Using lamb sales data to investigate associations between implementation of disease preventive practices and sheep flock performance

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Short title: Factors associated with sheep flock performance

Abstract

Although the United Kingdom (UK) is the largest lamb meat producer in Europe, there are limited data available on sheep flock performance and on how sheep farmers manage their flocks. The aims of this study were to gather evidence on the types of disease control practices implemented in sheep flocks, and to explore husbandry factors associated with flock productivity. A questionnaire focusing on farm characteristics, general husbandry and flock health management was carried out in 648 farms located in the UK over summer 2016. Abattoir sales data (lamb sales over 12 months) was compared to number of breeding ewes on farm to estimate flock productivity (number of lambs sold for meat/100 ewes/farm/year). Results of a multivariable linear regression model, conducted on 615 farms with complete data, indicated that farms vaccinating ewes against abortion and clostridial agents and administering a group 4/5 anthelmintic to ewes (as recommended by the Sustainable Control Of Parasites in Sheep Initiative, **SCOPS**) during quarantine had a greater flock productivity than farms not implementing these actions ($P < 0.01$ and $P = 0.02$ respectively). Flocks with maternal breed types had higher productivity indexes compared to flocks with either pure hill or terminal breeds ($P < 0.01$). Farms weighing lambs during lactation had greater productivity than those not weighing ($P < 0.01$). Importantly, these actions were associated with other disease control practices; e.g. treating individual lame ewes with an antibiotic injection, weaning lambs between 13 and 15 weeks of age and carrying out faecal eggs counts, suggesting that an increase in productivity may be associated with the combined effect of these factors. This study provides new evidence on the positive relationship between sheep flock performance and disease control measures and demonstrates that lamb sales data can be used as a baseline source of information on flock performance and for farm benchmarking. Further research is needed to explore additional drivers of flock performance.

Keywords:

Sheep; Questionnaire; Productivity; Vaccination; Husbandry

Implications (100 words max)

This study describes, for the first time, the types of disease control practices applied on commercial sheep farms in the **UK** (United Kingdom). The study is the first to assess the degree of penetration of these actions among the British sheep farming industry. Identification of husbandry practices with a positive association with sheep flock performance can be used to promote flock health practices among the sheep farming community. This study shows that lamb sales data can be used for a baseline comparison of productivity levels between farms.

Introduction

In 2016, 290 thousand tonnes of lamb meat were produced under extensive, grass-based systems located in the UK, accounting for 36% of the total European Union sheep meat production in that year (Food and Agriculture Organization Statistics). Despite the large size of the sheep population, there are limited data on how sheep farmers manage their flocks in the UK. The limited data available provides only numbers of sheep, mean production metrics from small samples of flocks and passive disease surveillance activies. Several surveys have gathered specific information on disease prevalence but none has collected information on whole sheep flock husbandry practices and their associations with flock output. Therefore, investigating factors affecting flock performance could prove beneficial for the sheep farming sector. In the past, research based on experimental studies has identified single factors with an impact on flock productivity, including genetics (Walkom et al., 2014), nutrition (Fraser et al., 2004), disease (Green et al., 1998), and reproduction (Kelly and Johnstone, 1982). However, comparisons on the relative importance of different factors have not ben established. .

To estimate the relative impact of multiple factors that influence flock production, a small number of international studies have investigated the effect of management practices on flock performance (Doré et al., 1987; Townsley and Parker, 1987; Bohan et al., 2017) showing that a number of management factors are associated with flock performance, but the different proxies of flock performance hamper a direct comparison between factors. This suggests that the use of a standardised metric based on abattoir data, could simplify the identification of factors with a consistent effect on flock performance. Although abattoir clinical feedback is routinely used for disease surveillance purposes, its use for monitoring livestock flock performance is limited.

Against this background, the aims of the current study were a) to gather key background information on current commercial flock management practices carried out in UK commercial sheep farms, b) explore the use of lamb abattoir sales data as a proxy of flock productivity; and c) to investigate the relationship between flock husbandry practices and flock productivity. Given that husbandry practices carried out on sheep enterprises are comparable between the UK and other sheep producing nations, the hypothesis explored in this study are likely to be relevant to a worldwide audience.

Material and methods

Questionnaire design

The questionnaire was composed of three sections: i) farm and flock characteristics), ii) animal movements on and off farm, and ii) flock disease control and prevention management practices. Decisions around which questions to include were taken from a literature review and the clinical experience of an author of this manuscript (FL). The first section of the questionnaire asked about farm location and altitude, flock size and breeds, participation in “environmental schemes”, other farm enterprises, and grassland area. The second part of the questionnaire inquired about animal movements in and off-farm such as number of lambs sold for meat per month, ewe culling rate and store lambs purchased. The final and largest section of the questionnaire focused on management of lambing and flock disease prevention and control actions. The first questions of this section asked about frequency of contact with a veterinary surgeon, flock information recording practices, criteria for selecting culling ewes and types of vaccines used in the flock. Then, questions on parasite control and procedures carried out in quarantined sheep were presented. The lambing management questions included type of procedures carried out in baby lambs. All questions referred to practices carried out from May 2015 to April 2016, except the questions relative to lambing management, which referred specifically to 2016. The questionnaire was piloted by FL on eight sheep farmers and their comments were used to make a final version of it. The final questions were entered in software specifically designed for the purpose of this study.

