Preventive Veterinary Medicine xxx (2015) xxx–xxx

Contents lists available at ScienceDirect
Preventive Veterinary Medicine
journal homepage: www.elsevier.com/locate/prevetmed

Sheep and farm level factors associated with contagious ovine digital dermatitis: A longitudinal repeated cross-sectional study of sheep on six farms

J.W. Angell*, D.H. Grove-White, J.S. Duncan

Department of Epidemiology and Population Health, Institute of Infection and Global Health, The University of Liverpool, Leahurst Campus, Neston, Wirral, CH64 7TE, UK

ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form 2 September 2015
Accepted 29 September 2015

Keywords:
Contagious ovine digital dermatitis
CODD
Footrot
Sheep
Welfare
Lameness

ABSTRACT

Contagious ovine digital dermatitis (CODD) is a cause of severe lameness in sheep in the UK currently affecting approximately 50% of farms. Six farms were studied in North Wales to investigate (1) the prevalence dynamics of CODD, (2) the association between sheep with CODD and potential risk factors and (3) the impact of CODD on lameness in sheep. The farms were visited at approximately two-month intervals between June 2012 and October 2013 and 6515 sheep were examined.

The mean sheep level prevalence of CODD varied between farms (2.5–11.9%). Within farms, prevalence may increase in the late summer/early autumn and after housing. Environmental risk factors included larger flocks, lowland pasture, lush pasture and poached pasture. Co-infection of a foot with footrot was strongly associated with CODD in that foot (OR: 7.7 95% CI: 3.9–15.5 $P < 0.001$) but negatively associated with co-infection of a foot with interdigital dermatitis (OR: 0.04 95% CI: 0.02–0.1 $P < 0.001$). Reinfection with CODD was observed in 78 individual sheep but there was no re-infection at foot level.

Lameness on all farms reduced during the study and seasonal changes in lameness followed similar patterns to those for CODD. Infection with CODD leads to a greater increase in locomotion score compared to footrot or interdigital dermatitis and CODD lesion grade was strongly associated with being lame. Sheep with CODD in more than one foot were more likely to be lame (OR: 25.0 95% CI: 12.5–49.9 $P < 0.001$) than those with just one foot affected (OR:10.0 95% CI: 8.6–11.6 $P < 0.001$).

The biggest risk factor for CODD is co-infection with footrot and therefore control of footrot should help reduce the risk of CODD on affected farms. Furthermore environmental risk factors for CODD are similar to those for footrot adding weight for control strategies that target both diseases in tandem. The routine repeated gathering of sheep for the purposes of treating all lame sheep might be an effective control strategy for lameness on some sheep farms. Effective systemic immunity to CODD in sheep appears to be lacking, as 78 sheep were observed to be re-infected with CODD during the survey. However, there is epidemiological evidence that there may be some local immunity within the foot warranting further investigation.

1. Introduction

Contagious ovine digital dermatitis (CODD) was first identified in the UK in 1997 (Harwood et al., 1997) and since then the proportion of UK farms affected has increased to approximately 50% (Duncan et al., 2014). The disease affects the digits of sheep and causes lameness due to the severe damage caused in affected feet (Winter, 2008; Phythian et al., 2013). A diagnosis is made on the basis of clinical signs (Angell et al., 2015a) and effective treatment remains problematic, partly due to the fact that as yet the aetiology is unclear (Duncan et al., 2014). Whilst the aetiopathogenesis of CODD is currently unclear, pathogens implicated in the aetiology of CODD are *Treponema* spp. including those associated with Bovine Digital Dermatitis (BDD) - *Treponema medium/Treponema vincentii* -like, *Treponema phagedenis* -like and *Treponema pedis* (Sullivan et al., 2015). Other pathogens implicated in CODD include *Dichelobacter nodosus* and *Fusobacterium necrophorum* (Naylor et al., 1998; Moore et al., 2005).

* Corresponding author. Tel.: +44 151 7946050; fax: +44 151 7946034.
E-mail address: jwa@liv.ac.uk (J.W. Angell).

http://dx.doi.org/10.1016/j.prevetmed.2015.09.016

A recent review highlighted the large gaps in our knowledge of this disease (Duncan et al., 2014) but we have identified a number of putative risk factors for CODD at farm level, from a questionnaire survey of 511 farms in Wales, UK (Angell et al., 2014). These included concurrent digital dermatitis in cattle on the farm, increasing flock size, concurrent footrot (FR), buying in sheep, adult sheep, time of year and housing sheep. To date though there have been no on farm epidemiological studies investigating risk factors for CODD on naturally affected farms. Furthermore, there has been recent interest in this disease from a welfare perspective due to the severity of lesions and the significant impact this is likely to have both in individual sheep and on the sheep industry as a whole (FAWC, 2011).

The aim of this study was to examine the epidemiology of CODD on six farms in North Wales. The three main objectives were: (1) to describe any temporal variation in CODD prevalence; (2) to investigate the association between sheep with CODD and potential risk factors; (3) to investigate the impact of CODD on lameness in sheep.

2. Materials and methods

The study protocol was approved by The University of Liverpool ethics committee (VREC 13) on 24th August 2011.

2.1. Study design and study population

The study is a prospective, repeated cross-sectional field survey of six sheep farms in North Wales, selected on known presence of CODD on the farm and farmer willingness to collaborate.

Farms were visited approximately bi-monthly over a 12 month period (June 2012–October 2013), although the visiting schedule was impacted by several factors including bad weather and breeding events. Farms with a range of production systems and breeds were selected, including hill, upland and lowland.

2.2. Sampling

At each visit all sheep on the farm were gathered from fields to handling pens and then visually inspected in groups of approximately ten sheep. All sheep on the farm were lameness scored in the pen using a four-point ordinal locomotion scoring system (Angell et al., 2015b). All lame sheep (score 1–3) were selected for further detailed examination, together with an equal or greater number of non-lame (score 0) control sheep, randomly selected from the same pen.

This sampling strategy was adopted as CODD is typically reported to be of low prevalence on affected farms (2.0% (IQR 1.0–5.0%)) (Angell et al., 2014). Furthermore not all sheep with CODD are lame (Phythian et al., 2013) thus non-lame sheep were also examined. Each selected sheep was examined in detail and covariate data recorded and entered into a Microsoft Access Database (Microsoft; USA).

Due to the dynamic nature of sheep flocks, it was impossible to re-sample the same animals at each visit. As such, a repeated cross-sectional sampling at farm level strategy, as described, was adopted. Therefore at each visit, a combination of previously sampled and previously un-sampled sheep were sampled (Table 1).

All the data collection, observations and examinations were made by the same person (JA) in order to reduce the risk of differential misclassification by different observers.

2.3. Farm and group level factors

Farm stocking density (Livestock units/hectare (Ha)) (DEFRA, 2010) was estimated using data supplied by the farmer (number and type of animals: grazeable land area). For beef cattle an average LU of 0.65 was used to take account of the different, varying and unquantifiable ages of beef cattle on the farm.

At each visit, the total number of sheep in each field was counted and field stocking density (sheep/Ha) for that visit calculated

The pasture moisture was assessed as: (1) 'Dry'—no moisture was observed on footwear following walking through the pasture, (2) 'Damp and well drained' – the ground was firm but the grass damp to touch and moisture evident on footwear, (3) 'Wet'—the ground would bear weight but was squelchy, (4) 'Boggy'—the ground was saturated and in places footwear would sink someway into the ground (Supplementary Fig. 1).

Supplementry material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2015.09.016.

Pasture quality was determined as: (1) 'Lush'—80% rye grasses, mostly leaf rather than stalk present, (2) 'Average'—approximately 50% rye grasses, some stalk and some leaf and (3) 'Rough'—moorland, marshland, virtually no rye grasses, and rushes, heather or bracken present (Supplementary Fig. 2).

Supplementry material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2015.09.016.

The mean compressed sward height in each field was measured using a plate meter (Filips Manual Folding Plate Meter; Jenquip, Feilding, New Zealand, (Jenquip, 2004))with the observer walking each field in a zig-zag pattern taking recordings every ten paces to obtain an accurate mean. Between 18 and 445 readings were taken per field (depending on size) to obtain the mean compressed sward height.

The sward cover in each field may vary and the amount of cover in each field was determined by eye as: (1) 'Good Coverage—all the field was visibly covered in grass, (2) 'Patches'—incomplete sward cover; some areas of the field were just soil (>5% to <50%), 3) 'Heavily Poached'—>50% of the sward was absent (Supplementary Fig. 3).

Supplementry material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2015.09.016.

2.4. Sheep factors

For each sheep examined in detail, the following data were recorded: ear tag number; locomotion score (Angell et al., 2015b); body condition score (Russel, 1984); age (estimated in whole years from the number of incisor teeth present (Spence and Aitchison, 1986) and breed. The cleanliness of the tail and perineal wool was recorded using an ordinal scoring system: (0) 'Clean', (1) 'Mild Staining'—small amounts of faecal material adhering to the wool, (2) 'Dirty'—obvious staining to wool and perineum, with/without small 'dags' (hardened accumulations of faecal debris adhering to the wool), (3) 'Large Dags'—heavily stained wool and perineum; large dags obviously present (Supplementary Fig. 4).

Supplementry material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2015.09.016.

For each examined sheep, each foot was examined and the following foot lesions were recorded if present: CODD, FR, interdigital dermatitis (ID), white-line/shelly hoof (WL), foot abscess (FA), granuloma (GR), interdigital hyperplasia (IH), joint infection (JI), injury (IN) and overgrown horn (OG). For the infectious foot conditions—FR, ID and CODD—if more than one lesion appeared to be present in the same foot e.g., footrot and CODD together, the combination was recorded. All CODD lesions were graded (1–5), and active CODD was defined as a lesion graded 1–4, grade 5 being a healed lesion (Angell et al., 2015a). All sheep were restrained and examined in dorsal recumbency using a Turn Over Crate (Harrington, Yorkshire, UK).

