Environmental and field characteristics associated with lameness in sheep: A study using smartphone lameness app for data recording

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Abstract

Background: Sheep lameness is a major concern among farmers and policy makers with significant impacts on animal welfare standards as well as financial and production performance. The present study attempts to identify the relative importance of environmental and farm-level management characteristics on sheep lameness.

Method: To address this objective, data was derived from the SPiLaMM project from 18 farms that used smartphone app to collect data, the British Geological Survey (BGS) and the Meteorological Office (Met Office) over 2016-2018. Data was analysed using a Multilevel Poisson Regression model.

Results: Temperature and higher length of pasture had a positive relationship with lameness while concentration of Selenium in soil and flock size had a negative relationship with lameness. In addition, results showed lower lameness levels for the bedrock class Mudstone, siltstone, limestone and sandstone (MSLS) in comparison to Sandstone (SD) and finally, lambs and ewes younger than 1 year old had lower levels of lameness than older ewes.

Conclusion: Findings of the present approach show the potential use of data collected via a smartphone app to study the epidemiology of disease. Furthermore, factors identified could be validated in intervention studies and generate data driven disease predictive models.

1 Introduction

Sheep lameness has been acknowledged by both farmers and veterinarians as one of the most significant issues for animal welfare (Kaler et al., 2010) mainly due to the pain that affected animals experience (O Callaghan et al., 2003). Furthermore, animal health problems relate not only to poor animal welfare but also to reduction of productivity (Gelasakis et al., 2015; King et al., 2016) along with financial losses (Wassink et al., 2010a). It has been estimated that lameness triggers annual losses of £24 to £84 million within the UK sheep industry (Nieuwhof and Bishop, 2005; Wassink et al., 2010b).

Most of the lameness incidents in the UK are triggered by footrot (FR) (Kaler and Green, 2008) which is an infectious disease and is caused by the anaerobic bacterium, *Dichelobacter nodosus* (Beveridge, 1941). FR has two clinical forms, in the first there is inflammation of the interdigital skin of the foot (interdigital dermatitis) while in the second the hoof horn gets separated from the underlying tissue (severe FR) (Witcomb et al., 2014). In the UK, the majority of the observational epidemiological research in the past decade has focussed on identifying farm-level management factors affecting the levels of lameness. The latter resulted in the development of current best practice on managing lameness in sheep. More specifically, management factors including isolation of purchased and returning sheep, vaccination of ewes with Footvax (MSD, n.d.) as well as prompt treatment of lame sheep within 3 days (without trimming) have been reported to be associated with lower prevalence while, routine trimming and foot bathing of ewes associate with higher prevalence of lameness (Kaler et al., 2012, 2010; Kaler and Green, 2008b; Winter et al., 2015). Interestingly, in an intervention study by Wassink et al. (2010b), the best practice recommendations were able to reduce the prevalence (number of existing cases at a particular time point) but unable to reduce the incidence (number of new cases during a specific time period) of lameness in one group. This highlights the importance of other factors possibly environmental factors that could influence the susceptibility of sheep and contribute to transmission of *D. nodosus* and thus, leading to disease. Unlike the increased knowledge that has emerged on management risk factors, the understanding of environmental characteristics that affect prevalence levels remains less studied in the UK and worldwide in general.

