicle Hardness:	*Hard: Like concrete or bare floor - too painful to drop to knees voluntarily* *Medium: Like foam or rubber - dropping to knees is unpleasant, but not painful* *Soft: Like a matress or deep bedding - painfree drop to knees*	***Bedding Coverage:***	*Full: Thick coating. Cannot see base through material* *Partial: Can see base through material in some areas* *Minimal: Bare sprinkling/no material. Can clearly see base*
Surface material:	*Concrete, Rubber mat, mattress, other*	***Bedding cleanliness:***	*Clean: <25% of cubicles soiled with manure* *Partly Dirty: 25-50% of cubicles soiled with manure* *Dirty: >50% of cubicles soiled with manure*
Bedding Type:	*None, Sand, Straw, Sawdust, Shavings, Woodchips, Sand, Lime, Other*		

Section 6 - Loose yard features (no cubicles)

Cows # __________ **Bedded area dimensions (m):** **Length** _________ **Width** _________

Access to extra outdoor area? e.g paddock/yard Yes ☐ No ☐

Bedding Type: None ☐ Straw ☐ Sand ☐ Sawdust ☐ Shavings ☐ Woodchips ☐ Other ☐ ____________

Bedding cleanliness:

- Clean ☐ <25% soiled with manure
- Partly dirty ☐ 25-50% soiled with manure
- Dirty ☐ >50% soiled with manure

Bedding Depth: ______

- Sparse ☐ *Minimal coverage. Floor visible through bedding. Drop to knees would be painful*
- Thin ☐ *Floor just covered but not visible through bedding. Drop to knees would be painful*
- Thick ☐ *Medium amount of coverage. Dropping to knees would be unpleasant but not painful*
- Very Thick ☐ *Dense and soft coverage. Pain-free drop to knees*

Passageway Slipperiness			
Floor Type	Slippery	Somewhat	Not
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐
	☐	☐	☐

Slippery: no grip, easy spinning

Somewhat slippery: some grip but can still slide or spin

Not slippery: good grip on abbrasive surface, can't slide or spin

Light level *(under centre of each roof line)*					*Former Shed #*
Point	**Bright**	**Dim**	**Dark**	**Light on?**	
1	☐	☐	☐	Yes ☐ No ☐	
2	☐	☐	☐	Yes ☐ No ☐	
3	☐	☐	☐	Yes ☐ No ☐	
4	☐	☐	☐	Yes ☐ No ☐	
5	☐	☐	☐	Yes ☐ No ☐	

Bright: Can comfortably read a newspaper from the centre of the pen.

Dim: Can read, with minimal strain, in the centre of the pen.

Dark: Difficult to read from centre of the pen.

Photo taken? ☐ Why?/ Of what?_______________________________________

Section 7 - Feed area (all housing types)

Feed Face	1	2	3	4	5
Rail Height 1 (pen floor to neckrail)					
Rail Height 2 (top of feed barrier to neckrail)					
Partitions	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
# within available length					
Bottom width					
Available Feedface Length:					
Covered feed area	Over☐ Fully ☐ No ☐	Over☐ Fully ☐ No ☐	Over☐ Fully ☐ No ☐	Over☐ Fully ☐ No ☐	Over☐ Fully ☐ No ☐
Feed available	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
feed area clean/ free of debris	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐	Yes ☐ No ☐
Former Shed #					

Over = Overhang
Fully = fully covered

Photo taken? ☐ Why?/ Of what?____________________________________

Section 8 - Other

Is there a scraper in the collecting yard? Yes ☐ No ☐

Details of the categorical scales used as part of the infrastructure measurements can be viewed below; including the overall condition of cubicles (Table A1), cubicle hardness (Table A2), cubicle cleanliness (Table A3), floor slipperiness (Table A4) and roadway surface condition (Table A5).

Table A1. Categories to determine the overall cubicle condition for each pen, described as the percentage of cubicles in disrepair (e.g. broken cubicles, torn mats etc.)

Category	Description
Very good	<5% of cubicles in disrepair
Good	<25% of cubicles in disrepair
Poor	25-50% of cubicles in disrepair
Bad	>50% of cubicles in disrepair

Table A2. Scale to categorise cubicle hardness. Cubicle hardness was measured using the ‘knee drop test’, as previously used by McFarland & Graves (1995). Cubicle hardness was measured for 5% of cubicles in each pen

Category	Description
Soft	Pain free drop to knees – like deep bedding
Medium	Dropping to knees unpleasant but not painful – like foam or rubber
Hard	Too painful to drop knees voluntarily – like concrete

Table A3. Cubicle cleanliness was measured for both the top half and the bottom half of each cubicle selected using a three-point scale. Cubicle cleanliness was measured for 5% of cubicles in each pen

Category	Description
Clean	<25% soiled with manure
Partly dirty	25-50% soiled with manure
Dirty	>50% soiled with manure

Table A4. Floor slipperiness was measured at the parlour entrance and exit using a scale adapted from De Vries et al. (2015)

Category	Description
Not-slippery	Good grip on abrasive surface, cannot spin on foot easily
Somewhat-slippery	Some grip, can still spin on foot
Slippery	No grip, can very easily spin on foot

Table A5. Categories to determine the roadway surface condition. Surface condition was recorded at the half-way point and end-point between the collecting yard and paddock, and at the gateway, for the roadway in use of the day of the visit. Surface condition was also recorded within the segment between the collecting yard entrance and the fifty meters along all roadways utilized.

Category	Description
very smooth	Even surface, well maintained with no broken or damaged surface, no large rocks or signs of erosion
Smooth	Mostly even surface, no broken sections, occasional holes or bumps, may have signs of machinery use or erosion
Rough	Somewhat uneven, larger stones, bumps and holes are common, signs of wear or erosion
Very rough	Extremely bumpy and uneven, coarse and broken surface, many large protruding rocks and holes

Lameness scoring

Lameness scoring to calculate the interobserver reliability took place on the Teagasc Moorepark research farm. Cows were scored individually as they left the crush following milking, on a flat concrete surface. At the start of the first visit a total of 55 cows were scored by the four scorers that would carry out lameness scoring during the grazing period. At the start of the second visit a total of 59 cows were scored by the three scorers that would carry out lameness scoring during the housing period. The same 59 cows were also scored again the following day to allow intraobserver relalibilities to be calculated for each scorer.

Weighted kappa coefficients as a measure of agreement were calculated in SAS version 9.4 (SAS Institute Inc.). This was calculated using the FREQ procedure with the 'test wtkap' statement. Weighted kappa was used to account for the fact that scores that differ by only one level are more similar than scores that differ by multiple levels (e.g. lameness score 0 vs 1 is a closer agreement than 0 vs 3). The interobserver agreement comparing individuals are reported in Table A6 and A7. The intraobserver agreement for each scorer are reported in Table A8. The mean weighted kappa coeficient for each assessment were all > 0.7. The distibution of each lameness score across the scorers, at each scoring session, can also be viewed in Tables A9 to A11.

Table A6. Interboserver reliability for lameness scoring, comparing four scorers that carried out lameness scoring during the grazing visit. A total of 55 cows were scored

Scorers	Interobserver agreement
1 vs 2	0.69
1 vs 3	0.70
1 vs 4	0.62
2 vs 3	0.84
2 vs 4	0.76
3 vs 4	0.75
Mean	0.73

Table A7. Interboserver reliability for lameness scoring, comparing three scorers that carried out lameness scoring during the housing visit. A total of 59 cows were scored

Scorers	Interobserver agreement
1 vs 2	0.91
1 vs 3	0.80
2 vs 3	0.85
Mean	0.85

Table A8. Intraobserver reliability for lameness scoring, for the three scorers that carried out lameness scoring during the housing visit. A total of 59 cows were scored

Scorer	Interobserver agreement
1	0.81
2	0.79
3	0.71
Mean	0.77

Table A9. Distribution of lameness scores for each of the four scorers during the interobserver reliability assessment at the start of the grazing visits

Lameness score	Scorer 1	Scorer 2	Scorer 3	Scorer 4
0	14	13	13	9
1	25	28	30	33
2	11	10	8	8
3	5	4	4	5

Table A10. Distribution of lameness scores for each of the three scorers during the intraobserver (first scoring session) and interobserver reliability assessment at the start of the housing visits

Lameness score	Scorer 1	Scorer 2	Scorer 3
0	13	11	17
1	32	32	27
2	13	15	13
3	1	1	2

Table A11. Distribution of lameness scores for each of the three scorers during the intraobserver reliability assessment (second scoring session) at the start of the housing visits

Lameness score	Scorer 1	Scorer 2	Scorer 3
0	17	14	19
1	25	29	27
2	16	15	11
3	1	1	2

The distribution of lameness scorers who assessed the herd at each visit can be viewed in Table A12. Of the herds scored during both the grazing and housing period, 35% (30 herds) were scored by the same scorer at both visits.

