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Publication date	2023-05-22
Publication information	McAloon, Conor G., Jamie A. Tratalos, Luke O'Grady, Simon John More, Guy McGrath, and et al. "An Observational Study of Ear-Tagged Calf Mortality (1 to 100 Days) on Irish Dairy Farms and Associations between Biosecurity Practices and Calf Mortality on Farms Participating in a Johne's Disease Control Program" 106, no. 7 (May 22, 2023).
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/25120
Publisher's version (DOI)	10.3168/jds.2022-22519

J. Dairy Sci. 106:4966–4977
https://doi.org/10.3168/jds.2022-22519

An observational study of ear-tagged calf mortality (1 to 100 days) on Irish dairy farms and associations between biosecurity practices and calf mortality on farms participating in a Johne's disease control program

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ABSTRACT

Postnatal mortality among replacement stock has a detrimental effect on the social, economic, and environmental sustainability of dairy production. Calf mortality rates vary between countries and show differences in temporal trends; most, however, are characterized by high levels of between-farm variability. Explaining this variation can be difficult because herd-level information on management practices relevant to calf health is often not available. The Irish Johne's Control Programme (IJCP) contains a substantial on-farm monitoring program called the Veterinary Risk Assessment and Management Plan (VRAMP). Although this risk assessment is largely focused on factors relevant to the transmission of paratuberculosis, many of its principles are good practice biocontainment policies that are also advocated for the protection of calf health. The objectives of this study were (1) to quantify mortality in ear-tagged Irish dairy calves between 2016 and 2020 using both survival and risk approaches, (2) to determine risk factors for 100-d cumulative mortality hazard in ear-tagged Irish dairy calves between 2016 and 2020, (3) to determine whether 100-d cumulative mortality hazard was higher in ear-tagged calves within herds registered in the IJCP versus those that were not registered in the IJCP and whether there were differences between these cohorts over time, and (4) within IJCP herds, to determine whether VRAMP score or changes in VRAMP score were associated with 100-d cumulative mortality hazard. Excluding perinatal mortality, the overall 100-d cumulative mortality hazard was 4.1%. Calf mortality was consistently underestimated using risk approaches that did not account for calf censoring. Cox proportional hazards models showed that cumulative mortality hazard was greater in male calves; particularly, calves born to Jersey breed dams and those with a beef breed sire. Mortality hazard increased with increasing herd size, was highest in calves born in herds that contract-reared heifers, and lowest in those born in mixed dairy-beef enterprises. Mortality hazard decreased over time with the mortality hazard in 2020 being 0.83 times that of 2016. Mortality hazard was higher in IJCP-registered herds than nonregistered herds (hazard ratio 1.06, 95% CI 1.01–1.12), likely reflecting differences in herds that enrolled in the national program. However, we detected a significant interaction between IJCP status (enrolled vs. not enrolled) and year (hazard ratio 0.96, 95% CI 0.92–1.00), indicating that the decrease in mortality hazard between 2016 and 2020 was greater in IJCP herds versus non-IJCP herds. Finally, increasing VRAMP scores (indicating higher risk for paratuberculosis transmission) were positively associated with increased calf mortality hazard. Postnatal calf mortality rates in Irish dairy herds declined between 2016 and 2020. Our study suggests that implementation of recommended biocontainment practices to control paratuberculosis in IJCP herds was associated with a reduction in calf mortality hazard.
Key words: paratuberculosis, calf mortality, calf welfare, biosecurity

INTRODUCTION

Improved calf health on dairy farms is associated with increased first-lactation production and increased longevity in the herd (Heinrichs and Heinrichs, 2011). Mortality among replacement stock represents both a

Received July 13, 2022.
Accepted January 23, 2023.
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lost opportunity for future herd production as well as a loss associated with the input costs in rearing calves to the point at which mortality occurred. Furthermore, mortality among replacement calves represents a key loss in production efficiency, requiring producers to rear additional animals than would otherwise be needed to maintain a given replacement rate, with a detrimental effect on environmental effects of dairy production (Capper and Cady, 2020). However, peri- and postnatal calf mortality is perhaps most important as an indicator of calf welfare, particularly given that the welfare of calves in dairy production systems internationally is under increasing scrutiny both from within industry and among consumers (Sweeney et al., 2022). Although low calf mortality rates cannot be considered a guarantee of high levels of calf welfare, high calf mortality rates are undoubtedly an indicator of poor calf welfare (de Vries et al., 2011; Mee, 2013; Osawe et al., 2021).

Dairy calf postnatal mortality risk (excluding perinatal mortality) varies considerably internationally (Reimus et al., 2020; Schild et al., 2020) with high between-herd variability (e.g., Lora et al., 2014). International studies have demonstrated variable trends in calf mortality in recent years. In the Netherlands, calf mortality increased in years before the implementation of a voluntary calf management tool (KalfOK) and decreased thereafter (Santman-Berends et al., 2021); however, in the United Kingdom, it has been relatively static in the first 3 mo of life between 2011 and 2018 (Hyde et al., 2020), whereas in the United States, preweaning calf mortality risk has declined between 1992 and 2014 (Urie et al., 2018).

