

Footbathing, formalin and foot trimming

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1 **Original article**

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4 **Footbathing, formalin and foot trimming: The 3Fs associated with granulomas and**
5 **shelly hoof in sheep**

6

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21 **Abstract**

22 Granulomas and shelly hoof (SH), are lesions of sheep feet. Our objective was to use
23 data from four questionnaires on lameness sent to English sheep farmers in 2004, 2013, 2014
24 and 2015 to further understanding of the risks and aetiologies of both lesions.

25

26 Granulomas were more likely in flocks where routine foot trimming (odds ratio [OR]
27 = 3.17; 95% confidence intervals [CI] 1.11 – 11.47) and routine footbathing (OR = 2.38; 95%
28 CI 1.19 – 4.83) were practised than where these management protocols were not. SH was
29 more likely in flocks that were footbathed in formalin compared with not footbathing (OR =
30 1.65; 95% CI 1.19 – 2.30), and was less common in flocks that stocked ewes at more than
31 eight vs. four per acre (OR = 0.34; 95% CI 0.17 – 0.68). There were weak associations
32 between SH and foot trimming. In 2004 only, SH was more likely in flocks where therapeutic
33 foot trimming was practised than not practised (OR = 2.24; 95% CI 1.12 – 4.68). In 2014
34 only, SH was marginally less likely in flocks where no feet bled during trimming, compared
35 with flocks not routinely trimmed (OR = 0.55; CI 0.30- 1.00); SH was not related to foot
36 trimming once severe footrot was included. We propose that flocks with granulomas and SH
37 would decrease if farmers stopped footbathing in general, in particular with formalin, and
38 avoided foot trimming whether as a therapeutic or routine practice. Further work is needed to
39 understand the role of stocking density.

40

41 *Keywords:* Contagious ovine digital dermatitis; Footrot; Lameness prevalence; Multivariable
42 models; Sheep flock management

43 **Introduction**

44 Lameness in sheep is one of the most important farm animal welfare concerns in the
45 UK (Goddard et al., 2006). It is estimated to cost the sheep industry £24 to £80 million per
46 annum (Nieuwhof and Bishop, 2005; Wassink et al., 2010b; Winter and Green, 2017) due to
47 its significant impact on productivity (Marshall et al., 1991; Glynn, 1993; Wassink et al.,
48 2010b). Footrot (both interdigital dermatitis and severe footrot) is the most common cause of
49 lameness in the United Kingdom. It is present in >95% flocks and causes approximately 70%
50 of lameness (Winter et al., 2015). Contagious ovine digital dermatitis (CODD), another
51 infectious cause of lameness, is present in >50% flocks and causes approximately 30% - 35%
52 of lameness in affected flocks (Angell et al., 2014; Winter et al., 2015).

53

54 Granulomas and shelly hoof (SH) are less prevalent causes of lameness in sheep.
55 They are present in 50% - 60% flocks and farmers generally attribute <3% lameness/lesions
56 to these conditions (Kaler and Green, 2008a; Winter et al., 2015). A granuloma is a
57 proliferation of highly vascularised connective tissue that protrudes through disrupted hoof
58 horn at the wall horn junction or through sole horn (Fig.1). It is very painful and sheep are
59 severely lame. Granulomas cause chronic lameness and sheep that have been lame for a long
60 period of time, and not bearing weight on the affected foot, often present with the wall horn
61 grown over the sole with the granuloma hidden from view. Granulomas are very difficult to
62 cure and often lead to premature culling of sheep (Winter, 2008). A professional review
63 suggests that the proliferation is a pathological response to trimming into the sensitive tissue
64 of the foot or as a result of untreated severe footrot (Winter, 2008).

65

66 Shelly hoof (SH) presents grossly as detachment of the hoof horn wall, typically the
67 abaxial wall, from the underlying epidermis, leaving a cavity between the wall and the sole

68 horn (Fig.1). SH per se does not cause lameness (Winter et al., 2015), however the impaction
69 of debris in the cavity formed by the detached horn, followed by penetration of a foreign
70 body, such as a thorn or stone, into sensitive tissue can lead to formation of an abscess and
71 then sheep become severely lame (Winter, 2008). Conington et al. (2010a) reported that wall
72 horn in cases of SH presents histologically as poorly keratinised epithelial horn cells with
73 microfissures and ‘unzipping’ of cell membranes that create microscopic crevices leading
74 deep into the horn. The authors hypothesised that this characteristic structure makes the hoof
75 physically weak, more permeable to moisture and highly vulnerable to entry of water-soluble
76 solutions and organisms that could further contribute to hoof breakdown. Conington et al.
77 (2010a) also reported a genetic component to SH. A professional review hypothesised that
78 physical damage, opportunistic bacteria/fungi or nutritional deficiency may cause SH (Winter
79 and Arsenos, 2009). While many farmers report low SH prevalence, some farmers report
80 high prevalence (Conington et al., 2010b) and the disease is of considerable concern for some
81 farmers (personal observation).