A review by Green and George (2008) highlighted that very little is known on survival times of *D. nodosus* and how soil characteristics such as type and chemical composition influence this. Within this context, recent literature has examined *D. nodosus* survival in reference to soil type (sand, silt, clay) and weather conditions (temperature) (Cederlöf et al., 2013; Muzafar et al., 2016). Furthermore, experimental approaches demonstrate that presence of micronutrients such as Selenium (Se) enhance the restoration of sheep immune functions hindered by FR and it has been suggested that exposing sheep to forage with increased Se is a sufficient way to achieve this natural restoration (Hall et al., 2013, 2009; Hugejiletu et al., 2013). However, little is known about the extent and the ways that variation in concentration of such chemicals in the soil (including Se) along with the type of soil (bedrock) associate with sheep lameness levels. Furthermore, observational studies have examined the effects of seasonality on prevalence demonstrating that the seasons of Autumn and Summer relate to increased lameness levels (Angell et al., 2018, 2015). Precision livestock farming offers a solution to record data on individual animals (e.g.smartphone app, EID technologies and sensors) and also enable the combination of data with other digital information systems (e.g. GIS) which could be beneficial for understanding the epidemiology of diseases (Kaler and Ruston, 2019). The aim of this study is collect data on lameness using lameness smartphone app and to explore associations between sheep lameness and potential risk factors among farm and field level features, chemical characteristics of soil, weather conditions and seasonality from a longitudinal study. Findings from this study enable a novel understanding of lameness in relation to the importance of environmental influencing factors.

2 Materials and methods

2.1 Dataset and variables

Farm characteristics and lameness levels were derived from the dataset constructed by the SPILLAM project[2]. SPILLAM is a project aiming to address the challenge of sheep lameness through developing hardware and software systems for lameness data collection. The software used in the study was developed by Farmwizard (Agriwebb company) in collaboration with University of Nottingham and Dunbia as part of a project funded by Innovate UK. The lameness smartphone app had the ability to a) record: information on individual sheep, lameness in field for groups, lameness treatments given, b) inform: videos and photos of lesions and lameness for farmers to support lameness recording , lameness best practice and seasonal advice and c) alert: reminders to record, significant changes in lameness levels (https://www.farmwizard.co.uk/sheep-manager). A total of 18 farms participated in this study. These farms were given training on using the smartphone lameness app .Also, training on lameness recording was provided to the farmers by a trained researcher who then also validated independently the lameness estimates . Lameness levels were validated as per methodology in King and Green (2011). Briefly, the reseracher visited the farm and independently assesed lameness. A sample of lame (up to 30) sheep were turned and lesions were recorded where the most common cause of lameness was found to be footrot (>97%).

Farmers logged the lameness levels for their fields from 2016 to 2018 onto their smartphone app, while sheep needed to be in the field for 14 days for a recording to occur. Minimum interval for lameness to be recorded was set to be one week. Farmers recorded number of animals in the field and also recorded lameness scores (0-6) for all animals based on Kaler et al. (2008). Based on that scale, sheep with locomotion lameness scores of 2 and above were considered lame in the context of the present analysis.

[2] Further information on the SPILLAM project can be found in the following link: https://spilamm2017.wixsite.com/spilamm

In terms of management of lameness, all farms treated lameness based on the best practice (Kaler et al., 2010). With regards to grass length measurements, farmers were given a sward stick and pasture length classed were explained. Farmers were asked to use this, however this was not validated. Even though there could be an error in the measurements, it does not affect the results per se as we don't expect these measurements to be biased. Further information on the raw data for pasture length in relation to count lame sheep is presented in fig. 1.

Using the farm location, environmental data (bedrock classification, soil chemical composition, weather characteristics) was derived from the British Geological Survey (BGS) (Rawlings et al. 2012, Smith, 2013) and the Meteorological Office (Met office) (Met Office, 2012). Weather variables included precipitation, mean, maximum and minimum temperature. The Met office variables comprised daily recordings and thus, were averaged in three different ways using three, seven and fourteen day rolling average windows representing the days immediately prior to the readings. Different combinations of the derived averages were modelled and the final selection was subject to performance of the model considering the AIC score.

The geographic reference of the farm businesses was obtained from farm addresses and thus, data from the three different sources (SPILaMM, BGS, Met Office) were merged geographically into a Geographic Information Systems (GIS) environment by spatial overlap. Detailed information on the examined variables is presented in Table 1. Finally, through a data cleaning process, ten recordings were omitted from the subset due to duplicates or missing values and errors. The final dataset includes 521 observations of sheep lameness at field level for the 18 farms capturing information for the years 2016, 2017 and 2018. Specifically, data collection started in August 2016 and finished in September 2018 and number of observations were 87, 374 and 60, respectively for the three years.