A significant challenge in interpreting calf mortality is that there are significant variations in the method of estimating and summarizing the risk of calf mortality on dairy farms. As well as reflecting the number of animals that died on farm, it is important that calf mortality metrics reflect days at risk for those calves. For example, in Ireland, male calves do not typically remain on farm and are often sold at the earliest opportunity to specialist dairy-to-beef rearing units. Therefore, the number of calves born is not an appropriate denominator for reflecting the risk of mortality on such farms. Recent studies have demonstrated that when calf mortality is measured using different definitions, the incidence of calf mortality, and even the ranking of herds, may change (Santman-Berends et al., 2019).

Significant farm- and animal-level risk and protective factors have been identified for calf mortality. Farm-level risk factors include calf under-nutrition (Torsein et al., 2011; Zucali et al., 2013; Urie et al., 2018), morbidity (Torsein et al., 2011; Zucali et al., 2013; Urie et al., 2018; Barry et al., 2020; Johnsen et al., 2021), herd size (Jorgensen et al., 2017; Reimus et al., 2020), calf grouping strategy (Gulliksen et al., 2009; Zucali et al., 2013; Reimus et al., 2020), season (Svensson et al., 2006; Gulliksen et al., 2009; Raboisson et al., 2013), region (Losinger and Heinrichs, 1997), and the farmers' attitude to calf rearing and welfare (Santman-Berends et al., 2014; Osawe et al., 2021). Calf-level risk factors include birth weight (Urie et al., 2018), serum immunoglobulin status (Zucali et al., 2013; Jorgensen et al., 2017; Urie et al., 2018), genotype (Raboisson et al., 2014), and sex (Raboisson et al., 2014).

Although the advent of statutory animal registration and identification systems has resulted in relatively robust data for quantifying mortality, there is often a dearth of information routinely collected on herd management practices relevant to the control of calf health. In Ireland, the Irish Johne's Control Programme (**IJCP**) was launched in 2013, first as a voluntary pilot program, by Animal Health Ireland for the control of paratuberculosis on Irish dairy farms (Gavey et al., 2021). Improved calf health through enhanced farm biosecurity is a stated objective of the IJCP (Gavey et al., 2021; Field et al., 2022). A key component of this program is a requirement for the completion of an annual herd-level Veterinary Risk Assessment and Management Plan (**VRAMP**) for all IJCP-registered herds, undertaken by an approved veterinary practitioner. The VRAMP provides the framework for a systematic review of factors associated with bioexclusion and biocontainment risks of Johne's disease (**JD**) for the herd, including consideration of "calf protective" measures that are considered to be beneficial for improving calf health generally (McAloon et al., 2016a). A lower VRAMP score reflects lower assessed biosecurity risk. Following the completion of VRAMP, the herd owner agrees to up to 3 management changes to reduce the likelihood of the introduction and spread of *Mycobacterium avium* subspecies *paratuberculosis* (the causative agent of JD; Gavey et al., 2021). All VRAMP data are collected centrally in an electronic format.

Johne's disease control is often stated as being associated with benefits for calf health. Specifically, feeding and hygiene practices recommended for paratuberculosis control are expected to benefit calf health by reducing exposure to infectious diseases and supporting calf nutrition including provision of adequate colostrum. However, to date, there has been limited evidence to support this claim. Therefore, the aim of the present study was to investigate the associations between biocontainment practices collected as part of the IJCP and calf mortality on Irish dairy farms. Specifically, the objectives of this study were (1) to quantify mortality in ear-tagged Irish dairy calves between 2016 and 2020 using both survival and risk based approaches, (2) to determine risk factors for 100-d cumulative mortality hazard in ear-tagged Irish dairy calves between 2016 and 2020, (3) to determine whether 100-d cumulative mortality hazard was higher in ear-tagged calves within herds registered in the IJCP versus those that were not registered in the IJCP and whether there were differences between these cohorts over time, and (4) within IJCP herds, to determine whether VRAMP score, or changes in VRAMP score were associated with 100-d cumulative mortality hazard.

MATERIALS AND METHODS

Data Description

In the Republic of Ireland, the Animal Identification and Movement system contains all birth, death, and movement registrations for all bovine animals in the country. Under Irish law (S.I. No. 30, 2017), all bovine births including stillbirths and abortions must be registered. All calves must be tagged within 20 d of birth. Calves that die within this period, or those that are dead at birth or that are aborted, must be tagged, and both the birth date and the date of death of the animal must be registered with the Department of Agriculture, Food and the Marine (Dublin, Ireland). Stillbirths are defined as any calf that is registered that was not alive at birth. Data consisting of herd ID, date of birth, date of movement off farm, date of death on farm (for those that died on farm), and date of export (for those that were exported) were extracted from the Animal Identification and Movement for all calves born between January 1, 2016, and June 30, 2020. This represented all the registration data for all herds in the country over this time period. Institutional Animal Care and Use Committee approval was not required for this study since it was an analysis of data routinely collected under national legislation.

A pseudonymized herd reference was used to match these data to a herd classification database. The herd classification assigns herd type based on a range of demographic and transport variables and was developed by combining expert knowledge and machine learning (Brock et al., 2021). These data were then additionally matched to the results of all VRAMP conducted on herds registered in the IJCP between October 20, 2016, and May 6, 2021. The specific questions and scoring methods of the VRAMP are reported in detail elsewhere (McAloon et al., 2017). Briefly, a series of questions and observations relevant to paratuberculosis transmission are assigned risk assessment scores in 4 areas as follows: pre-weaned calves risk assessment (section 1), weaned calf risk assessment (section 2), adult cow risk assessment (section 3), and calving area risk assessment (section 4). For the purpose of this study, we used the total score for each section as well as the total overall score summed across all the sections.