82

83 There is a body of published evidence that routine foot trimming and routine
84 footbathing are associated with a higher prevalence of all lameness. Treating individual sheep
85 lame with footrot rather than incorporating foot trimming and footbathing into routine flock
86 management protocols reduces the prevalence of footrot (Kaler and Green, 2009; Winter et
87 al., 2015; Witt and Green 2018). The only evidence of benefit from footbathing is for the
88 treatment of interdigital dermatitis (Clifton and Green, 2016). Which factors are effective in
89 the control of CODD are not well understood. However, recent studies indicate that CODD is
90 typically introduced by newly introduced sheep and that once it is endemic in flocks, CODD
91 can be controlled effectively using the same management protocols that control footrot

92 (Angell et al., 2016; Dickins et al., 2016). To the authors' knowledge, there are no published
93 studies reporting risk factors for granulomas and SH.

94

95 The aim of the current study was to use data from four questionnaires sent to English
96 sheep farmers in 2004, 2013, 2014 and 2015 to investigate associations between management
97 of lameness and farm characteristics with the presence of granulomas and SH to generate
98 hypotheses on the risks for, and possible aetiologies of, these lesions.

99

100 **Materials and methods**

101 *Ethical approval*

102 All questionnaire data used in this paper originates from studies that had ethical
103 approval from when this was required by the University of Warwick's Biomedical and
104 Scientific Research Ethics Committee (BSREC). For the 2013-2014 questionnaires this was
105 BSREC 159-01-12; approved 07 December, 2011. For the 2015 questionnaire this was
106 BSREC REG0-2014-620; approved 02 April, 2014. Ethical approval was not required in
107 2004.

108

109 *Questionnaires and responses*

110 In 2004, a postal questionnaire was sent to a random sample of 3000 English sheep
111 farms selected from lists using the RAND function in Microsoft Excel and obtained from the
112 Agriculture and Horticulture Development Board (AHDB) stratified by region of England
113 (South west, South east, Central, North west and North east) and by flock size within each
114 region (Kaler and Green, 2008a, 2009). The questionnaire contained a photograph and a
115 description of granuloma and shelly hoof (Fig.1). Farmers were asked to identify each lesion
116 and estimate its prevalence in their flock, as well as answering questions on the prevalence of

117 lameness and management of lameness; approximately 6% of the target population was
118 surveyed (Kaler and Green, 2008a, 2009). In 2013, similar questions were posed in a
119 questionnaire sent to 4000 lowland sheep farmers in England with >199 ewes; lists were
120 obtained from the Department for Environment, Food and Rural Affairs (DEFRA) and
121 AHDB who selected flocks randomly stratified by county and size (Winter et al., 2015). In
122 2004 and 2013, randomization to select farms was achieved by assigning each farm a number
123 using the number autofill function in Microsoft Excel and then generating a second random
124 list of numbers in the same number range and corresponding to the number of farms required
125 using the RAND function in Microsoft Excel. Farms were assigned to the questionnaire
126 group if the number assigned to them was generated in the random number list. The lists for
127 the 2013 questionnaire may have included some of the 809 respondents from 2004. In 2014,
128 an abridged version of the 2013 questionnaire was sent to 1355/4000 compliant farmers who
129 responded to the 2013 questionnaire (Grant et al., 2018). Finally, in 2015, 722 compliant
130 farmers who responded to the 2014 questionnaire were invited to participate in a study which
131 included completing a questionnaire; 192/722 agreed to participate and 144 (75%) completed
132 the questionnaire (Prosser et al., unpublished data). A further 18 farmers from the 2014 study
133 who participated in a clinical trial (Witt and Green, 2018) and an additional five farmers from
134 another clinical trial (Monaghan et al., unpublished data) also completed the questionnaire,
135 resulting in 167 responses to the 2015 questionnaire. Consequently, farmers who responded
136 to the 2015 questionnaire had also responded to the questionnaires in 2014 and 2013 and
137 farmers who responded to the 2014 questionnaire had also responded to the 2013
138 questionnaire. Data from 2004 were from a separate random sample of English sheep farmers
139 selected from lists using the RAND function in Microsoft Excel with unknown overlap in
140 responses from farmers in 2004 and other years. Data were collected on granulomas in 2004
141 and 2015 and SH in 2004, 2013 and 2014. Farmer responses to questions in Fig.1 were used

142 to identify flocks where granulomas and SH were present and to estimate the percentage of
143 granulomas and SH that farmers observed. Farmers were asked whether they practised
144 therapeutic and routine foot trimming in all four questionnaires; in addition, for 2013-2015,
145 the proportion of sheep that bled when trimmed was requested. Careful trimming is defined
146 here, as in Winter et al. (2015), as trimming where no sheep in a flock bled when routinely
147 trimmed.