Table A12. Number of herds each scorer lameness scored at each visit

Scorer	Number of herds lameness scored	
	Visit 1	Visit 2
1	27	39
2	38	25
3	33	21
4	1	0

Appendix B: Paper 1 supplementary material

Calculating odds ratios

Odds ratios were calculated using the unstandardised coefficients from each model. The exponential of each coefficient gives the odds ratio. This is based on a one-unit increase for continuous variables. Some odds ratios were altered to represent a unit change of 0.1, 10 and 100 for ease of interpretation.

Predictors provided to the models

The variables provided to the Enet and mBIC models are reported in table B1. Variables not provided to the models due to near zero variance are reported in Table B2.

Figure B1. The predictors (n = 197) provided to the elastic net regression model and the logistic regression model using modified Bayesian Information Criterion to determine risk factors for lameness in Irish pasture-based dairy cows

	Predictor	Categories (categorical data)
Cow-level	Body condition score	< 3
		3
		3.25
		> 3.25
		Missing
	Age (years)	n/a
	Age of first calving (months)	n/a
	Breed	Holstein Friesian
		Other pure breeds
		Cross breeds
	Parity	1
		2
		3

	4
	5
	> 5
Calving interval (days)	First calving (i.e. no calving interval)
	< 354
	354 - 369
	370 – 387
	> 387
	Missing
Days in milk (days calved)	n/a
Calving difficulty (scale described by Mee et al., 2011)	1 (no assistance)
	2-4 (slight/ considerate/ veterinary assistance)
	Missing
Milking state	Milking
	Dry
	Missing
305-day milk yield (litres)	< 5738
	5738 – 6636
	6637 – 7552
	> 7552
	Missing
Average somatic cell count (cells/ml)	< 37,000
	37,000 – 54,000
	55,000 – 99,000
	> 99,000
	Missing
Days till next calving (days)	< 77
	77 – 172
	173 – 242
	> 242

		Missing
	Predicted transmitting ability for lameness	Negative Zero Positive
	Health sub-index	n/a
	Maintenance sub-index	n/a
	Economic breeding index	n/a
Herd-level - visit details	Visit period	Grazing Housing
	Visit month	April 2019 May 2019 June 2019 July 2019 August 2019 September-November 2019 December 2019 January - February 2020
Herd-level - Shed measurements	Proportion of feed passages narrow (< 5 m if backed onto cubicles and < 4 m if not backed onto cubicles; Ohnstad, 2012)	n/a
	Proportion of feed passages of recommended width (≥ 5 m if backed onto cubicles and ≥ 4 m if not backed onto cubicles; Ohnstad, 2012)	n/a
	Proportion of shed passages narrow (< 3 m; Ohnstad, 2012)	n/a
	Proportion of shed passages of recommended width (≥ 3 m; Ohnstad 2012)	n/a
	Proportion of sheds with cross alleys present	n/a
	Proportion of sheds with automatic scrapers present	n/a
	Proportion of cubicles cantilever	n/a

	Proportion of cubicles Newton Rigg (front & rear fixed)	n/a
	Proportion of cubicles with high curb height (> 0.25 m; Clarke, 2016)	n/a
	Proportion of cubicles with low curb height (< 0.2 m; Clarke, 2016)	n/a
	Proportion of cubicles with recommended curb height (0.2 m – 0.25 m; Clarke, 2016)	n/a
	Proportion of cubicles short in length (< 2.3 m wall facing cubicles; < 2.2 m head to head cubicles/ single row with no wall; Clarke, 2016)	n/a
	Proportion of cubicles of recommended length (≥ 2.3 m wall facing cubicles; ≥ 2.2 m head to head cubicles/ single row with no wall; Clarke, 2016)	n/a
	Proportion of cubicles with short lunge space (< 0.6 m; AHDB, 2012)	n/a
	Proportion of cubicles of recommended lunge space (≥ 0.6 m; AHDB, 2012)	n/a
	Proportion of cubicles with low neck rail height (< 1.15 m; Clarke, 2016)	n/a
	Proportion of cubicles with recommended neck rail height (≥ 1.15 m; Clarke, 2016)	n/a
	Proportion of cubicles with narrow width (< 1.15 m; Clarke, 2016)	n/a
	Proportion of cubicles of recommended width (≥ 1.15 m; Clarke, 2016)	n/a
	Proportion of sheds with enough space per cow (one cubicle per cow – this is the minimum recommendation, ideally 1.1 cubicles per cow; 7.5 m^2 per cow for bedded area; AHDB, 2012)	n/a
	Proportion of sheds with dead ends	n/a

	Proportion of pens that are loose housing (i.e. straw yard)	n/a
	Proportion of pens with < 0.65 m per cow at the feed face	n/a
	Proportion of cubicle surfaces classed as hard (knee drop test)	n/a
	Proportion of cubicles with a think mat (≥ 2 cm)	n/a
	Proportion of cubicles with a thin mat (< 2 cm)	n/a
	Proportion of cubicles where the top half was clean	n/a
	Proportion of cubicles where the top half was partly dirty	n/a
	Proportion of cubicles where the top half was dirty	n/a
	Proportion of cubicles where the bottom half was clean	n/a
	Proportion of cubicles where the bottom half was partly dirty	n/a
	Proportion of cubicles where the bottom half was dirty	n/a
Herd-level - Milking facilities	Slope present in collecting yard	Yes No
	Space per cow in collecting yard (m^2/cow)	n/a
	Proportion of collecting yard entrances < 4 m	n/a
	Proportion of collecting yard entrances 4 m – 5 m	n/a
	Proportion of collecting yard entrances > 5 m	n/a
	Backing gate present in collecting yard	Yes No

Proportion of collecting yard smooth concrete	n/a
Proportion of collecting yard grooved concrete	n/a
Proportion of collecting yard slats	n/a
Cows per cluster	n/a
Proportion of milking parlour grooved concrete	n/a
Proportion of milking parlour smooth concrete	n/a
Parlour floor slipperiness	Not slippery Somewhat slippery/ Slippery
Step present at parlour entrance	Yes No
Slope present at parlour entrance	Yes No
Turn present at parlour entrance	Yes No
90 degree turn present at parlour entrance	Yes No
180 degree turn present at parlour entrance	Yes No
Door (human size) present at parlour entrance	Yes No
Step present at parlour exit	Yes No
Slope present at parlour exit	Yes No
90 degree turn present at parlour exit	Yes No
180 degree turn present at parlour exit	Yes

		No
	Door (human size) present at parlour exit	Yes No
	Turning distance at parlour exit (first milking unit to end wall; metres)	n/a
	Proportion of floor at parlour exit grooved concrete	n/a
	Proportion of floor at parlour exit smooth concrete	n/a
	Footbath type	Permeant Temporary No footbath
	Footbath length (metres)	< 3 ≥ 3 No footbath
Cow tracks - 50 m section following collecting yard	Proportion of cow tracks at 50 m following collecting yard narrow based on herd size (3.5 m for first 50 cows, 0.01 m per cow subsequently; Tuohy et al., 2019)	n/a
	Proportion of cow tracks with no verge at 50 m following collecting yard	n/a
	Proportion of cow tracks with a small verge at 50 m following collecting yard (≤ 50 cm; Tuohy et al., 2017)	n/a
	Proportion of cow tracks with a large verge at 50 m following collecting yard (≤ 50 cm; Tuohy et al., 2017)	n/a
	Proportion of cow tracks with a ditch present within the first 50 m following collecting yard	n/a
	Proportion of cow tracks subsoil within the first 50 m following collecting yard	n/a
	Proportion of cow tracks slats within the first 50 m following collecting yard	n/a