Data collection

The population under study comprised commercial sheep farmers supplying finished lambs to a major British food retailer. Nine hundred and twenty farmers who regularly supplied and were engaged with the retailer, were selected for the study and asked to respond to the questionnaire. Out of these, 746 accepted, and 615 provided sufficient data to be used in a final model (initial response rate = 81%, final model response rate = 67%). Farmers who agreed to participate were visited during summer 2016 by twelve trained, interviewers who were independent of the retailer and researchers. Interviewer training, undertaken by FL, included an explanation of the purpose of the questionnaire with discussion and clarification of individual questions where necessary. During training, the interviewers undertook role play scenarios to ensure consistency while asking the questions in a conversational style. Responses were entered into questionnaire software. Before the farm visit, abattoir sales data (i.e. monthly lamb sales) for each farm were provided by the meat processors and entered in the study software. During the visit, farmers were asked to validate these records by comparing them with their own. If necessary, lamb sales records were amended to account for lambs sold for meat to other parties.

The questionnaire responses and corresponding abattoir sales data for each farm were provided to the authors of this paper in a spreadsheet, with farmers and farms identity coded to maintain their anonymity.

Data cleaning

Farm, flock and lamb sales records were imported to Stata Version 15 (Stata Corp., College Station, TX) software for data cleaning and analysis (n=746). Farms purchasing store lambs were excluded from the dataset (n=80) as purchased lambs would interfere with the calculation of the flock productivity index, which focused on lambs born on farm. In order to detect data entry errors or farms with biologically implausible values, indexes representing the number of lambs born/ewe/year and the number of lambs sold/ewe/year were calculated and compared with industry reference values. Based on this, a cut-off of maximum level of 2.0 lambs sold for meat per ewe per year was set, and farms with values above this were excluded from the analysis (n=18). The final sample was composed of 648 farms.

Statistical analyses and model building

Following coding of categorical variables, descriptive statistics were calculated. Since not all respondents answered all questions, denominators are reported when relevant. Descriptive statistics of variables with more than 300 data points were evaluated and reported but to avoid loss of analytic power, only variables with a minimum of 475 data points were carried forward to be tested in multivariable analysis. Median and interquartile ranges (**IQR**) were used to represent the spread of the distributions due to the skewness of the responses. Chi-squared tests were used to explore pairwise associations between categorical variables

We defined flock productivity as the "number of lambs sold for meat per 100 ewes per year" (relative to period between June 2015 and June 2016) and this was the outcome of interest in this study. This index was based exclusively on sales of lambs sold for meat, not comprising animals kept or sold for breeding.

The explanatory variables of interest were flock management practices carried out between April 2015 and June 2016. In order to explore management factors most likely to be associated with flock productivity (number of lambs sold for meat per 100 ewes per year), univariable linear regressions were carried out. Following this screening process, variables with $P \leq 0.1$ and at least 475 data points were taken forward as well as variables considered potential confounders. Non-linear effects were tested by adding polynomial terms of the continuous variables into the model. Interactions terms were tested between terms that were included in the final model, although it was recognised that the sample size may have been limiting for identification of interaction terms (Gelman, 2018).

Model assumptions were checked. The normal distribution of residuals was assessed by visual observation of the plotted residuals and observation of the kernel density estimate. The homoscedasticity (constant variance) of the residuals was verified both graphically and by running the Breusch-Pagan test (*P*-values >0.05). Absence of multicollinearity in the model was assessed by examining the variance inflation factor. The overall influence of each observation on the final model was checked by calculating the Cook's distance (Dohoo et al., 2003).

Due to the great number of variables assessed in the context of this study and the inherent increased risk of multicollinearity, we also compared the multiple regression model results with the results of a penalised regression method, elastic net (Zou and Hastie, 2005; Kuhn and Johnson, 2013). Additionally, we conducted analysis using Multivariate Adaptive Regression Splines **(MARS)** (Friedman, 1991; Kuhn and Johnson, 2013) to investigate non-linear relationships between the predictors and the outcome.

Results

Descriptive statistics

Farm and flock characteristics. The median flock size and median farm grassland area were 500 ewes (IQR 269 – 900) and 118 hectares (IQR 60 – 235) respectively (648/648 observations). Seventy-seven per cent (500/648) of the farms operated a mixed enterprise (beef and sheep). Overall, the number of lambs sold finished per 100 ewes per year was 108 (IQR 82 – 135) (648 observations). Detailed information about farm characteristics and animal movements in and off farm is provided in Table 1 and supplementary material table S1.

Frequency of contact with a veterinary surgeon. Sixty-seven per cent (242/362) of the farmers indicated they had one visit from the veterinarian, 15% had two visits, 14% had three or more visits in the last year and only 2% had no visits from a vet.

Culling management. Ewe age was indicated by 42% (272/641) of respondents as the primary reason for selecting ewes for culling, followed by mastitis (25%) and tooth loss (21%); lameness, infertility, prolapse or poor condition was indicated by only 2% of the farmers. For record keeping of culling information, 69% of the farmers (236/341) used a notebook, 25% an **EID** (electronic identification) handheld, 6% a computer and 2% a smartphone.

