

# Pure

## Scotland's Rural College

### **The contribution of previous lameness events and body condition score to the occurrence of lameness in dairy herds: a study of two herds**

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1 **Interpretive Summary**

2 The Contribution of Previous Lameness Events and Body Condition Score to the Occurrence  
3 of Lameness in Dairy Herds: A Study of Two Herds

4 Randall

5 Low body condition score (BCS; a measure of fatness) and occurrence of previous lameness  
6 are risk factors for lameness in dairy cows. Estimating the contribution that risk factors make  
7 towards the total number of disease events in a population can identify control measures that  
8 could lead to the largest improvements on-farm. Using longitudinal data, repeated lameness  
9 bouts were found to contribute to a very large proportion of total lameness, highlighting the  
10 importance of this risk factor. In these herds, a lower proportion of total lameness may be  
11 avoidable by moving BCS into optimum ranges, compared to reducing repeated lameness  
12 bouts.

13 EVALUATING THE CONTRIBUTION OF RISK FACTORS FOR LAMENESS

14

15 **The Contribution of Previous Lameness Events and Body Condition Score to the**  
16 **Occurrence of Lameness in Dairy Herds: A Study of Two Herds**

17

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32 **Key words**

33 Lameness, dairy cattle, population attributable fraction, body condition score, previous  
34 lameness events

35

36

## ABSTRACT

37 It has been demonstrated that low body condition and previous occurrence of  
38 lameness increase the risk of future lameness in dairy cows. To date the population  
39 attributable fraction (PAF), which provides an estimate of the contribution that a risk factor  
40 makes towards the total number of disease events in a population, has not been explored for  
41 lameness using longitudinal data. Estimation of PAF helps to identify control measures that  
42 could lead to the largest improvements on-farm. The aim of this study was to use longitudinal  
43 data to evaluate the proportion of lameness that could be avoided in two separate herds (two  
44 populations), through i) reduced recurrence of previous lameness events ii) and moving body  
45 conditions score (BCS) into optimal ranges.

46 Data were obtained from two UK dairy herds; Herd A, a 200-cow herd with 8 years of  
47 data from a total of 724 cows where lameness events were based on weekly locomotion  
48 scores (LS; 1 to 5 scale) and Herd B, a 600-cow herd with data recorded over 44 months from  
49 a total of 1,040 cows where treatment of clinical cases was used to identify lameness events.  
50 The PAF for categories of BCS were estimated using a closed equation appropriate for  
51 multiple exposure categories. Simulation models were used to explore theoretical scenarios to  
52 reflect changes in BCS and recurrence of previous lameness events in each herd.

53 For Herd A, 21.5% of the total risk periods (cow-weeks) contained a lameness event  
54 (LS 3, 4 or 5), 96% of which were repeat events and 19% were recorded with BCS < 2 (3-  
55 weeks previously; 0 to 5 scale). When lameness events were based on two consecutive weeks  
56 of LS 4 or 5, 4% of risk periods were recorded as lame, of which 89.5% were repeat events.  
57 For Herd B, 16.3% of the total risk periods (consecutive 30-days) contained a lameness event  
58 (72.6% were repeat events) and 20% were recorded with BCS  $\leq$  2 (0 to 120 days previously).  
59 The median PAF for all previous lameness was between 79 and 83% in the two herds.  
60 Between 9 and 21% of lameness events could be attributed to previous lameness occurring >

61 16 weeks before a risk period. The median PAF estimated for changes in BCS were in the  
62 region of 4 to 11%, depending on severity of lameness.

63 Repeated bouts of lameness made a very large contribution to the total number of  
64 lameness events. This could either be because certain cows are initially susceptible and  
65 remain susceptible, due to the increased risk associated with previous lameness events, or due  
66 to interactions with environmental factors. This area requires further research.

67

68

## INTRODUCTION

69 Numerous risk factors for lameness in dairy cattle have been reported in the literature,  
70 including risk factors related to the external environment such as flooring surfaces and time  
71 spent standing (Galindo and Broom, 2000, Bergsten et al., 2015) as well as animal-based  
72 factors which might impact on structure and function of the claw such as milk yield, body  
73 condition score and previous lameness events (Green et al., 2014, Randall et al., 2015). Low  
74 body condition score (BCS) and previous lameness are both risk factors for lameness that  
75 occur repeatedly over time and have been highlighted as important for lameness control  
76 (Hirst et al., 2002, Bicalho et al., 2009, Green et al., 2014, Randall et al., 2015, Randall et al.,  
77 2016). Randall et al. (2015) showed that relatively low body condition precedes and is  
78 associated with an increased risk of a first lameness event in a cow's life. Consequently,  
79 management strategies to maintain appropriate body condition scores may provide an  
80 opportunity for the dairy industry to reduce lameness in herds. Hirst et al. (2002)  
81 demonstrated that dairy heifers with lameness causing claw horn lesions were at greater risk  
82 of lameness in subsequent lactations. A recent study suggested that this relationship might be  
83 explained by development of new bone, 'exostosis', on the distal phalanx (Newsome et al.,  
84 2016). If this is an irreparable anatomical change to the foot it would contribute towards an  
85 increased risk of a cow becoming lame again. Odds ratios reported for these two risk factors

86 indicate that they are highly associated with lameness; for example the OR associated with  
87 moving from non-lame to lame state for cows with BCS 1.00 – 1.75 at calving versus 2.50 –  
88 2.75 was 7.73 (2.37 – 17.71) and the OR associated with clinical lameness for cows having  
89 been identified lame 31 – 60 days previously versus no previous lameness was 13.80 (10.58 –  
90 17.78) (Green et al., 2014, Lim et al., 2014).

91 The population attributable fraction (PAF) provides an estimate of the contribution  
92 that a risk factor makes to the total disease burden in a population. Knowledge of the PAF of  
93 risk factors can facilitate decision-making for farmers and policy makers to maximise disease  
94 reduction with existing resources when the knowhow exists, or it can influence funders of  
95 research (Steenland and Armstrong, 2006) when knowledge to reduce impact of risk factors  
96 is not known.

97 There are a range of formulas used to calculate PAF and these have different  
98 limitations, such as biases arising when adjusted estimates of relative risk are used or when  
99 the exposure is across different levels (Rockhill et al., 1998, Benichou, 2001, Steenland and  
100 Armstrong, 2006). Where risk factors vary over time, the method used to estimate PAF must  
101 account for repeated risk events. In addition, a risk factor can be complex, for example, cows  
102 in a herd have a range of body conditions rather than a uniform BCS of e.g. 3 so assessing a  
103 change in BCS to reduce the PAF needs to use a continuous scale for BCS. Simulation can be  
104 used to estimate PAF to allow for sources of uncertainty, such as uncontrolled confounding,  
105 to be incorporated into estimates (Steenland and Armstrong, 2006) as well as allowing for  
106 more complex scenarios to be investigated (Hudson et al., 2014).

107 The aim of this study was to investigate the contribution of previous lameness and  
108 BCS to the occurrence of total lameness events in two UK dairy herds. A novel simulation-  
109 based approach to estimating PAF was used.