Data Cleaning

For the present study, we only considered calves born in herds with a dairy herd classification. Therefore, the data set was restricted to herds with a main herd type classification of dairy or mixed. The herd type descriptor consisted of the following 5 mutually exclusive categories: typical dairy (a dairy enterprise rearing own replacements and not rearing males), dairy using contract rearer to rear replacements, dairy not rearing replacements and not using contract rearing, dairy herd raising its own males, and mixed (an enterprise engaged in dairying and beef production). To remove calves that may have been born as part of a beef enterprise on the same premises, the data set was filtered to only include calves with a dairy breed dam. Dairy breed dams were identified as dams with the following breed types, or crossbreeds with the predominant breed of the following: Ayrshire, Holstein-Friesian, Jersey, Montbeliarde, Danish Red, Norwegian Red, Rotbunt, and Swedish Red. Other minor dairy breeds (with less than 1,000 registrations) were removed from the data set. For further analysis, the predominant breed of the dam was used as the dam breed (e.g., "Jersey" and "Jersey cross" were both considered "Jersey").

Next, "dairy-beef" calves were identified as calves with a dairy breed dam and a non-dairy breed sire. Dairy breed sires were identified as bulls registered as 1 of the following breeds: Ayrshire, Holstein/Friesian, Guernsey, Jersey, Milking Shorthorn, Montbeliarde, Danish Red, Norwegian Red, Rotbunt, and Swedish Red. Calves born to all other breed sires were considered dairy-beef calves. Herd size, according to the number of all animals registered in the herd in May 2019, was converted to a categorical variable based on the quintiles of the distribution of herd sizes. Calves reported as stillborn (i.e., those that were born dead) were removed from the data set and, therefore, not included in the definition of calf mortality, given that the risk factors for stillbirth are considered separate to those for postnatal calf mortality (Mee et al., 2022). Finally, herds with less than 20 animals (based on number of all animals present in the herds as assessed in May 2019) were removed from the data set.

Our definition of a calf mortality "event" therefore consisted of calves that were alive at birth, registered with the Department of Agriculture, Food and the Marine in accordance with national legislation, and subsequently registered dead with a date of death within 100 d of birth, and before any movement off the farm.

Calves that were moved off farm and died on another farm were not included.

Data Analysis

Objective 1: Mortality Rates in Irish Dairy Calves Between 2016 and 2020 Using Both Survival and Risk Approaches. We calculated 100-d cumulative mortality hazard using Kaplan-Meier survival curves to account for calf days at risk. Calves were right censored if moved off farm or were at 100 d of age, whichever occurred first. For comparison, we also present estimates of the 100-d calf mortality risk defined as the number of mortality events in calves less than 100 d of age on their farm of birth, divided by the number of calves born on the farm. Previous work has demonstrated that calf mortality risk underestimates calf mortality (Santman-Berends et al., 2019). Nonetheless, the metric is still frequently used by industries to quantify calf mortality. The degree to which mortality risk underestimates calf mortality is expected to vary according to different production systems. Therefore, we considered that there was value in comparing how this metric compares with other measures of calf mortality in the Irish dairy production system. Both metrics were presented at the animal level, disaggregated by sex, dam and sire breed, and year. Both metrics were also presented at the herd level and summarized as the mean, median, and 5th and 95th percentiles.

Objectives 2 and 3: Determining Risk Factors for Calf Mortality Hazard in Irish Dairy Calves Between 2016 and 2020 and Their Association with IJCP Registration. Objective 2 was addressed by developing an animal-level Cox proportional hazards model using herd of birth as a gamma frailty effect. Ties were handled using Efron's approximation (Efron, 1977). Mortality was the event of interest. Calves were right censored if they moved off farm, or were at 100 d of age, whichever occurred first, and contributed to the population at risk per unit time only until this point. Calves moved onto the farm were not considered in the analysis. Year of birth, sex, dam breed, sire breed type (dairy versus beef), and herd type were fitted as covariates. All variables were considered of interest and were therefore included in the final multivariable model irrespective of their univariate *P*-values.

To evaluate the variation attributable to herd, the median hazard ratio (**MHR**) was calculated. The MHR is analogous to the median odds ratio in multilevel logistic regression and may be defined as the median relative change in the hazard of the occurrence of the outcome when comparing identical subjects from 2 randomly selected different clusters that are ordered by risk (Austin et al., 2017). The MHR was calculated as the upper quantile of an $F(2\sigma^{-2}, 2\sigma^{-2})$ distribution, with σ^2 representing the variance of the gamma frailty term.

To address objective 3, an additional variable ("IJCP_herd": yes/no) indicating whether the herd had registered in the IJCP at any stage during the observation period (according to the existence of a VRAMP for that herd) was created, and this variable along with an interaction with year of birth was forced into the model. All other predictors were retained in the model, irrespective of whether they were statistically significant or not. Proportional hazards assumption and time dependence of effects were assessed for each variable separately by visual examination log-log plots of hazard curves and distributions of Schoenfeld residuals (Schoenfeld, 1982; Hess, 1995).