Lambing management. Twelve per cent (79/663) of the farms started lambing in January, 21% in February, 46% in March and 18% in April. Not all farms weaned lambs at the same age: 38% of the flocks weaned lambs between 15 - 17 weeks of age, 24% weaned lambs when they were 17 weeks or more, 20% weaned lambs between 13 -15 weeks and 18% at 11-13 weeks. Less than half of the farmers weighed the lambs at least once during lactation (45%, 287/632). Additional procedures carried out in new born lambs are presented in Table S2.

Vaccination practices. Thirty-nine per cent (252/648) of the farmers vaccinated ewes against both clostridial diseases and abortion agents. Fifty-five per cent (354/648) of the farmers vaccinated ewes against clostridial diseases only, 2% vaccinated their ewes against abortion agents only (Chlamydia abortus or Toxoplasma), and 5% (34/648) of farmers did not use any vaccines in their flock.

Endoparasites control. *When asked about the reasons for administrating anthelmintics to lambs, 50% (318/631) of farmers indicated using anthelmintics based on a pre-defined schedule, 28% based on presence of clinical signs compatible with endoparasitism, 19% based on results of Faecal Egg Counts (**FEC**),* *3% on grazing history and less than 1% on lamb live weight gains.* Seventy-one per cent (452/633) of farmers did not carry out a FEC in the previous year and 12% conducted a FEC up to three times. The great majority (>80%) of farmers did not test for anthelmintic resistance in their flock. For information on anthelmintic resistance types please refer to Table S3.

Flock biosecurity. Only a small proportion of farms was breeding their own replacement ewes and rams (31% and 10% of the flocks, respectively). For additional information on procedures carried out during quarantine, please refer to Table 2. A very small proportion of farms screened their flock for “iceberg” infectious diseases during the previous year: for instance, only 5% (32/640) of the farms screened their flock for Maedi-Visna (**MV**), and less than 2% of farms screened their flock for Caseous Lymphadenitis (**CLA**), Border disease or Ovine Johne's Disease (**OJD**).

Associations between variables

Figure 1 summarises the significant associations found between flock management practices. For instance, a farmer weighing lambs during lactation was more likely to perform several other practices (e.g. treating individual lame ewes with an antibiotic injection, weaning lambs at age 13-15 weeks of age, treating lame ewes individually with an antibiotic injection, testing for flock anthelmintic resistance, and purchasing ewe replacements from farms) than a farmer not doing so. A farmer vaccinating against both clostridial and abortive agents was more likely to footbath ewes during quarantine, wean lambs between 13 and 15 weeks of age, perform FEC counts in lambs and record culling information using an EID device and have a greater number of visits from a veterinary surgeon. For the *P*-values of the associations between these variables please refer to Supplementary Table S4.

The proportion of farms applying management practices varied by UK region (Table 3). While there was wide variation in the proportion of farms weighing lambs during lactation (from 32% in Northern Ireland to 71% in the North of England), there was little difference in the proportion of farms treating lame sheep with the best practice among regions (from 79% to 95%).

Multivariable regression model of flock and husbandry factors associated with flock productivity (number of lambs sold/ewe/year)

A greater flock productivity (i.e. a higher number of lambs sold for meat per 100 ewes) was associated with a number of flock husbandry practices in multivariable analysis (Table 4). Weighing lambs during lactation, administering a Group 4/5 anthelmintic (monepantel or combination of derquantel and abamectin, respectively) to ewes during quarantine, and vaccinating ewes against both abortion (*Chlamydophila abortus* or Toxoplasma) and clostridial agents were associated with a greater flock productivity. Additionally, flocks with maternal or terminal types showed higher productivity when compared to flocks with pure hill or pedigree breeds. Being part of an environmental stewardship scheme showed a negative association with flock productivity. In contrast, being a lowland farm (i.e. farm located below 200 m of altitude) was associated with a higher flock performance. This model explained 26% of the total variance (R^2= 0.26).

Due to the fact that the variable “vaccinating ewes against both clostridial and abortion agents” was strongly associated with the variable “ewes were treated for lameness individually with an antibiotic injection”, an alternative model using this variable instead was built. This predictor had a coefficient of 8.8 (C.I. 1.1 – 16.4), meaning that, according to this model, treating individual lame ewes with an antibiotic injection was associated with an additional production of 8.8 lambs per 100 ewes per farm per year. This alternative model explained approximately the same proportion of model variance (0.25 in contrast to 0.26).

Model fit results

The major assumptions of a linear regression model were confirmed by visual observation. All observations had a Cook's distance ≤ 0.3, suggesting that no observations had a large influence on the outcome (Dohoo et al., 2003). The best elastic net model and the MARS models were very similar to the multiple linear regression model, with similar coefficients and model fit. This suggested that multicollinearity was not an issue and that non-linear relationships were not present within the data, indicating that the model coefficients were reliable.

Discussion

Current sheep flock health management practices in the United Kingdom

This is the first large-scale study investigating flock health practices carried out during a full production cycle on commercial UK sheep farms. The study brings new insights on the actions carried out at quarantine, vaccination practices, infectious diseases screening, main source of replacement animals and reasons for selecting of animals for culling.