Regarding the study area of the analysis, farm businesses under consideration spanned geographically across England and Wales while the majority of them was located in the regions of Midlands and Southwest along with Wales (Fig. 2).

2.2 Multilevel Poisson Regression model

The employed dataset comprised of repeated lameness recordings over time for the various farms and fields and thus, multilevel statistical analysis was incorporated to account for the nested observations (Solano et al., 2015). Furthermore, a Poisson model was employed as count data on lame sheep per field has been used as the dependent variable in the modelling (Winter et al., 2015). Additionally, the assumption of mean being equal to variance was violated as variance was greater than the mean indicating that the data was over dispersed. To account for this, the model was fitted using a quasi-Poisson method. Furthermore, a check for autocorrelation was conducted by considering the Variance

Inflation Factor (VIF) to check all predictor variables. No issues were identified as the estimates for all variables were below the threshold of 3 as discussed by Zuur et al., (2010).

More specifically, the Multilevel Poisson Regression model was constructed to explore the explanatory power of environmental and farm-level variables in variations of sheep lameness prevalence. The model was constructed using the statistical software R and specifically the package "lme4" which provides functions for fitting mixed models (Bates et al., 2015; R Core Team, 2018). The dependent variable of the model was offset by the natural logarithm of total sheep in the field that was imported to adjust for differences in population sizes (here flock size). In addition, the log link function was used and the model is in the following form:

$$\text{Number of lame sheep in field}_{fkd} \sim a + \beta_{fkd}X_{fkd} + e_{fkd} + offset$$

Where $\sim$ is the log link function, a is the intercept, β_{fkd} are the coefficients for a vector of X_{fkd} explanatory variables which vary by the levels fkd, e_{fkd} is the residual and offset is the natural logarithm of the number of sheep in each field. Three levels were applied in the current approach as random effects representing observations of farms ($k = 1, \dots, K$) containing fields ($f = 1, \dots, F_K$) for the different dates of recordings of lameness ($d = 1, \dots, D_{FK}$).

Table 1 List of variables considered in the analysis

Variable category	Variable	Levels / Range
Sheep	Sheep category	Ewe (1 year and older)
		Lamb and Ewe (younger than 1 year)
		Ram
Farm	Pasture Length	Short - up to 5cm
		Medium - 6 to 10 cm
		Long - longer than 10 cm
	Pasture Type	Forage crop
		New leys
		Permanent
	Flock size (class)	I - up to 50 sheep
		II - 51 to 100 sheep
		III - 101 to 200 sheep
		IV - 201 to 400 sheep
Environment	Seasonality	Autumn (Sep/Oct/Nov)
		Spring (Mar/Apr/May)
		Summer (Jun/Jul/Aug)
		Winter (Dec/Jan/Feb)
	Topography (Altitude)	0 to 250 m
	Chemical Soil condition - Se concentration	0.2 to 1.3 mg kg^{-1}
	Bedrock type (Rock classification scheme)	Limestone with subordinate sandstone and argillaceous rocks (LSSA)
		Mudstone, siltstone and sandstone (MDSS)
		Mudstone, siltstone, limestone and sandstone (MSLS)
		Sandstone, limestone and argillaceous rocks (SLAR)
Climate	Precipitation - fourteen day rolling average	0 to 8.5 mm
	Minimum Temperature - three day rolling average	-5 to 16 ^{o}C
	Maximum Temperature - three day rolling average	3 to 26 ^{o}C

3 Results

Results of the multivariable multilevel model are presented in Table 2. Results indicate that there were statistically significant associations between sheep lameness and the variables of sheep category, length of pasture, seasonality, Se concentration in soil, temperature, flock size and bedrock type. The median observation of the response variable in the model was 0.02 (or equivalently, 2% prevalence). More specifically, the latter indicates that of all the sheep in all the fields, 2% were lame. Detailed information on the results of the regression is presented in Table 2. In interpreting these results it is important to take into consideration that the estimates are related to the dependent variable by the log link and thus, it is essential to first exponentiate the coefficients. Following, in the cases that the exponentiated value j_n for variable n is less than one then the effect of the independent variable is negative and for each extra unit of it, the dependent variable decreases by $(1 - j_n) * 100$ percent. The same estimation was used for coefficients above one and taking the absolute value of this calculation gives the percentage of increase. Furthermore, as several explanatory variables were categorical, the modelling results were interpreted in relation to a reference group.