Objective 4: Determining Whether VRAMP Score or Changes in VRAMP Score Were Associated with 100-d Calf Survival Probability in IJCP Herds. To investigate the association between calf mortality rates and changes in VRAMP scores over time, the data were first restricted to calves within herds that had 2 or more VRAMP conducted. Next, a series of lagged variables were created to indicate the herd's numeric change (either positive or negative) in VRAMP score in each of the scoring sections from the previous VRAMP. Veterinary Risk Assessment and Management Plan data were then combined with the calf-level survival data according to the herd ID and with the year of VRAMP corresponding to the year of birth for each calf. When multiple VRAMP were conducted in the same year, only 1 VRAMP was chosen to represent the management practices on that farm in that year. In this case, the earliest VRAMP was chosen as being most representative of the management practices during the calving season because most Irish dairy farms operate a seasonal, spring-calving system. Calf data from herd-years without VRAMP data and from herds without VRAMP data were removed. Cox proportional hazards survival models were created using the same event of interest and predictors as for objective 3, but with the VRAMP scores and change in scores from the previous VRAMP used as predictors instead of the IJCP status variable. Given the correlation between VRAMP scores in different sections, separate models were produced for the overall VRAMP score, and for each of the 4 sections (pre-weaned calf risk assessment, weaned calf risk assessment, adult cow risk assessment, calving area risk assessment) separately.

All data cleaning, joining, and analysis was conducted in R-studio (version 2022.02.3) and R (version 3.6.2l; R Core Team, 2013) using the 'tidyverse' (Wickham et al., 2019), 'survival' (Therneau and Lumley, 2013), and 'ggplot2' (Wickham, 2016) packages.

RESULTS

Descriptive Statistics

After initial data cleaning, there were birth, death, and movement data for 6,611,249 calves from 16,154 dairy herds born between January 1, 2016, and June 29, 2020. Of these, 132,028 (approximately 2%) were labeled as "stillborn" (that is dead at birth) and removed from the data set, leaving 6,479,221 records for analysis. In total, 16,026 herds had births registered in 2019. Of these, 6,948 herds were classified as "typical dairies" with a mean number of calf births (excluding stillbirths) in 2019 of 103; 436 herds were classified as "using contract rearing" with a mean number of calf births (excluding stillbirths) in 2019 of 165; 987 herds were classified as "not rearing and not contract rearing," with a mean number of calf births (excluding stillbirths) in 2019 of 69; 2,459 herds were classified as "dairy herds rearing males" with a mean number of calf births (excluding stillbirths) in 2019 of 95; and 5,196 herds were classified as "mixed herds," with a mean number of calf births (excluding stillbirths) in 2019 of 58.

Mortality in Irish Dairy Calves: Mortality Risk and Cumulative Mortality Hazard

The animal-level comparisons between 100-d mortality risk and cumulative mortality hazard are shown in Table 1. Across the whole study period, animal-level mortality risk in the first 100 d of life was 3.2% (208,138/6,559,236). The 100-d mortality risk in female calves was 3.0% (95,858/3,194,022), whereas in males it was 3.3% (112,280/3,365,214). Risk decreased from 3.4% (42,034/1,224,821) in 2016 to 2.9% in 2020 (37,766/1,309,242), was lowest in calves born to Montbeliarde and Montbeliarde-cross dams (2.9%, 1,233/42,969), and was highest in calves born to Jersey and Jersey-cross dams (5.5%, 13,341/240,656). In comparison, the cumulative 100-d calf mortality hazard was 4.0% across the whole study period. In females, it was 3.4%, whereas in males it was 4.8%; additionally, in 2016, it was 4.2%, whereas in 2020 it was 3.7%. The cumulative 100-d calf mortality hazard was lowest in calves born to Montbeliarde and Montbeliarde-cross dams (3.7%), highest in those born to Jersey and Jersey-cross dams (7.3%), and it was 2.9% and 5.4% for calves born in mixed herds and herds that contract-reared their heifers, respectively.

At farm level, the mean and median 100-d calf mortality risks were 2.9% and 2.0%, respectively, and ranged from a 5th percentile of 0% to a 95th percentile of 8.4%. Calf mortality risk was lowest in mixed herds at 2.6%, and highest in those dairy herds that contract-reared their replacements (3.8%). Mean and median herd-level mortality hazard was 3.6% and 2.9% respectively and ranged from a 5th percentile of 0% to a 95th percentile of 10.6%. Mortality hazard was higher than mortality risk for every herd with a mean difference of +0.75%. The difference was +1.9% or greater in 10% of herds.

VRAMP Herds Versus Non-VRAMP Herds

Veterinary Risk Assessment and Management Plan data were present for 1,696 herds. Of these, 328 had 1 VRAMP, 778 had 2, 560 had 3, and 30 had 4 or more VRAMP conducted between 2016 and 2020. In herds with 2 or more VRAMP, the mean time between the first and last VRAMP assessment was 1.6 yr. The mean change in overall VRAMP score from first to last VRAMP was a reduction of 8 units, whereas the median was a reduction of 6 units. Higher VRAMP scores are associated with higher risk of paratuberculosis transmission and the maximum possible total VRAMP score is 227. In total, 62% of herds (843/1,368) reduced their score between first and last VRAMP, 30% (413/1,368) increased their score, whereas the remainder (8%, 112/1,368) remained on the same score. For calves born in IJCP-registered herds, the 100-d mortality risk was 3.6% (35,889/999,336) compared with 3.1% (172,249/5,559,900) for calves that were born in non-IJCP herds. After accounting for censoring, the 100-d

Table 1. Comparison between risk and hazard approaches to quantifying animal-level calf mortality in 6,559,236 calves from 16,154 Irish dairy herds between 2016 and 2020