148

149 *Data preparation and analysis*

150 All four datasets were clean because they had been used in previous analyses (Kaler
151 and Green, 2008a, 2009; Winter et al., 2015, Grant et al., 2018; Prosser et al., unpublished
152 data). The data were stored in Microsoft Excel. Responses were excluded if there were no
153 data on the presence of granulomas or SH. Explanatory variables were selected from the
154 questionnaires to test the following hypotheses. For granulomas, treatment variables e.g.
155 treated footrot with foot trimming, were used to test the hypothesis that management
156 protocols used for footrot were associated with presence of granulomas. Farm characteristics,
157 e.g. stocking rate, were used to test the hypothesis that certain types of farms had a higher
158 risk of granulomas. In addition, for SH, biosecurity variables e.g. the flock mixed with other
159 flocks, were used to test the hypothesis that SH is an infectious disease (Supplementary
160 Tables 1 and 2, respectively).

161

162 The global mean period prevalence of granulomas, SH and all lameness were
163 estimated and prevalence of lameness in flocks with and without granulomas and SH were
164 calculated. Previous work has reported that farmers recognise lameness (Kaler and Green,
165 2008b; King and Green, 2011) and foot lesions, but do not necessarily identify lesions
166 correctly (Kaler and Green, 2008a). Consequently, the prevalence of granulomas and SH by

167 correct (identifying the lesion in the photograph; Fig.1) and incorrect (identifying the lesions
168 as anything else, but most commonly footrot) identifying the lesions were investigated using
169 Mann Whitney tests. Binomial logistic regression models in R version 3.4.1¹ (R Core Team
170 2018) were used to investigate univariable and multivariable associations between the
171 presence of granulomas and SH and management protocols and farm characteristics. The data
172 from 2004 and 2015 were used to investigate granulomas and data from 2004, 2013 and 2014
173 were used to investigate SH; each year was modelled separately. The models took the
174 following form:

$$175 \quad y_j \sim \alpha + \beta_j X_j + e_j$$

176 where y_j is the probability that a flock has granulomas / SH, \sim is a logit link function, α is
177 the intercept and β_j represents the series of vectors of coefficients of explanatory variables
178 for X_j that vary by farm j and e_j is the residual random error that follows a binomial
179 distribution.

180

181 The results were assessed using Wald's test for significance, that is 95% confidence
182 intervals did not include unity. Variables significant at $P \leq 0.05$ in the univariable analysis
183 were tested in the multivariable model using manual forward stepwise selection. All variables
184 were then retested using manual forward stepwise selection regardless of their significance in
185 the univariable analysis to check for residual confounding (Cox and Wermuth, 1996) and
186 were included in the model if significant. Where two variables were highly correlated, the
187 most biologically relevant was kept in the model. Presence of other lesions (interdigital
188 dermatitis, severe footrot and CODD) in the flock were tested in the models to investigate
189 residual confounding. Correlations between the variables in the multivariable models and

¹ See: R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. <https://www.R-project.org> (accessed 30 May 2019).

190 between lesions were investigated using chi-square tests. The model fit was investigated by
191 visually comparing the ranked expected values against the observed values.

192

193 **Results**

194 *Farmer response proportions*

195 *Granulomas*

196 Of the 809 (27%) and 922 (68%) farmers that responded to questionnaires in 2004
197 and 2015, 89-95% answered questions regarding granulomas and flock size. Granulomas
198 were reported in 54-63% flocks (Supplementary Table 3). The median flock size was 220
199 (interquartile range [IQR], 90-450) in 2004 and 400 (IQR, 223-600) in 2015. The geometric
200 mean (95% confidence intervals [CI]) farmer reported prevalence of lameness was 8.1% (8.0-
201 8.1%) in 2004 and 4.1% (3.7-4.7%) in 2015. The prevalence of granulomas was right skewed
202 meaning the distribution was positive on the x axis with a long tail to the right. Flock
203 prevalence in affected flocks ranged from 0.0-8.0% (upper quartile range, 1.0-8.0% in 2004;
204 1.2-7.0% in 2015; Supplementary Table 3).