To ensure the welfare of the sheep, all sheep with a foot lesion were treated as per the usual protocol for that farm agreed between

Table 1
Number of times individual sheep were sampled, stratified by whether they were lame or not lame and whether they had active CODD.

Number of times a sheep was sampled	Total number (n = 6,515)	N (%) Lame (n = 1,447)		N (%) Non-lame (n = 4,812)		N (%) with missing lameness data (n = 256)		N (%) with active CODD (n = 733)	
1	2497	472	(18.9)	1946	(77.9)	79	(3.2)	236	(9.5)
2	2054	452	(22.0)	1508	(73.4)	94	(4.6)	228	(11.1)
3	1197	318	(26.6)	812	(67.8)	67	(5.6)	186	(15.5)
4	416	118	(28.4)	283	(68.0)	15	(3.6)	53	(12.7)
5	235	54	(23.0)	180	(76.6)	1	(0.4)	17	(7.2)
6	116	33	(28.5)	83	(71.6)	0	(0.0)	13	(11.2)

the farmer and their own veterinary surgeon. Treatments included long acting oxtetracycline injection (Alamycin LA; Norbrook), or long acting amoxicillin injection (Betamox LA; Norbrook), oxytetracycline spray (Alamycin spray; Norbrook) and foot trimming.

2.5. Data analysis

The data were cleaned and checked for inconsistencies. All analyses were conducted using STATA IC 13 (Statacorp, TX). Probability values of <0.05 were taken as significant. Three analysis strategies were employed: (1) the prevalence of lameness and lesions were estimated; (2) modelling associations between farm, environmental, sheep and foot factors and the primary outcome, namely the presence of active CODD at foot level; (3) examining associations between farm, environmental and sheep factors with the primary outcome, namely a sheep being recorded as lame (locomotion score >0).

1) Prevalence

Lameness and lesion prevalence were calculated as the number of sheep affected, as a proportion of the flock. Due to the sampling strategy, the true flock prevalence of lameness or specific foot lesions was estimated from the sampled data using the formula:

$$P = \frac{(N_{\text{case}} + N_{\text{est}})}{N_{\text{tot}}}$$

P: estimated prevalence

N_{case}: number of recorded cases in examined sheep—lame and not lame.

N_{est}: estimated number of cases in un-sampled flock—not lame.

N_{tot}: total number of sheep in the flock.

The estimated number of cases in the un-sampled flock (N_{est}) was calculated from the sample data using the formula:

$$N_{\text{est}} = \left[\frac{\text{NL}_{\text{case}}}{\text{NL}_{\text{tot}}}\right] \times N_{\text{uns}}$$

NL_{case}: the number of sheep with a specified foot disease that were not lame at examination

NL_{tot}: the total number of examined sheep that were not lame

N_{uns}: N_{tot} minus the total number of sheep sampled

The estimated prevalence for lameness, and for each lesion was calculated for each visit and for each farm and then from these individual estimates, an overall mean estimated prevalence was calculated for all six farms over all 32 visits.

2.5.1. Distribution of lesions

The distribution of specific lesions by age was assessed using the Chi-squared test. The proportional distribution of lesions between front and back feet was investigated using the Z test.

2) CODD as an outcome

2.5.2. Descriptive statistics for CODD

The proportional distribution of CODD lesion grades in affected feet was investigated using the Z test.

2.5.3. Modelling

Univariable and multivariable logistic regression were employed to investigate associations between the primary outcome variable—presence of active CODD at foot level - and potential farm, environmental, sheep and foot explanatory variables (Table 2). A foot was considered the primary unit rather than a sheep as CODD often affects only one or two feet in a sheep (Duncan et al., 2011; Angell et al., 2015a).

Due to the non-random sampling strategy, probability weights were used in all regression models, defined as the probability of a non-lame sheep being sampled (PWT). For lame sheep PWT = 1 as all lame sheep were sampled. For non-lame sheep PWT was calculated as:

$$\text{PWT} = \left[\frac{N_{\text{nl}}}{\text{FS}_{\text{visit}} - N_{\text{lame}}}\right]^{-1}$$

N_{nl}: the number of non-lame sheep examined at the visit.

FS_{visit}: total flock size at the visit.

N_{lame}: the total number of lame sheep at the visit.

A multivariable logistic regression model with the binary outcome variable being the presence of active CODD at foot level was fitted using a backward elimination strategy whereby a full model was built and then each variable removed in turn. Model fit was assessed using the Bayesian Information Criterion (BIC) (Long, 1996). For a model M_k with deviance D (M_k) the BIC is estimated as: $\text{BIC}_k = D(M_k)\text{-df}_k * \ln N$, where df_k is the degrees of freedom associated with the deviance and N is the sample size. The more negative the BIC_k the better the model fit, with an absolute difference in BIC between two models of >6 offering strong support for the model with the smallest BIC. Variables were removed if this led to improved model fit. The omitted variables were then added back in turn and the variable retained if it improved model fit, until no more variables could be added. Interactions in the final model were considered for inclusion if considered plausible and retained if they improved model fit.

Variables were generated to code for the presence of lesions in the other three feet belonging to the sheep e.g., a binary variable for 'other feet in a sheep with FR' coded as 1 if any of the three other feet in the sheep had FR together with the foot in question, or coded as 0 if the other three feet did not have FR (Table 2).

Clustering of feet within sheep was accounted for by fitting the model using robust standard errors—random effects could not be used due to the use of probability weights. This final model was then used to assess the associations between the outcome and the included covariates adjusted for each other.

2.5.4. Time covariates

To allow modelling of seasonal changes if present, four time covariates (X_1 X_2 X_3 X_4) were generated as follows: X_1 = cos(2πt/365.25), X = sine(2πt/365.25), X_3 = cos(4πt/365.25),

Table 2
Description of variables collected at sampling visits for initial inclusion in statistical analyses.

Variable	Description and coding of variable
Farm and environment	
Flock size/50	Number of sheep in the flock divided by 50.
Land type	1 = Hill
	2 = Upland/lowland
	3 = Lowland
Farm stocking density	The number of LU per hectare for the farm
Field stocking density	The number of sheep per hectare in each field at sampling
Pasture moisture	1 = Dry
	2 = Damp and well drained
	3 = Wet
	4 = Boggy
Pasture quality	1 = Lush
	2 = Average
	3 = Rough
Sward height (cm)	The mean compressed sward height in each field at sampling
Sward cover	1 = Good coverage
	2 = Patches
	3 = Heavily poached
Sheep variables	
Age	1 = Lamb
	2 = Yearling
	3 = Adult
Body condition score	1 = Very thin
	2 = Lean
	3 = Average
	4 = Fat
	5 = Obese
Perineal cleanliness	0 = Clean
	1 = Mild staining
	2 = Dirty
	3 = Large dags
	0 = Clean
	1 = Some dirt present
Foot lesions	
Other digit with active CODD	0 = No other digit in same sheep with active CODD
	1 = 1 or more digits in same sheep with active CODD
Other digit with healed CODD	0 = No other digit in same sheep with healed CODD
	1 = 1 or more digits in same sheep with healed CODD
Co-infection with FR in same foot	0 = No co-infection with FR in same foot
	1 = Co-infection with FR in same foot
Other digit with FR	0 = No other digit in same sheep with FR
	1 = 1 or more digits in same sheep with FR
Co-infection with ID in same foot	0 = No co-infection with ID in same foot
	1 = Co-infection with ID in same foot
Other digit with ID	0 = No other digit in same sheep with ID
	1 = 1 or more digits in same sheep with ID
Other digit with WL	0 = No other digit in same sheep with WL
	1 = 1 or more digits in same sheep with WL
Other digit with FA	0 = No other digit in same sheep with FA
	1 = 1 or more digits in same sheep with FA
Other digit with GR	0 = No other digit in same sheep with GR
	1 = 1 or more digits in same sheep with GR
Other digit with IH	0 = No other digit in same sheep with IH
	1 = 1 or more digits in same sheep with IH
Other digit with IN	0 = No other digit in same sheep with IN
	1 = 1 or more digits in same sheep with IN
Other digit with OG	0 = No other digit in same sheep with OG
	1 = 1 or more digits in same sheep with OG
Other digit with any other foot disease	0 = No other digit in same sheep with any other foot disease
	1 = 1 or more digits in same sheep with any other foot disease

$X_4 = \text{sine}(4\pi t/365.25)$ where t = day with day 1 being the first sample date. These were forced into all the models as a composite (harmonic regression (Stolwijk et al., 1999)) together with the interaction with year. All four covariates were included to allow the modelling of annual and six-monthly variation within the study period.

Seasonal changes in the prevalence of CODD were described graphically by obtaining the logit prediction of a foot having active CODD estimated from the regression models, using the time covariates with year included as an interaction term as the sole explanatory variables, and then calculating the inverse logit i.e. the prevalence. Confidence intervals were not presented due to there being only one farm visited on each day.

3) Lameness as an outcome

Due to the sampling strategy (described above) the data could be examined as a case control study with lame sheep as cases, and non-lame sheep as randomly selected controls.