Category	100-d calf mortality risk[1] (%)	100-d cumulative calf mortality hazard (%)
Overall	3.2 (208,138/6,559,236)	4.1
Sex		
Female	3.0 (95,858/3,194,022)	3.5
Male	3.3 (112,280/3,365,214)	4.8
Year of birth		
2016	3.4 (42,034/1,224,821)	4.5
2017	3.0 (39,051/1,284,924)	3.9
2018	3.5 (47,017/1,347,098)	4.4
2019	3.0 (42,270/1,393,151)	3.9
2020	2.9 (37,766/1,309,242)	3.7
Dam breed		
Ayrshire	3.7 (510/13,939)	4.8
Holstein-Friesian	3.1 (190,008/6,158,167)	4.0
Jersey	5.5 (13,341/240,656)	7.4
Montbeliarde	2.9 (1,233/42,969)	3.8
Danish Red	3.6 (37/1,042)	4.5
Norwegian Red	2.9 (2,146/73,147)	4.0
Rotbunt	2.8 (694/24,513)	4.5
Swedish Red	3.5 (169/4,803)	4.6

[1]Mortality risk expressed as a percentage. Raw numbers are shown in parentheses.

Table 2. Results of multivariable Cox proportional hazards model (Model 1) of the factors associated with calf mortality in 6,559,236 calves from 16,154 Irish dairy herds; birth herd is included as a gamma frailty effect

Variable	Category	Hazard ratio	Lower 95% CI	Upper 95% CI	*P*-value
Sex	Female	Referent			
	Male	1.45	1.43	1.46	<0.001
Dam breed	Ayrshire	0.95	0.86	1.06	0.350
	Friesian	Referent			
	Jersey	1.16	1.13	1.18	0.000
	Montbeliarde	1.04	0.98	1.11	0.170
	Norwegian Red	0.94	0.90	0.99	0.011
	Rotbunt	1.00	0.92	1.09	0.970
	Danish Red	0.93	0.67	1.30	0.690
	Swedish Red	1.13	0.95	1.33	0.160
Sire breed	Dairy	Referent			
	Beef	1.19	1.18	1.20	<0.001
Year of birth	2016	Referent			
	2017	0.86	0.85	0.87	<0.001
	2018	0.96	0.95	0.97	<0.001
	2019	0.84	0.83	0.85	<0.001
	2020	0.83	0.81	0.84	<0.001
Herd size	Quintile 1: 20–135	Referent			
	Quintile 2: 135–195	1.13	1.09	1.18	<0.001
	Quintile 3: 195–267	1.19	1.14	1.24	<0.001
	Quintile 4: 267–394	1.25	1.19	1.31	<0.001
	Quintile 5: >394	1.58	1.50	1.66	<0.001
Herd type	Dairy (typical)	Referent			
	Dairy (using contract rearing)	1.20	1.10	1.31	<0.001
	Dairy (not rearing replacements)	0.98	0.91	1.04	0.460
	Dairy (rearing male calves)	0.85	0.81	0.89	<0.001
	Mixed herd	0.65	0.62	0.67	<0.001

calf mortality hazard was 4.6% and 3.9% for calves born in IJCP and non-IJCP herds, respectively.

Risk Factors for Calf Mortality Hazard in Irish Dairy Calves Between 2016 and 2020 (Model 1)

Visual examination log-log plots of hazard curves and distributions of Schoenfeld residuals illustrated that the proportional hazards and time dependence of effects assumptions were satisfied for each of the variables examined. Results of the Cox proportional hazards model are shown in Table 2. The mortality hazard ratio in male calves was 1.45 (95% CI 1.43–1.46) times that of female calves, highest in calves born to Jersey and Jersey-cross dams (HR: 1.16, 1.13–1.18), and lowest in calves born to Norwegian Red dams (HR: 0.94, 0.90–0.99). Calf mortality hazard in calves born to other dam breeds was not significantly different to the referent category (Holstein-Friesian). Calf mortality hazard was higher when the sire was a beef breed compared with a dairy breed (HR 1.19, 1.18–1.20), was significantly and positively associated with herd size, was highest in calves born in 2016, and lowest in those born in 2020. Finally, mortality hazards were higher on dairy farms that contract rear their heifers (i.e., on the farm of birth, not on the contract-rearing farm) and lowest in mixed herds. Based on the estimated gamma frailty effect, the MHR was 2.60, indicating that, accounting for individual calf characteristics, the median increase in hazard of mortality when comparing a calf born on a farm with higher mortality compared with a farm with lower mortality was 2.60 times the hazard on the lower risk farm.

Association Between Calf Mortality and IJCP Registration (Model 2)

The results of the multivariable Cox proportional hazards model investigating the association between IJCP status and calf mortality are shown in Table 3. Herds registered in the IJCP had a significantly higher calf mortality rate than those that were not registered in the IJCP. However, the interaction between IJCP and year of birth shows that IJCP-registered herds reduced their calf mortality to a greater extent than non-IJCP-registered herds between 2016 and 2020.