205

206 *Shelly hoof (SH)*

207 There were 809 (27%), 1354 (34%) and 922 (68%) responses from farmers who
208 received a questionnaire in 2004, 2013 and 2014, respectively. Of these, 84-86% answered
209 questions on shelly hoof and flock size, with 58-76% reporting shelly hoof in their flock
210 (Supplementary Table 3). The median flock size ranged from 225 ewes (IQR, 95-460) in
211 2004, to 340 ewes (IQR, 220-540) in 2013 and 320 ewes (IQR, 220-518) in 2014. The
212 geometric mean (95% CI) farmer reported prevalence of lameness was 6.9% (6.4-7.3%),
213 3.7% (3.3-3.9%) and 3.3% (3.1-3.5%) in 2004, 2013 and 2014, respectively. In flocks with
214 SH, the prevalence of lesions was mostly <5%, however, in each year, some flocks had very

215 high prevalence. The upper quartile flock prevalence range was 3.8-37.5% in 2004, 5.0-
216 70.0% in 2013 and 5.0-95.0% in 2014 (Supplementary Table 3).

217

218 *Farmer identification and prevalence of granuloma and shelly hoof*

219 *Granuloma*

220 In 2004 and 2015, 56% ($n=288/516$) and 98% ($n=155/158$) of farmers identified
221 granulomas correctly from a photograph (Fig. 1). There was no significant difference in
222 median flock prevalence of lameness by farmer identification of granuloma (Table 1).

223

224 *Shelly hoof*

225 In 2004, 2013 and 2014, 28% ($n=134/477$), 73% ($n=787/1079$) and 76% ($n=605/800$)
226 farmers, respectively, identified SH correctly from the photograph (Fig.1). Only 55%
227 ($n=356/642$) farmers correctly identified SH in both 2013 and 2014; 7% ($n=43/642$)
228 identified SH incorrectly in both years, and 37% farmers identified SH correctly once in 2013
229 or 2014. However, the median prevalence of SH was not significantly different between
230 flocks where farmers correctly and incorrectly identified SH and identification of SH was not
231 significantly associated with flock prevalence of lameness (Table 1).

232

233 *Univariable and multivariable binomial logistic regression models of factors associated with* 234 *the presence of granulomas and SH*

235 *Granulomas*

236 The univariable associations between management variables and presence of
237 granulomas in 2004 and 2015 are listed in Supplementary Table 1 and the multivariable
238 models are presented in Table 2. In 2004, granulomas were more likely to be present in
239 flocks where routine footbathing (odds ratio [OR] = 1.71; 95% CI 1.26 – 2.32) was practised

240 compared with those where routine footbathing was not practised and in flocks where farmers
241 practised therapeutic foot trimming of lame sheep (OR = 2.07; 95% CI 1.03 – 4.32)
242 compared with flocks where farmers did not practise therapeutic foot trimming. In 2015,
243 granulomas were more likely to be present in flocks where routine footbathing (OR = 2.38;
244 95% CI 1.19 – 4.83) and routine trimming (OR = 3.17; 95% CI 1.11 – 11.47) were practised
245 compared with flocks where these management protocols were not practised. When other
246 foot lesions were added to the models, only CODD in 2015 was significantly associated with
247 the presence of granulomas; all management variables remained significant in this model
248 (data not shown).

249

250 Shelly hoof

251 The univariable associations between management variables and the presence of SH
252 in 2004, 2013 and 2014 are listed in Supplementary Table 2 and the multivariable models are
253 in Table 3. Approximately 94% farmers practised therapeutic foot trimming in 2004 (Table
254 4) and SH was significantly more likely to be present in flocks where farmers practised
255 therapeutic foot trimming compared with flocks where this was not practised (OR = 2.24;
256 95% CI 1.12 – 4.68). Approximately 65% farmers practised routine footbathing of sheep
257 (Table 4) and SH was more common in flocks where footbaths were used compared to where
258 they were not used (OR = 1.81; 95% CI 1.33 – 2.46). In 2013, SH was more likely to be
259 present in flocks where sheep were routinely footbathed, and this was significantly associated
260 with flocks footbathed in formalin (OR = 1.65; 95% CI 1.19 – 2.30) compared with flocks
261 never footbathed or footbathed with other products. The likelihood of SH was lower as
262 stocking density increased from fewer than four to more than eight ewes per acre (OR = 0.34;
263 95% CI 0.17 – 0.68). In 2014, routine foot trimming was associated with increased
264 likelihood of SH (data not shown). However, SH was less likely to be present (Wald's $P =$

265 0.047; OR = 0.55; 95% CI 0.30 – 1.00) in flocks where farmers reported that no feet bled
266 during trimming (these were carefully, but not excessively, trimmed), compared with flocks
267 that were not routinely trimmed. When other foot lesions were tested in the models, ID,
268 CODD and severe footrot were significantly associated with the presence of SH in 2004,
269 2013 and 2014. The only change in the management variables was in 2014 when careful foot
270 trimming became non-significant ($P = 0.44$).