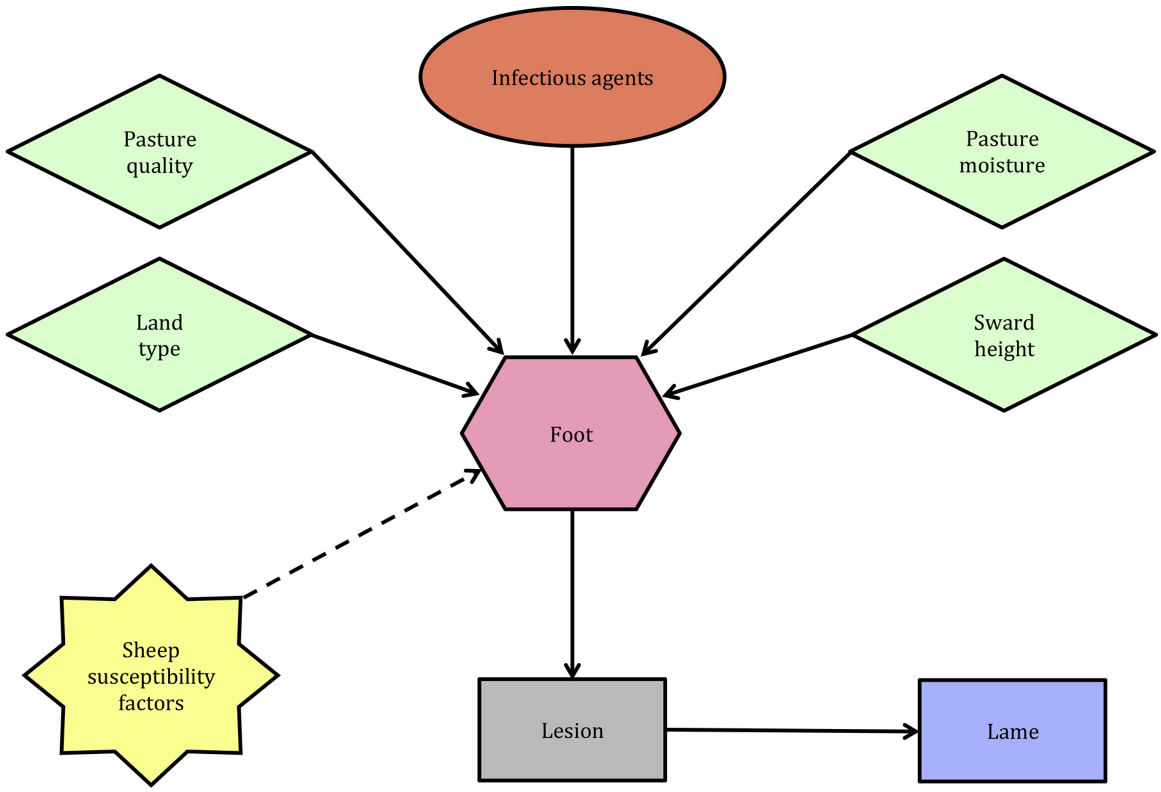

Fig. 1. A theoretical causal diagram for lameness in sheep. Field level variables (green triangles) affect the foot (pink hexagon) to increase the susceptibility to infectious agents (red oval). The 'sheep susceptibility factors' (yellow star) represent unmeasured and unquantified determinants that make a sheep more susceptible to developing a foot lesion, be they genetic, nutritional or other factors. These host-pathogen-environment interactions lead to the development of a lesion (grey rectangle), which may cause pain and the behaviours observed as lameness (blue rectangle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.5.5. Statistical analysis

Descriptive statistics were estimated at sheep level, together with univariable logistic regression analyses where appropriate. The t-test was used to compare the mean locomotion score of sheep with different combinations of different infectious foot lesions.

With regards to the presence of CODD, for all those sheep with just one foot affected (which was the majority with that lesion) the probability of lameness at sheep level was modelled by CODD grade, and marginal means were used to represent this graphically. Multivariable analyses were not attempted with lameness as an outcome, as following the construction of a theoretical causal diagram (Fig. 1) it is clear that lameness – a behaviour associated with the perception of pain when moving – is most commonly due to the presence of a foot lesion. Other factors operate at a level above – at sheep level, and in order to model lameness at foot level it would be necessary to know which leg specifically the sheep was lame on.

Table 3
Farm attributes of the six study farms in North Wales, as reported for June 2012.

Farm	Land type	Total size (Hectares)	Total number of breeding ewes (LU*)	Total number of cattle (LU*)	Stocking density (SD): number of livestock units per hectare	Breeds
1	Hill	186.2	740 (44.4)	30 (19.5)	Total LU = 63.9 SD: 0.34 LU/Ha	Welsh Mountain (99.4%) Other breeds (0.6%)
2	Lowland	360.2	500 (50.0)	50 (32.5)	Total LU = 82.5 SD: 0.23 LU/Ha	Scottish Blackface (21.4%) Mule (43.7%) Suffolk/Suffolk Cross (20.7%) Other breeds/ crossbreeds (14.2%)
3	Lowland/Upland	111.3	870 (87.5)	150 (97.5)	Total LU = 185.0 SD: 1.66 LU/Ha	Lleyn/Lleyn Cross (31.3%) Easy Care/Easy Care Cross (63.2%) Other Lowland Crossbreeds (5.5%)
4	Lowland	72.8	300 (33.0)	120 (78.0)	Total LU = 111.0	Mule (70.5%)char_dotchar_ Charolais Cross (20.5) Other Lowland Crossbreeds (9.0%)
5	Lowland/Upland	68.8	460 (50.6)	240 (156.0)	Total LU = 206.6	Suffolk Cross (43.4%)char_dotchar_ Mule (34.8%) Texel Cross (18.7%) Other Lowland Crossbreeds (3.1%)
6	Upland	97.1	400 (32.0)	0 (0.0)	Total LU = 33.8	Lleyn/Lleyn Cross (85.1%)char_dotchar_ Mule (10.7%) Other Lowland Crossbreeds (4.2%)

* Livestock units (LU): Lowland ewes 0.11, Upland ewes 0.08, Hill ewes 0.06, Cattle 0.65 (DEFRA, 2010).

For some animals e.g., those observed to be locomotion score 1, this was not possible and as such the data were therefore not available for this type of analysis.

2.5.6. Time

Seasonal changes for the probability of a sheep being lame were described by plotting the logit prediction of a sheep being lame from a regression model, using the time covariates with year included as an interaction term.

3. Results

3.1. Study population

All six farms were commercial sheep farms in North Wales. They ranged in size from 300 to 870 breeding ewes and from 68.8 to 360.2Ha (Table 3).

Visits commenced on 14th June 2012 and were completed on 3rd October 2013. Five out of the six farms remained in the study for the full six visits; one dropped out after three visits due to farmer time constraints. In total, therefore 32 visits were made with 22,724 sheep presented for inspection of which 6515 sheep were examined from all six farms giving a sampling proportion of 28.7%.

Of the 6515 examined sheep, 1447 (22.2%; 95% CI: 21.2–23.2%) were lame (locomotion score >0) and 4812 (73.9%; 95% CI: 72.8–74.9%) were not lame (locomotion score 0) giving an approximate ratio of 1:3, lame: not lame; 256 sheep had missing locomotion scoring data (Table 1).

Table 1 details the number of re-sampled sheep per visit. The proportions of those re-sampled that were lame, not-lame and had active CODD were approximately similar at each visit.

1) Prevalence

Due to the nature of the study, incidence could not be estimated, although obviously incidence will impact on prevalence. The mean estimated prevalence of lameness (locomotion score >0), over all 32 visits and all six farms, was 6.7% (95% CI: 5.0–8.4%). For the following lesions the on farm sheep prevalence was estimated: CODD 5.1% (95% CI: 3.3–6.8), FR 5.0% (95% CI: 3.2–6.8%), ID 13.3% (95% CI: 7.0–19.6%), WL 36.7% (95% CI: 28.7–44.7%), FA 1.9% (95% CI: 1.3–2.4%), OG 15.4% (95% CI: 9.2–21.6%), GR 0.4% (95% CI: 0.2–0.6%), IH 1.0% (95% CI: 0.3–1.7%), IN 0.2% (95% CI: 0.0–0.4%) and JI 0.1% (95% CI: 0.0–0.3%). The prevalence of CODD varied by farm and by visit (Fig. 2).

3.2. Distribution of lesions

The distribution of lesions varied significantly ($P \leq 0.001$) by age for CODD, FR, ID, GR, WL, FA, IH and OG (Table 4). The proportion of lesions in front and back feet varied significantly ($P < 0.001$) for CODD, FR, ID, WL, IH, IN and OG (Table 5). The lesions CODD, ID, IH, JI and IN were observed more in back feet and FR, WL and OG were observed more in the front feet. Granulomas and FA were found equally between the front and back feet.

2) CODD as an outcome

3.3. Descriptive statistics for CODD

Of the 6515 sheep examined, 1047 had CODD (16.1% [95% CI: 15.2–16.9]), of which 733 had an active lesion (11.3% [95% CI: 10.5–12.0]). Of the 26,060 feet examined there were in total 1143 feet with CODD (4.4% [95% CI: 4.1–4.6%]), of which 775 feet had an active CODD lesion (3.0% [95% CI: 2.8–3.2%]). The proportion of feet with CODD lesions varied by grade (Fig. 3).

For sheep over one year of age: 78 individuals were found to have active CODD in a foot at one visit and were also found to have active CODD in another foot on at least one other subsequent visit; 17 individuals were found to have healed CODD in a foot at one visit and then active CODD in another foot at a subsequent visit. No individual sheep was found to have active CODD in the same foot on two consecutive occasions. No sheep had active CODD in a foot previously classified as healed CODD.