Association Between VRAMP Scores and Calf Mortality in IJCP Herds (Model 3)

The results of the Cox proportional hazards survival models investigating the association between mortality hazard and VRAMP section scores are shown in Table 4. Accounting for other variables, higher VRAMP scores in sections 1, 3, and 4, as well as the total VRAMP score, was positively associated with calf mortality haz-

Table 3. Results of a multivariable Cox proportional hazards model (Model 2) on the association between Irish Johne's Control Programme (IJCP) herd status[1]

Variable	Category	Hazard ratio	Lower 95% CI	Upper 95% CI	*P*-value
IJCP status	Non-IJCP herd	Referent			
	IJCP herd	1.06	1.01	1.12	<0.001
IJCP × year of birth	IJCP herd: Year of birth 2016	Referent			
	IJCP herd: Year of birth 2017	0.98	0.94	1.01	0.210
	IJCP herd: Year of birth 2018	0.97	0.94	1.01	0.140
	IJCP herd: Year of birth 2019	0.97	0.94	1.01	0.110
	IJCP herd: Year of birth 2020	0.96	0.92	1.00	0.027

[1]Registered (IJCP herd; 999,336 calves in 1,696 herds), not registered (non-IJCP herd; 5,559,900 calves in 14,458 herds), and calf mortality. Birth herd is included as a gamma frailty effect. Variables from Model 1 (calf sex, breed, sire breed, year of birth, herd size, and herd type) were also included but are not shown.

ard. In addition, the change in score from the previous VRAMP score was positively associated with mortality hazard in sections 1, 4, and for the total score, with increasing mortality hazard with positive increases in VRAMP score. The largest effect size was found for section 1, where each 10-unit increase in score resulted in a 1.10-times increase in mortality hazard (HR 95% CI 1.06–1.15), and each 10-unit positive change from the previous VRAMP resulted in a 1.08 (95% CI 1.04–1.11)-times increase in the calf mortality hazard.

DISCUSSION

The key findings in this study were an overall 100-d cumulative mortality hazard of 4.1%, with a decrease in calf mortality from 2016 to 2020. The degree to which mortality risk underestimated calf mortality compared with mortality hazard varied according to how the data were disaggregated. Calf mortality was significantly (both statistically and clinically) higher in Jerseys and male calves. Mortality was also higher in herds using contract rearing and IJCP herds. Within IJCP herds, we found a positive association between paratuberculosis risk assessment scores (VRAMP) and mortality hazard.

This study illustrates the value in using survival analyses to appropriately quantify calf mortality in dairy herds where substantial numbers of calves are censored before the end of the observation period. Accordingly, it was demonstrated that calf mortality differed between risk and survival-based methods and was consistently higher in analyses which accounted for censoring. This finding is similar to those of Santman-Berends et al. (2019), who found that methods which appropriately accounted for calf days at risk tended to result in higher estimates of calf mortality than those that did not.

Calf mortality rates estimated in the present study were relatively low compared with international comparisons (Compton et al., 2017). However, published

Table 4. Results of 5 separate Cox proportional hazards survival models (Model 3a–3e) investigating the association between VRAMP scores (absolute and change from previous assessment) and hazard of mortality for 211,450 calves from 1,172 herds[1]

VRAMP section model	Variable[2]	HR[3]	HR lower 95%	HR upper 95%	*P*-value
Model 3a: Section 1—Pre-weaning heifer risk assessment	Score	1.10	1.06	1.15	<0.001
	Change from previous assessment	1.08	1.04	1.11	<0.001
Model 3b: Section 2—Weaned heifers risk assessment	Score	1.02	0.94	1.12	0.630
	Change from previous assessment	0.95	0.89	1.02	0.140
Model 3c: Section 3—Adult cows risk assessment	Score	1.05	1.01	1.10	0.012
	Change from previous assessment	0.88	0.83	0.93	<0.001
Model 3d: Section 4—Calving area risk assessment	Score	1.07	1.02	1.11	0.002
	Change from previous assessment	1.04	1.01	1.07	0.021
Model 3e: Total score	Score	1.04	1.02	1.06	<0.001
	Change from previous assessment	1.02	1.00	1.04	0.013

[1]Separate models were built for each section (sections 1–4) and for the total score. Variables from Model 1 (calf sex, breed, sire breed, herd size, and herd type) were also included in each of these models (Models 3a–3e) but are not shown. VRAMP = Veterinary Risk Assessment and Management Plan.

[2]Each unit represents a 10-point difference in the VRAMP score.

[3]HR = hazard ratio.

calf mortality rates are notoriously problematic to compare between countries, owing to differences in methodology and age bands into which calf mortality is stratified (Compton et al., 2017; Santman-Berends et al., 2019). For example, Raboisson et al. (2014) reported calf mortality rate (accounting for calf months at risk) and mortality risk from 0 to 2 and from 3 to 30 d of age, and from 1 to 6 mo of age and examined risk factors using probit and linear regression models. On the other hand, Hyde et al. (2020) reported calf mortality risk in the first 3 mo of life and investigated risk factors using multivariate adaptive regression spline models. Therefore, the differences between our estimates and international figures may be reflective of differences in reporting or methodology, or may reflect "true" lower mortality hazard in Irish dairy calves.

It is also notable that calf mortality decreased in our study between 2016 and 2020. Further data would be required to infer whether these differences were indicative of long-term trends or year to year variation.

The hazard ratio may be defined as the ratio of the hazard rates between an exposed versus a reference group. We found that the hazard ratio of mortality in male dairy calves was 1.45 times that of female calves. This estimate is based on the assumption that all calves are registered. If some calf births that occur before registration are not recorded in compliance with national legislation, it is possible that the true estimate may be even higher. The finding of higher mortality among male dairy calves is consistent finding in the literature (Raboisson et al., 2013; Pannwitz, 2015; Hyde et al., 2020). Male calves in dairy production have a lower economic value than females and, potentially, is reflected in the greater risk of mortality. The consistency of this finding is a major challenge for the dairy industry internationally that urgently needs addressing.