With regards to sheep category, for Lamb and Ewe (younger than 1 year) , sheep lameness decreased by 25% (while keeping the rest of the predictors fixed) in reference to Ewe category. Furthermore, considering pasture length, findings suggest that for medium (6 – 10 cm) and short (up to 5 cm) length lameness decreased by 17% and 32% respectively in comparison to long (>10 cm) length. Regarding seasonality, results show that for Spring, Summer and Winter lameness is increased in comparison to Autumn by 44%, 64% and 100% respectively. Concerning Se soil concentration results show that for each extra unit of Se in the soil, lameness decreased by 84%. Concentration values of Se range from 0.2 to 1.3 mg kg^{-1} and thus, it may be more appropriate to suggest that for each extra 0.1 Se units in the soil (e.g. increasing from 0.2 to 0.3 mg kg^{-1}), lameness decreased by 8.4%. With regards to flock size, results demonstrate that flock sizes of 51 to 100, 101 to 200 and 201 to 400 sheep have decreased levels of lameness in comparison to the reference category (flock size of up to 50 sheep) by 25%, 36% and 51% respectively.

The three day rolling average of maximum temperature has a positive relationship with lameness levels. Specifically, it is estimated that for one extra degree there is an increase of 3% of lameness. The fourteen-day rolling average of rainfall had no statistically significant effect on lameness. The maximum and minimum temperature averages were highly correlated and thus only the rolling average of maximum temperature was left in the final model to test whether warmer conditions have an effect.

A statistically significant negative association was identified between bedrock type and lameness. Specifically, the class MSLS showed decreased lameness levels by a factor of 80% when compared to the reference category of Sandstone. The variable of altitude was initially considered in the modelling however, no statistical association was observed between them and lameness levels.

Finally, concerning the goodness of fit of the model, the results indicate that the proportion of variance explained by the fixed factors (marginal) is 0.31 while proportion of variance explained by both the fixed and random factors (conditional) is 0.94.

Table 2 Multilevel Poisson Regression model results

	N Farms	N obs	Estimate	Std. Error	z value	Exponentiated estimate	Effect	Pr(>|z|)	
(Intercept)	18		-1.130	0.919	-1.229	0.323		0.219	
Sheep Category Ewe (>=1 year)	18	291	Ref.						
Sheep Category Lamb and Ewe younger than 1 year	16	96	-0.290	0.090	-3.214	0.748	-25%	0.001	**
Sheep Category Ram	5	13	-0.177	0.280	-0.631	0.838		0.528	
Pasture Length >10 cm (long)	11	145	Ref.						
Pasture Length 6-10 cm (medium)	16	192	-0.183	0.089	-2.054	0.832	-17%	0.040	*
Pasture Length up to 5 cm (short)	15	182	-0.384	0.114	-3.375	0.681	-32%	<0.001	***
Pasture Type Forage Crop	2	9	Ref.						
Pasture Type New Leys	6	27	0.487	0.471	1.035	1.628		0.301	
Pasture Type Permanent	18	487	0.388	0.451	0.860	1.474		0.390	
Season Autumn	10	177	Ref.						
Season Spring	11	115	0.366	0.138	2.658	1.442	44%	0.008	**
Season Summer	9	100	0.494	0.119	4.135	1.639	64%	<0.001	***
Season Winter	12	127	0.694	0.164	4.232	2.002	100%	<0.001	***
Selenium concentration	18	521	-1.850	0.735	-2.516	0.157	-84%	0.012	*
Precipitation (2 week mean)	18	521	-0.034	0.024	-1.452	0.966		0.147	
Maximum temperature (3 day mean)	18	521	0.029	0.013	2.244	1.029	3%	0.025	*
Flock size up to 50	15	171	Ref.						
Flock size 51 to 100	17	173	-0.292	0.122	-2.392	0.746	-25%	0.017	*
Flock size 101 to 200	14	102	-0.443	0.149	-2.971	0.642	-36%	0.003	**
Flock size 201 to 400	7	73	-0.713	0.173	-4.114	0.490	-51%	<0.001	***
Bedrock type SLAR	2	10	Ref.						
Bedrock type LSSA	2	31	-0.880	0.992	-0.887	0.415		0.375	
Bedrock type MDSS	2	81	-0.873	0.624	-1.399	0.418		0.162	
Bedrock type MSLS	13	397	-1.623	0.816	-1.990	0.197	-80%	0.047	*