The results suggest that the uptake of disease prevention practices in the studied farms was relatively poor. Only 10% and 18% of the respondents footbathed newly purchased sheep (for lameness prevention) and administered a recommended anthelmintic drug, respectively, and a low proportion screened their flock for anthelmintic resistance or production limiting infectious diseases. Considering the large numbers of sheep that are being moved between farms in the UK and that 82% of the flocks of this study were not “closed” (i.e. female replacement animals were not bred on farm), the relatively low rate of application of disease prevention practices may be cause for concern from a disease transmission perspective. The lack of baseline data on uptake of disease control measures by UK sheep farmers does not allow an evaluation of trends over time; however, these results were not unexpected. Previous studies showed that the extensive nature of sheep farming coupled with the lack of labour to gather sheep act as barriers for implementation of disease control practices (Morgan-Davies et al., 2006).

Farmers’ responses on how flock decisions are made and type of records collected suggest that flock record keeping in the sheep farms was low, confirming previous evidence (Kaler and Green, 2013a); the fact that 82% of the respondents did not ear tag any lamb during the previous lambing season suggests that lamb performance recording was not a priority. Use of anthelmintics “based on a pre-defined schedule” was preferred over other types of assessment that required use of records and the selection of ewes for culling was mainly based on ewe age, rather than metrics such as lameness or low productivity, which require record keeping but are more useful from a flock productivity point of view. Poor record keeping is likely to be a missed opportunity for improved production efficiencies because keeping records is crucial for the evaluation of production system alternatives (Croston and Pollot, 1994; Kaler and Green, 2013).

In light of the concerns regarding antibiotic usage, it is worthy of note that a relatively high proportion of farmers indicated having administered oral antibiotics prophylactically to newborn lambs (31%) and that 5% did so with an unlicensed product. In line with these results, a recent study quantifying the amount of antibiotics prescribed to sheep enterprises reported that 47% of studied flocks were prescribed oral antibiotics for newborn lambs, although type of usage (treatment/prophylaxis) was not specified (Davies et al., 2017). An even higher proportion (68%) of farmers administrating oral antibiotics prophylactically to newborn lambs was reported by Douglas and Sargison (2018), however, the study design and type of farms studied differed, which may explain the differences found.

Associations between flock performance and husbandry practices

This is the first study to use data provided by abattoirs about numbers of lambs sold to estimate flock performance. The identification of flock management decisions associated with greater productivity is of potential interest for the development of the sheep farming industry. Flock breed was a powerful factor explaining flock productivity (i.e. number of lambs sold for meat per 100 ewes per year per farm). Flocks with maternal breeds (i.e. Welsh 'half-bred', North of England 'mule') had a greater productivity than flocks composed of "pure hill", "terminal" or "pedigree" breeds. A partial explanation of this is the greater number of breeding animals kept or sold by 'pure' or 'pedigree' flocks, which were not accounted for by this study. Maternal breeds tend to show higher fertility, fecundity and good mothering traits (Bradford, 1972), possibly contributing to greater flock outputs. Similar results were reported by Bohan *et al.* (2017). Interestingly, weighing lambs during lactation was associated with a greater flock productivity, possibly because data on lamb weights allows more targeted management interventions in nutrition and endoparasite control. Weighing lambs was also reported by Townsley and Parker (1987) to be associated with higher flock productivities. A positive association between higher flock productivity and vaccinating the flock against abortion agents (toxoplasmosis/chlamydiosis) was also observed. This is likely to be due to a lower number of lamb deaths during pregnancy and the first weeks of life, resultant from protection against the former infectious agents. Both toxoplasmosis and chlamydiosis have a relatively high prevalence in the UK (Hutchinson et al., 2011) and a considerable impact in sheep farming (Buxton et al., 2007). Additionally, an association between flock productivity and administrating a ‘Group 4’ or ‘Group 5’ anthelmintic to ewes during quarantine was observed, which is line with the guidelines promoted by the Sustainable Control of Parasites (**SCOPS**) initiative (McMahon et al., 2013). Increasing resistance rates to older anthelmintics is leading to a lower efficacy of treatments against endoparasites (Sargison et al., 2007; Glover et al., 2017) and a consequent increase of the related deleterious effects of these on sheep production. In contrast, resistance to Group 5 anthelmintics has not been reported and resistance to group 4 anthelmintics only recently reported (Hamer et al., 2018). A greater number of days to finish lambs not treated with Group 5 products has been reported in the literature (Miller et al., 2012), which again aligns with results found in this study.

Farms located in lowland areas (below 200m of altitude) tended to have a greater flock productivity. Lower areas of the country are generally associated with greater agricultural outputs (Croston and Pollot, 1994). Additionally, farms that were part of an environmental stewardship schemes showed lower productivity per ewe than farms not part of these programs. Environmental schemes promote a responsible use of land and protection of the natural environment, and are not always compatible with more intensive flock management options (such as application of grassland fertilizer), which may explain the differences seen.

Importantly, administrating antibiotics prophylactically at lambing time was not associated with an increase in flock productivity. Given the current concerns about antibiotic usage in livestock and the relatively high proportion of farms administrating oral antibiotics prophylactically to new born lambs observed in this and previous studies, this is worthy of note.

It is important to highlight that despite limited numbers of observations being available for some explanatory variables, there appears to be a set of disease control practices identified in our final model that were associated with other actions (Figure 1). Further research is needed to carefully quantify the impact of specific health management practices on productivity and to ensure that relationships identified are truly causal.