110

## MATERIALS AND METHODS

111

### 112 **Study Herds**

113 Data were obtained from two UK dairy herds, where detailed and accurate herd  
114 records were available. Study herds and datasets have been described in detail by Randall et  
115 al. (2015) and Green et al. (2014). They are summarised here briefly;

116 ***Herd A.*** A total of 724 Holstein Friesian dairy cows managed on the Langhill herd  
117 held at the Scotland's Rural College's Crichton Royal research farm, Dumfries, Scotland with  
118 data recorded over an 8 year period from 2003 to 2011 (Randall et al., 2015). Cows were  
119 managed on a long-term 2 x 2 factorial genetic and feeding system study; select and control  
120 genetic lines (Pryce et al., 1999), were divided equally into low-forage (LF) and high-forage  
121 (HF) groups and managed as one herd of approximately 200 cows, as described in detail by  
122 Chagunda et al. (2009). LF cows were continuously housed whilst HF cows were grazed  
123 during the summer grazing period (typically March to November). Cows were milked three  
124 times daily and the herd was all-year round calving. Target yields were 13,000 and 7,500 kg  
125 per cow per year for LF and HF cows, respectively. Housing was the same for LF and HF  
126 cows; cubicles with mattresses and automatically scraped grooved concrete passageways.  
127 Regular footbathing was carried out and a professional foot trimmer attended the whole herd  
128 twice a year. Locomotion scores (LS) were recorded weekly by trained assessors on a 1 to 5  
129 scale (Manson and Leaver, 1988). Lameness (LS 4 or 5 on a single occasion or 2 successive  
130 scores of LS 3) were treated by a veterinarian on a weekly basis before 2006 and every 2  
131 weeks after this time. Severely lame cows were treated within 24 hours by trained farm staff.  
132 BCS was measured weekly using a 0 to 5 scale with increments of 0.25 (Mulvany, 1977). All  
133 health, production and management data were recorded in a database.

134 ***Herd B.*** A total of 1,040 Holstein dairy cows on one dairy farm in Somerset, England  
135 with data recorded over 44 months between 2008 and 2011 (Green et al., 2014). Cows were

136 milked twice daily in a 60 point rotary parlour and continuously housed all year around, apart  
137 from summer when grazed during the last 2 months of lactation. Rations were formulated  
138 with the aim of maximising yield whilst minimising feed costs and fed to milking cow groups  
139 (early, mid and late lactation) accordingly. Biotin was added at 20mg/cow/day. Housing was  
140 modern free stall accommodation with water mattresses in cubicles and solid concrete  
141 passageways with automatic scrapers. Mean yearly yield was approximately 10,000 kg per  
142 cow per annum. A professional foot trimmer attended the herd each month; typically cows at  
143 the end of lactation and with mis-shapen feet were trimmed, with a minimum routine foot  
144 trim once per year. Daily observations of the herd by senior herdsman identified lame cows  
145 which were treated under veterinary direction using standard protocols, generally within 2 to  
146 3 days. Body condition score was recorded at 60 day intervals throughout the study period,  
147 by the head herdsman with appropriate training to prevent drift in scoring, on a scale of 0 to 5  
148 in 0.5 increments (based on examination of the transverse processes of the lumbar vertebrae,  
149 the ribs, ischial tuberosity, ligaments of the pelvis and surrounding fat (Green et al., 2014)).  
150 Health, production, BCS and lameness treatments were recorded in Interherd (National Milk  
151 Records).

152

### 153 **Statistical Analysis**

154 To account for the longitudinal nature of the data, risk factors where events varied at  
155 repeated measurements were lagged (e.g. BCS, previous lameness and milk yield) and frailty  
156 models were constructed to take into account repeated measures of the outcome (lameness  
157 events). The main difference between Herd A and Herd B was in defining lameness events;  
158 Herd A was based on weekly locomotion scoring whilst Herd B was based on treatment for  
159 lameness from the farmer's records. For Herd A two separate definitions for a lameness event  
160 were investigated; these were a) one-week with LS 3, 4 or 5 (less severe lameness) and b)

161 two consecutive weeks with LS 4 or 5 (more severe lameness). There were three stages to  
162 estimating the PAFs; (i) constructing models to estimate adjusted relative risks (RR) for BCS  
163 and previous lameness, (ii) estimating PAF for BCS categories to compare estimates using  
164 closed equation and simulation approaches and (iii) using simulation to estimate PAF for  
165 changes in BCS and occurrence of previous lameness within the two herds to quantify the  
166 contribution of these risk factors to total lameness in each herd.

167 The annual incidence rate of lameness was calculated as [number of new  
168 lameness events divided by number of cow-weeks at risk] multiplied by 52 for Herd A and  
169 [number of new lameness events divided by number of cow-months at risk] multiplied by 12  
170 for Herd B. For Herd A The weekly incidence rates over the study period were calculated as  
171 the number of new lameness events divided by the number of cows eligible (i.e. those cows  
172 not lame in the previous risk period) and prevalence was calculated as number of lameness  
173 events divided by number of observations.

174

175 *Stage 1: General approach to modelling; estimating coefficients for previous*  
176 *lameness and body condition score*

177 Data handling and model construction are described in detail by Randall et al. (2015)  
178 for Herd A and Green et al. (2014) for Herd B.

179 Binary outcomes investigated for Herd A were LS 3, 4 or 5 in one week (Model 1a)  
180 and LS 4 or 5 over two consecutive weeks (Model 1b). The model outcome in Herd B was  
181 also binary; yes / no for treatment of lameness (all causes included; sole haemorrhage (SH),  
182 sole ulcer (SU)/white line disease (WLD) and digital dermatitis (DD)) (Model 2). Mixed  
183 effects logistic regression models were constructed in MLWin 2.28 (Rabash et al., 2009).  
184 Where possible, missing observations were included as a categorical variable and fitted  
185 within the models to minimise loss of data. Initial parameter estimation for model parameters

186 was carried out by iterative generalized least square procedures (Goldstein, 2003) and using  
187 forward selection of explanatory variables; explanatory variables were left in the model if the  
188 95% credible interval of the odds ratio did not include unity. Final parameter estimates were  
189 made using Markov chain Monte Carlo (MCMC) to reduce biased estimates (Rabash et al  
190 2009), using procedures previously described by Green et al. (2004). A burn-in of 1,000  
191 iterations was used, with final parameter estimates being based on a minimum further 9,000  
192 iterations. Chain mixing and stability were assessed visually.

193 Models took the form;

194  $Lame_{ij} \sim \text{Bernoulli}(\text{probability} = \pi_{ij})$

195  $\text{Logit}(\pi_{ij}) = \alpha + \beta_1 X_{ij} + \beta_2 X_j + u_j$

196  $[u_j] \sim N(0, \sigma_v^2)$

197 Where subscripts  $i$  and  $j$  denote the  $i$ th observation of the  $j$ th cow respectively.  $\pi_{ij}$  =  
198 probability of a lame outcome for the  $i$ th observation of the  $j$ th cow.  $\alpha$  = intercept value,  $\beta_1$  =  
199 vector of coefficients for  $X_{ij}$  (Herd A included logarithm of the week of the study up to the  
200 power 3),  $X_{ij}$  = vector of covariates associated with each observation,  $\beta_2$  = coefficients for  
201 covariates  $X_j$ ,  $X_j$  = vector of covariates associated with each cow,  $u_j$  = random effect to  
202 account for residual variation between cows (assumed to be normally distributed with mean =  
203 0 and variance =  $\sigma_v^2$ ) and residual error.