3.4. Univariable analysis

The presence of active CODD at foot level varied significantly by farm flock size, farm land type, flock size at each visit, pasture moisture, pasture quality, pasture coverage and year (Table 6). No association was found for stocking density at each visit, sward height and perineal cleanliness.

3.5. Multivariable analysis

The final multivariable logistic regression model with robust standard errors, for the presence of active CODD at foot level ($n = 23{,}776$ feet; 5944 sheep from six farms) showed significant associations with farm identity, pasture coverage, FR, the absence of co-infection with ID, the absence of WL in the other feet of a sheep with CODD and time - including interaction with year (Table 7). Interactions considered but not retained included flock size interacting with land type.

3.6. Time

The prevalence of feet with an active CODD lesion, across all six farms over time was predicted from a model containing the four time covariates with year included as an interaction term (Fig. 4). This showed significant variation in the prevalence of CODD over the six farms over time. In 2012 a significant increase in prevalence was observed in late summer/early autumn. In 2013 an increase in prevalence was observed in spring and early summer, and it appears that a further increase in prevalence may also have occurred in late summer/early autumn in 2013, prior to the termination of the study.

3) Lameness as an outcome

3.7. Descriptive statistics for lameness

Of the 1047 sheep with CODD, 664 (63.4% [62.0–64.9]) were recorded as being lame (locomotion score >0).

The mean locomotion score for sheep with active CODD was 1.7 (95% CI: 1.7–1.8) (Fig. 5). This was significantly greater ($P < 0.001$) than that for sheep with FR: mean locomotion score 0.9 (95% CI: 0.8–1.0) or ID: mean locomotion score 0.5 (95% CI: 0.4–0.5). There was no significant difference in mean locomotion score between sheep with active CODD only and those with concurrent infection with CODD and ID: mean locomotion score 1.7 (95% CI: 1.5–1.9) ($P = 0.8$), or between those with active CODD only and those with concurrent infection with CODD and FR: mean locomotion score 2.0 (95% CI 1.8–2.2) ($P = 0.07$).

3.8. Univariable analyses

Lowland land, increased pasture moisture, rough pasture, a longer sward and age (lambs and adults, compared to yearlings) were all positively associated with an increased probability of a sheep being lame (Table 8). Of the foot lesions: CODD, FR, ID,

Please cite this article in press as: Angell, J.W., et al., Sheep and farm level factors associated with contagious ovine digital dermatitis: A longitudinal repeated cross-sectional study of sheep on six farms. PREVET (2015), http://dx.doi.org/10.1016/j.prevetmed.2015.09.016

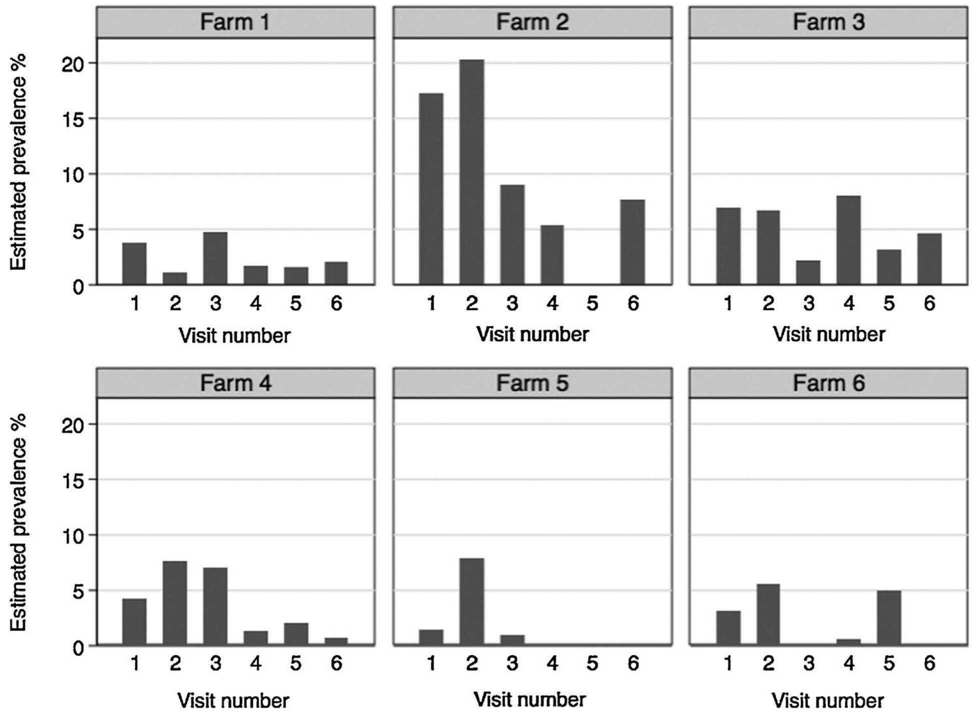

Fig. 2. Estimated prevalence of active CODD by farm determined at each visit.
N.B. For Farm 2 visit 5, and Farm 6 visits 3 and 6, some of the data were missing preventing accurate prevalence estimates. For Farm 5 visits 4–6, all data were missing for these visits due to the termination of the study on that farm.

Table 4
Foot lesions in sheep stratified by age. The percentages (95%CI) refer to the number of sheep in the age group with a given lesion; from the 6515 sheep examined.

Disease	Total number of sheep with disease	Lamb (<1 year)			Yearling (1 year)			Adult (≥2years)			*P*-value*
		n	%	(95% CI)	*n*	%	(95% CI)	*n*	%	(95% CI)	
CODD (active)	733	174	23.8	(20.8–28.0)	81	11.1	(9.0–13.6)	477	65.2	(61.6–68.5)	<0.001
Footrot	526	200	38.0	(34.0–42.3)	39	7.4	(5.5–10.0)	287	54.6	(50.3–58.8)	<0.001
Interdigital dermatitis	851	371	43.6	(40.3–47.0)	82	9.6	(7.8–11.8)	398	46.8	(43.4–50.1)	<0.001
White line	2,179	187	8.6	(7.5–9.8)	393	18.0	(16.5–19.7)	1599	73.3	(71.5–75.2)	<0.001
Foot abscess	164	16	9.8	(6.0–15.4)	18	11.0	(7.0–16.8)	130	79.3	(72.3–84.8)	<0.001
Granuloma	36	1	2.8	(0.4–18.7)	2	5.6	(1.3–20.8)	33	91.7	(76.1–97.4)	0.001
Interdigital hyperplasia	54	1	1.9	(0.02–12.7)	2	3.7	(0.09–14.2)	51	94.4	(83.6–98.3)	<0.001
Joint infection	14	5	35.7	(13.7–66.0)	2	14.3	(2.9–48.0)	7	50.0	(23.2–76.8)	0.512
Injury	19	6	31.6	(13.7–57.3)	1	5.3	(0.06–33.8)	12	63.2	(38.0–82.7)	0.361
Overgrown	894	65	7.3	(5.7–9.2)	126	14.1	(12.0–16.5)	703	78.6	(75.8–81.2)	<0.001
Total number of sheep in each age group		1,484			1,044			3,979			

* Chi-squared test.

Table 5
Lesion distribution by front and back feet in affected sheep, from the 6515 sheep examined.

Disease	Total number of sheep with disease	Sheep with disease in FRONT feet			Sheep with disease in BACK feet			Sheep with disease in BOTH FRONT and BACK feet concurrently			*P* value*
		n	%	(95% CI)	*n*	%	(95% CI)	*n*	%	(95% CI)	
CODD (all grades)	1047	469	44.8	(41.8–47.8)	636	60.7	(57.8–63.7)	58	5.5	(4.3–7.1)	<0.001
CODD (active)	733	311	42.4	(38.9–46.0)	0468	63.8	(60.3–67.3)	46	6.3	(4.7–8.3)	<0.001
Footrot	526	354	67.3	(63.3–71.3)	248	47.1	(42.9–51.4)	76	14.4	(11.4–17.5)	<0.001
Interdigital dermatitis	851	432	50.8	(47.4–54.1)	652	76.6	(73.8–79.5)	233	27.4	(24.4–30.4)	<0.001
White line	2180	1641	75.3	(73.5–77.1)	1315	60.3	(58.3–62.4)	776	35.6	(33.6–37.6)	<0.001
Foot abscess	164	88	53.7	(45.9–61.4)	78	47.6	(39.8–55.3)	2	1.2	(0.00–2.9)	0.269
Granuloma	36	18	50.0	(32.8–67.2)	18	50.0	(32.8–67.2)	0	–	–	1.0
Interdigital hyperplasia	54	9	16.7	(6.4–26.9)	49	90.7	(82.8–98.7)	4	7.4	(0.2–14.6)	<0.001
Joint infection	14	4	28.6	(1.5–55.6)	10	71.4	(44.4–98.5)	0	–	–	0.023
Injury	19	5	26.3	(4.5–48.1)	14	73.7	(51.9–95.5)	0	–	–	0.004
Overgrown	894	667	74.6	(71.7–77.5)	457	51.1	(47.8–54.4)	230	25.7	(22.9–28.6)	<0.001

* *Z*-test of proportions comparing the proportion of front feet affected with the proportion of back feet affected.