	Proportion of cow tracks grooved concrete within the first 50 m following collecting yard	n/a
	Proportion of cow tracks smooth concrete within the first 50 m following collecting yard	n/a
	Proportion of cow tracks ‘other’ surface material within the first 50 m following collecting yard	n/a
	Proportion of cow tracks classified as rough/very rough within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a steepest slope of zero degrees within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a steepest slope of ≤ 10 degrees within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a steepest slope of > 10 degrees within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a consistent width within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with sharp turns within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a narrow channel in surface (indicating a single file path created by cows) within the first 50 m following collecting yard	n/a
	Proportion of cow tracks with a low number of stones at 50 m following the collecting yard (0 - 8 quadrat squares contain stones)	n/a
	Proportion of cow tracks with a medium number of stones at 50 m following the	n/a

	collecting yard (9 - 17 quadrat squares contain stones)	
	Proportion of cow tracks with a high number of stones at 50 m following the collecting yard (18 - 25 quadrat squares contain stones)	n/a
	Proportion of cow tracks where the transition from concrete to another surface material was within 50 m following the collecting yard	n/a
	Proportion of cow tracks where the transition from concrete to another surface material was subsoil	n/a
Cow tracks – measured at two points (half way and end point to paddock) on the cow track in use on the day of the grazing visit	Cow track wide enough based on herd size (3.5 m for first 50 cows, 0.01 m per cow subsequently; Tuohy et al., 2019)	Wide enough at both point Wide enough at singular point Narrow at both points
	Proportion of cow track with no verge at points measured	n/a
	Proportion of cow track with small verge (≤ 50 cm) at points measured	n/a
	Proportion of cow track with large verge (> 50 cm) at points measured	n/a
	Ditch present at points measured	Present at both points Present at singular point Absent at both point
	Proportion of cow track earthen at points measured	n/a
	Proportion of cow track subsoil at points measured	n/a
	Proportion of cow track stones at points measured	n/a
	Proportion of cow track concrete/tarmac at points measured	n/a
	Surface condition at points measured	Rough/ Very Rough at both points

		Rough/ Very Rough at singular point Very smooth/ smooth at both points
	Camber (One-side slope – 4% recommended; two-sided slope – 6% recommended; Teagasc, 2016)	As recommended at both points As recommended at singular point Not as recommended at both points
	Proportion of cow track with no slope at points measured	n/a
	Proportion of cow track with slope ≤ ten degrees at points measured	n/a
	Proportion of cow track with slope > ten degrees at points measured	n/a
	Water erosion at points measured	Present at both points Present at singular point Absent at both point
	Proportion of cow track with low number of stones present (0 – 8 quadrat squares contain stones)	n/a
	Proportion of cow track with medium number of stones present (9 - 17 quadrat squares contain stones)	n/a
	Proportion of cow track with high number of stones present (18 – 25 quadrat squares contain stones)	n/a
Paddock gateway – gateway in use on the day of the grazing visit	Gateway number of quadrat squares containing stones	n/a
	Gateway number of stones categorised	0 – 8 quadrat squares contain stones 9 - 17 quadrat squares contain stones

		18 - 25 quadrat squares contain stones
	Gateway width (metres)	n/a
	Gateway wider then cow track	Wider Narrower
	Ditch present at gateway	Yes No
	Proportion of gateway surface earthen	n/a
	Proportion of gateway surface subsoil	n/a
	Proportion of gateway surface stones	n/a
	Gateway surface condition	Very smooth/ smooth Rough/ very rough
Survey data	Days fully housed in 2018 (prior to study starting)	n/a
	Days at grass in 2019 (year of study)	n/a
	Farm size (hectares)	n/a
	Herd size	n/a
	Stocking rate (cows per hectare)	n/a
	Number cows per full time staff member	n/a
	Increase in cows numbers in the last five years	n/a
	Percent increase in cow numbers in the last five years (%)	0 ≤ 30 > 30
	Percent increase in farm size (hectares) in the last five years	0 ≤ 30 > 30
	New cow tracks in the last five years	Yes No
	Renovated cow tracks in the last five years	Yes No
	How often repair roadways	≥ once per year

	Once every two years < once every two years As needed Never
Open herd	Yes No
Ever milk once a day (i.e. end of lactation)	Yes No
Bring cows in from the paddock with a motorised vehicle	Yes No
Dog present when bringing in cows from the paddock	Yes No
How are cows encouraged into the parlour	Herd Enter on their own
Max holding time in the collecting yard	n/a
Total walking distance considered when deciding order to graze paddocks	Yes No
Separate lame cow group	Yes No Sometimes
Herd health plan that contains lameness protocols	Yes No
Farmer familiar with lameness scoring	Yes No
Keeps hoof trimming records	Yes No
Keeps records of lame cows	Yes No
Footbath frequency	Never Irregularly - < 12 times per year

	Regularly - ≥ 12 times per year
Solutions used in footbathing routine	Copper sulphate
	Formalin
	Copper sulphate and Formalin
	Other (no copper sulphate and Formalin)
	No footbathing
Antibiotics ever used in footbath	Yes
	No
Number of cows until footbath solution is changed	≤ 200 cows
	> 200 cows
	No footbathing
Clean feet prior to footbathing	Yes
	No
	No footbathing
Provided any advice on footbathing	Yes
	No
	No footbathing
Carry out routine trimming of entire herd	Yes
	No
Time between identifying lame cow and treating (hrs)	12
	24
	48
	> 48
Farmer had hoof trimming training	Course
	Other training
	No training
Percentage of herd treated for lameness in year prior to study according to the farmer (%)	≥ 10
	< 10

Who treats lame cows	Farmer only Professional (trimmer/vet) only Both farmer and professional
Wait for a number of cows to be lame before treating	Yes No
Re-examine a lame cow after treatment	Yes – always Yes – if still lame Never
Length of time until a bandage on the hoof is removed	≤ 3 days > 3 days Other (i.e. does not bandage; based on trimmer/veterinary recommendation)
Walking distance to furthest paddock	n/a
Average walking distance to paddock	n/a
Furthest paddock pat of the regular grazing rotation	Yes No
Cow tracks used for machinery	No – cows only Yes – both cows and machinery
Cows cross a road to get to paddock	Yes No
Over/underpass present on cow tracks	Yes No
Cows housed based on parity	Yes No
Cow groups change throughout the year	Yes No
Heifers introduced to cow group	Before calving After calving

Heifer housing type before joining cow group	Cubicles (stalls)
	Slats
	Other type or combination of cubicles/slats
Frequency of automatic scraper (times per day)	≥ 7
	< 7
	No automatic scraper used
Cubical cleaning frequency (dry cows)	< once a day
	Once a day
	Twice a day
Cubical cleaning frequency (milking cows)	< once a day
	Once a day
	Twice a day
Cubical bedding frequency (dry cows)	Once a day
	Twice a day
	Other
	Never
Cubical bedding frequency (milking cows)	Once a day
	Twice a day
	Other
Total concentrate fed during 2019 lactation (kg/cow)	≤ 750
	750 – 1000
	> 1000
Dry cows fed ‘other’ feed type during housing (excluded concentrate, silage, hay, straw and minerals)	Yes
	No
Concentrate fed to dry cows when housed	Yes
	No
Milking cows fed ‘other’ feed type during housing (excluded concentrate, silage, hay, straw and minerals)	Yes
	No
Minerals fed to milking cows when housed	Yes

	No
Fresh feed fed frequency (dry cows)	< once a day Once a day
Fresh feed fed frequency (milking cows)	< once a day Once a day
Push feed in frequency	< once a day Once a day
Cows held after milking prior to returning to paddock	Yes No Sometimes
Farmer age (years)	≥ 50 < 50 Multiple farmers (ages differ)
Number of years full time farming (years)	≥ 25 < 25 Multiple farmers (years farming differ)
Part of a knowledge transfer programme	Yes No
Farmer considers lameness a problem in their herd	Yes No
Herd lameness prevalence changed in the last two years (farmers opinion)	Increased Decreased Stayed the same
Farmers prediction of number of lame cows vs. lameness scoring result	Overestimated/correct estimation Underestimated
Proportion of the herd with digital dermatitis during the 2019 lactation (according to the farmer)	No digital dermatitis ≤ 5% > 5%