We also found higher mortality in dairy-beef cross calves. This in contrast to Hyde et al. (2020) and Raboisson et al. (2013), who found that dairy-beef cross calves had lower mortality. One possible reason for this difference is that in contrast to all-year-round calving systems, most Irish dairy farms operate a pasture-based and condensed calving season, typically 12 wk in duration. Dairy sires are used at the start of the seasonal breeding period to generate replacement dairy animals, with beef sires being used later in the breeding season (both natural service and AI) to generate nonreplacement dairy-beef cross calves. It is, therefore, expected that dairy-beef crosses would be born in the final third of the calving season. The accumulation of calf movement through the calf rearing facilities may lead to a greater pathogenic challenge for calves born later in the season. It is also possible that these calves could experience a lower standard of care as a result of lower economic value compared with that of replacement calves. In addition, Irish dairy farmers describe the calving season as a period of "intense work" (Mulkerrins et al., 2022); therefore, it is possible that calf health monitoring may decline somewhat in the latter half of the season. The importance of the timing of birth in a seasonally calving system has been reported previously with respect to perinatal mortality (Cuttance et al., 2017).

We found that both male and female calves born to Jersey dams were at a much higher risk of mortality, and that this risk was higher in male versus female Jersey calves. Jersey male calves have a particularly low economic value, which might be reflected in their risk of mortality. The breed has been specifically highlighted by Irish farmers in a recent qualitative study exploring Irish farmers opinions regarding male dairy calves (Maher et al., 2021). However, high mortality rates were also observed in Jersey female calves. Previous studies have demonstrated an association between low birth weight and increased mortality in dairy calves, generally (McCorquodale et al., 2013), and this finding might be a reflection of lower birth weight in this breed rather than any breed effect per se. However, recent studies have demonstrated differences in immunological response to infectious diseases in Jersey calves, suggesting that that this breed may have reduced disease resilience compared with Holstein calves (McConnel et al., 2022). Further studies to understand the reasons behind these higher rates of mortality in Jersey calves are urgently needed.

We also observed higher mortality in calves born in herds that use contract rearing. It should be pointed out that once animals moved to a contract rearer in these herds, they were right censored and, therefore, the risk relates to the risk on the birth farm only. One potential reason for this observation is that replacement dairy animals in these herds are sent to a contract rearer, with only lower value crossbred animals remaining for rearing on the home farm. It may also indicate some degree of reverse causality in that farms may have been more likely to contract-out heifer rearing if they had previously experienced poor control of calf diseases. A further explanation could be that we chose to calculate herd size based on the total numbers of animals present in May of 2019. At this point in time, in herds using contract rearing, replacement heifers would have been moved off the home farm leading to an underestimate of herd size. Because we also observed a positive association between herd size and mortality hazard, it is therefore possible that accounting for herd size, our estimate for contract-rearing herds could have been biased upwards. Furthermore, we also found that the lowest mortality hazard was associated with calves born in "mixed" herds. Although steps were taken to remove non-dairy breed calves from the analysis, it is likely that a proportion of these animals were reared as beef rather than dairy animals. Lower mortality rates in these systems have been observed in previous analyses (Hyde et al., 2020).

The association between herd size and calf mortality is consistent with some studies internationally (Reimus et al., 2020) and may be related to differences in management practices between these herds. In our study, given the data sets at our disposal, we calculated herd size as the total number of animals present on the farm in May 2019. Caution should be applied when comparing coefficients for this variable between studies because those studies may calculate herd size based on the number of adult cows and because our estimates are conditional on the other variables present in the model. However, although herd size and a range of individual animal characteristics accounted for some of the variation in mortality hazard, it is notable that the variation in calf mortality appears to be dominated to some extent by the unexplained variation between farms. We found a MHR of 2.6, which can be described as the median increase in mortality hazard when a calf with identical individual characteristics, and an identical herd size, moves from a randomly selected lower to a randomly selected higher risk herd. In this case, the MHR is numerically higher than the individual risk factors found in our study. This finding demonstrates that a significant amount of herd practices affecting calf mortality are unaccounted for in our study and suggests that the greatest improvements in calf mortality may be achieved by focusing efforts toward identifying and improving those practices.

In addition, we found that IJCP herds had a significantly higher mortality hazard than non-IJCP herds. Previous studies have demonstrated that IJCP herds may not be representative of Irish dairy herds in general and tend to have larger herd sizes (McAloon et al., 2016b). The reason why mortality would be higher in these herds is again not clear. One explanation could be that many herds may join the IJCP because they are known to have JD-infected animals in the herd, or because they have problems managing the infection in the herd. Deficiencies in herd bioexclusion and biocontainment might be part of the reason why these problems exist in the herd and may also be shared risk factors for poor calf health and high calf mortality.