204 **Explanatory variables included in the models for Herd A were;** weeks in milk, week  
205 of the study, parity (categorical 1 to 4 +), age at first calving (categorical < 24, 24 to 27, 28 to  
206 30, 31 to 33 and greater than 33 months), BCS change 0 to 4 weeks post-calving (categorised  
207 as 0 = loss, 1 = no change, 2 = gain), body weight (categorical < 550, 550 to 700 and > 700  
208 kg), assessor of locomotion and body condition, feed – genetic group and milk yield 16  
209 weeks previously (average daily kg per week; categorical < 12, 12 to 24, 25 to 37, 38 to 50  
210 and > 50 kg). Variables of interest were time since previous lameness (categorised in 4 week

211 intervals from time t to > 16 weeks), and BCS (categorical < 2, 2, 2.25, 2.5, 2.75, 3 and > 3).  
212 **Explanatory variables included in the model for Herd B were;** parity (categorical 1 – 6 +),  
213 year quarter, month in herd, days in milk (at the end of a 30-day period), milk yield (kg per  
214 day) measured at the most recent monthly milk recording, yield lagged by one month.  
215 Variables of interest were time since previous lameness **event** (data were available from  
216 2002, categorised in 30 day intervals from time t to >120 days) and BCS >2 lagged by 0 to 2  
217 months and 2 to 4 months.

218 Posterior predictions were used to assess model fit by visual comparison to the  
219 observed data (Gelman et al., 1996). Standardized residuals at the cow level (level 2) were  
220 also assessed for normality (Rabash et al., 2009). The Hosmer-Lemeshow test (Hosmer and  
221 Lemeshow, 1989) was used as a statistical test for goodness-of-fit. Cow level residuals were  
222 found to be over-dispersed and non-normal for Models 1a and 1b, therefore random effects  
223 were removed; this improved model fit such that it was very good without random effects and  
224 were used as the final models.

225

### 226 ***Descriptive statistics and results from modelling***

227 Herd A: **Of the 724 cows ever in Herd A, 674 (93.0%) had at least one week with LS**  
228 **3, 4 or 5 and 375 (51.8%) had at least one lameness event with LS 4 or 5 for two consecutive**  
229 **weeks.** There were a total of 79,565 and 78,698 cow weeks at risk in Models 1a and 1b,  
230 respectively. The number of lameness events were 17,114 and 3,572 respectively for Models  
231 1a and 1b. **The annual incidence rate of lameness was 7.4 cases per cow-year when a**  
232 **lameness event was one week LS 3, 4 or 5 and 0.7 cases per cow-year when a lameness event**  
233 **was two consecutive weeks LS 4 or 5. The weekly incidence rates over the study period are**  
234 **shown in Figure 1 for Models 1a (one-week LS 3, 4 or 5) and 1b (two consecutive weeks LS**  
235 **4 or 5), respectively. Figure 1 also shows the prevalence for each week of the study period for**

236 Models 1a (one-week with LS 3, 4 or 5) and 1b (two consecutive weeks LS 4 or 5),  
237 respectively. Both weekly incidence rates and prevalence of LS 3, 4 or 5 increased during the  
238 second half of the study period for Herd A. Figure 2 shows the frequency distribution for  
239 number of consecutive weeks with LS 3, 4 or 5 and LS 4 or 5, respectively, demonstrating  
240 that the majority of lameness events had a duration of one week. The median BCS was 2.25  
241 (range, 0.75 to 4.25) for Herd A. The proportion of the cow-week risk periods exposed to  
242 BCS categories < 2, 2, 2.25 and 3 were 0.19, 0.23 (0.24 for Model 1b), 0.26 and 0.05,  
243 respectively for Models 1a and 1b. The proportion of observations where there was a  
244 previous lameness event in the 1 to 4 weeks prior was 0.4; 5 to 8 weeks was 0.38; 9 to 12  
245 weeks was 0.36; 13 to 16 weeks was 0.34; and > 16 weeks was 0.73 for Model 1a. For Model  
246 1b the proportion of observations where there was a previous lameness event in the 1 to 4  
247 weeks prior was 0.079; 5 to 8 weeks was 0.074; 9 to 12 weeks was 0.070; 13 to 16 weeks was  
248 0.067; and > 16 weeks was 0.29. Odds ratios and 95% credible intervals from Models 1a and  
249 1b for BCS and previous lameness are reported in Table 1. For all other covariates included  
250 in the final model, parameter values and significance were similar to those previously  
251 reported (Randall et al., 2015). Assessment of model fit was considered good. For Model 1a,  
252 BCS 3-weeks previously was positively associated with the lameness outcome  $LS \geq 3$ . BCS =  
253 3, 3-weeks previously had the lowest odds ratio i.e. the lowest risk of lameness and therefore  
254 was used as the baseline category for simulations described below in Stage 2. BCS < 2 had  
255 the highest odds ratio (OR (95% credible interval) = 1.29 (1.15 to 1.45)) compared with the  
256 baseline category. Previous lameness variables were also significant; lameness in the  
257 previous 1 to 4 weeks compared with no previous lameness had the highest odds ratio (OR  
258 (95% credible interval) = 3.65 (3.48 to 3.83)). For Model 1b, BCS one week previously had  
259 the largest effect size and therefore was left in the final model. As for Model 1a, BCS = 3 had  
260 the lowest odds ratio and was used as the baseline category for simulations in Stage 2. BCS <

261 2 had the highest odds ratio compared with the baseline category BCS = 3 (OR (95% credible  
262 interval) = 1.66 (1.27 to 2.16)). Previous lameness variables were also associated with a  
263 significant risk in lameness; lameness in the previous 1 to 4 weeks had the highest odds ratio  
264 (OR (95% credible interval) = 18.72 (16.97 to 20.66)) compared with no previous lameness.

265 Herd B: A total of 14,530 risk periods were obtained from 1,040 cows from Herd B  
266 and the mean number of observations was 10 (range 1–36) per cow. The annual incidence  
267 rate for the study period was 1.4 cases per cow-year. 14,461 body condition scores were  
268 included in the data set; the median BCS was 2.5 (range, 1 to 5). In total, 647 cows were  
269 treated for lameness; the proportion of observations where there was exposure to previous  
270 lameness 1 to 30 days ago, 31 to 60 days ago, 61 to 90 days ago, 91 to 120 days ago and  
271 greater than 120 days ago were 0.21, 0.10, 0.05, 0.04, 0.17 respectively. Of the 1,040 cows  
272 62.2% were ever lame during the study. Odds ratios and 95% credible intervals from Model 2  
273 for the explanatory variables of interest (BCS and previous lameness) are reported in Table 1.  
274 For all other covariates included in the final model, parameter values and significance have  
275 previously been reported (Green et al., 2014). For Model 2, BCS > 2 in the last 0 to 2 months  
276 or 2 to 4 months was associated with a decreased risk of lameness (all causes; SU, SH/WLD  
277 and DD) compared with BCS ≤ 2; OR (95% credible interval) = 0.63 (0.55 to 0.73) and 0.74  
278 (0.60 to 0.90) respectively. All previous lameness categories were associated with an  
279 increased risk of lameness compared with no previous lameness; previously lame 1 to 30  
280 days ago had the highest odds ratio (OR (credible interval) = 19.69 (15.70 to 24.69).

281

282 ***Stage 2: Comparing closed and simulation-based approaches to estimating PAF.***  
283 Exposure to BCS categories for each of the herds' data was used to estimate PAF using  
284 closed formula and simulation.