R squared: 0.31 (marginal), 0.94 (conditional)

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

Random effects:

Groups	Name	Variance	Std.Dev.
Farm	(Intercept)	0.4923	0.7016
Field	(Intercept)	0.4426	0.6653
Date	(Intercept)	0.3802	0.6166

Number of obs: 519, groups: N_intfield, 177; Nperfield, 21; Num_farm, 18

3.1.1 Model diagnostics

The regression analysis was followed by assumption testing to examine whether assumptions were met in the modelling. Furthermore, it was assumed that the variance of the residuals is equal among the various model levels which was satisfied in the model. Finally, the distribution of the residuals was examined for the assumption of normality and a normal probability QQ plot and a histogram of the model residuals suggested that the assumption was met.

4 Discussion

In the current study a range of potential environmental risk factors for sheep lameness were examined. This is the first study using observational data of sheep lameness from multiple farms in the UK that quantifies and signifies the relationship between lameness and Se concentration in the soil. Findings of the current study suggest that Se has a negative relationship with lameness prevalence. This finding is in line with relevant experimental research showing that Se as a micronutrient has a positive effect in restoring sheep immune functions negatively affected by footrot (one of most common cause of lameness) (Hall et al., 2013; Hugejiletu et al., 2013). Furthermore, (Hall et al., 2009) a positive effect is to be identified for sheep exposed to increased-Se forage, that have been infected by footrot.

This is also the first attempt to examine whether soil type has an impact on sheep lameness prevalence. According to the findings of this approach, the bedrock class MSLS (Mudstone, siltstone, limestone and sandstone) is associated with a decrease in lameness levels when compared to soil type SD (Sandstone). In a report by Agriculture and Horticulture Development Board, UK (2016) it is recommended that application of limestone can work as a prevention method for sheep lameness. However, interestingly the quantified findings and recommendations remain fairly limited on the importance of this parameter. Through a different context, Muzafar et al. (2016) indicate that clay soils (here classes containing mudstone) provide fairer conditions for the survival of *D. nodosus* in comparison to sand soils (here sandstone). However, the rock classification scheme provides a range of classes where each represents a composition of various materials in the soil (Table 1). Specifically, the classes MSLS and SD have some common chemical features (Sandstone and Limestone) while they differ in the rest of their materials (Mudstone, Argillaceous rocks and Conglomerate) (Table 1). Thus, further investigation is needed to enable the identification of the particular materials in the soil that have an association with sheep lameness.

Additionally, in our approach a positive relationship was identified between pasture length and lameness levels (pasture length higher than 10 cm had increased lameness in comparison to up to 5cm and 5 to 10 cm). The latter is in line with Angell et al. (2018) who suggest that sheep are more likely to have footrot when grazing longer swards. Pastures of longer length tend to retain higher levels of moisture when compared to shorter length pastures. As a result, sheep standing in longer pastures have their feet exposed in more humid conditions in comparison to those standing on shorter length pastures and thus, providing adequate conditions for the development of lameness.