Results of this study confirmed that flock genetics are a relevant factor explaining flock productivity, and also that health-related husbandry practices are an important aspect of flock performance. The relevance of disease control practices for the performance of more intensively reared livestock species is well recognised (Dorea et al., 2010), but to the authors’ knowledge this is the first time such a relationship has been observed in sheep farming. Since health-related factors explained 26% of the overall flock productivity, it is likely that factors such as flock nutrition, grassland management, farmer objectives or farmer attitudes (Townsley and Parker, 1987; Denney et al., 1990) could help to explain additional variability between farms.

This study illustrated that lamb sales data can be a useful source of information for baseline farm benchmarking which is less sensitive to recall bias issues than other sources of data reliant exclusively on farmer records. However, a drawback of the productivity index used in this study (i.e. number of lambs sold for meat per 100 ewes per year) is that farms keeping or selling a higher number of breeding animals, and therefore selling fewer lambs to the abattoir, will be classified as less productive . Future research that incorporates these additional aspects of lamb productivity would be beneficial.

Limitations of this study

It is difficult to be certain that the sample of farms responding to the survey was representative of the target population (i.e. commercial sheep farmers supplying finished lambs to a major British food retailer); farms that decided to participate in the development group may have been systematically different from those not participating (e.g. flock size, geographical distribution). Therefore a baseline assumption in our study is that the biological associations identified in this research would remain applicable to this wider population. Unfortunately a lack of published data (on general farm characteristics) hampers any comparison between our study and target populations which could help to confirm representativeness.

Other potential areas of bias in the sample population could have arisen from volunteer bias (responders being different from non-responders), recall bias (farmers having difficulty recalling practices carried out during the previous year), interviewer bias (answers to questions to questions being influenced by the person asking questions) and acceptability bias (farmers tending to give replies they feel place them in a good light).

Given the response rate (67%), the extent of volunteer bias is likely to be minimal. The very high response rate of this study could be due to three reasons. Firstly, all the data requested were to be collected at a single farm visit which required minimal effort from the farmer. Secondly, and perhaps more importantly, farmers were asked to participate by a party purchasing their lamb, with whom they already had a history of business and goodwill. And thirdly, we believe farmers were interested to know the results of the research and were told they were going to receive feedback on results.

Acceptability bias could have arisen because data were collected on behalf of a retailer and responses could have been biased if respondents considered that the answers provided may not have been anonymous. However, the distribution of the answers on sensitive areas suggests that there was no systematic alignment of responses with what is considered ‘best practice’. Responses were compared with data from previous studies, when available, and the responses did not differ considerably. For instance, rates of prophylactic usage of antibiotics at lambing were only slightly below that previously reported (Davies et al., 2017) and some farmers reported the use of antibiotics unauthorised for use in sheep.

Interviewer bias could have arisen from aspects of social desirability (especially relevant in sensitive questions) or normative question order effects (i.e. respondents adjusting their answers to take into account answers to earlier questions) (Dillman et al., 2009). To minimize this bias, interviewers were thoroughly trained on how to administer the questionnaire. A term for “interviewer” could have been used in the statistical models for adjust for any systematic influences of the interviewers but unfortunately this information was not available. Therefore, a baseline assumption of the study is that the influence of interviewer was minimal and, in particular, did not affect relationships between predictor variables and lamb production.

A final potential source of bias was recall bias. This was limited by carefully phrasing questions and using abattoir-reported data (which was further validated by farmers’ records) to estimate flock productivity. Furthermore, farmers were asked to use records to confirm their responses wherever possible.

Despite the possible limitations of this study, the associations found between husbandry practices and flock productivity represent the first evidence in identification of important management strategies with beneficial impacts on the productivity of commercial sheep flocks.

Conclusions

Results of the current study provide plausible estimates of the extent of implementation of disease control practices in commercial sheep flocks supplying finished lambs to a major British food retailer. The study offers novel insights into the importance of disease control practices and routine monitoring for greater flock efficiencies, highly pertinent for the sheep farming industry. The research also illustrated that lamb sales data are a useful and easily available source of information on flock performance although the accuracy of the productivity index could be further enhanced by collecting information on breeding lambs kept and sold for breeding and by incorporating more detailed abattoir data (such as carcass grades or deadweight information). Further research is needed to explore additional factors with a potential influence on flock productivity including an assessment of generalizability based on model cross-validation.

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Declarations of interest

The authors have declared that no competing interests exist.

Ethics statement

The study was approved by School of Veterinary Medicine and Science Ethics Committee (no: 1537 150907).

Software and data repository resources

Stata 15 was used for data cleaning and analysis. The model was not deposited in an official repository.

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Tables

Table 1. Farm and flock characteristics of 645 sheep farms participating in the study, stratified by farm geographical location and farm altitude.