Table B2. Variables not provided to the models due to near zero variance

	Variable	Categories (categorical data)
Cow-level	Birthed twins	Yes No
Herd-level - Shed measurements	Proportion of pens that are loose housing - straw yard	n/a
	Proportion of pens that are loose housing – not bedded (e.g. slats)	n/a
	Proportion of sheds with no feed passage measurements	n/a
	Proportion of sheds with no passage measurements	n/a
	Proportion of cubicles in poor or bad condition	n/a
	Proportion of cubicles in good or very good	n/a
	Proportion of cubicles with short bed length (<1.75 m; Clarke, 2016)	n/a
	Proportion of cubicles with recommended bed length (≥ 1.75 m; Clarke, 2016)	n/a
	Proportion of cubicles with no bed length measurement (due to no brisket board)	n/a
	Proportion of cubicles with short diagonal length (<2.2 m; AHDB, 2012)	n/a
	Proportion of cubicles with recommended diagonal length (≥ 2.2 m; AHDB, 2012)	n/a

	Proportion of cubicle type 'Other' (excludes cantilever and Newton Rigg)	n/a
	Proportion of cubicles with no lunge space measurement (due to no neck rail)	n/a
	Proportion of cubicle surfaces classed as soft (knee drop test)	n/a
	Proportion of cubicle surfaces classed as medium (knee drop test)	n/a
	Proportion of cubicles with a mattress	n/a
	Proportion of cubicles that are concrete only (i.e. no bedding/mat/mattress)	n/a
Herd-level - Milking facilities	Turn present at parlour exit	Yes No
	Proportion of collecting yard surface 'other' (excludes smooth concrete, grooved concrete and slats)	n/a
	Proportion of milking parlour slats	n/a
	Proportion of floor at parlour exit 'other' (excludes smooth concrete and grooved concrete)	n/a
Cow tracks – measured at two points (half way and end point to paddock) on the cow track in use on the day of the grazing visit	Proportion of cow track surface material 'other' at points measured (excludes earthen, subsoil, stones and concrete/tarmac)	n/a
	Proportion of cow tracks with a narrow channel in surface (indicating a single file path created by cows) at points measured	n/a
Paddock gateway – gateway in use on the day of the grazing visit	Proportion of gateway surface material 'other' at points measured (excludes earthen, subsoil, and stones)	n/a

Survey data	Attended agricultural education program	Yes No
	Milking cows fed silage during housing	Yes
	Dry cows fed minerals during housing	Yes No
	Who does the routine trimming	Trimmer No routine trimming on the farm
	Routine trim on both front and back hooves	Yes Back only No routine trimming on the farm
	Number routine trims per year	Once Twice No routine trimming on the farm
	Carries out lameness scoring	Yes No
	Lameness detection technology used	Yes No

Descriptive statistics for final predictor variables

Descriptive statistics for the continuous and categorical predictors that came out in the final model are reported in Table B3 and B4, respectively. Table B4 also reports the lameness prevalence for each category of each predictor

Table B3. Descriptive statistics for continuous predictor variables that came out of the triangulated models. Statistics based on 20,209 cows

Continuous predictor	Median (IQR)	Min	Max
Age (yr)	5 (3-7)	2	15
Grazing platform size (ha)	45 (36-49)	14	101
Herd size	137 (108-176)	38	253
Distance to turn after milking (m)	2.64 (2.13-3.25)	0.98	8.61
Prop of slats in first 50 m of cow tracks	0 (0-0.03)	0	0.8
Proportion of gateway surface stones	0 (0-0)	0	1

Table B4. Lameness prevalence for each categorical predictor variables that came out of the triangulated models. Based on 20,209 cows

Categorical predictor	Number of cows	Cow-level lameness prevalence (%)
PTA		
Positive	3852	15.8
Zero	2584	10.6
Negative	13772	6.9
Lameness is considered a problem by the farmer		
Yes	9104	11.7
No	11104	7.1
Proportion of the herd that had digital dermatitis		
No DD	12420	2.6
<equal 5%	3762	14.1
>5%	4026	25.4
Proportion of herd treated for lameness		
<10%	9911	7.4
>equal 10%	10297	10.8

[1]During the current lactation, according to the farmer
[2]In the year before the study started (2018), according to the farmer

Appendix C: Paper 2 supplementary material

Scorer effect

For cows scored during both the grazing and housing period, the impact of scorer on lameness was modelled using logistic regression. The binary outcome variable for each cow was lameness status (0 = not lame, 1 = lame). The predictors were visit (grazing or housing) and scorer (scorer 1-4). Farm was also included as a random effect. The results are reported in Table C1. Both the scoring period and the scorer did not significantly impact the odds of lameness.

Table C1. Multilevel logistic regression model to determine the impact of visit and scorer on the odds of lameness

	Estimate	SE	OR	*P*-value
Intercept	-2.312	0.085		
Housing period	-0.070	0.053	0.93	0.184
Scorer 2	-0.022	0.086	0.98	0.797
Scorer 3	-0.054	0.085	0.95	0.531
Scorer 4	-1.238	0.660	0.29	0.061

Lameness prevalence

Lameness prevalence for different cow track surfaces are report in Table C2. This table is adapted from Table 3 within Paper 2. Lameness prevalence for various parameters in Paper 2 are also reported in Table C3.

Table C2. Proportion of farms with each cow track surface material and the lameness prevalence during the grazing period for each surface type

	First 50m[1]		Cow track in use[2]	
Cow track surface material	Farms with surface material present (%)	Average lameness prevalence (%)	Farms with Surface material present (%)	Average lameness prevalence (%)
Subsoil	83	9.5	91	9.6
Concrete (smooth, grooved)	70	10.3	38	10.3
Concrete slats	26	12.9	1	20
Stones/gravel	19	9.4	18	11.7
Earthen (grass/soil)	7	12.5	42	9.9
Tarmac	5	9.2	1	10.4
Astro-turf	1	3.3	0	n/a

[1]Measurements taken within the first 50 m from the collecting yard on all cow tracks
[2]Measurements taken on the cow track in use on the day of the grazing visit at the end-point of the cow track and at the half-way point between the collecting yard and paddock

Table C3. Lameness prevalence during grazing and housing for various parameters reported in Paper 2

Variable	Number farms	Lameness prevalence	
		Visit 1	Visit 2
Familiar with lameness scoring			
Yes	43	10.0	9.6
No	56	9.9	9.3
Lameness scores herd			
Yes	1	23.5	n/a
No	98	9.7	9.4
Lameness detection technology			
Yes	1	11.0	14.6
No	98	9.9	9.4

Records lame cows			
Yes	21	8.9	8.6
No	78	10.1	9.7
Lameness herd health plan			
No	98	9.7	23.5
Yes	1	9.4	n/a
Routine trims whole herd			
No	93	9.6	9.0
Yes	6	14.8	15.6
Preventative footbathing			
Regularly (> 12 times per year)	31	11.4	10.5
Irregularly (≤ 12 times per year)/ when required	25	10.3	10.1
Never	43	8.6	8.3
Footbath product			
Copper sulphate only	19	11.3	9.7
Formalin only	10	10.2	14.9
Formalin and copper sulphate	7	7.3	7.7
Other	11	12.0	11.5
Change footbath solution after			
≤ 200 cows	32	10.0	10.3
> 200 cows	22	11.5	9.9
Cleans hooves prior to footbathing			
N	29	10.5	9.1
Y	25	10.8	8.63
Uses an antibiotic footbath			
N	90	9.4	9.2
Y	9	15.0	11.7
Carries out lameness treatment			
Farmer and trimmer	37	9.2	10.4
Farmer	26	10.9	8.9
Trimmer	36	9.8	8.7

Treat cow within			
12	20	8.8	10.0
24	27	8.8	8.4
48	23	11.1	8.5
>48	27	11.0	11.1
Waits for more than one cow to be lame before treating			
No	78	9.7	9.1
Yes	21	10.6	10.3
Re-examines cow after treatment			
N	18	9.1	9.1
If still lame	70	9.7	9.2
Y	11	12.2	11.7
Uses a vehicle to bring cows in from the paddock			
No	55	10.3	9.4
Yes	43	9.2	9.3
Uses a dog to bring cows in from the paddock			
No	64	10.1	9.4
Yes	34	9.1	9.2
Held cows back after milking			
Yes	21	11.5	9.2
Sometimes	25	9.8	9.7
Never	39	9.4	9.4
New cow tracks in the last 5 years			
N	61	10.3	9.1
Y	38	9.1	10.1
Renovated cow tracks in the last 5 years			
N	65	10.0	9.3
Y	34	9.6	9.8
Backing gate present			
N	19	9.4	9.4