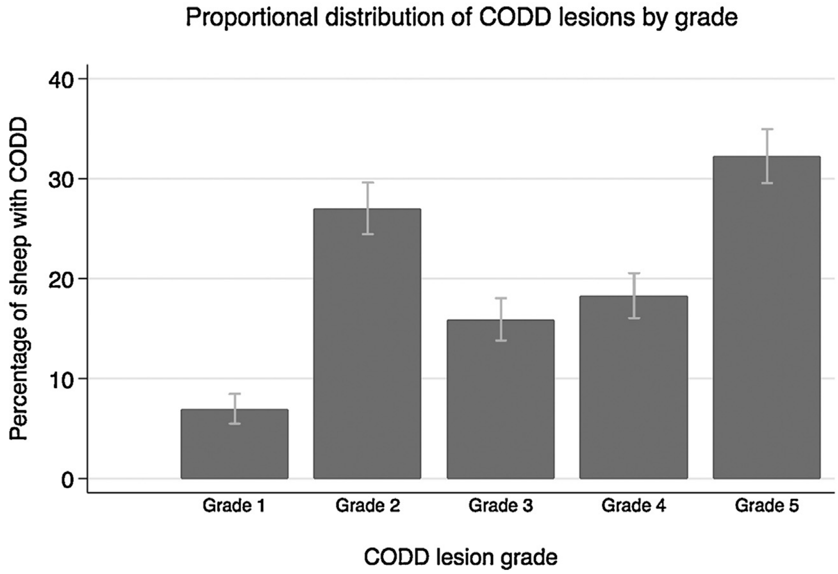

Fig. 3. The proportion of CODD lesions of each grade, from 1143 feet with CODD lesions. The capped spikes represent the 95% confidence intervals for each proportion.

GR, FA and IN were all positively associated with being lame and WL and OG were negatively associated with being lame. Active CODD was very strongly associated with lameness (OR 29.4, 95% CI: 23.8–36.3), and lesion grade was also significant with those sheep with lesions graded 2 or 3 most strongly associated with lameness (Table 8 and Fig. 6). Sheep with more than one foot affected with CODD (OR 25.0, 95% CI: 12.5–49.9) were much more likely to be lame than sheep with just one foot affected (OR 10,0, 95% CI: 8.6–11.6). There was no association with flock size, BCS, perineal cleanliness, IH and JI.

3.9. Time

Lameness improved markedly over the course of the study, 2013 OR 0.3 (95% CI: 0.2–0.5). There were seasonal peaks in late summer/early autumn in both 2012 and 2013 (Fig. 7), although the peak in 2013 is much smaller than that in 2012.

4. Discussion

4.1. Study limitations

The sampling strategy of sampling all lame sheep but only a proportion of non-lame sheep was designed in order to identify the greatest number of sheep and feet with CODD at each visit within the practical constraints of the study. As such, given the dynamic changes within sheep flocks throughout the year this cross-sectional sampling strategy enabled sheep with and without CODD to be examined, whilst allowing for population changes within each flock. As such, at each visit there were a proportion of sheep re-sampled from previous visits and also a proportion examined that were not sampled previously, either due to the individual being a new entrant to the flock or simply for having not been sampled (Table 1). To account for seasonal variations over time harmonic regression was used. Probability weights were employed in

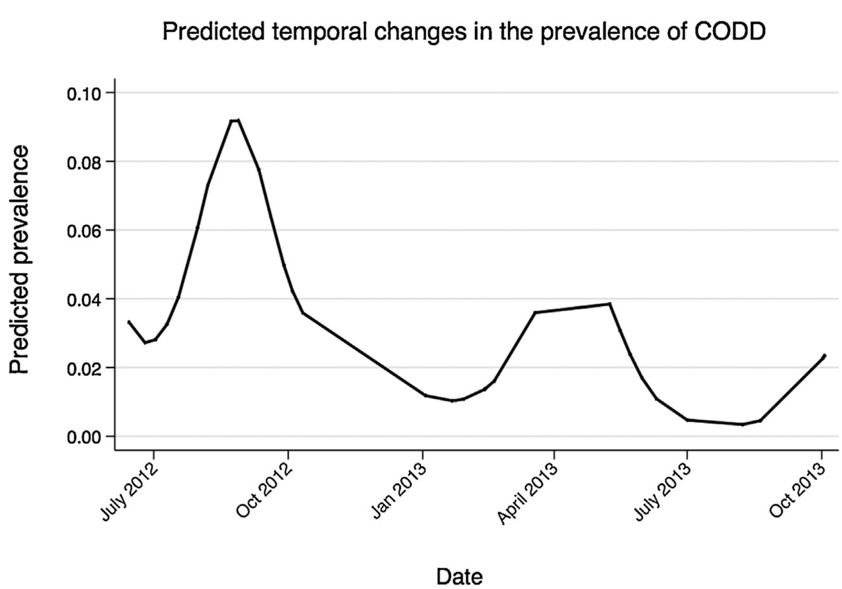

Fig. 4. Predicted temporal changes in the prevalence of CODD.

Table 6
Univariable analyses of the associations between covariates and active CODD at foot level.

	N with CODD	% with CODD	Odds Ratio	95% CI	*P* value
Farm and environment					
Farm flock size (*n* = 26,060)					
300 (*n* = 4,856)	150	3.1	(Baseline odds = 0.003)		
400 (*n* = 2,960)	50	1.7	1.4	0.5–3.4	0.5
460 (*n* = 1,968)	39	2.0	1.1	0.5–2.8	0.8
500 (*n* = 4,696)	234	5.0	6.1	2.9–12.7	<0.001
740 (*n* = 6,304)	62	1.0	1.2	0.5–2.8	0.7
870 (*n* = 5,276)	240	4.6	3.6	1.7–7.7	0.001
Farm land type (*n* = 26,060)					
Hill (*n* = 6,304)	62	1.0	(Baseline odds = 0.003)		
Upland/lowland mixed (*n* = 10,204)	329	3.2	1.9	1.1–3.3	0.024
Lowland (*n* = 9,552)	384	4.0	1.4	0.8–2.7	0.248
Flock size at visit (number of sheep) (*n* = 25,332)					
210-390 (*n* = 5,236)	60	1.2	(Baseline odds = 0.002)		
396-600 (*n* = 6,296)	172	2.7	2.1	0.8–5.2	0.119
655-711 (*n* = 3,696)	82	2.2	3.3	1.3–8.5	0.014
738-1227 (*n* = 5,564)	222	4.0	5.1	2.1–12.2	<0.001
1405-1821 (*n* = 4,540)	209	4.6	5.0	2.0–12.2	<0.001
Pasture moisture (*n* = 25,932)					
Dry (*n* = 3,392)	35	1.0	(Baseline odds = 0.003)		
Wet (*n* = 22,540)	736	3.3	2.2	1.3–4.0	0.006
Pasture quality (*n* = 24,332)					
Lush (*n* = 2,568)	143	5.6	(Baseline odds = 0.002)		
Average (*n* = 11,932)	359	3.0	3.5	2.4–5.2	<0.001
Rough (*n* = 9,832)	241	2.5	2.5	1.7–3.7	<0.001
Pasture coverage (*n* = 24,332)					
Good coverage (*n* = 16,988)	516	3.0	(Baseline odds = 0.004)		
Patches (*n* = 6,212)	189	3.0	1.7	1.1–2.6	0.021
Heavily poached (*n* = 1,132)	38	3.4	6.9	3.7–12.8	<0.001
Time					
Year (*n* = 26,060)					
2012 (*n* = 9,496)	470	5.0	(Baseline odds = 0.01)		
2013 (*n* = 16,564)	305	1.8	0.3	0.2–0.5	<0.001
Sheep variables					
Body condition score (*n* = 25,148)					
1 (*n* = 2,720)	117	4.3	(Baseline odds = 0.008)		
2 (*n* = 11,512)	346	3.0	0.8	0.5–1.3	0.4
3 (*n* = 9,628)	269	2.8	0.5	0.3–0.8	0.005
4 (*n* = 1,272)	28	2.2	0.5	0.2–1.1	0.07
5 (*n* = 16)	0	0	–	–	–
Age (*n* = 26,028)					
Lamb (*n* = 5,936)	190	3.2	(Baseline odds = 0.008)		
Yearling (*n* = 4,176)	84	2.0	0.7	0.3–1.5	0.4
Adult (*n* = 15,916)	500	3.1	0.6	0.4–0.8	0.005
Foot variables					
CODD (*n* = 26,060)					
No other feet in the sheep with active CODD (*n* = 23,832)	695	2.9	(Baseline odds = 0.005)		
Other feet in the sheep with active CODD (*n* = 2,228)	80	3.6	3.9	2.3–6.7	<0.001
Footrot (*n* = 26,060)					
No footrot in the same foot (*n* = 25,333)	689	2.7	(Baseline odds = 0.005)		
Footrot present in the same foot (*n* = 727)	86	11.8	7.3	3.9–13.7	<0.001
No other feet in the sheep with footrot (*n* = 24,335)	715	2.9	(Baseline odds = 0.005)		
Other feet in the sheep with footrot (*n* = 1,725)	60	3.5	2.7	1.4–5.3	0.003
Scald (*n* = 26,060)					
No scald in the same foot (*n* = 24,623)	770	3.1	(Baseline odds = 0.005)		
Scald present in the same foot (*n* = 1,437)	5	0.4	0.1	0.03–0.2	<0.001
White line (WL) lesion (*n* = 26,060)					
No other feet in the sheep with WL (*n* = 18,362)	592	3.2	(Baseline odds = 0.006)		
Other feet in the sheep with WL (*n* = 7,698)	183	2.4	0.5	0.3-0.8	0.001
Foot abscess (*n* = 26,060)					
No other feet in the sheep with FA (*n* = 25,564)	764	3.0	(Baseline odds = 0.005)		
Other feet in the sheep with FA (*n* = 496)	11	2.2	3.5	1.0–12.3	0.047

order to account for the non-random sampling strategy but still obtain meaningful estimates of prevalence and risk factor impact. It would have been preferable to physically examine every sheep on the farm at each visit, but practically this was not possible. As a consequence, all prevalence values are estimates based on the observed data.