285 A formula for multiple exposure categories described by Hanley (2001) was used for  
286 the closed method:

$$PAF = \frac{P_1\{RR_1 - 1\} + P_2\{RR_2 - 1\}}{1 + P_1\{RR_1 - 1\} + P_2\{RR_2 - 1\}}$$

287 Where,

288 PAF = population attributable fraction

289 P = prevalence of exposure

290 RR = relative risk (calculated from the coefficients estimated for each BCS category from  
291 Models 1a, 1b and 2).

292 The simulation approach used posterior predictions of the number of lameness events to  
293 estimate PAF (Gelman, 2000). Models 1a, 1b and 2 were imported into OpenBUGS version  
294 3.2.3 (Lunn et al., 2009) alongside raw data from the respective herds. Coefficients were  
295 estimated from the models using Markov chain Monte Carlo (MCMC) and a burn-in of 4,000  
296 iterations and a further 6,000 iterations for final parameter estimates based on visual  
297 inspection of chain mixing and stability. The number of lameness events were predicted  
298 from Models 1a, 1b and 2 for the herd raw data (baseline exposure) and with exposure to  
299 each of the BCS categories sequentially removed (i.e. coefficients equal to zero). The  
300 posterior prediction for PAF was calculated as the difference in number of lameness events  
301 with and without exposure to each BCS category present as a proportion of the total number  
302 of lameness events occurring in the herd. PAF are reported only for the BCS categories that  
303 had a significant association with the outcome (lameness events).

304 ***Stage 3. Estimating PAF for BCS and previous lameness.*** Simulation was used to  
305 explore more complex scenarios by quantifying the contribution that BCS and previous  
306 lameness made towards the total number of lameness events within each herd. Scenarios

307 explored are summarised in Table 2. Models 1a, 1b and 2 were imported into OpenBUGS  
308 alongside raw data from respective herds. For the BCS scenarios, additional categories were  
309 created for 0.5 added to the BCS score for each cow with  $BCS < 3$  for each week in the herd  
310 (i.e. 0.5 BCS gain across the whole herd apart from cows with BCS 3 or above) and 0.5 taken  
311 away from each BCS score (i.e. 0.5 BCS loss across the whole herd) in the Herd A dataset;  
312 data were imported to OpenBUGS. Exposure distributions for the BCS categories are  
313 summarised in Table 3. Coefficients were estimated from the models using Markov chain  
314 Monte Carlo (MCMC) and a burn-in of 4,000 iterations and a further 6,000 iterations for final  
315 parameter estimates, based on visual inspection of chain mixing and stability. The number of  
316 lameness events for the herd exposed to each of the scenarios (0.5 BCS gain and 0.5 BCS  
317 loss) and not exposed to these distributions (i.e. the BCS distribution of the raw herd data as a  
318 baseline) were predicted. Posterior predictions for PAF were calculated as the difference in  
319 number of lameness events as a proportion of the total number of lameness events. For the  
320 previous lameness scenario, the raw herd data was used as the baseline scenario, with  
321 exposure to previous lameness removed for the altered scenario (i.e. all coefficients for  
322 previous lameness categories equal to zero). The number of lameness events for the herd  
323 exposed and unexposed to previous lameness events were predicted. Posterior predictions for  
324 PAF were calculated as the difference in the number of lameness events as a proportion of the  
325 total number of lameness events.

326 To remove the effect of lameness that occurred just prior to a risk period and explore  
327 only the impact of lameness events that occurred earlier, Models 5.1a, 5.1b and 5.2 were used  
328 to estimate PAF of lameness events that occurred a minimum of 5 weeks before a current  
329 case and a minimum of 16 weeks before a current case. For models 1a and 1b the effect of  
330 previous lameness events that occurred in the 4 to 8, 9 to 12, 13 to 16 and  $> 16$  weeks  
331 previously were investigated. As these were separate covariates in the model, to investigate

332 their effect, the relevant coefficients were set to equal zero, where the baseline was no  
333 previous lameness in that time period. For model 2, the effect of previous lameness events  
334 that occurred in the previous 31 to 60, 61 to 90, 90 to 120 and > 120 days were investigated.  
335 These were included as categories for the explanatory variable previous lameness where the  
336 baseline was none. Coefficients for the weeks being investigated were set to equal zero. The  
337 analyses were repeated as described above.

338

## 339 RESULTS

### 340 Comparison of closed and simulation approach for estimating population attributable 341 fractions

342 The PAF estimated using both closed and simulation methods are presented in Table  
343 4.

344 **Model 1a.** Using closed calculation methods, PAF for exposure to each BCS category  
345 were; 4.49% for BCS < 2 three weeks previously, 2.66% for BCS 2 and 2.38% for BCS 2.25  
346 (total = 10.61%). The median (95% credible interval) PAF predicted using simulation were  
347 3.10 % (1.71 – 4.54), 1.73% (0.14 – 3.33), 1.50% (-1.31 – 3.13) for BCS < 2, 2 and 2.25  
348 respectively.

349 **Model 1b.** The PAF for exposure to BCS categories calculated using the closed  
350 method were; 8.90% for BCS < 2 one week previously, 6.00% for BCS = 2 and 4.68% for  
351 BCS = 2.25 (total = 19.57%). **Using simulation**, the median (95% credible interval) predicted  
352 PAF for BCS categories < 2, 2 and 2.25 were 7.64% (2.81 – 11.23%), 5.58% (1.05 – 9.18%)  
353 and 3.93% (-0.76 – 7.74%), respectively.

354 **Model 2.** The PAF for BCS categories calculated using closed method were 9.83 %  
355 for BCS < 2 in the 1 to 60 days previously and 5.92 % for BCS < 2 in the 61 to 120 days  
356 previously. Median PAF (95% credible interval) predicted using simulation was 7.49% (4.03

357 – 10.78) and 4.28% (0.64 – 7.72%) for BCS < 2 in the 1 to 60 days previously and 61 to 120  
358 days previously, respectively.

359

### 360 **Estimating PAF for BCS and previous lameness.**

361 Results of the scenarios investigated are presented in Table 5.

362 ***Body condition score.*** A gain in BCS of 0.5, in cows BCS 3 or less, across the whole  
363 herd for the 8 years of data available for Herd A resulted in a reduction of 600 predicted  
364 lameness events, where the outcome was LS 3, 4 or 5 (Model 1a). The median PAF (95 %  
365 credible interval) for this change in exposure was -3.54 % (-5.86 – -1.28%) i.e. 3.54% of  
366 lameness events in the herd may be avoidable if all cows with BCS < 3 in the 3 weeks  
367 previously were exposed to a 0.5 gain in BCS. When the lameness severity threshold was 2  
368 consecutive weeks LS 4 or 5 (Model 1b) there was a greater reduction in lameness events  
369 with a median PAF of -8.06% (-13.12 - -2.22%). A loss in 0.5 BCS across all BCS score  
370 categories for Model 1a resulted in an additional 1030 predicted lameness events and the  
371 median PAF (95% credible interval) for this exposure was 5.99% (3.36 – 8.74%) i.e. 5.99%  
372 of lameness in the herd may be avoidable by not exposing the herd to a loss in BCS of 0.5.  
373 The median PAF (95%) for this exposure using Model 1b, where lameness severity threshold  
374 was increased, was 11.2% (5.52 - 17.33%).