However, the significant interaction term in the present study demonstrates that herds in the IJCP decreased their herd mortality rate to a greater extent between 2016 and 2020 than non-IJCP herds. This may be due to the influence of changes implemented as part of the IJCP program. Further evidence for this is given by the finding that within IJCP herds, calves born in herds with lower VRAMP scores overall as well as in sections 1, 3, and 4 had a lower calf mortality hazard. Importantly, and independent of the absolute score, calves born in herds that decreased their score from the previous VRAMP also had a decreased mortality hazard. This suggests that implementation of recommended biocontainment practices to control paratuberculosis in IJCP herds was associated with a reduction in calf mortality. Previous work from the Netherlands has shown that calves entering veal units sourced from herds that are paratuberculosis “unsuspected” had a lower risk than those with a status of “unfavorable” (Santman-Berends et al., 2018). Our findings build on this work by demonstrating that management practices implemented for the control of paratuberculosis are associated with reduced calf mortality, independent of herd status. Although this is not a surprising finding, it has, to our knowledge, not been documented heretofore and is of importance in the context of paratuberculosis control programs internationally.

Although the current study makes valuable use of the data captured as part of the IJCP, it should be remembered that the VRAMP itself is a subjective scoring assessment conducting by multiple trained veterinary practitioners on any given day. Previous studies have shown that a significant proportion of the variation in VRAMP scores has been attributed to the veterinarian conducting the assessment (Pieper et al., 2015). In addition, in seasonally calving herds, the time of the assessment is unlikely to coincide with the busy period for both the veterinary practitioner and the dairy farmer of calving and early calf husbandry, meaning that scores assigned on the day might not reflect management in the herd at the time during which most calves are present in the herd. Indeed, in the majority (approximately 70%) of cases, VRAMP assessments were be conducted in autumn, some months after a predominant spring-calving period. We decided to use 1 VRAMP assessment per year and prioritized the first VRAMP conducted in the calendar year. Consequently, we cannot be sure that the VRAMP data collected on the date of the assessment more accurately reflects management in the preceding or following calving season.

In terms of reflecting mortality in Irish calves, we restricted our assessment of risk to the herds where the calves were born. Calves that moved off farm were censored from the analysis. However, it could be the case that mortality rates in these animals may be higher or lower than those that did not move off farm, in which case our overall estimate of calf mortality could be a biased estimate of calf mortality at a national level. Similarly, calves that moved onto the farm were also not included in our analysis. Although the number of calves moved onto dairy farms in the first 100 d of life is expected to be very small, it is possible that calf mortality in this cohort could be different than those that did not move onto the farm.

Furthermore, our analysis was based on calves that were registered on the Animal Identification and Movement database. Although the recording of all births, including stillbirths and those that die before they are ear-tagged and registered, is a legal requirement (SI No. 30, 2017), this does not necessarily ensure that the practice is universally and completely implemented. It is therefore possible that some calves may die on farm before registration and that the farmer may not register these births. If this occurred, our mortality estimates would be biased downwards. One way in which this may be investigated is to examine the proportion of male calf births registered in the data set. Because male calves are at a higher risk of mortality, if there were substantial numbers of calf mortality events that occurred before the calf was registered and the farmer neglected to register the birth and the death, we would expect a decrease in the proportion male calf births registered. In contrast, we found in our data set that the proportion of male birth registrations was consistently 0.51 in each year of the data set, which is approximately equal to the expected secondary sex ratio in cattle (Foote, 1977).

Our analysis was based on a large animal registration data set comprising data from over 6.5 million calves in 16,154 dairy herds. The size of the data set in this instance increases the chance that small associations that might be considered clinically insignificant may be identified as having a statistically significant association with the outcome of interest. In determining the clinical significance of any statistically significant association identified in the study, it is important that the effect estimate, the unit of increase (for continuous variables), as well as the exposed proportion of the variable are considered.

Although a goal of this study was to look at farm VRAMP scores and their association with calf mortality, further analysis could be done to identify specific management practices (as captured through the individual question response) in the VRAMP that are most influential in predicting herd-level calf mortality. In addition, the management aspects of the VRAMP include 3 agreed actions to be taken to reduce the risk of spread of JD. Further analyses of these data may also be useful to explain variation in calf mortality.

Our study adds to the international literature quantifying mortality in the dairy sector and may have relevance for other seasonally calving pasture-based dairy systems. Our findings are of particular importance in the context of paratuberculosis control programs internationally. Although there is some variation in these programs, many incorporate an on-farm component involving on an on-farm risk assessment. Our study has shown that within herds in the IJCP, calves born in herds that had better practices for the control of paratuberculosis, and those that implemented changes favorable to the control of paratuberculosis between consecutive on-farm assessments, had a lower mortality hazard independent of the paratuberculosis status of the herd. Although observational studies are inherently weak in terms of evidence basis, in our view, the longitudinal consideration of VRAMP scores in our analysis provides good evidence that paratuberculosis control measures have beneficial effects on calf mortality. We are unaware of similar analyses demonstrating this finding internationally.

CONCLUSIONS

Postnatal calf mortality in Irish dairy herds declined between 2016 and 2020. Calf mortality was consistently underestimated using risk approaches that did not account for calf censoring. Higher calf mortality rates were found in male calves, Jersey calves, calves born in herds that contract-reared their replacements, and calves born in herds registered in a JD control program, the IJCP. However, there was a greater decline in calf mortality rates over time in herds registered than not registered in this program. Furthermore, IJCP risk assessment scores were associated with increased mortality hazard, suggesting that implementation of recommended biocontainment practices to control paratuberculosis in IJCP herds was associated with a reduction in calf mortality.

ACKNOWLEDGMENTS

This study was conducted as part of the Surveillance Welfare and Biosecurity (SWAB) project funded by the Irish Department of Agriculture Food and the Marine (Dublin, Ireland; RSF 17/2/230). The authors have not stated any conflicts of interest.

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