The results are clearly impacted by the particular study farms chosen. Due to financial and time constraints only six farms could be studied. Consequently in all the models, farm and environmental factors may be strongly influenced by the individual farms – as shown by the model in Table 7 - and as such these data should be interpreted cautiously. For example the farm land-type asso-

Table 7
Multivariable logistic regression model with robust standard errors, including covariates associated with the probability of diagnosing active CODD at foot level. In this final model $n = 23,776$ feet (5944 sheep, of which 3591 had been examined more than once (see Table 1)).

	Odds ratio	95% CI	*P* value
Farm and environment			
Farm 1	1.2	0.5–2.7	0.7
Farm 2	4.7	2.5–8.8	<0.001
Farm 3	4.4	2.2–8.8	<0.001
Farm 4 (Baseline)			
Farm 5	1.5	0.6–3.9	0.4
Farm 6	2.6	1.2–5.9	0.02
Pasture coverage (patches or heavily poached)	2.3	1.5–3.5	<0.001
Foot variables			
Co-infection with footrot in same foot	7.7	3.9–15.5	<0.001
Co-infection with interdigital dermatitis in same foot	0.04	0.02–0.1	<0.001
Other feet in the sheep with WL	0.5	0.3–0.9	0.01
Time			
Year 2013	$2.5e^{-6}$	$1.4e^{-11}$–0.5	0.04
X1	$1.2e^{5}$	0.2–$6.7e^{10}$	0.09
Year × X1	$1.5e^{-5}$	$3.0e^{-11}$–8.0	0.1
X2	$1.4e^{5}$	1.5–$1.3e^{10}$	0.04
Year × X2	$3.6e^{-6}$	$3.8e^{-11}$–0.3	0.03
X3	0.7	0.2–2.9	0.6
Year × X3	2.0	0.4–10.2	0.4
X4	$2.6e^{2}$	0.9–$7.1e^{4}$	0.05
Year × X4	$1.3e^{-3}$	$3.1e^{-6}$–0.5	0.03
Baseline odds (Farm 4, good coverage, no footrot no interdigital dermatitis and no other feet in the sheep with WL)	$2.4e^{2}$	$1.6e^{-3}$–$3.6e^{7}$	

ciations seen for both CODD and lameness could be simply a farm effect rather than a true association. Whilst this is an obvious weakness, the study is strengthened by the wide range of farms - in terms of farm type, location, breed, mixture of farm enterprises and production targets - and as such provide a reasonable cross-section of current UK sheep farming. Furthermore, the small sample size enabled a much more detailed examination of a large number of sheep feet over a prolonged time frame compared with other study designs, and allowed for the specific analysis of sheep and foot factors.

A further limitation is the impact of the observer effect. To ensure that the welfare of the sheep was not compromised, sheep with foot lesions at examination were treated as per the farmer's normal routine. The reduction in lameness and CODD on all the farms over the study period may be due to this effect. In light of this the seasonal changes reported in this paper should be interpreted cautiously due to this possible observer effect.

1) Prevalence

Due to the nature of the study design, prevalence and not incidence is estimated, although prevalence will be impacted by the incidence rate. Contagious ovine digital dermatitis is widespread with reported between farm prevalence estimates of between 13% and 53% (Wassink et al., 2003; Kaler and Green, 2008; Angell et al., 2014). The present study shows wide variation between farms

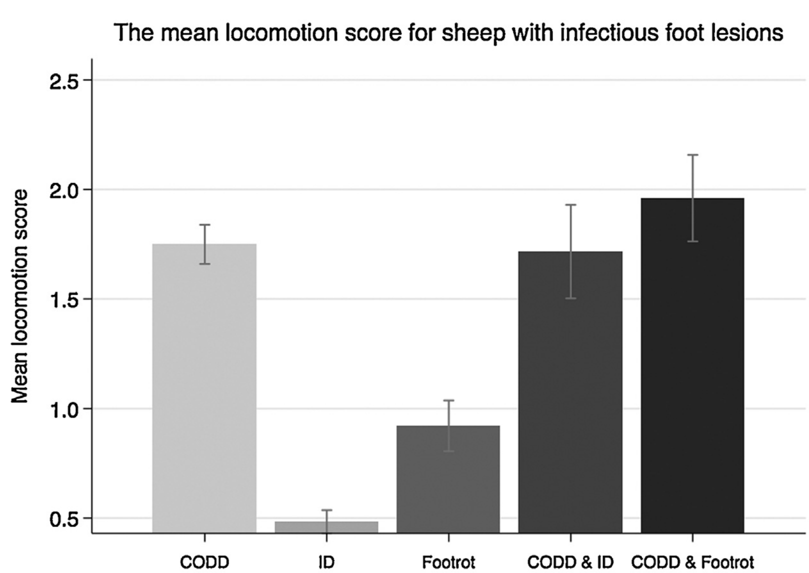

Fig. 5. The mean locomotion score for sheep with infectious foot lesions, from the 6515 sheep examined. The capped spikes represent the 95% confidence intervals for each mean value. Cases of CODD in this figure are all active CODD (grades 1–4).

Table 8
Univariable analyses of the associations between covariates and a sheep being lame.

	N examined sheep lame	% examined sheep lame	Odds ratio	95% CI	*P* value
Farm and environment					
Land type (Hill as baseline) (*n* = 6,259)	1,447	23.1	1.3	1.2–1.4	<0.001
Pasture moisture (*n* = 6,228)	1,382	24.8	3.6	2.7–4.7	<0.001
Pasture quality					
Lush (*n* = 2,271)	456	20.1	(Baseline odds = 0.25)		
Average (*n* = 2,920)	742	25.4	1.4	1.2–1.5	<0.001
Rough (*n* = 637)	194	30.5	1.7	1.4–2.1	<0.001
Sward height (cm) (4351)	1,085	24.9	1.2	1.1–1.2	<0.001
Sheep variables					
Age (*n* = 6,256)					
Lamb (*n* = 1,480)	401	27.1	1.8	1.5–2.2	<0.001
Yearling (*n* = 1,011)	174	17.2	(Baseline odds = 0.21)		
Adult (*n* = 3,765)	871	23.1	1.4	1.2–1.7	<0.001
Foot variables					
CODD all grades(*n* = 1,026)	664	64.7	10.4	9.0–12.1	<0.001
CODD active (*n* = 729)	612	84.0	29.4	23.8–36.3	<0.001
CODD grade					
Grade 1 (*n* = 68)	52	76.5	18.5	10.5–32.5	<0.001
Grade 2 (*n* = 270)	248	91.9	64.1	41.2–99.7	<0.001
Grade 3 (*n* = 163)	152	93.3	78.5	42.4–145.5	<0.001
Grade 4 (*n* = 174)	116	66.7	11.4	8.2–15.7	<0.001
Grade 5 (*n* = 297)	52	17.5	1.2	0.9–1.6	0.234
CODD in more than one foot (6259)					
No CODD (*n* = 5,233)	783	15.0	(Baseline odds = 0.18)		
1 foot affected (*n* = 972)	620	63.8	10.0	8.6–11.6	<0.001
2–4 feet affected (*n* = 54)	44	81.5	25.0	12.5–49.9	<0.001
Footrot (*n* = 516)	323	62.6	6.9	5.7–8.3	<0.001
Scald (*n* = 835)	343	41.1	2.7	2.3–3.2	<0.001
White line lesion (*n* = 2,046)	439	21.5	0.9	0.8–0.99	0.030
Overgrown (*n* = 863)	169	19.6	0.8	0.7–0.9	0.008
Granuloma (*n*36)	23	63.9	6.0	3.0–11.8	<0.001
Foot abscess (*n* = 164)	98	59.8	5.2	3.8–7.2	<0.001
Injury (*n* = 18)	9	50.0	3.3	1.3–8.4	0.011

(mean prevalence: 2.5–11.9%) and within a farm over the year (e.g., for farm 2 range: 5.3–20.3%). Currently in the UK, national prevalence figures are used to describe levels of disease on farms and to provide targets for disease control (FAWC, 2011). These findings have implications for this approach to describe disease levels, in that point prevalence refers to one point in time, and prevalence can vary widely over a year. This begs the question—what is meant by "farm prevalence". For example, farm 2 (Fig. 2) demonstrated a wide range in disease point prevalence estimates. At one observation, prevalence may be at or below a particular target and at another outside it, and in using either figure independently, neither represents the true disease status of that flock – except at that

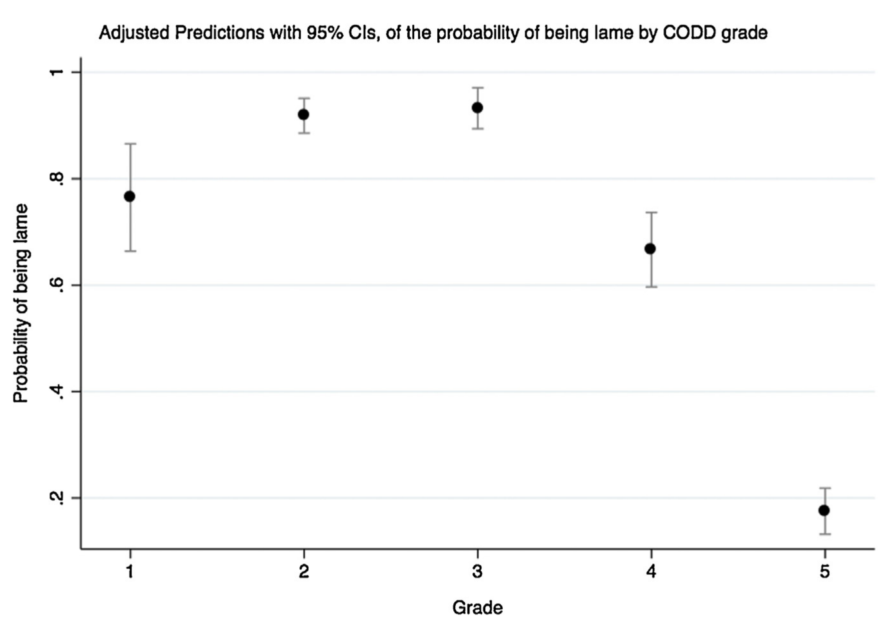

Fig. 6. The adjusted marginal mean probability of being lame by CODD grade. The capped spikes represent the 95% confidence intervals for each probability.