Y	80	10.0	9.4
Collecting yard space			
Less 1.2 m^2 per cow	28	9.5	8.8
More 1.2 m^2 per cow	70	10.0	9.7
Less 1.5 m^2 per cow	52	9.4	8.5
More 1.5 m^2 per cow	46	10.5	10.3
Collecting yard predominant surface (>50%)			
Smooth concrete	24	10.7	10.8
Grooved concrete	30	8.9	8.2
Slats	30	11.1	10.0
Parlour entrance – step present			
Yes	63	9.6	10.3
No	36	10.0	9.0
Parlour entrance – slope present			
Yes	30	11.6	10.1
No	69	9.1	9.2
Parlour entrance – sharp turn present			
Yes	40	9.2	8.6
No	59	10.3	10.0
Parlour entrance – door present			
Yes	23	9.9	9.8
No	76	9.9	9.3
Parlour exit – step present			
Yes	26	10.6	11.2
No	73	9.6	8.8
Parlour exit – slope present			
Yes	23	9.0	8.1
No	76	10.1	9.8
Parlour exit – sharp turn present			
Yes	95	10.0	9.6
No	4	5.8	5.6

Parlour exit – door present			
Yes	15	9.6	10.4
No	84	9.1	9.3
Rough/very rough cow track in first 50 m			
Yes	52	9.9	8.7
No	44	9.6	10.0
Cow track with a sharp turn in first 50 m			
Yes	79	9.9	9.6
No	20	9.5	9.0
Cow track with inconsistent width in first 50 m			
Yes	79	10.0	9.8
No	20	9.4	8.1
Rough/very rough recorded on cow track in use			
Yes	65	10.3	9.9
No	34	9.1	8.5
Gateway narrow that cow track			
Yes	9	10.1	8.9
No	90	9.8	9.4
Gateway condition			
Smooth/very smooth	44	10.4	10.0
Rough/very rough	54	9.6	9.2
Gateway surface present			
Earth (soil/grass)	84	9.9	9.4
Subsoil	43	9.4	9.4
Stones	23	10.5	10.3
Additional loose housing			
No	75	10.0	9.5
Yes	10	10.4	8.8
Enough feeding space per cow (≥ 0.6 m per cow)			
All pens	5	7.7	5.6
Some pens	32	10.0	8.4

No pens	48	10.3	10.5
Dead-ends present			
All pens	45	10.0	10.0
Some pens	35	10.6	9.3
No pens	4	6.3	5.7
Enough space per cow within housing (1.1 cubicles per cow)			
All pens	21	10.4	9.5
Some pens	36	10.0	9.9
No pens	28	9.9	8.8
No matting/bedding on cubicles (concrete only)			
All pens	4	9.9	13.5
Some pens	6	14.9	12.8
No pens	74	9.6	8.8

Appendix D: Paper 3 supplementary material

Lesion prevalence

It must be highlighted that lesion prevalence reported in Paper 3 relates to lesions causing lameness. Only lame cows, as assessed through lameness scoring, were examined and had lesion prevalence recorded. Examining lesion prevalence through alternative study designs may lead to differences in the lesion prevalence reported. Including both lame and non-lame cows in the examination could increase the prevalence of mild lesions or lesions that less commonly cause lameness, such as digital dermatitis and sole haemorrhages. For example, in a recent study 55% of cows with digital dermatitis were not lame based on visual assessment (Thomas et al., 2022). This shows that digital dermatitis is common in non-lame cows. An alternative and less time consuming method to examine digital dermatitis prevalence of the whole herd would be through parlour scoring.

Association between digital dermatitis and sole ulcers

In Paper 3 an association was found between sole ulcers and digital dermatitis. A plausible theory for the association is that cows that are stood in manure and therefore have a higher risk of digital dermatitis, will also have softer hooves. Borderas et al. (2004) reported that claw horn that was soaked in water became softer, and that lesion severity increased with reduced claw hardness. It is also possible that an increased standing time which is a known risk for sole ulcers (Eriksson et al., 2021), would also increase the time in contact with manure, increasing digital dermatitis.

Interaction between track width and surface material

Paper 3 reported that narrow cow tracks (within the first 50 m from the collecting yard) reduced the risk of digital dermatitis. It was discussed that a possible theory for this was that subsoil was more common for narrow tracks, and concrete was more common for wider tracks. This interaction between track width and surface material could have been explored further through looking at the interaction within the risk factor models in Paper 1. However, this was not carried out due to the small numbers that would be within each category of width and surface type (e.g. wide and subsoil).

Appendix E: Paper 4 supplementary material

Farmer cover letter and questionnaire

Teagasc
Agriculture and Food Development Authority

University of Nottingham
UK | CHINA | MALAYSIA

Animal and Grassland Research & Innovation Centre
Moorepark
Fermoy
Co. Cork

30/09/2021

RE: Farmer survey on the use of pain relief and lameness in Irish dairy herds

Dear Herd Owner,

Teagasc, in conjunction with the University of Nottingham, would like to invite you to participate in a survey. Participation is entirely voluntary, and there is no obligation to take part, but we would really appreciate your time and interest in completing the survey.

The aim of the study is to investigate the use of pain relief in Irish dairy herds. Pain relief is important for animal welfare reasons and for the recovery of sick and lame dairy cows; the survey also examines lameness in more detail. Information from this study will ultimately help to improve the treatment and welfare of dairy cows in Ireland.

A proportion of Irish dairy farmers who currently allow Teagasc access to their information, through ICBF, have been sent the survey via post. We are inviting you to participate in this research study by completing the attached survey and returning in the pre-paid envelope. There is also the option of completing the survey online via the following link (https://forms.office.com/r/79G0VkHTuH) or by scanning the QR code below. The survey will take approximately 15 minutes to complete.

The survey is completely anonymous, so please do not include your name. If you choose to participate in this survey, please answer all questions as honestly as possible. By participating, you:

- Give consent for the researchers to use the information provided as part of a research study, which may lead to reports, published papers and/or conference presentations
- Acknowledge that the study is anonymous and that you will not provide your name or any other personal data
- Understand that the study is being conducted for research purposes
- Understand that you can request to see a summary of the findings

If you have any questions regarding this project, feel free to contact Natasha Browne via email (natasha.browne@teagasc.ie).

We thank you for taking the time to read this letter and would be very grateful for the completion of the survey.

Sincerely,

Dr. Muireann Conneely (Principal researcher)

Dr. Chris Hudson (Researcher)

Natasha Browne (PhD. Candidate)

Scan to complete online

Farmer survey on pain relief and lameness in Irish dairy cows

If preferred, the survey can also be completed online using the following link (https://forms.office.com/r/79G0VkHTuH) or by scanning the QR code on the cover letter.

PART 1: DEMOGRAPHICS

Please circle the answer or fill in the grey box as required:

1. **Gender:**
2. **Year you were born:**
3. **Highest level of education:** Junior Certificate Leaving Certificate Bachelor Degree Postgraduate degree (i.e. MSc, PhD)
4. **Background before farming:** Rural Urban Rural & Urban
5. **Number of years farming (full time):**
6. **Farm location (county):**
7. **Herd size:**

PART 2: YOUR OPINION ON THE USE OF ANALGESICS IN DAIRY COWS

For each statement below on the use of analgesics (pain relief), tick the box that reflects your opinion best.

Statement	Agree	Not sure	Disagree
Analgesics may mask deterioration in the animal's condition.	☐	☐	☐
Cattle benefit from receiving analgesic drugs as part of their treatment.	☐	☐	☐
Some pain is necessary to stop the animal becoming too active.	☐	☐	☐
Cattle recover faster if given analgesic drugs.	☐	☐	☐
Drug side effects limit the usefulness of giving analgesics to cattle.	☐	☐	☐
Farmers are happy to pay the costs involved with giving analgesics to cattle.	☐	☐	☐
Farmers would like cattle to receive analgesia but cost is a major issue.	☐	☐	☐
Farmers do not know enough about controlling pain in cattle.	☐	☐	☐
Vets do not discuss controlling pain in cattle with farmers enough.	☐	☐	☐

PART 3: USE OF ANALGESICS

For each procedure and condition below, select whether **you** would like an **adult dairy cow or calf** under your care to receive pain relief that **lasts more than 24 hours**, and what you would consider an acceptable cost for a course of pain relief for this procedure/ condition? Tick **one box per question**, for each procedure/ condition.