	Number of farms	Median flock size (IQR – Inter-quartile range)	Median farm grassland area (Ha) (IQR)	Proportion of farms supported by an environmental stewardship[1]	Median number of lambs sold finished per 100 ewes per year (IQR)
Scotland	10% (64/645)	746 (IQR 450 – 1418)	291 (IQR 136 – 632)	25% (16/64)	107 (IQR 80 – 139)
North East and North West	16% (105/645)	900 (IQR 586 – 1300)	326 (IQR 196 – 540)	69% (72/105)	121 (IQR 96 – 147)
West Wales	38% (244/645)	356 (IQR 193 – 646)	78 (IQR 46 – 129)	59% (143/244)	97 (IQR 74 – 125)
North Wales and West midlands	22% (141/645)	544 (IQR 284 – 904)	120 (IQR 62 – 202)	60% (85/141)	104 (IQR 81 – 126)
South Wales, South West and South East	10% 63/645)	645 (IQR 315 – 900)	100 (IQR 60 – 175)	78% (49/63)	121 (IQR 104 – 146)
Northern Ireland	4% (28/645)	176 (IQR 117 – 317)	66 (IQR 26 – 115)	36% (10/28)	138 (IQR 115 – 160)
Lowland (0 – 200 m)	42% (270/646)	360 (IQR 192 - 750)	88 (IQR 45- 175)	54% (146/270)	118 (IQR 90 -148)
Upland/Hill (>201 m)	58% (376/646)	640 (IQR 348-1000)	140 (IQR 78 - 317)	61% (230/376)	100 (IQR 78 -124)

1 Environmental stewardships used to be defined as “an agri-environment scheme that provides funding to farmers and other land managers in England to deliver effective environmental land management” (from http://webarchive.nationalarchives.gov.uk/20140605104008/http://www.naturalengland.org.uk/ourwork/farming/funding/es/default.aspx , accessed at 27th February 2018), but this classification was recently updated and new categories apply. At the time of this survey, 58% of the studied farms were integrated in at least one type of environmental stewardships, such as “Higher level scheme” or “Sites of special interest”.

Table 2. Source of replacement sheep and health and control practices undertaken during quarantine to ewes and rams.

Husbandry practices		Ewes (% of farms)	Rams (% of farms)
Source of replacements	Replacements from livestock markets only	42% (165/392)	61% (325/526)
	Replacements direct from farm only	21% (83/392)	23% (120/526)
	Replacements direct from livestock markets and farm	6% (23/392)	6% (29/526)
	Did not buy in replacements	31% (121/392)	10% (52/526)
Procedures at quarantine	Administrated either a Group 4 or Group 5 anthelmintic (as recommended by SCOPS guidelines)[1]	32% (198/615)	28% (173/615)
	Applied a footbath	14% (65/475)	22% (103/475)

[1] The SCOPS (Sustainable Control Of Parasites in Sheep Initiative) group was created to develop sustainable strategies for control of parasites in sheep. According to SCOPS manual, "broadspectrum anthelmintics can be divided into five groups on the basis of chemical structure and mode of action: group 1 - Group 1 - BZ, Benzimidazole; Group 2 - LV, Levamisole (LV); Group 3 - ML, Macrocyclic lactones Group 4 – AD, Amino-acetonitrile derivatives; and Group 5-SI, Spiroindoles". Available at http://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

Table 3. Proportion of sheep farms carrying out disease control and prevention practices by region.

	Scotland	North of England	West Wales	North Wales and West midlands	South Wales and South of England	Northern Ireland
Proportion of farms weighing lambs during lactation	45% (29/64)	70% (74/105)	35% (86/244)	44% (62/141)	51% (32/63)	32% (9/28)
Proportion of farms vaccinating the breeding flock against abortion agents only	60% (39/64)	29% (30/105)	64% (156/244)	71% (100/141)	43% (27/63)	57% (16/28)
Proportion of farms vaccinating the breeding flock against abortion agents and clostridial agents	38% (24/64)	70% (74/105)	30% (74/244)	28% (39/141)	51% (32/63)	39% (11/28)
Proportion of farms giving a Group 4 anthelminthic to ewes during quarantine	16% (10/64)	28% (29/105)	18% (46/244)	13% (19/141)	21% (13/63)	14% (4/28)
Proportion of farms treating lame sheep according to the best practice	89% (57/64)	96% (101/105)	87% (212/244)	87% (123/141)	87% (55/63)	79% (22/28)
Median number of lambs sold for meat/100 ewes/year (IQR)	107 (IQR 80 – 139)	121 (IQR 96 – 147)	97 (IQR 74 – 125)	104 (IQR 81 – 126)	121 (IQR 104 – 146)	138 (IQR 115 – 160)

Table 4. Multivariable regression model of sheep flock characteristics and husbandry practices associated with flock productivity (number of lambs sold per 100 ewes per year) (n=615, R^2= 0.25).

	n	**Coefficient**	**Standard error**	**P-value**	**[95% Confidence interval]**	
Intercept		83.3	6.5	<0.01	70.5	96.1
Farm was not part of an environmental stewardship scheme	258	Reference category				
Farm was part of an environmental stewardship scheme	357	-10	2.7	<0.01	-15.2	-4.8
Farm elevation – Uplands/Highlands	360	Reference category				
Farm elevation – Lowlands	255	6.2	2.8	0.03	0.7	11.8
Flock size	615	-6.0 E-03	<0.1	0.1	-0.01	0.01
Total grassland area	615	6.0 E-04	<0.1	0.92	-0.01	0.01
Flock main breed type: pure hill breed[1]	234	Reference category				
Flock main breed type: terminal[2]	150	19.1	3.9	<0.01	11.5	26.6
Flock main breed type: rare or pedigree breeds[3]	17	21.5	8.1	<0.01	5.5	37.5