271

272 *Correlations between explanatory variables in the multivariable models and with footrot and*
273 *CODD*

274 There were significant ($P \leq 0.05$) correlations between variables in the multivariable
275 models. Typically, there were positive correlations between routine and therapeutic foot
276 trimming and footbathing. Stocking density was positively associated with footbathing and
277 positively and negatively associated with foot trimming in different models (Supplementary
278 Table 4). All lesions that were recorded in a single year were positively correlated with each
279 other.

280

281 *Model fit*

282 The model fits were reasonable, with predicted values following the pattern of
283 observed for both granulomas and SH (Supplementary Figs.1-5).

284

285 **Discussion**

286 This is the first study to provide evidence that the associations between therapeutic
287 foot trimming and routine footbathing and all lameness (Kaler and Green, 2009; Winter et al.,
288 2015) are associated with specific lesions, granulomas and SH, in addition to footrot

289 (Wassink et al., 2003; Kaler and Green, 2009) and CODD (Dickins et al., 2016). These
290 findings are discussed in detail below.

291

292 Granuloma data was available from 2004 and 2015. These data came from two
293 independent randomly selected samples of English sheep farmers, the degree of overlap in
294 farmers between these two samples is unknown, but it is likely to be low given a population
295 of >35,000 sheep farmers in England². Additionally, given the time interval of 13 years, even
296 if some of the farmers were the same, practices changed (Winter et al., 2015), so it seems
297 reasonable to assume that the datasets were independent. Consequently, the consistency
298 between results for both years (Table 2) provides confidence in their robustness. We
299 hypothesised that foot trimming could damage the foot structure and so lead to proliferation
300 of connective tissue i.e. a granuloma. The results indicate that routine and therapeutic foot
301 trimming are associated with the presence of granulomas (Table 2) and support the
302 hypothesis that damaging connective tissue in the foot is associated with trimming. In both
303 questionnaires, therapeutic and routine foot trimming were positively correlated and so the
304 presence of one or the other in the final models is in part because the degree of correlation
305 was sufficient to exclude the other. There is insufficient statistical power in the 2015 dataset
306 to explore whether excessive routine foot trimming vs. all routine foot trimming, was
307 associated with granulomas. Despite this, we conclude that granulomas are associated with
308 the practice of foot trimming. Granulomas were also more likely to be present in flocks that
309 were footbathed in both datasets. It is not clear why this might be. However, if formalin was
310 the main footbathing product in 2004 and 2015, as it was in 2013 (73% farmers; Winter et al.,
311 2015), and formalin can cause neoplasia and damage cells (see below), then either reduced

² See: AHDB, 2018. UK Sheep Yearbook 2018. Agriculture and Horticulture Development Board.
<http://beefandlamb.ahdb.org.uk/wp-content/uploads/2018/10/UK-Sheep-Yearbook-2018.pdf> (Accessed
14 March 2019).

312 regrowth of excessively trimmed hoof horn, or proliferation of digit connective tissue, or
313 both, could lead to granuloma. This requires further study.

314

315 SH data were available for 3 years, 2004 and 2013 and 2014; respondents from 2014
316 were a subset of those who replied in 2013. In all 3 years, routine footbathing was associated
317 with increased risk of SH, providing a consistent association. In 2013, we identified increased
318 risk associated with formalin footbaths. Formalin is carcinogenic, causing nasopharyngeal
319 cancer in animals and humans (Swenberg et al., 1980; Hauptmann et al., 2004) and at
320 concentrations >5% in footbaths it causes skin inflammation in cattle (Cornelisse et al., 1982)
321 and sheep (Ross, 1983), and hard keratinous-like material in the interdigital skin (Pyror,
322 1959). Formalin is also used post mortem to fix tissues. It acts by dehydrating cells which
323 harden and form cross-links to create an insoluble meshwork (Thavarajah et al., 2012). The
324 combination of inflammation of living skin and tough dead cells in the outer layers of skin
325 and horn could exacerbate the micro- and macro-disintegration of the white line observed in
326 SH (Conington et al., 2010a). The association between SH and formalin could possibly be
327 reverse causality, with farmers with SH in their flock using formalin footbaths. However,
328 footbaths are not a recommended treatment for SH and farmers rarely change their behaviour
329 (Wassink et al., 2005; Wassink et al., 2010a), so it is likely that these farmers had been using
330 formalin footbaths for many years and are still reporting SH.