Procedure/ condition	**Would you like a cow under your care to receive pain relief that lasts ≥ 24 hours**	**What would you consider an ACCEPTABLE TOTAL cost for a course of pain relief for each procedure/ condition?**				
		€0	**€0 - €5**	**€5 - €15**	**€15 - €30**	**>€30**
Treatment of a sole ulcer (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Sole haemorrhage/ bruising (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
White line disease with sub-sole abscess (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
White line disease NO sub-sole abscess (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Claw amputation (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Caesarean section (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Dystocia - foetal-maternal disproportion requiring traction (Cow)*	Yes ☐ No ☐	☐	☐	☐	☐	☐
Calving - no assistance required (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Left displaced abomasum surgery (Cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Mastitis - clots in milk only (cow)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Disbudding (Calf)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Surgical castration (Calf)	Yes ☐ No ☐	☐	☐	☐	☐	☐
Castration with Burdizzo (Calf)	Yes ☐ No ☐	☐	☐	☐	☐	☐

* Difficult calving due to an oversized calf, requiring a moderate “pull”

PART 4: PAIN ASSESSMENT

In your opinion, how painful do you think the following conditions and procedures are for **adult dairy cows and calves**? Assume **NO** pain relief is provided. Circle **ONE** number from 1 (no pain) to 10 (worst pain imaginable).

Condition	***No Pain***									***Worst pain***
Left displaced abomasum (Cow)	1	2	3	4	5	6	7	8	9	10
Neck Callouses *e.g*. caused by feed barrier (Cow)	1	2	3	4	5	6	7	8	9	10
Acute metritis (Cow)	1	2	3	4	5	6	7	8	9	10
Swollen hock (Cow)	1	2	3	4	5	6	7	8	9	10
Hock with hair loss (Cow)	1	2	3	4	5	6	7	8	9	10
Acute toxic *E-coli* mastitis (Cow)	1	2	3	4	5	6	7	8	9	10
Mastitis - clots in milk only (Cow)	1	2	3	4	5	6	7	8	9	10
Digital dermatitis (Cow)	1	2	3	4	5	6	7	8	9	10
White line disease with sub-sole abscess (Cow)	1	2	3	4	5	6	7	8	9	10
White line disease NO sub-sole abscess (Cow)	1	2	3	4	5	6	7	8	9	10
Sole haemorrhage/ bruising (Cow)	1	2	3	4	5	6	7	8	9	10
Pneumonia (Calf)	1	2	3	4	5	6	7	8	9	10
Procedure	***No Pain***									***Worst pain***
Treatment of a Sole Ulcer (Cow)	1	2	3	4	5	6	7	8	9	10
Claw Amputation (Cow)	1	2	3	4	5	6	7	8	9	10
Caesarean section (Cow)	1	2	3	4	5	6	7	8	9	10
Dystocia - foetal-maternal disproportion requiring traction (Cow) *	1	2	3	4	5	6	7	8	9	10
Calving - no assistance required (Cow)	1	2	3	4	5	6	7	8	9	10
Left Displaced Abomasum surgery (Cow)	1	2	3	4	5	6	7	8	9	10
Disbudding (Calf)	1	2	3	4	5	6	7	8	9	10
Surgical castration (Calf)	1	2	3	4	5	6	7	8	9	10
Castration with Burdizzo (Calf)	1	2	3	4	5	6	7	8	9	10

* Difficult calving due to an oversized calf, requiring a moderate "pull"

PART 5: EMPATHY QUESTIONS

For each statement below, circle **ONE** number from 0 (does not describe me well) to 4 (describes me well).

Statement	***Does NOT describe me well***				***Describes me very well***
I often have tender, concerned feelings for animals less fortunate than others.	0	1	2	3	4
I sometimes find it difficult to see things from the animals point to view.	0	1	2	3	4
Sometimes I don't feel very sorry for animals when they have problems or suffer.	0	1	2	3	4
I try to understand the reasons behind an animal's undesired behaviour before making a decision.	0	1	2	3	4
When I see an animal being treated badly, I feel protective towards it.	0	1	2	3	4
I sometimes try to understand animals better by imagining how things look from their perspective.	0	1	2	3	4
Animals' misfortunes do not usually disturb me a great deal.	0	1	2	3	4
If I'm sure I'm right about how to handle an animal, I don't waste time trying to think what might be causing the animals behaviour.	0	1	2	3	4
When I see animals being treated unfairly, I sometimes don't feel very much pity for them.	0	1	2	3	4
I am often quite touched by things that I see happen.	0	1	2	3	4
I believe that there are two sides to every question and try to look at them both.	0	1	2	3	4
I would describe myself as an animal lover.	0	1	2	3	4
When I am disappointed or angry because of how an animal behaves, I usually try to put myself in its place for a while.	0	1	2	3	4
Before scolding an animal, I try to imagine how I would feel if I were in its place.	0	1	2	3	4

PART 6: LAMENESSS IN ADULT DAIRY COWS

Please circle the answer or fill in the grey box as required:

1. **How many cows in your herd have been lame in the <u>last year?</u>**

   Of these lame cows, how many (if any) received pain relief?

2. **How do you decide whether to give a cow pain relief for lameness or not?**

3. **If you do not use pain relief for lameness, why not (select all that apply)?**

   I do use pain relief   Never occurred to me   Vet never suggested it   Too expensive

   I don't think the cow needs it   Other:

4. **What hoof lesion do you believe is the biggest cause of lameness in your herd?**

5. **Do you feel like you are doing enough to reduce lameness in your herd?** Yes   No   Unsure

6. **Do you consider your knowledge of lameness management adequate?** Yes   No   Unsure

7. **Do you feel there are enough resources available to you, to increase your knowledge in lameness management?** Yes   No

8. **What has prevented you from doing more to reduce lameness in your herd?**

9. **What would motivate/help you to improve lameness in your herd?**

10. **Is your herd lameness scored?** [*Lameness scoring, also known as mobility scoring, is a method used to detect lame cows. It involves scoring each cow individually as they walk, from 0 (good mobility) to 3 (severely impaired mobility)*]

    Yes – How many times per year?   No

    If you answered 'No', what is your reasoning for not lameness scoring your herd?

    If you answered 'No', do you think having your herd regularly lameness scored would benefit your herd? Yes   No   Unsure

11. **Who treats your lame cows?** Yourself/farm staff   Trimmer   Vet   None

12. **Do you have a lame cow group that you keep closer to the parlour (i.e. so they do not have to walk as far)?** Yes No

If you answered 'No', what is your reasoning for not having a separate lame group?

13. **On average how many days is there between detecting a lame cow and getting her treated (in the last year)?**

14. **What is the longest time between detecting a lame cow and getting her treated (in the last year)?**

15. **If a cow is not treated within 24 hours of detecting she is lame, what is the main reason for the delay?**

16. **Have you received any advice on lameness from your vet in the last year?** Yes No

17. **Would you like your vet to be more involved in managing lameness on your farm?** Yes No

18. **Do you have a herd health plan written down, which includes lameness protocols (i.e. methods for detecting lameness, what to do if you detect a lame cow, methods of preventing lameness such as footbathing etc.)?** Yes No

If you answered 'No', what is your reasoning for not having a herd health plan for lameness?

If you answered 'No', do you think your farm would benefit from having a herd health plan for lameness? Yes No Unsure

Thank you for giving your time to complete this questionnaire

Please return using the pre-paid envelope

Veterinarian cover letter and questionnaire

Animal and Grassland Research & Innovation Centre
Moorepark
Fermoy
Co. Cork

08/09/2021

RE: Vet survey on the use of pain relief and lameness in Irish dairy herds

Dear Veterinary Practitioner,

Teagasc, in conjunction with the University of Nottingham, would like to invite you to participate in a survey. Participation is entirely voluntary, and there is no obligation to take part, but we would really appreciate your time and interest in completing the survey.

The aim of the study is to investigate the use of pain relief in Irish dairy herds. As you are aware, pain relief is important for animal welfare reasons and for the recovery of sick and lame dairy cows; the survey also examines lameness in more detail. Information from this study will ultimately help to improve the treatment and welfare of dairy cows in Ireland.