Towards this direction, findings of the current approach demonstrate that the flock size has a negative association with sheep lameness prevalence. Specifically, it is demonstrated that larger flocks relate to lower levels of lameness. This finding is in accordance to Winter et al., (2015) who also report that increased flock size is linked to decreased lameness. On the contrary, similar approaches find either a positive relationship (Angell et al., 2018) or no association (Kaler and Green, 2008b) between flock size and lameness. According to Dickins et al. (2016), lower lameness percentages for larger flock sizes as a finding may indicate a density dependency in the systems under consideration. A potential interpretation is that larger flocks may be managed with more effective and commercially oriented production strategies (Gelasakis et al., 2013) where biosecurity measures may be more precise and standardised (Dickins et al. 2016).

A positive association was observed between maximum temperature (of the last 3 days prior to recording) and sheep lameness. Our findings are in line with Green and George (2008) and Smith et al. (2014) who have suggested the impacts of climate on the transmission of footrot. Furthermore, Raadsma and Egerton (2013) argue that footrot transmission within infected sheep depends on presence of adequate temperatures and previous hydration of the interdigital skin. With regards to moisture, studies have identified precipitation as a significant parameter triggering increased levels of prevalence (Abbott and Lewis, 2005). However, in the current study there was no such association identified. In a relevant context, Wassink et al. (2003) have also reported a lower prevalence of lameness in areas with higher levels of rainfall indicating that variations in prevalence are perhaps driven more drastically by management factors at the farm level.

Results of the current study point out a relationship between seasons and lameness. Particularly, in the current study all seasons had increased lameness when compared to the reference group which was Autumn. Among the seasons, Spring estimated the smallest increase in comparison to Autumn. This finding is in contrary to Angell et al., (2015b) who reported increased prevalence during Autumn and Summer. To an extent, seasonal increase in lameness imply effects of fair climatic conditions for the survival of the bacterium (warm and wet conditions). However, Wassink et al., (2003) reported that within the UK, even areas with such conditions (Southwest England and South Wales) had lower levels of FR in comparison to areas with lower average temperatures. In that sense, it seems likely that lameness may be affected by a combination of parameters in addition to weather conditions, such as management practices at the farm level.

Furthermore, in this study, differences were identified among the different sheep categories (here relating to age groups). The categories of Lamb and Ewe (younger than one year) had lower lameness levels when compared to the Ewe category. This result is in line with Angell et al. (2018) who showed decreased lameness levels for yearling sheep in comparison to lambs and adult ewes. However, there is possibility that older ewes are more likely to have poor foot confirmation and poor conformation increases susceptibility to footrot due to reduction in resistance with increasing age (Kaler et al., 2010).

Although this study gave us insights into various environmental factors associated with lameness, it does not imply causality. The impact of variables identified in the current study need to be studied further and validated on farms with wider geographical area. No animal management factors were included in the current study as all farmers followed best practice to manage lameness, however, other variables such as the length of the stay in a particular field and whether new sheep were introduced could impact on infection pressure. Unfortunately, this was unknown in the current study. This study used farmers reporting to identify lameness; despite this lameness levels are unlikely to be biased given farmers were trained and independently validated before the start of the study, In addition, previous studies suggest farmers can identify lameness accurately (Kaler and Green, 2008a; King and Green, 2011).

In this study a smartphone app was used to record lameness levels, the study demonstrates its usefulness in line with other precision livestock technologies to be able to generate long term disease data on farm, something vastly lacking on sheep farms (Kaler and Green, 2013; Kaler and Ruston, 2019). In addition, use of the app improved data recording on farm (results not shown).

In conclusion, the findings of the present analysis enable a novel understanding of the ways and the extent that environmental and farm-level management characteristics associate with sheep lameness prevalence. Using technology such as the one used in this study for data gathering alongside data on environmental and field variables could help us build predictive models for lameness as well as a tool for managing lameness. This could be of essential value for policy makers as well as farmers aiming to tackle and reduce lameness prevalence levels.