331

332 The associations between foot trimming and SH were inconsistent; therapeutic foot
333 trimming was a risk in 2004 but not in other years and all routine foot trimming was not
334 associated with SH in any study, although careful routine foot trimming with no bleeding,
335 was only associated with reduced risk in 2013, but this association was confounded by the
336 presence of severe footrot in the flock. Many observational and interventional studies have

337 reported that foot trimming is detrimental. It increases the flock prevalence of all lameness
338 (Kaler and Green, 2009; Winter et al., 2015), severe footrot (Wassink et al., 2003) and
339 CODD (Dickins et al., 2016), delays healing (Kaler et al., 2010) and increases the
340 reoccurrence of footrot (Kaler et al., 2010). We consider that the inconsistent and weak
341 association and confounding associated with the presence of severe footrot indicates that foot
342 trimming is not a potential cause of SH and that the recommendation to avoid foot trimming
343 sheep is still robust.

344

345 In our study, SH was more likely to occur in flocks at stocking densities of fewer than
346 four ewes per acre compared with more than eight ewes per acre. This is consistent with SH
347 being more common in flocks on poor quality pasture. Winter and Arsenos (2009) suggested
348 that physical damage was a risk factor for SH. Features of poor quality pasture include
349 uneven surfaces, stones, or very dry or wet pasture, which might increase the risk of physical
350 damage to the white line and predispose to formation of SH. The presence of farm tracks are
351 a risk factor for white line disease in dairy cattle (Barker et al., 2009) and so give some
352 credence to this hypothesis by analogy (Bradford Hill, 1965). Additionally, if the grass was
353 poor quality, sheep could be malnourished and develop poor quality horn, as hypothesised by
354 Conington et al. (2010a). Sheep kept at low stocking densities are often different breeds from
355 those farmed at higher stocking densities; this might indicate breed differences in
356 susceptibility to SH, as well as the within-breed differences reported by Conington et al.
357 (2010b). However, there are a plethora of other management factors associated with low vs.
358 high stocking densities that could act as risk factors for SH.

359

360 There were no significant associations and varying patterns of positive and negative
361 coefficients between biosecurity variables and granulomas and SH between the years of study

362 (Supplementary Tables 1 and 2). This indicates that there were no strong or consistent risks
363 with biosecurity variables and we hypothesise that granulomas and SH are unlikely to be of
364 infectious origin, introduced into flocks by incoming sheep. Additionally, the distribution of
365 granulomas and SH within flocks provides further clues, as many flocks did not have lesions,
366 most affected flocks had very low prevalence and only a few had very high prevalence (Kaler
367 and Green, 2008a). This is not typical of infectious disease and suggests that granulomas and
368 SH are non-infectious diseases and that where there is a high prevalence there is a farm-
369 specific risk.

370

371 In studies by Conington et al. (2010a; 2010b), the prevalence of SH in 27 flocks
372 ranged from 0-76%. In the current study, the range of SH was 0% to 37-95%, indicating there
373 were some flocks with a similar prevalence of SH to those reported by Conington et al.
374 (2010a; 2010b), but many hundreds with low prevalence. The within-flock prevalence of
375 lesions was a farmer estimate from recollection of foot examinations. It is therefore likely to
376 be an underestimate of the true prevalence of SH, since the farmers are unlikely to have
377 examined all feet simultaneously. Even if the prevalences reported here and elsewhere are not
378 representative of the within-flock prevalence of granulomas and SH across the population of
379 English sheep flocks, our data are robust enough to estimate the risk of granulomas and SH in
380 flocks, as long as the presence of a lesion did not bias farmers' responses. This seems
381 unlikely but cannot be determined from our data. When findings were consistent across the
382 questionnaires, the robustness of the results is greater. However, because farmers from 2013-
383 2015 were the same, the robustness is less than for independent studies.

384

385 **Conclusions**

386 This is the first study to associate footbathing, formalin and foot trimming with
387 granulomas and SH in sheep flocks. These management protocols were associated with
388 reduced risk of SH, but less consistently. We conclude that the current recommended
389 management protocols of avoiding footbathing and foot trimming to minimise lameness and
390 footrot and CODD also contribute to reduced risk of granulomas. Further work is required to
391 understand whether granulomas are more likely to occur when formalin is used and to
392 investigate the role of formalin footbaths and low stocking density on the occurrence of SH.