Vet practices registered with the Veterinary Council of Ireland have been sent this survey via post. We are inviting all vets that work with dairy cows to participate in this research study by completing the attached survey and returning in the pre-paid envelope. We ask that at least one vet from your practice completes the survey; however, we would very much appreciate as many vet responses as possible. The survey can also be completed online via the following link (https://forms.office.com/r/Bm385FZwpb) or by scanning the QR code below. The survey will take approximately 15 minutes to complete.

The survey is completely anonymous, so please do not include your name. If you choose to participate in this survey, please answer all questions as honestly as possible. By participating, you:

- Give consent for the researchers to use the information provided as part of a research study, which may lead to reports, published papers and/or conference presentations
- Acknowledge that the study is anonymous and that you will not provide your name or any other personal data
- Understand that the study is being conducted for research purposes
- Understand that you can request to see a summary of the findings

If you have any questions regarding this project, feel free to contact Natasha Browne via email (natasha.browne@teagasc.ie).

We thank you for taking the time to read this letter and would be very grateful for the completion of the survey by vets at your practice.

Sincerely,

Dr. Muireann Conneely (Principal researcher)

Dr. Chris Hudson (Researcher)

Natasha Browne (PhD. Candidate)

Scan to complete online

Vet survey on pain relief and lameness in Irish dairy cows

If preferred, the survey can also be completed online using the following link (https://forms.office.com/r/Bm385FZwpb) or by scanning the QR code on the cover letter.

PART 1: DEMOGRAPHICS

Please circle answer or fill in the grey box as required:

1. **Gender:**
2. **Year you were born:**
3. **Background before veterinary education:** Rural Urban Rural & Urban
4. **Location of veterinary school:** Ireland UK Other
5. **Year of graduation:**
6. **Postgraduate education undertaken/ undertaking:** None Certificate Diploma Postgraduate degree (MSc, PhD)
7. **Veterinary practice location (county):**
8. **Practice position:** Partner/clinical lead Employee
9. **Proportion of time spent treating cattle (%):**

PART 2: YOUR OPINION ON THE USE OF ANALGESICS IN DAIRY COWS

For each statement below on the use of analgesics, tick the box that reflects your opinion best.

Statement	Agree	Not sure	Disagree
Analgesics may mask deterioration in the animal's condition.	☐	☐	☐
Cattle benefit from receiving analgesic drugs as part of their treatment.	☐	☐	☐
Some pain is necessary to stop the animal becoming too active.	☐	☐	☐
Cattle recover faster if given analgesic drugs.	☐	☐	☐
Drug side effects limit the usefulness of giving analgesics to cattle.	☐	☐	☐
Farmers are happy to pay the costs involved with giving analgesics to cattle.	☐	☐	☐
Farmers would like cattle to receive analgesia but cost is a major issue.	☐	☐	☐
Farmers do not know enough about controlling pain in cattle.	☐	☐	☐
Vets do not discuss controlling pain in cattle with farmers enough.	☐	☐	☐

PART 3: USE OF ANALGESICS

The following question relates to **your** use of **NSAIDS** (e.g. meloxicam, flunixin, ketoprofen, carprofen) in cattle on dairy farms. The question lists some procedures/conditions commonly dealt with in cattle that you **may or may not** consider require NSAIDS. Tick **one box per question**, for each procedure/condition.

Procedure/ condition	**Would you provide NSAIDs for the following conditions**	**If yes, for what proportion of cases would you use NSAIDS**	**What would you consider an ACCEPTABLE TOTAL cost for a course of analgesia for each procedure/ condition?** 0€	€0 - €5	€5 - €15	€15 -€30	> €30
Treatment of a sole ulcer (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Sole haemorrhage/ bruising (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
White line disease with sub-sole abscess (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
White line disease NO sub-sole abscess (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Claw amputation (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Caesarean section (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Dystocia - foetal-maternal disproportion requiring traction (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Left displaced abomasum surgery (Cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Mastitis - clots in milk only (cow)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Disbudding (Calf)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Surgical castration (Calf)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐
Castration with Burdizzo (Calf)	Yes ☐ No ☐	%	☐	☐	☐	☐	☐

PART 4: PAIN ASSESSMENT

In your opinion, how painful do you think the following conditions and procedures are for **adult dairy cows and calves**? Assume **NO** analgesic/anaesthetic agents are provided. Circle **ONE** number from 1 (no pain) to 10 (worst pain imaginable).

Condition	***No Pain***									***Worst pain***
Left displaced abomasum (Cow)	1	2	3	4	5	6	7	8	9	10
Neck callouses *e.g.* caused by feed barrier (Cow)	1	2	3	4	5	6	7	8	9	10
Acute metritis (Cow)	1	2	3	4	5	6	7	8	9	10
Swollen hock (Cow)	1	2	3	4	5	6	7	8	9	10
Hock with hair loss (Cow)	1	2	3	4	5	6	7	8	9	10
Acute toxic *E-coli* mastitis (Cow)	1	2	3	4	5	6	7	8	9	10
Mastitis - clots in milk only (Cow)	1	2	3	4	5	6	7	8	9	10
Digital dermatitis (Cow)	1	2	3	4	5	6	7	8	9	10
White line disease with sub-sole abscess (Cow)	1	2	3	4	5	6	7	8	9	10
White line disease NO sub-sole abscess (Cow)	1	2	3	4	5	6	7	8	9	10
Sole haemorrhage/ bruising (Cow)	1	2	3	4	5	6	7	8	9	10
Calf pneumonia	1	2	3	4	5	6	7	8	9	10
Procedure	***No Pain***									***Worst pain***
Treatment of a sole ulcer (Cow)	1	2	3	4	5	6	7	8	9	10
Claw amputation (Cow)	1	2	3	4	5	6	7	8	9	10
Caesarean section (Cow)	1	2	3	4	5	6	7	8	9	10
Dystocia - foetal-maternal disproportion requiring traction (Cow)	1	2	3	4	5	6	7	8	9	10
Left displaced abomasum surgery (Cow)	1	2	3	4	5	6	7	8	9	10
Calving - no assistance required (Cow)	1	2	3	4	5	6	7	8	9	10
Disbudding (Calf)	1	2	3	4	5	6	7	8	9	10
Surgical castration (Calf)	1	2	3	4	5	6	7	8	9	10
Castration with Burdizzo (Calf)	1	2	3	4	5	6	7	8	9	10

PART 5: EMPATHY QUESTIONS

For each statement below, circle **ONE** number from 0 (does not describe me well) to 4 (describes me well).

Statement (ANIMAL VERSION)	***Does NOT describe me well***			***Describes me very well***	
I often have tender, concerned feelings for animals less fortunate than others.	0	1	2	3	4
I sometimes find it difficult to see things from the animals point to view.	0	1	2	3	4
Sometimes I don't feel very sorry for animals when they have problems or suffer.	0	1	2	3	4
I try to understand the reasons behind an animal's undesired behaviour before making a decision.	0	1	2	3	4
When I see an animal being treated badly, I feel protective towards it.	0	1	2	3	4
I sometimes try to understand animals better by imagining how things look from their perspective.	0	1	2	3	4
Animals' misfortunes do not usually disturb me a great deal.	0	1	2	3	4
If I'm sure I'm right about how to handle an animal, I don't waste time trying to think what might be causing the animals behaviour.	0	1	2	3	4
When I see animals being treated unfairly, I sometimes don't feel very much pity for them.	0	1	2	3	4
I am often quite touched by things that I see happen.	0	1	2	3	4
I believe that there are two sides to every question and try to look at them both.	0	1	2	3	4
I would describe myself as an animal lover.	0	1	2	3	4
When I am disappointed or angry because of how an animal behaves, I usually try to put myself in its place for a while.	0	1	2	3	4
Before scolding an animal, I try to imagine how I would feel if I were in its place.	0	1	2	3	4

PART 6: LAMENESSS IN DAIRY COWS

Please circle the answer or fill in the grey box as required:

1. **How involved with lameness management have you been in the last year (circle <u>all</u> that apply)?**

   None   Treating lame cows   Putting preventative measures in place (i.e. footbathing)

   Identifying areas of risk for lameness on farms   Lameness detection (i.e. lameness scoring)

   Creating lameness management plans

2. **Do you consider your knowledge in lameness management adequate?**

   Yes   No   Unsure

3. **Have you undertaken any CPD in pain management?**

Yes No

4. **Have you undertaken any CPD in lameness?**

Yes No

5. **Do you enjoy/ want to do lameness work on dairy farms?**

Yes No

If 'NO', why not?