375 ***Previous Lameness.*** When the effect of exposure to all previous lameness events was  
376 removed across the whole herd the predicted number of lameness observations was reduced  
377 by 7576 observations for Herd A where the outcome was LS 3, 4 or 5 (Model 1a) and 2812  
378 observations where outcome was LS 4 or 5 on 2 consecutive weeks (Model 1b). Of the  
379 predicted lameness events, 80.69% (79.01 – 82.26%) and 78.75% (76.40 – 80.98%) were  
380 attributable to exposure to previous lameness events over the study period for these two  
381 outcomes in Herd A (Model 1a and 1b), respectively. When the effect of exposure to

382 previous lameness was removed across the whole herd in Herd B (Model 2) the predicted  
383 number of lameness events was reduced by 1652 events; 82.69% (79.28 – 85.61%) of  
384 lameness treatments were attributable to previous lameness over the study period in Herd B.

385 When PAF was estimated for lameness events that occurred at least 5 weeks  
386 previously, the median (95% credible interval) PAF were 58.97% (56.11 - 61.67%), 41.67%  
387 (36.90 to 46.19%) and 46.31% (42.08 to 50.14%), respectively for Models 1a, 1b and 2.

388 When PAF was estimated for lameness events that occurred at least 16 weeks  
389 previously, the median (95% credible interval) PAF were 9.34% (5.14 – 13.58%), 11.36%  
390 (5.49 to 17.09%) and 21.07% (16.30 to 25.50%), respectively for Models 1a, 1b and 2.

391

392

## DISCUSSION

393

### 394 Previous Lameness Events

395 This is the first study to quantify the PAF of previous lameness events in cattle on  
396 herd level lameness. Estimates of PAF for the two herds suggested that between 79% and  
397 83% of lameness was attributable to exposure to previous lameness events (regardless of  
398 when they occurred), indicating that this is an important risk factor. When the effect of  
399 lameness events that occur > 4 weeks and > 16 weeks previously were investigated, the  
400 contribution from previous lameness reduced markedly, although it was still considerable.  
401 This finding suggests that lameness might last for some duration (as shown in Figure 2) or  
402 that cows can take a considerable amount of time to recover, but that some do fully recover.  
403 It appears from these results that a large proportion of the total lameness events in these herds  
404 are accounted for by an accumulation of repeat cases. Across the two herds between 52 and  
405 93% of cows were ever lame during their respective study periods, indicating that significant  
406 resources are going into treating a large number of lameness cases.

407           The challenge therefore is to understand why repeat cases are occurring and how to  
408 prevent them. The number of repeat lameness events could be influenced by the duration of  
409 time individual animals spend within the herd and therefore if cows are not culled for being  
410 lame they may experience a higher number of repeat lameness events. It is also possible that  
411 there are some other environmental or animal-based factors that could explain a high number  
412 of repeat lameness events in certain cows. For example, there may be an interaction between  
413 previous lameness and the environment that influences whether cows will go on to have  
414 repeated lameness events. It may also be important to prevent the occurrence of the first  
415 lifetime lameness event, although based on this analysis it is not possible to know whether it  
416 was the first lifetime lameness event or some other environmental or animal-based interaction  
417 which is important in consigning a cow to repeat lameness events. In addition, findings from  
418 this study highlight that early and effective treatment of lameness reducing the likelihood of  
419 recurrence or cases becoming chronic (Thomas et al., 2015) may also be crucial to lameness  
420 control at a herd level.

421           It is widely reported that lameness events increase the risk of future lameness events  
422 occurring (Hirst et al., 2002, Green et al., 2014, Randall et al., 2015). Hirst et al. (2002)  
423 investigated the relationship between lameness in heifers and the association with future risk,  
424 reporting a positive association between claw horn lesions and future risk. These findings  
425 were similar to those reported by Randall et al. (2016); more severe claw horn disruption  
426 lesions occurring around the time of first calving were associated with a long-term increased  
427 risk of lameness. One hypothesis for this association is that underlying pathology carries over  
428 from one case to the next making future cases more likely. The increase in lameness  
429 prevalence or risk with increasing parity that is widely reported would support this hypothesis  
430 (Barker et al., 2009, Randall et al., 2015, Solano et al., 2015). In addition, Newsome et al.  
431 (2016) demonstrated that bone development on the caudal aspect of the distal phalanx at

432 slaughter were positively associated with claw horn lesions during life, providing evidence  
433 for underlying pathology being associated with previous lameness. An additional element to  
434 the hypothesis explaining the association between previous and future lameness and  
435 increased lameness risk with increasing parity is that hypersensitivity and reduction in  
436 pressure pain thresholds may develop as a result of long term pain associated with lameness.  
437 Although poorly understood, it is widely reported in the medical literature that disease can  
438 lead to long term changes in the nociceptive nervous system leading to allodynia (pain  
439 associated with non-noxious stimuli) and hyperalgesia (noxious stimuli causing pain of  
440 longer duration and higher intensity than normal) (Nielsen and Henriksson, 2007,  
441 Latremoliere and Woolf, 2009, Woolf, 2011). Laven et al. (2008) demonstrated that there is a  
442 long duration of allodynia associated with lameness even after treatment, highlighting the  
443 importance of lameness prevention. When the high prevalence of lesions in heifers reported  
444 by Maxwell et al. (2015) and Capion et al. (2009) is considered, this becomes even more  
445 significant.

446         The findings from this study highlight the importance of previous lameness events as  
447 a risk factor for lameness and therefore the urgent need for further research to identify how to  
448 prevent the occurrence of repeat lameness events.

449

#### 450 **Body Condition Score**

451         The results of this study demonstrated the impact of changing BCS across the whole  
452 herd; 4% of all lameness events (one-week with LS 3, 4 or 5) could potentially be avoidable  
453 with exposure to a 0.5 increase in BCS in all cows with BCS < 3, whilst 8% of all lameness  
454 events may be preventable by avoiding exposure to a loss of 0.5 BCS. These figures  
455 increased to 6% and 11%, respectively, when the lameness severity threshold was increased.  
456 Previous studies have demonstrated that BCS is a risk factor for lameness in all ages of dairy

457 cattle (Hoedemaker et al., 2009, Green et al., 2014, Lim et al., 2014). Randall et al. (2015)  
458 found that cows with  $BCS < 2$  in the previous 3 weeks were at greatest risk of lameness in a  
459 longitudinal study using the same dataset from Herd A as in the current study. Similarly,  
460 Green et al. (2014) has shown that cows with  $BCS \leq 2$  were more likely to be treated for  
461 lameness in the following 2 and 2 to 4 months compared with cows  $BCS > 2$ , using the same  
462 dataset from Herd B as in the current study. However, this is the first study to evaluate the  
463 importance of BCS changes at a herd level in terms of its impact on the total amount of  
464 lameness in a dairy herd using simulation that accounts for variability. This is an important  
465 step forward from identifying BCS as a risk factor for lameness towards quantifying the  
466 effect that this risk factor has on the proportion of lameness events in herds that could be  
467 prevented if BCS was altered. Alawneh et al. (2014) calculated PAF for liveweight using  
468 closed equations and demonstrated that the population level impact of a decrease in  
469 liveweight over the first 50 days in milk was relatively small; a 3% (95% confidence interval  
470 = 1 – 6%) reduction in the incidence risk of lameness was reported if excessive liveweight  
471 loss was prevented. The impacts of BCS reported for each of the scenarios investigated in this  
472 study are similarly relatively small compared with the impact of previous lameness events.  
473 Although, in herds with fewer repeated lameness events, BCS relatively could be more  
474 important.