393

394 **Conflict of interest statement**

395 None of the authors has any other financial or personal relationships that could
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397

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404

405 **Appendix A: Supplementary material**

406 Supplementary data associated with this article can be found, in the online version at doi:

407

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539 **Table 1**

540 Median (interquartile range) flock prevalence of lameness, granuloma and shelly hoof (SH)
 541 identified by farmers from questionnaires completed by sheep farmers in England in 2004,
 542 2013, 2014 and 2015.

| Year | Granuloma | Granuloma | <i>P</i> ^a | SH | SH | <i>P</i> ^a |
|---------------|-------------------------|---------------------------|-----------------------|-------------------------|---------------------------|-----------------------|
| | correctly identified | incorrectly identified | | correctly identified | incorrectly identified | |
| Lameness % | | | | | | |
| 2004 | 8 (5-10) | 8 (5-10) | 0.88 | 10 (5-15) | 10 (5-15) | 0.25 |
| 2013 | - | - | | 4 (2-5) | 4 (2-6) | 0.88 |
| 2014 | - | - | | 3 (2-5) | 3 (2-5) | 0.53 |
| 2015 | 5 (2-7) | 15 (1.5-15) | 0.28 | - | - | |
| Granuloma % | | | | | | |
| 2004 | 0.25 (0.0-1.0) | 0.5 (0.0-1.1) | <0.01 | 0.6 (0.3-1.1) | 0.8 (0.3-1.5) | 0.72 |
| 2013 | - | - | | - | - | |
| 2014 | - | - | | - | - | |
| 2015 | 0.9 (0.0-1.0) | 5 (0.0-10.0) | 0.68 | - | - | |
| Shelly hoof % | | | | | | |
| 2004 | 0.6 (0.0-2.0) | 0.5 (0.0-2.1) | 0.40 | 10 (5-40) | 20 (10-50) | 0.03 |
| 2013 | - | - | | 2.0 (1.0-5.0) | 3.0 (1.0-5.0) | 0.78 |
| 2014 | - | - | | 2.0 (1.0-5.0) | 3.0 (1.4-5.0) | 0.11 |
| 2015 | - | - | | - | - | |

543

544 - Data not collected

545 ^a *P* calculated from Mann-Whitney tests comparing prevalence of SH and granulomas by
 546 correct and incorrect farmer identification of lesions.

547 **Table 2**

548 Binomial regression models of factors associated with the presence of granulomas in 2004
 549 and 2015

| Model term | Category | Number of flocks | % | OR | 95% CI | |
|--|----------|---------------------|-------|------|--------|-------|
| 2004 | | | | | | |
| Footbathing ^a | No | 265 | 34.42 | 1.00 | | |
| | Yes | 500 | 64.94 | 1.71 | 1.26 | 2.32 |
| Trim to treat sheep lame with footrot | No | 35 | 4.55 | 1.00 | | |
| | Yes | 723 | 93.90 | 2.07 | 1.03 | 4.32 |
| 2015 | | | | | | |
| Routine footbathing ^a | No | 68 | 43.04 | 1.00 | | |
| | Yes | 90 | 56.96 | 2.38 | 1.19 | 4.83 |
| Routine foot trim | No | 131 | 82.91 | 1.00 | | |
| | Yes | 27 | 17.09 | 3.17 | 1.11 | 11.47 |

550

551 OR, odds ratio; 95% CI, 95% confidence interval

552 ^a Footbathing product data not collected

553 **Table 3**

554 Binomial regression models of factors associated with the presence of shelly hoof (SH) in
 555 sheep flocks in 2004, 2013 and 2014

| Model term | Category | Flocks, <i>n</i> | % | OR | 95% CI | |
|--|---------------------------|---------------------|-------|------|--------|------|
| 2004 | | | | | | |
| Footbathing ^a | No | 261 | 34.71 | 1.00 | | |
| | Yes | 486 | 64.63 | 1.81 | 1.33 | 2.46 |
| Trim to treat sheep lame with footrot | No | 35 | 4.65 | 1.00 | | |
| | Yes | 705 | 93.75 | 2.24 | 1.12 | 4.68 |
| 2013 | | | | | | |
| Ewe stocking rate | <4/acre | 385 | 42.73 | 1.00 | | |
| | 4-8/acre | 451 | 50.06 | 0.75 | 0.55 | 1.02 |
| | >8/acre | 36 | 4.00 | 0.34 | 0.17 | 0.68 |
| Footbathing ^a | No | 341 | 37.85 | 1.00 | | |
| | Yes: formalin used | 411 | 45.62 | 1.65 | 1.19 | 2.30 |
| | Yes: formalin not used | 145 | 16.09 | 1.38 | 0.90 | 2.16 |
| 2014 | | | | | | |
| Routine foot trim | No trim | 295 | 48.92 | 1.00 | | |
| | Trim: no bleeding | 53 | 8.79 | 0.55 | 0.30 | 1.00 |
| | Trim: bleeding | 244 | 40.46 | 1.13 | 0.78 | 1.64 |