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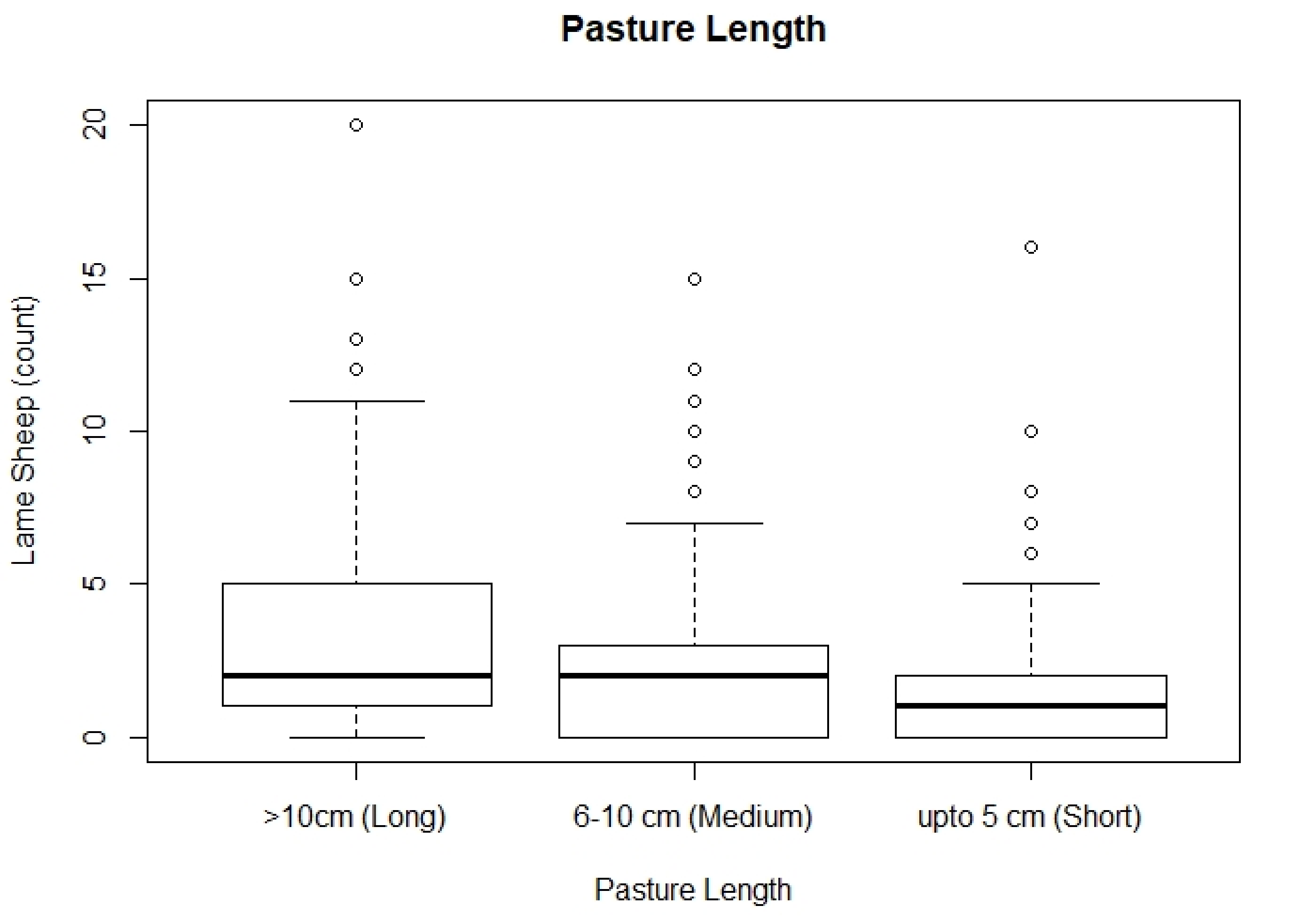
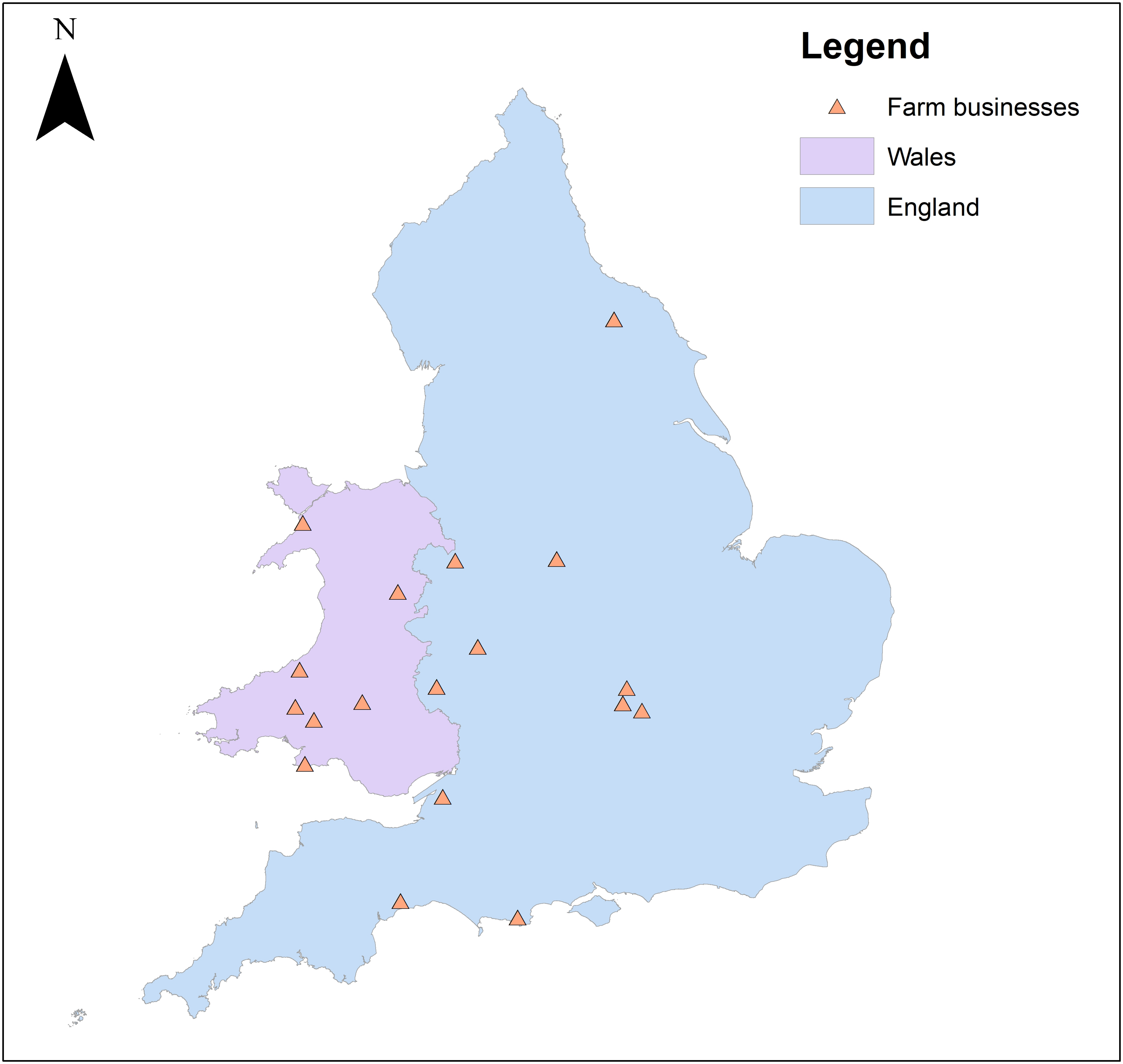


Pasture Length
Lame Sheep (count)
0
5
10
15
20
>10cm (Long)
6-10 cm (Medium)
upto 5 cm (Short)
Pasture Length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Legend
Farm businesses
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