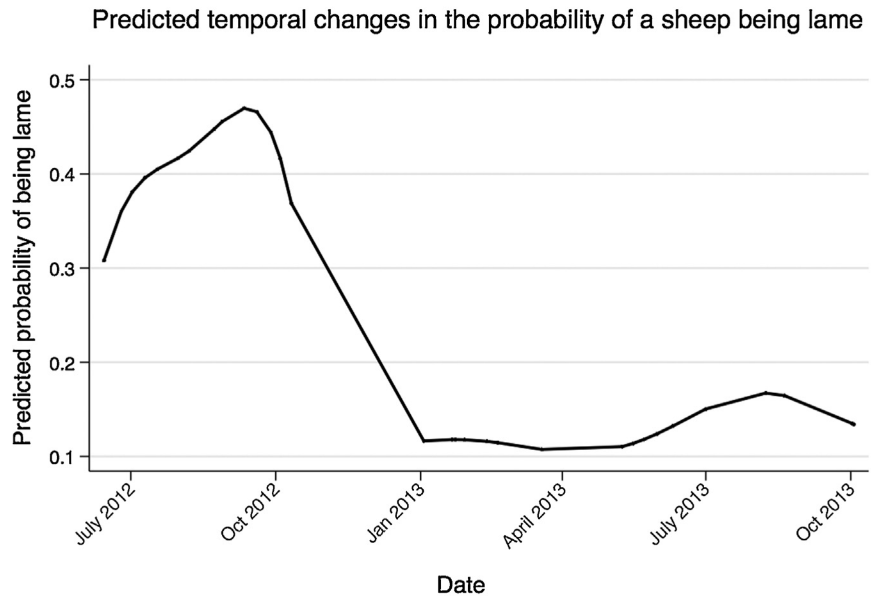

Fig. 7. Predicted temporal changes in the probability of a sheep being lame.

point in time. Consequently, it is necessary for more meaningful measures to be developed in order to achieve reliable targets that may be used to reduce lameness in the national flock. In reality, only repeat surveys on farms over a minimum of 12 months with samples taken in different seasons would allow an accurate description of lameness on a farm.

4.2. Distribution of lesions

The distribution of lesions between the front and back feet varied for different lesions. In this study CODD was more prevalent in back feet compared with front feet, in agreement with Duncan et al. (2011); Duncan et al. (2012). In cattle hind foot lesions predominate, with the causes well documented (Read and Walker, 1998; Sogstad et al., 2005). However, the reason for this distribution in sheep is less obvious. Furthermore, the reverse distribution was found for FR, with front feet affected more, in contrast to Duncan et al. (2012). The biological significance of these observations is uncertain.

4.3. Age

In this study, yearling sheep showed fewest lesions from infectious foot conditions (CODD, FR and ID). This could be a reflection on the management practices on sheep farms. Yearling sheep tend to be replacement breeding ewes to replace those culled out of a flock, and it is likely that farmers will select ewe lambs that show no evidence of having been lame. These sheep also tend to be managed separately until first parturition, which may reduce the risk of becoming infected from the rest of the flock.

Both CODD and FR were found more in adult sheep than lambs, and this may reflect the more chronic nature of these diseases. However, ID was found to be evenly distributed between lambs and ewes, adding weight to theories whereby ewes and lambs may be considered to be potential sources of infection for each other (Kaler et al., 2010). This has implications for control in that reducing disease in one group may help reduce the risk of infection in the other.

2) CODD as an outcome

Grade 1 CODD lesions were significantly under represented compared to other grades. This may be for a number of reasons: Firstly these lesions being less severe may result in lower locomotion scores hindering detection (Table 8). Secondly these lesions may be short-lived progressing to grade 2 lesions rapidly. This highlights the need for intensive longitudinal studies of individuals with natural infections of CODD in order to determine the time frames for lesion progression.

In this study individual sheep were observed to have active CODD more than once. However, we did not observe any re-infection or recrudescence at foot level. In cattle there is poor humoral immunity to *Treponema* spp. (Walker et al., 1997; Demirkan et al., 1999; Refaai et al., 2013) and the same is suspected in sheep (Dhawi et al., 2005). However, these data suggest that in sheep there may be adequate cellular immunity at foot level. Histopathology of affected feet may demonstrate cellular evidence to help understand this further.

4.4. Factors associated with CODD

In this study the biggest single factor associated with CODD in sheep was co-infection with FR (OR: 7.7 [95% CI: 3.8–15.5]). This corroborates findings by Duncan et al. (2012) who also found a strong association (OR: 3.83 [95% CI: 2.61–5.62]) between FR and CODD. It is not known whether there is a synergism between the two diseases, whether *D. nodosus* is required in the aetiology of CODD or whether the same environmental conditions lead to an increased susceptibility for both diseases. There is a need for controlled experimental studies to investigate this.

In this study, sheep were more likely to have CODD if they were part of larger flocks, on lowland pasture, lush pasture or poached pasture and despite the small sample size it is biologically plausible that all these factors may play a causal role in increasing the probability of sheep acquiring CODD. Increasing flock size has been associated with CODD in a previous study (Angell et al., 2014) and it is plausible that with larger flocks the ability to identify and manage individuals with disease may be impaired.

It is also feasible that those environmental conditions that favour FR may also favour CODD. Stewart (1989) reported that predisposing factors for FR included lush pasture and moisture, both of which maximise grass production, allowing higher stocking densities thereby favouring transmission. In this study, increased stocking densities *per se* were not associated with CODD however

Please cite this article in press as: Angell, J.W., et al., Sheep and farm level factors associated with contagious ovine digital dermatitis: A longitudinal repeated cross-sectional study of sheep on six farms. PREVET (2015), http://dx.doi.org/10.1016/j.prevetmed.2015.09.016

poaching which may be associated with increased stocking densities was associated with CODD.

In this study co-infection with ID was negatively associated with CODD (OR:0.04, 95% CI:0.02–0.1). This is perhaps surprising given the strong associations between FR and ID (Stewart, 1989; Wassink et al., 2003; Green and George, 2008). It is possible that early FR as ID is a predisposing factor for CODD, damaging the skin and allowing access for *Treponema* spp. but by the time CODD is diagnosed the ID lesion may have become obliterated.

Therefore, this study adds weight to the argument that on farm interventions for CODD should include a focus on FR control—for which effective control strategies already exist.

4.5. Seasonal changes in CODD prevalence

In this study an increase in CODD prevalence was noted in late summer/early autumn. This is consistent with numerous anecdotal observations by farmers and veterinary surgeons. One possible explanation is that at this time of year there is the greatest number and mass of sheep on the farm (all the ewes, many of the lambs and the lambs are at their biggest size) resulting in an overall increased stocking density at farm level. It is also consistent with observed seasonal fluctuations seen with FR (Clements and Stoye, 2014) and with observed environmental risk factors for FR such as increased rainfall and warmer temperatures (Green and George, 2008).

A second (smaller) increase in prevalence was observed in the spring, and this is consistent with an increase in infection pressure following housing for lambing, a practice which occurred on five of the six farms. It is also consistent with observed increases in FR prevalence following housing (Whittington, 1995; Clements and Stoye, 2014), and consistent with farmers' perceptions that housing leads to an increase in CODD prevalence (Angell et al., 2014).

3) Lameness as an outcome

In this study CODD, FR and ID were all associated with lameness (Table 8). However, the mean locomotion score for sheep with CODD was much greater than that for sheep with FR or ID (Fig. 5). This suggests that whilst these infectious diseases are all associated with lameness, CODD has the greatest impact on the welfare of individuals, which is in agreement with Phythian et al. (2013) who observed that whilst 59.0% of sheep with FR and 61.5% of sheep with ID were lame, 83.9% of sheep with CODD were lame.

This severe welfare impact is likely to be due to the extensive pathology seen in affected feet (Angell et al., 2015a). This is supported by this present study that shows strong associations between lameness severity and CODD lesion grade. Sheep with partial and complete under-running of the hoof horn (grades 2 and 3) had greater odds of being lame compared to those with grade 1 lesions or healing lesions (grade 4) (Table 8). Furthermore, as expected sheep with more than one foot affected were more likely to be lame than those with just one foot affected.

In this study, the lesions WL and OG were both not associated with lameness. Traditionally these lesions would have been treated using foot paring. These data would therefore support recent opinions suggesting that the paring of feet with these lesions is at best unnecessary (Kaler et al., 2010; Smith et al., 2014). Indeed GR - which are caused by over trimming (Winter, 2004) -whilst at low prevalence on these farms, were strongly associated with lameness (OR: 6.0 [95% CI: 3.0–11.8]).