475

#### 476 **Comparison of closed and simulation-based approaches for estimating population** 477 **attributable fractions**

478 Formulas for calculating population attributable risk or fractions have been derived  
479 for different epidemiologic designs, including situations where there are more than one  
480 exposure level or where confounding factors exist (Benichou, 2001). However there are  
481 limitations in the use of these formulas when applied to more complex scenarios that are

482 often present in real-life situations which mean they are not directly useable in application.  
483 Simulation can be useful in addressing these issues by modelling dynamic interactions  
484 between individual animals or groups of animals whilst taking into account factors that may  
485 vary within and across levels of influence. Galea et al. (2010) used obesity as an example to  
486 demonstrate how traditional analytical approaches, which focus on the isolation of single  
487 disease states and causes, has been challenged by the recognition of dynamic and complex  
488 interactions of factors influencing disease outcomes. Complex systems dynamic models can  
489 offer an alternative approach. Simulation models parameterized using observations from  
490 epidemiological data can be used to investigate inputs and outputs of a complex system and  
491 therefore become useful as a tool to test different scenarios. The use of simulation for  
492 estimating PAF where data has repeated measures is a novel approach. Therefore estimates  
493 using a closed equation method were compared to those using simulation. In this study the  
494 formula applicable for multiple exposure levels was used to calculate the PAF for BCS  
495 categories using data from two herds. Results using this closed method were compared to the  
496 results generated from posterior predictions. Simulation methods estimated PAF values that  
497 were within the 95% credible interval for PAF estimated using closed methods. These results  
498 illustrate that simulation based approaches produce similar, although slightly more  
499 conservative, estimates of PAF. As simulation methods account for the variability and can  
500 propagate this through the model to be included in the posterior predictions, the simulation-  
501 based results may be the more realistic figure for PAF.

502

### 503 **Study Limitations and Generalisability**

504 The main findings of this study were demonstrated in two UK herds with different  
505 methods of lameness detection. The PAF of comparable scenarios were similar in both herds  
506 giving an indication for possible generalisability of these findings to herds with similar

507 management systems. Although it should be recognised that the PAF estimates reported here  
508 are only applicable to changes in the original exposure distribution in these herds i.e. in herds  
509 with a higher median BCS compared with these study herds, the PAF for changes in BCS  
510 may differ to that reported in this study. The mean prevalence of lameness over the study  
511 period in Herd A for LS 3, 4 or 5 was 21.3%, which is lower than prevalence rates reported in  
512 other UK studies (Archer et al., 2010, Barker et al., 2010).

513 This study only investigated the population level impacts of the risk factors body  
514 condition score and previous lameness. The impact of other risk factors, including  
515 environmental risk factors should also be quantified to understand how these effect lameness  
516 at a herd level compared to the risk factors explored in this study.

517

## 518 **CONCLUSIONS**

519 This study quantified the impacts of the risk factors BCS and the occurrence of  
520 previous lameness events on herd level lameness. A loss in BCS of 0.5 across the herd was  
521 estimated to contribute towards 6% of the total number of lameness events (one-week with  
522 LS 3, 4 or 5), indicating that this proportion of total lameness could potentially be avoidable  
523 in the herds investigated. When the lameness severity threshold was increased (2 consecutive  
524 weeks LS 4 or 5) this figure increased to 11%. By comparison, between 79% and 83% of  
525 lameness events were estimated to be attributable to exposure to all previous lameness events  
526 and between 9% and 21% attributable to exposure to lameness events that occurred at least  
527 16 weeks previously. These findings suggest that repeated lameness events (i.e. an  
528 accumulation of previous lameness events) contributes towards an over-whelming proportion  
529 of the total amount of lameness in the herds investigated. Interactions with environmental or  
530 animal-based factors may be important for influencing whether animals go on to have  
531 repeated lameness events. Preventing the first case of lameness could potentially be important

532 in avoiding an escalation of repeated lameness events. A novel approach to estimating PAF  
533 using simulation enabled complex scenarios to be investigated whilst accounting for  
534 variability within the herds in this study using longitudinal data with repeated measures.

535

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541

542 **Conflicts of interest:** none identified

543

544

545

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645

646

647 Table 1. Results of Model 1a, 1b and 2 for explanatory variables body condition score (BCS) and  
 648 previous lameness using data obtained from the Scotland's Rural College (SRUC) Research and  
 649 Innovation Centre dairy herd (Model 1a and 1b) and a 600-cow herd in Somerset, UK (Model 2)\*

Variable	N <sup>1</sup>	Odds ratio	Lower 95% CrI <sup>2</sup>	Upper 95% CrI
Model 1a; outcome = one-week with LS 3, 4 or 5				
Total N = 79565				
BCS 3 wk previously				
3	3612	Baseline		
<2	14762	1.29	1.15	1.45
2	18603	1.14	1.02	1.27
2.25	20711	1.11	1.00	1.23
2.5	11444	1.07	0.96	1.19
2.75	4385	1.03	0.91	1.16
>3	2046	1.05	0.91	1.22
Previous lameness (LS 3,4 or 5)				
None	38133	Baseline		
1 to 4 wk	31483	3.65	3.48	3.83
None	3672	Baseline		
5 to 8 wk	30041	2.15	2.05	2.27
None	35636	Baseline		
9 to 12 wk	28687	1.64	1.53	1.77
None	34547	Baseline		
13 to 16 wk	27373	1.52	1.44	1.59
None	12218	Baseline		
>16 wk	57690	1.21	1.12	1.31
Model 1b; outcome = 2 consecutive weeks with LS 4 or 5				
Total N = 78698				
BCS 1 wk previously				
3	3718	Baseline		
<2	15122	1.66	1.27	2.16
2	18910	1.44	1.11	1.87
2.25	20990	1.29	1.00	1.66
2.5	11632	1.06	0.82	1.37
2.75	4481	1.11	0.83	1.48
>3	2119	1.16	0.84	1.61
Previous lameness (2 consecutive LS 4 or 5)				
None	67770	Baseline		
1 to 4 wk	6181	18.72	16.97	20.66
None	65262	Baseline		
5 to 8 wk	5812	1.99	1.78	2.22
None	62901	Baseline		
9 to 12 wk	5517	1.51	1.34	1.69
None	60682	Baseline		
13 to 16 wk	5245	1.48	1.32	1.67
None	46587	Baseline		
>16 wk	23064	1.62	1.46	1.79
Model 2; outcome = all causes of lameness (SH, SU/WLD and DD) <sup>3</sup>				
BCS				
BCS > 2 last 0 to 2 m		0.63	0.55	0.73
BCS > 2 last 2 to 4 m		0.74	0.60	0.90

Previous lameness

	Baseline		
None			
1 to 30 days ago	19.69	15.70	24.69
31 to 60 days ago	13.75	10.72	17.64
61 to 90 days ago	14.51	10.76	19.58
91 to 120 days ago	13.99	10.08	19.40
>120 days ago	16.02	12.50	20.53

650 <sup>1</sup>N = Number of observations

651 <sup>2</sup>CrI = credible interval

652 \* Only coefficients for explanatory variables BCS and previous lameness are reported here. Other  
653 covariates tested were found to be significant as reported by Randall et al. (2015) and Green et al.  
654 (2014)

655 <sup>3</sup>SH, SU/WLD and DD = sole haemorrhage, sole ulcer/white line disease and digital dermatitis

656

657 Table 2. Description of scenarios investigated for two UK dairy herds described by Green et al.  
 658 (2014) and (Randall et al., 2015).