556

557 OR, odds ratio; 95% CI, 95% confidence interval

558 ^a Footbathing with any product was associated with significantly higher OR for shelly hoof in
559 2013; footbathing product data not collected in 2004 and 2014

560 **Table 4**

561 The number and percentage of flocks by management protocols for lameness in England in
 562 2004, 2013, 2014 and 2015^a.

| Variable | 2004 (<i>n</i> =752) | | 2013 (<i>n</i> =901) | | 2014 (<i>n</i> =603) | | 2015 (<i>n</i> =158) | |
|-----------------------------------|-----------------------|----|-----------------------|----|-----------------------|----|-----------------------|----|
| | <i>n</i> | % | <i>n</i> | % | <i>n</i> | % | <i>n</i> | % |
| Trimmed feet as footrot treatment | | | | | | | | |
| No | 35 | 5 | | | | | 62 | 39 |
| Yes | 705 | 94 | | | | | 88 | 56 |
| Never | | | 38 | 4 | 28 | 5 | | |
| Always | | | 345 | 38 | 110 | 18 | | |
| Sometimes | | | 161 | 18 | 257 | 43 | | |
| Usually | | | 292 | 32 | 174 | 29 | | |
| Routine foot trimming practised | | | | | | | | |
| No | 173 | 23 | 395 | 44 | 295 | 49 | 131 | 83 |
| Yes | 572 | 76 | 487 | 54 | 303 | 50 | 27 | 17 |
| Never | | | | | | | | |
| Bled during routine trimming | | | | | | | | |
| No trimming | | | 395 | 44 | 295 | 49 | | |
| No bleeding | | | 60 | 7 | 53 | 9 | | |
| Bleeding | | | 408 | 45 | 244 | 40 | | |
| Used footbaths | | | | | | | | |
| No | 261 | 35 | 341 | 38 | 248 | 41 | 68 | 43 |
| Yes | 486 | 65 | | | 355 | 59 | 90 | 57 |
| Yes: Used formalin | | | 411 | 46 | | | | |

| | | | | | | | | |
|------------------------------------|-----|----|-----|----|-----|----|-----|----|
| Yes: Did not use formalin | | | 145 | 16 | | | | |
| Used Footvax | | | | | | | | |
| No | 649 | 86 | 693 | 77 | 470 | 78 | 98 | 62 |
| Yes | 97 | 13 | 194 | 22 | 132 | 22 | 55 | 35 |
| Checked feet of sheep pre-purchase | | | | | | | | |
| Always | | | 254 | 28 | 130 | 22 | | |
| Usually | | | 182 | 20 | 126 | 21 | | |
| Sometimes | | | 125 | 14 | 75 | 12 | | |
| Never | | | 135 | 15 | 97 | 16 | | |
| Did not purchase | | | 192 | 21 | 167 | 27 | | |
| Isolated new sheep | | | | | | | | |
| Never | | | 102 | 11 | 50 | 8 | | |
| Sometimes | | | 73 | 8 | 39 | 6 | | |
| Usually | | | 133 | 15 | 93 | 15 | | |
| Always | | | 393 | 44 | 266 | 44 | | |
| No new arrivals | | | 176 | 20 | 138 | 23 | | |
| Sheep left the flock then returned | | | | | | | | |
| No | | | 548 | 61 | | | | |
| Yes | | | 339 | 38 | | | | |
| Flock mixed with other flocks | | | | | | | | |
| No | | | 838 | 93 | | | | |
| Yes | | | 35 | 4 | | | | |
| Don't know | | | 5 | 1 | | | | |
| Farm type | | | | | | | | |
| Lowland | | | 766 | 85 | | | 140 | 87 |

| | | | | | | | | | |
|---------------|-----|----|-----|----|-----|----|----|--|----|
| Hill | | | 25 | 3 | | | | | |
| Upland | | | 94 | 10 | | | | | |
| Hill/Upland | | | | | | | 16 | | 10 |
| Organic farm | | | | | | | | | |
| No | | | 849 | 94 | | | | | |
| Yes | | | 41 | 5 | | | | | |
| Stocking rate | | | | | | | | | |
| <4 ewes/acre | 361 | 48 | 385 | 43 | 266 | 44 | 69 | | 44 |
| 4-8 ewes/acre | 241 | 32 | 451 | 50 | 296 | 49 | 84 | | 53 |
| >8 ewes/acre | 102 | 14 | 36 | 4 | 28 | 5 | | | |

563

564 ^a Blank cells,

565 **Figure legend**

566

567 Fig. 1. Example photograph and description of granuloma (A), and shelly hoof (B), also
568 known as white line separation or degeneration, provided to farmers in questionnaires to
569 investigate their ability to identify common foot lesions.