4.6. Seasonal changes in lameness

The probability of being lame reduced significantly throughout the study. It is likely that due to the farms being studied, the very act of doing so helped reduce the overall burden of disease. In this study two of the farms had large areas of rough extensive grazing such that observation of lame individuals at pasture was on frequent occasions impossible. Furthermore to gather sheep on one of these areas took on average 3–4 h and was only possible in the right weather conditions. To expect farmers to be able to identify lame individuals in these situations, promptly catch them and treat them is highly impractical and unrealistic. An alternative strategy might be planned repeated gathering in order to treat affected individuals, as occurred by default in the present study.

5. Conclusions

Sheep with CODD present a considerable welfare concern, particularly as there remains very little robust evidence for effective treatment and control. Within farm prevalence is variable and there may be seasonal effects that could aid targeted intervention strategies. Furthermore, this study demonstrated that point prevalence is highly inaccurate in determining the overall disease and associated welfare situation on a farm.

Footrot is consistently observed to be significantly associated with CODD although it is unknown if it is an interactive or causal association. Indeed given the 'bacterial soup' in diseased feet it might be more helpful to consider the conditions CODD, FR and ID under the umbrella of 'infectious foot disease' and adopt control and intervention strategies in a microbiologically broader and less individualistic way.

The intervention of studying these commercial farms, had a surprisingly positive impact on the overall lameness of the flocks and as such challenge the accepted advice of the prompt treatment of lame individuals with antibiotic therapy as the 'best' option for all farms. Those farms with more extensive grazing – particularly hill and mountain farms – may benefit from a different approach such as the planned regular gathering of sheep for the purpose of inspection and treatment, an idea that requires further investigation.

Acknowledgements

This study was supported by a grant from the British Veterinary Association Animal Welfare Foundation. The funder had no role in study design; collection, analysis and interpretation of data; in writing the report; or in the decision to submit for publication. We gratefully acknowledge the farmers involved in the study for their compliance in gathering their sheep for the study. Thanks to Leigh Sullivan, Soffi Jones, Lisa Wharton, Kyle Tindall-Reed, Brian Angell, Anna Angell, Victoria-Ann Moxon, Michael Sullivan, Daniel Bell and Erica Swan for their assistance with entering data on farms.

References

Angell, J.W., Blundell, R., Grove-White, D.H., Duncan, J.S., 2015a. Clinical and radiographic features of contagious ovine digital dermatitis and a novel lesion grading system. Vet. Rec. 176, 544–552.
Angell, J.W., Cripps, P.J., Grove-White, D.H., Duncan, J.S., 2015b. A practical tool for locomotion scoring in sheep: reliability when used by veterinary surgeons and sheep farmers. Vet. Rec. 176, 521–523.
Angell, J.W., Duncan, J.S., Carter, S.D., Grove-White, D.H., 2014. Farmer reported prevalence and factors associated with contagious ovine digital dermatitis in Wales: a questionnaire of 511 sheep farmers. Prev. Vet. Med. 113, 132–138.
Clements, R.H., Stoye, S.C., 2014. The 'Five Point Plan': a successful tool for reducing lameness in sheep. Vet. Rec. 175, 225.
DEFRA, 2010. Definition of Terms used in Farm Business Management. In: DEFRA (Ed.), 37.
Demirkan, I., Walker, R.L., Murray, R.D., Blowey, R.W., Carter, S.D., 1999. Serological evidence of spirochaetal infections associated with digital dermatitis in dairy cattle. Vet. J. 157, 69–77.
Dhawi, A., Hart, C.A., Demirkan, I., Davies, I.H., Carter, S.D., 2005. Bovine digital dermatitis and severe virulent ovine foot rot: a common spirochaetal pathogenesis. Vet. J. 169, 232–241.
Duncan, J.S., Angell, J.W., Carter, S.D., Evans, N.J., Sullivan, L.E., Grove-White, D.H., 2014. Contagious ovine digital dermatitis: an emerging disease. Vet. J. 201, 265–268.

Duncan, J.S., Grove-White, D., Moks, E., Carroll, D., Oultram, J.W., Phythian, C.J., Williams, H.W., 2012. Impact of footrot vaccination and antibiotic therapy on footrot and contagious ovine digital dermatitis. Vet. Rec. 170, 462.

Duncan, J.S., Grove-White, D., Oultram, J.W., Phythian, C.J., Dijk, J.V., Carter, S.D., Cripps, P.J., Williams, H.J., 2011. Effects of parenteral amoxicillin on recovery rates and new infection rates for contagious ovine digital dermatitis in sheep. Vet. Rec. 169, 606.

FAWC, 2011. Opinion on Lameness in Sheep. in: Council, F.A.W. (Ed.) http://www.fawc.org.uk, London.

Green, L.E., George, T.R., 2008. Assessment of current knowledge of footrot in sheep with particular reference to *Dichelobacter nodosus* and implications for elimination or control strategies for sheep in Great Britain. Vet. J. 175, 173–180.

Harwood, D.G., Cattell, J.H., Lewis, C.J., Naylor, R., 1997. Virulent footrot in sheep. Veterinary record. Letters 140, 687.

Jenquip, 2004. Filip's Manual Folding Plate Meter, Manufacturer's instructions.

Kaler, J., Green, L.E., 2008. Naming and recognition of six foot lesions of sheep using written and pictorial information: a study of 809 English sheep farmers. Prev. Vet. Med. 83, 52–64.

Kaler, J., Medley, G.F., Grogono-Thomas, R., Wellington, E.M., Calvo-Bado, L.A., Wassink, G.J., King, E.M., Moore, L.J., Russell, C., Green, L.E., 2010. Factors associated with changes of state of foot conformation and lameness in a flock of sheep. Prev. Vet. Med. 97, 237–244.

Long, J.S., 1996. Regression Models for Categorical and Limited Dependent Variables. Sage Thousand Oaks, CA.

Moore, L.J., Woodward, M.J., Grogono-Thomas, R., 2005. The occurrence of treponemes in contagious ovine digital dermatitis and the characterisation of associated *Dichelobacter nodosus*. Vet. Microbiol. 111, 199–209.

Naylor, R.D., Martin, P.K., Jones, J.R., Burnell, M.C., 1998. Isolation of spirochaetes from an incident of severe virulent ovine footrot. Vet. Rec. 143, 690–691.

Phythian, C.J., Cripps, P.C., Grove-White, D., Jones, P.H., Michalopoulou, E., Duncan, J.S., 2013. Observing lame sheep: evaluating test agreement between group-level and individual animal methods of assessment. Anim. Welf. 22, 417–422.

Read, D.H., Walker, R.L., 1998. Papillomatous digital dermatitis (footwarts) in California dairy cattle: clinical and gross pathologic findings. J. Vet. Diagn. Invest. 10, 67–76.

Refaai, W., Ducatelle, R., Geldhof, P., Mihi, B., El-shair, M., Opsomer, G., 2013. Digital dermatitis in cattle is associated with an excessive innate immune response triggered by the keratinocytes. BMC Vet. Res. 9, 193.

Russel, A., 1984. Body condition scoring of sheep. In Practice 6, 91–93.

Smith, E.M., Green, O.D., Calvo-Bado, L.A., Witcomb, L.A., Grogono-Thomas, R., Russell, C.L., Brown, J.C., Medley, G.F., KilBride, A.L., Wellington, E.M., Green, L.E., 2014. Dynamics and impact of footrot and climate on hoof horn length in 50 ewes from one farm over a period of 10 months. Vet. J. 201, 295–301.

Sogstad, A.M., Fjeldaas, T., Osteras, O., 2005. Lameness and claw lesions of the Norwegian red dairy cattle housed in free stalls in relation to environment, parity and stage of lactation. Acta Vet. Scand. 46, 203–217.

Spence, J., Aitchison, G., 1986. Clinical aspects of dental disease in sheep. In Practice 8, 128–135.

Stewart, D.J., 1989. Footrot of sheep. In: Egerton, J.R., Yong, W.K., Riffkin, G.G. (Eds.), Footrot and Foot Abscess of Ruminants. CRC Press, Florida, pp. 5–45.

Stolwijk, A.M., Straatman, H., Zielhuis, G.A., 1999. Studying seasonality by using sine and cosine functions in regression analysis. J. Epidemiol. Community Health 53, 235–238.

Sullivan, L.E., Clegg, S.R., Angell, J.W., Newbrook, K., Blowey, R.W., Carter, S.D., Bell, J., Duncan, J.S., Grove-White, D.H., Murray, R.D., Evans, N.J., 2015. The high association of bovine digital dermatitis *Treponema* spp. with contagious ovine digital dermatitis lesions and the presence of *Fusobacterium necrophorum* and *Dichelobacter nodosus*. J. Clin. Microbiol. 53, 1628–1638.

Walker, R.L., Read, D.H., Loretz, K.J., Hird, D.W., Berry, S.L., 1997. Humoral response of dairy cattle to spirochetes isolated from papillomatous digital dermatitis lesions. Am. J. Vet. Res. 58, 744–748.

Wassink, G.J., Grogono-Thomas, R., Moore, L.J., Green, L.E., 2003. Risk factors associated with the prevalence of footrot in sheep from 1999 to 2000. Vet. Rec. 152, 351–358.

Whittington, R.J., 1995. Observations on the indirect transmission of virulent ovine footrot in sheep yards and its spread in sheep on unimproved pasture. Aust. Vet. J. 72, 132–134.

Winter, A.C., 2004. Lameness in sheep, 1. Diagnosis. In Practice 26, 58–63.

Winter, A.C., 2008. Lameness in sheep. Small Ruminant Res. 76, 149–153.

Please cite this article in press as: Angell, J.W., et al., Sheep and farm level factors associated with contagious ovine digital dermatitis: A longitudinal repeated cross-sectional study of sheep on six farms. PREVET (2015), http://dx.doi.org/10.1016/j.prevetmed.2015.09.016