Flock main breed type: maternal type[4]	214	22.4	3.4	<0.01	15.8	29
Farmer did not weigh lambs during lactation	340	Reference category				
Farmer weighed lambs during lactation	275	12.2	2.7	<0.01	6.8	17.6
Quarantined ewes were not given a Group-4/5 anthelmintic at quarantine[5]	417	Reference category				
Quarantined ewes were given a Group-4/5 anthelmintic at quarantine[5]	198	8.7	3.5	0.02	1.3	15.1
Ewes were not vaccinated	31	Reference category				
Ewes were vaccinated against clostridial agents only	346	8.6	6	0.15	-3.2	20.4
Ewes were vaccinated against abortion agents and clostridial agents	238	17.4	6.2	0.01	5.2	29.6
Newborn lambs were not given oral antibiotics prophylactically	450	Reference category				

Newborn lambs were given oral antibiotics prophylactically	165	-3.1	3	0.31	-9.0	2.8

[1] Welsh mountain, Balwen Welsh Mountain, Swaledale, Blackface, Rough fell, Herdwick, Nelson South Wales Mountain, Kerry Hill, Badger face, Beulah Speckled Face, Easycare, North Country Cheviot, Welsh Mountain Hill Flock, Welsh Hill Speckled Face, and Cheviot breeds.

[2] Texel, Suffolk, Meatlinc, Berrichon, Dorset Down, Southdown, Hampshire Down, Beltex, Blue Texel and Charollais breeds.

[3] Jacob, Exmoor horn, LLanwenog, Bluefaced Leicester, Charmoise Hill, Dorset Horn and Devon Closewool breeds.

[4] Welsh half-bred, Welsh mule sheep, North of England mule, Scotch Mule, Romney and Lleyn breeds.

[5] The SCOPS (Sustainable Control Of Parasites in Sheep Initiative) group was created to develop sustainable strategies for control of parasites in sheep. According to SCOPS manual, “broadspectrum anthelmintics can be divided into five groups on the basis of chemical structure and mode of action: group 1 - Group 1 - BZ, Benzimidazole; Group 2 - LV, Levamisole (LV); Group 3 - ML, Macrocyclic lactones Group 4 – AD, Amino-acetonitrile derivatives; and Group 5-SI, Spiroindoles”. Available at http://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

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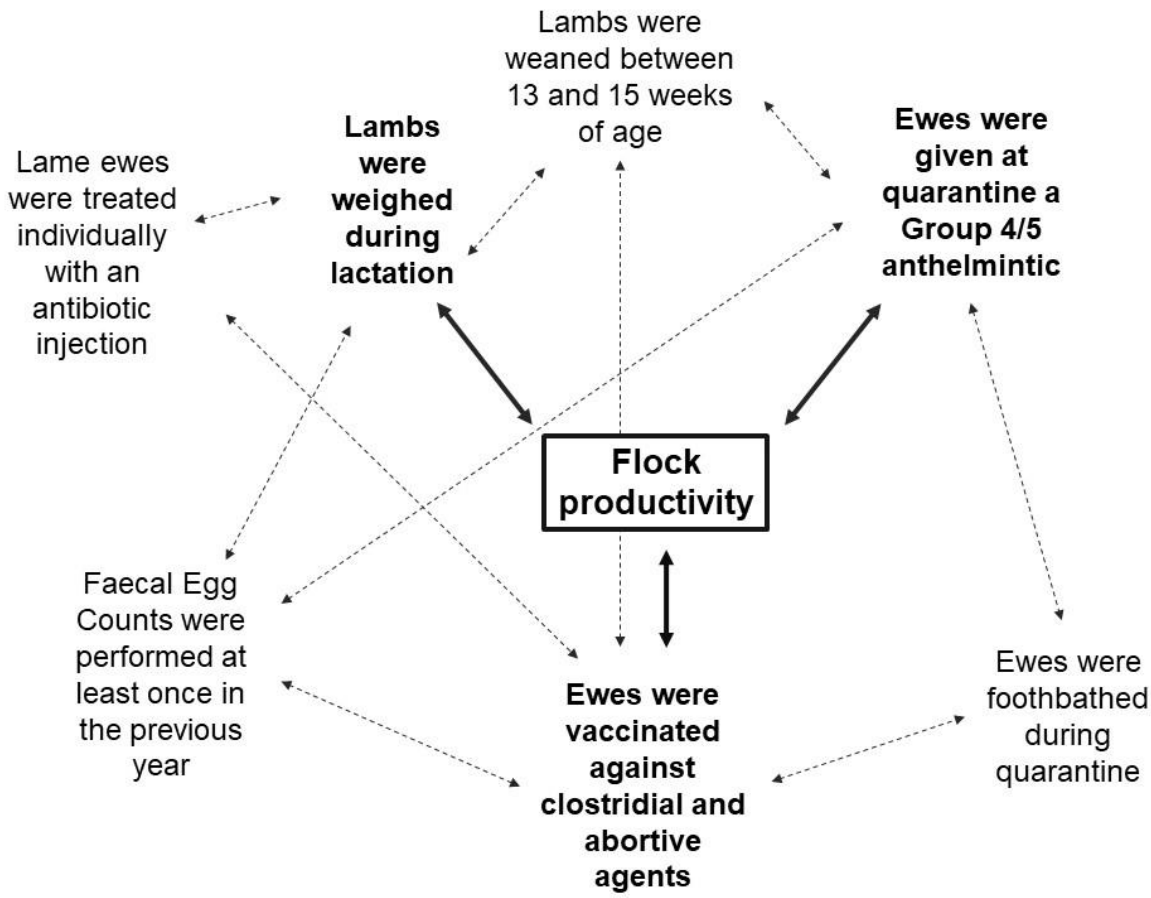

Figure 1. Associations between husbandry practices and their relationship with flock productivity (defined as the number of lambs sold for meat per 100 ewes per year). Please note that arrows represent associations rather than causality between variables. The *bold arrows* represent associations between the model predictors and flock productivity, and the *dashed arrows* indicate associations (assessed with a chi^2 test) between the model predictors and other flock management practices. A greater flock productivity was associated with the variables “lambs were weighed during lactation”, “ewes were vaccinated both against clostridial and abortion agents”, and “ewes were given a group 4/5 anthelmintic”. Several other variables were associated with these, suggesting that a greater flock productivity is associated with the implementation of a wider set of “good practices”.