Herd	Model	Outcome (interval)	Scenario	description
A	1a	LS <sup>1</sup> 3,4 or 5 (weekly)	BCS gain	Whole herd gains 0.5 BCS if < 3
			BCS loss No previous lameness	Whole herd loses 0.5 BCS Effect of all previous lameness events removed
	1b	2 consecutive LS 4 or 5 (weekly)	BCS gain	Whole herd gains 0.5 BCS if < 3
			BCS loss No previous lameness	Whole herd loses 0.5 BCS Effect of all previous lameness events removed
B	2	Clinical lameness; all causes (60 days)	No previous lameness	Effect of all previous lameness events removed

659 <sup>1</sup>LS = locomotion score

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661 Table 3. Proportion of observation in each body condition score (BCS) category for scenarios  
 662 investigated for Herd A; 724 cows held at the Scotland's Rural College (SRUC) Research and  
 663 Innovation Centre. Observations relate to weekly scoring of cows i.e. cow-week risk periods.

BCS categories	Baseline		BCS gain		BCS loss	
	No. observations	Proportion	No. observations	Proportion	No. observations	Proportion
Model 1a; total observations = 79565						
<2	14762	0.19	1323	0.02	54076	0.68
2	18603	0.23	4121	0.05	11444	0.14
2.25	20711	0.26	9318	0.12	4385	0.06
2.5	11444	0.14	18603	0.23	3612	0.05
2.75	4385	0.06	20711	0.26	1321	0.02
3	3612	0.05	15056	0.19	575	0.01
>3	2046	0.03	6431	0.08	150	0.002
Model 1b; total observations = 78698						
<2	15122	0.19	1380	0.02	55022	0.69
2	18910	0.24	4224	0.05	11632	0.15
2.25	20990	0.26	9518	0.12	4481	0.06
2.5	11632	0.15	18910	0.24	3718	0.05
2.75	4481	0.06	20990	0.26	1369	0.02
3	3718	0.05	15350	0.19	587	0.01
>3	2119	0.03	6600	0.08	163	0.002

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Table 4. Population attributable fraction (PAF) calculated using closed equations and a simulation-based approach using data recorded from 2 UK dairy herds; 724 cows held at the Scotland's Rural College (SRUC) Research and Innovation Centre over an 8 year period (Model 1a and 1b) and 1,040 cow herd in Somerset, UK over a 44 month period (Model 2)\*.

BCS category	Closed calculation					Simulation-based approach					
	N <sup>a</sup>	Proportion of total N	Odds	Relative Risk	PAF (%)	Number of lameness observations			PAF (%)		
						Median <sub>baseline</sub>	Median <sub>exp</sub>	No. Observations attributable to exposure	Median	2.5	97.5
<b>Model 1a</b>											
3 <sup>b</sup>	3612	0.05	Baseline								
< 2	14762	0.19	0.07	1.27	4.49	3400	3929	529	3.10	1.71	4.54
2	18603	0.23	0.06	1.13	2.66	3675	3969	297	1.73	0.14	3.33
2.25	20711	0.26	0.06	1.10	2.38	3869	4123	256	1.50	-1.31	3.13
	Total N for herd: 79565										
<b>Model 1b</b>											
3 <sup>c</sup>	3718	0.09	Baseline								
< 2	15122	0.19	0.009	1.60	8.90	731	1003	272	7.64	2.81	11.23
2	18910	0.24	0.008	1.38	6.00	704	905	201	5.58	1.05	9.18
2.25	20990	0.26	0.007	1.23	4.68	719	861	142	3.93	-0.76	7.74
	Total N for herd: 78698										
<b>Model 2</b>											
1 – 60 d <sup>d</sup> ; BCS > 2	7525	0.52	Baseline								
1 – 60 d; BCS < 2	2935	0.20	0.11	1.47	9.83	428	578	150	7.49	4.03	10.78
61 – 120 d; BCS > 2	2102	0.14	Baseline								
61 – 120 d; BCS < 2	2789	0.19	0.09	1.30	5.92	373	458	85	4.28	0.64	7.72
	Total N for herd: 14530										

\* Only results where BCS categories were significant (95% credible intervals for odds ratios did not include 1.00) have been reported in this table.

<sup>a</sup>N: Number of observations (observations relate to; Herd A, weekly risk periods for each cow and Herd B, consecutive 60 day risk periods for each cow)

<sup>b</sup>BCS 3 weeks previous to lameness events, <sup>c</sup>BCS 1 week previous to lameness events, <sup>d</sup>d = days

Table 5. Population attributable fraction for body condition score (BCS) and previous lameness estimated by simulation-based approach using data recorded from 2 UK dairy herds; 724 cows held at the Scotland's Rural College (SRUC) Research and Innovation Centre over an 8 year period (Herd A) and 1,040 cow herd in Somerset over a 44 month period (Herd B).\*

Scenario		Number of lameness observations <sup>1</sup>			PAF (%)		
		Median <sub>baseline</sub> <sup>2</sup>	Median <sub>exp</sub> <sup>3</sup>	N <sub>exp</sub> <sup>4</sup>	Median	2.5%	97.5%
<b>Herd B</b>							
Model	BCS gain	17110	16510	-600	-3.54	-5.86	-1.28
1a	BCS loss	17110	18140	1030	5.99	3.36	8.74
	No previous lameness	17110	3304	-13806	-80.69	-79.01	-82.26
Model	BCS gain	3571	3282	-289	-8.06	-13.12	-2.22
1b	BCS loss	3571	3968	397	11.20	5.52	17.33
	No previous lameness	3571	759	-2812	-78.75	-76.40	-80.98
<b>Herd B</b>							
Model 2	No previous lameness	1998	346	-1652	-82.69	-79.28	-85.61

<sup>1</sup>Observations relate to; Herd A, weekly risk periods for each cow and Herd B, consecutive 60 day risk periods for each cow