6. **Where have you obtained most of your knowledge about lameness in dairy cows (please circle one only)?**

Undergraduate training (vet school) Journals /articles Continuing education lectures

Experience gained in practice Commercial literature / data sheets

Other:

7. **Do you feel like there are enough opportunities to upskill in the area of dairy cow lameness?**

Yes No

If NO, what opportunities would you like available?

8. **Do you feel like farmers are doing enough to reduce lameness in their herd?**

Yes No Unsure

9. **Do you think farmers would benefit from having a written herd health plan including lameness protocols (i.e. methods for detecting lameness, what to do if they detect a lame cow, methods of preventing lameness such as footbathing etc.)?**

Yes No Unsure

10. What percentage of your dairy farmers have you discussed lameness with in the last year?

At herd level e.g. footbathing: %

At cow level e.g. treating individual cow: %

11. What do you think is the main reason that prevents farmers from doing more to reduce lameness in their herd?

12. What hoof lesion do you believe is the biggest cause of lameness on farms you have treated?

13. How would you treat a white line lesion?

14. How would you treat digital dermatitis?

Thank you for giving your time to complete this questionnaire

Please return using the pre-paid envelope

Opinions on pain and analgesics

The additional predictors offered to each logistic regression model regarding opinions on pain and analgesics are reported in Table E1. The equation for the logistic regression models is as followed [Equation E1]:

$$p(y) = \frac{e^{(\beta_0 + \boldsymbol{\beta_1 x})}}{1 + e^{(\beta_0 + \boldsymbol{\beta_1 x})}} \qquad \text{[E1]}$$

Where $p(y)$ is the fitted probability of the binary outcome y, β_0 is the intercept term and $\boldsymbol{\beta}_1$ is the vector of coefficients for the vector of the input values $\boldsymbol{x}$.

Model fit was assessed using the Hosmer-Lemeshow test. For each model (1 model per statement), the test assessed whether the observed probabilities were significantly different to the predicted probabilities for each decile (groups ranked by predicted risk), using a chi-squared test. Predicted probabilities were calculated using the 'predict' function in R. The equation for the Hosmer-Lemeshow test is shown by Equation E2:

$$\chi^2_{HL} = \sum_{i=1}^{G} \frac{O_i - E_i)^2}{E_i\left(1 - \frac{E_i}{n_i}\right)} \qquad \text{[E2]}$$

Where O_i is the observed probabilities in the ith group, E_i is the expected probabilities in the ith group, and n_i is the number of observations in the ith group. G represents the number of groups (10 in this case). All models gave a P-value of ≥ 0.05, indicating no significant difference between predicted and observed probabilities, therefore, good model fit can be assumed.

Table E1. Predictor categories for the logistic regression models on the agreement of statements regarding pain and analgesics. All predictors were offered to the original model for each statement, however, predictors may not have remained in the final models due to backwards selection

Predictor	Categories (categorical data)
Group	Farmer
	Veterinarian
Gender	Male
	Female
Age	≤40
	41–55
	> 55
Background	Rural
	Urban, and rural & urban
Location of farm/veterinary practice	Connacht
	Leinster
	Munster
	Ulster
Empathy	<31
	31–40
	>40

Factors associated with NSAID use

Mixed effects logistic regression models were used to assess factors associated with NSAID use. The first model looked at the odds of a farmer wanting NSAIDs used, and the second model looked at the odds of whether a veterinarian used NSAIDs in ≥50% cases. Predictors offered to the veterinarian model and the farmer model are reported in Table E2 and E3, respectively. The mixed effect logistic regression model equation [E3] can be written as followed:

$$p(y) = \frac{e^{(\beta_o + \beta_1 x + v_j)}}{1 + e^{(\beta_o + \beta_1 x + v_j)}} \qquad [E3]$$

Where $p(y)$ is the fitted probability of the binary outcome y, β_0 is the intercept term and $\boldsymbol{\beta}_1$ is the vector of coefficients for the vector of the input values $\boldsymbol{x}$ and v_j represents the random effect term reflecting respondent (assumed to be drawn from a normal distribution with zero mean).

Odds ratios were calculated as the exponential of the estimates from each model. This is based on a one-unit increase for continuous variables.

The Hosmer-Lemeshow test was used to assess model fit of the mixed effects logistic regression models. The equation [E2] for the Hosmer-Lemeshow test is reported in the previous section on ‘Opinions on pain and analgesics’ within this appendix. The output from the Hosmer-Lemeshow test gave a P-value of 0.261 for the farmer model and 0.977 for the veterinarian model. Given both P-values are ≥ 0.05, model fit was deemed acceptable.

Table E2. Predictor categories for the model on the odds of a farmer wanting NSAIDs used. All predictors were offered to the original model (except those with non-zero variance[1]), however, predictors did not all remain in the final model due to backwards selection

Predictor	Categories (categorical data)
Condition	Dystocia
	Caesarean
	Treatment of sole ulcer
	Sole haemorrhage
	White line abscess
	White line (no abscess)
	Digit amputation
	LDA surgery
	Mastitis
	Disbudding (calf)
	Surgical castration (calf)
	Burdizzo castration (calf)
Pain score	≤3
	4
	5
	6
	7
	8
	9

	10
Survey format	Online
	Post
Gender	Male
	Female
Age (yrs)	≤40
	41–55
	> 55
Background	Rural
	Rural & urban
	Urban
Veterinary school location	Ireland
	Other
Graduation year	<1991
	1991–2005
	2006–2021
Postgraduate qualification	Yes
	No
Veterinary practice location	Connacht
	Leinster
	Munster
	Ulster

Position	Employee
	Partner/clinical lead
Proportion time treating cattle (%)	<51
	51–80
	>80
Empathy score	<31
	31–40
	>40
Statement A	Agree
	Disagree
Statement B[1]	Agree
	Disagree
Statement C	Agree
	Disagree
Statement D[1]	Agree
	Disagree
Statement E	Agree
	Disagree
Statement F	Agree
	Disagree
Statement G	Agree
	Disagree

Statement H	Agree Disagree
Statement I	Agree Disagree

[a]Analgesics may mask deterioration in the animal's condition
[b]Cattle benefit from receiving analgesic drugs as part of their treatment
[c]Some pain is necessary to stop the animal becoming too active
[d]Cattle recover faster if given analgesic drugs
[e]Drug side effects limit the usefulness of giving analgesics to cattle
[f]Farmers are happy to pay the costs involved with giving analgesics to cattle
[g]Farmers would like cattle to receive analgesia but cost is a major issue
[h]Farmers do not know enough about controlling pain in cattle
[i]Vets do not discuss controlling pain in cattle with farmers enough

Table E3. Predictor categories for the model on the odds of a whether a veterinarian used NSAIDs in ≥50% cases. All predictors were offered to the original model (except those with non-zero variance[1]), however, predictors did not all remain in the final model due to backwards selection

Predictor	Categories (categorical data)
Condition	Dystocia
	Caesarean
	Treatment of sole ulcer
	Sole haemorrhage
	White line abscess
	White line (no abscess)
	Digit amputation
	LDA surgery
	Mastitis
	Disbudding (calf)
	Surgical castration (calf)
	Burdizzo castration (calf)
Pain score	≤3
	4
	5
	6
	7
	8

	9
	10
Survey format	Online
	Post
Gender	Male
	Female
Age (yrs)	≤40
	41–55
	> 55
Highest level education	Level 3
	Level 4 & 5
	Level 6
	Level 7 & 8
	Level 9 & 10
	None
Background[1]	Rural
	Urban, and rural & urban
Full time farmer (yrs)	≤20
	21–35
	>35
Farm location	Connacht
	Leinster

	Munster
	Ulster
Herd size	<100
	100–150
	>150
Empathy score	<31
	31–40
	>40
Statement A	Agree
	Disagree
Statement B	Agree
	Disagree
Statement C	Agree
	Disagree
Statement D	Agree
	Disagree
Statement E	Agree
	Disagree
Statement F	Agree
	Disagree
Statement G	Agree
	Disagree

Statement H	Agree Disagree
Statement I	Agree Disagree

[a]Analgesics may mask deterioration in the animal's condition
[b]Cattle benefit from receiving analgesic drugs as part of their treatment
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