Supplementary material

Using lamb sales data to investigate associations between implementation of disease preventive practices and sheep flock performance *(animal journal)*

Eliana Lima, Fiona Lovatt, Peers Davies and Jasmeet Kaler

Table S1. Animal movements on the studied sheep farms.

Animal movements on farm	**Median (IQR - Inter quartile range) per farm**
Number of ewes purchased	0 (IQR 0-50)
Number of store lambs purchased	0 (IQR 0-0)
Number of lambs sold finished to the abattoir	317 (140-588)
Number of lambs sold finished to other parties	52 (IQR 0-340)
Flock culling rate	14% (IQR 9% - 19%)

Table S2. Husbandry procedures undertaken during 2016 lambing period on the studied sheep farms.

	All lambs (% of farms)	**Some lambs** (% of farms)	**No lambs** (% of farms)
Ear tagging	12% (44/380)	6% (23/380)	82% (312/380)
Disinfecting lamb navel with iodine	68% (426/632)	22% (141/632)	10% (65/632)
Giving the lamb supplementary colostrum	3% (13/431)	48% (211/431)	48% (207/431)
Administering spectinomycin orally	31% (174/557)	28% (154/557)	41% (229/557)
Administer "oral tablet"	5% (23/420)	2% (6/420)	93% (391/420)

Table S3. Proportion of farms testing for broad-spectrum anthelmintic resistance in their sheep flock (Group 1 - Benzimidazole; Group 2 – Levamisole, and Group 3 – macrocyclic lactones)[1]

	Group 1 anthelmintics – Benzimidazole	**Group 2 anthelmintics – Levamisole**	**Group 3 anthelmintics – Macrocyclic lactones**
Proportion of farms carrying out a anthelmintic resistance test	19% (119/624)	14% (96/642)	12% (77/626)
Proportion of farms reporting evidence of anthelmintic resistance[2]	34% (41/119)	57% (55/96)	68% (53/77)
Proportion of farms reporting no evidence of anthelmintic resistance[2]	66% (78/119)	32% (31/96)	32% (24/77)

[1] The SCOPS (Sustainable Control of Parasites) group was created to develop sustainable strategies for control of parasites in sheep. According to SCOPS manual, "broad-spectrum anthelmintics can be divided into five groups on the basis of chemical structure and mode of action: group 1 - Group 1 - BZ, Benzimidazole; Group 2 - LV, Levamisole (LV); Group 3 - ML, Macrocyclic lactones Group 4 – AD, Amino-acetonitrile derivatives; and Group 5-SI, Spiroindoles". Available at http://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

[1] Out of those testing for anthelmintic resistance in the flock.

Table S4. Type of associations between disease control practices on the studied sheep farms. The associations between variables were assessed with a chi² test. A minimum number of 475 observations was required for a variable to be tested and all variables were coded in binary form to facilitate interpretation of the results.

	Farmer weighed lambs between birth and weaning	Quarantined ewes were given Group 4/5 anthelmintics	Ewes were vaccinated against Clostridial and abortion agents	Spectinomycin antimicrobial was administrated prophylactically to newborn lambs
Ewes were footbathed during quarantine	0.248	<0.001	<0.001	<0.001
Lame ewes were treated individually with an antimicrobial injection	<0.001	0.810	<0.001	0.429
Number of times Faecal Egg Counts were performed in a year	<0.001	0.014	0.063	0.531
Reason for worming lambs	<0.001	0.217	<0.001	0.139
Flock was screened for iceberg diseases in the previous year	0.073	0.139	<0.001	0.578
Flock resistance testing against Group 1 anthelmintics	<0.001	0.178	0.01	0.645
Flock resistance testing against Group 2 anthelmintics[2]	0.002	0.934	0.029	0.863
Flock resistance testing against Group 3 anthelmintics[2]	0.028	0.721	0.008	0.566
Method for recording culling information - notebook	0.673	0.073	0.019	0.785
Lamb age at weaning	<0.01	0.313	<0.01	0.035

[1]The SCOPS (Sustainable Control of Parasites) group was created to develop sustainable strategies for control of parasites in sheep. According to SCOPS manual, "broad-spectrum anthelmintics can be divided into five groups on the basis of chemical structure and mode of action: group 1 - Group 1 - BZ, Benzimidazole; Group 2 - LV, Levamisole (LV); Group 3 - ML, Macrocyclic lactones Group 4 – AD, Amino-acetonitrile derivatives; and Group 5-SI, Spiroindoles". Available at http://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

[2] Out of those testing for anthelmintic resistance in the flock.