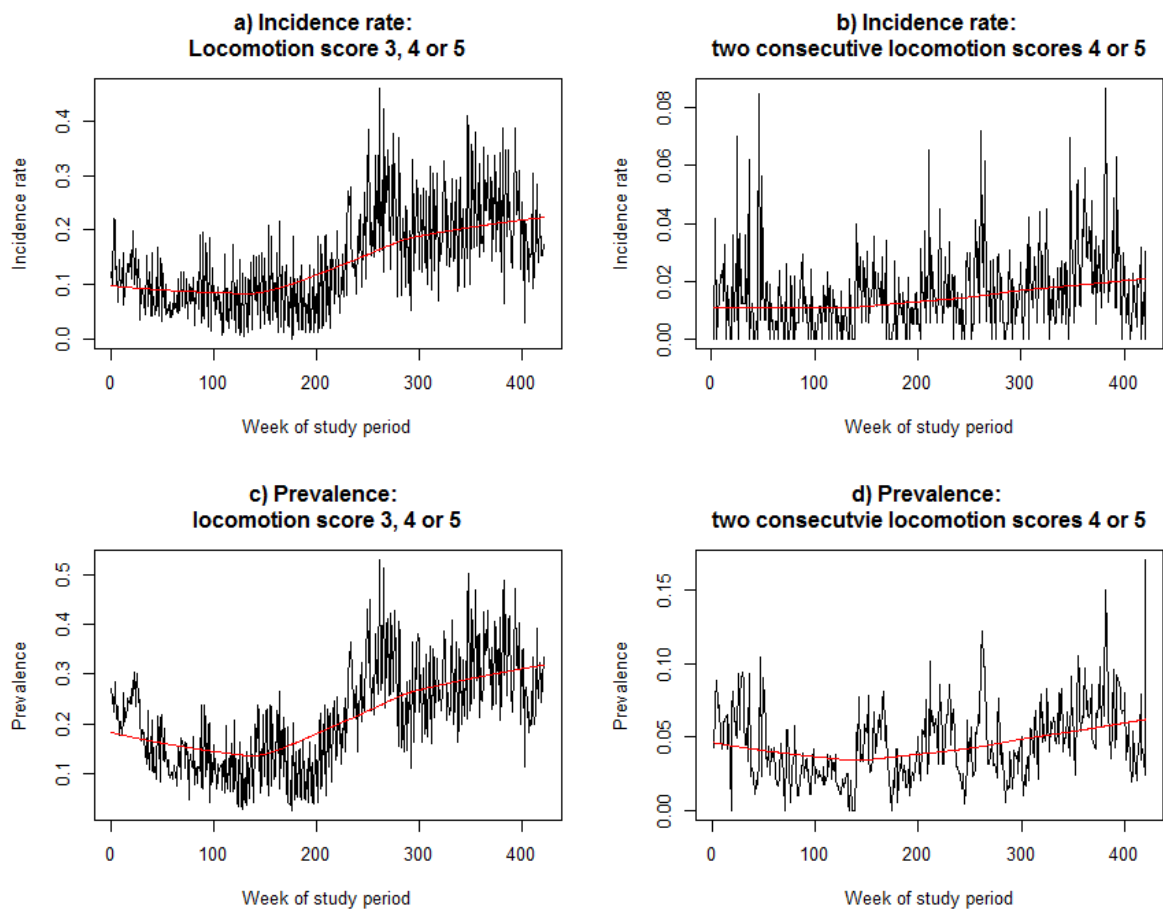
<sup>2</sup>Median<sub>baseline</sub> = median number of lameness observations for the baseline scenario

<sup>3</sup>Median<sub>exp</sub> = median number of lameness observations for the exposed scenario

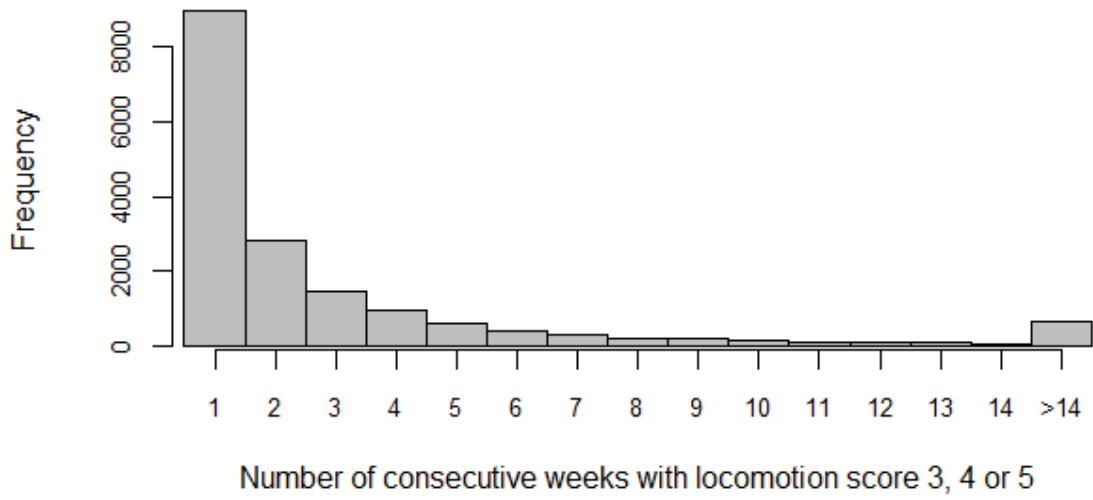
<sup>4</sup>N<sub>exp</sub> = Number of observations attributable to exposure

\*Where the exposure has a protective effect, the PAF is reported as negative e.g. a gain in BCS reduces the risk of lameness (see Table 1) and therefore this exposure will result in less lameness events.

Randall, Figure 1



**a) Locomotion score 3, 4 or 5**



**b) Locomotion score 4 or 5**

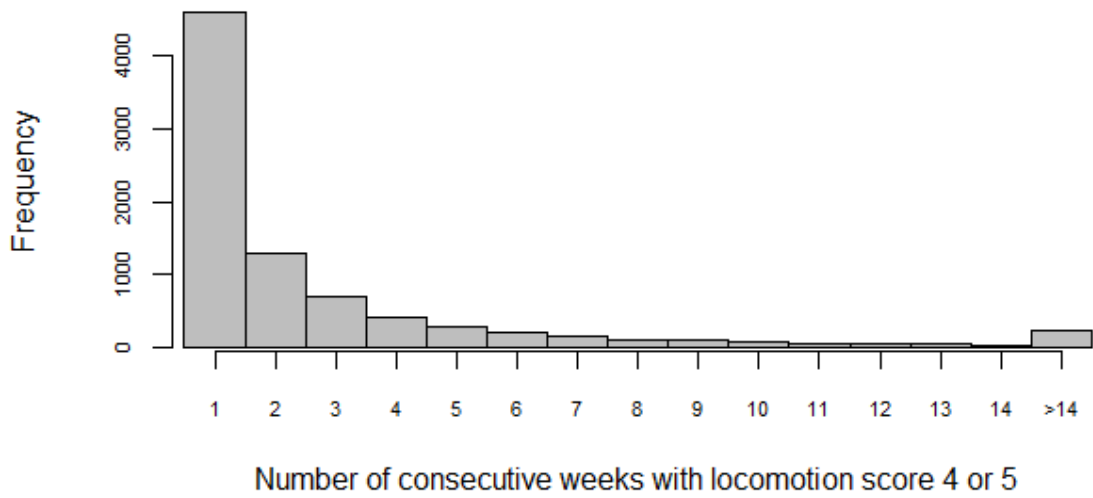


Figure 1. Weekly lameness incidence rate and prevalence over 421 weeks of the study period 2003 to 2011 for Herd A, 724 cows held at the Scotland's Rural College (SRUC) Research and Innovation Centre. The black line shows the weekly incidence rate and the red line shows locally weighted linear regression line created using the lowess function in R (R Core Team, 2016). In (a) and (c) lameness event is defined as locomotion score 3, 4 or 5. In (b) and (d) lameness event is defined as two consecutive weeks of score 4 or 5.

Figure 2. Frequency distributions showing the number of consecutive weeks that cows were locomotion scored as 3, 4 or 5 (a) and 4 or 5 (b) in Herd A, 724 cows held at the Scotland's Rural College (SRUC) Research and Innovation Centre, over the study period 2003 to 2011.