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Studentship Project: Final Report

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CONTENTS

1. Abstract

The primary aim of this research was to address the lack of knowledge regarding factors influencing productivity on UK sheep farms, with a specific focus on the role of farm and farmer characteristics, flock management strategies and animal-related factors. The metrics of productivity of interest in this study were defined at individual level as 'lamb growth rate' and at flock level, as 'the number or value of lambs produced on farm'. A second objective of this work was to define a comprehensive productivity metric based on abattoir data and lamb sales (representing the 'value of lambs produced on farm') that could be used to compare different farm types. Given the importance of data collection and record-based decision making for more informed farm management, a third objective was to enhance the understanding of factors that influence the use of tools for recording on sheep farms, and to evaluate the impact of both farmer characteristics and attitudes towards flock recording technology.

Although further confirmatory studies are required, results of the research indicated that integrated management of health and nutrition of a sheep flock appear critical to productivity. Specific disease control practices associated with flock productivity were; vaccination against abortive and clostridial agents, control of mastitis and lameness in ewes, prevention of pregnancy toxaemia, improved ewe selection to minimise prolapses and fertility, and prevention of pneumonia, joint ill and arthritis in lambs. Body condition scoring of ewes was also found to be an important factor although the optimal timing to score was unclear and is yet to be fully elucidated. Grassland management practices appeared to play a key role in productivity and these included making use of rotational grazing, increasing use of fertilizer and maximising stocking rates. Interestingly, flock size had no clear relationship with flock productivity, indicating that both small and large farms can have high levels of productivity.

Importantly, the set of management strategies identified with a positive relationship with productivity are likely to be practical and implementable on most of sheep farms. An additional key implementable practice in most of the flocks is the collection of more frequent and accurate flock records; it was interesting to observe that an association between better recording practices and greater productivity was present throughout this research. This work also suggested that farmer attitudes appear to have a role in driving productivity, and as motivators and barriers for adoption of agricultural precision tools. Farmers with more a more positive attitude towards proactive business decision making tended to have increased farm productivity. In terms of farmer's attitudes towards electronic identification of sheep, three factors associated with the technology were important in differentiating adopters from non-adopters, 'practicality', 'usefulness' and 'external pressure and negative feelings'

In summary, this research has made a significant contribution to the expansion of current knowledge of factors influencing the productivity of UK commercial sheep farms.

2. Introduction

2.1. Sheep productivity; a review of past research

To remain sustainable, sheep farms need to maximise income whilst controlling costs and in particular, this means maximising income from lamb production. In this thesis, the key research questions concerned factors that influenced lamb production and in this context, lamb production was defined either at individual level as lamb growth rate or at flock level, as the number or value of saleable lambs produced on farm .

Despite the importance of lamb production to sheep farm profitability, there is very limited literature in this area. In particular, there is a notable lack of research evaluating the concurrent influence of multiple farm or farmer-related factors on lamb numbers, value or growth rates. Research conducted to date is summarised below; the first section describes research on lamb growth rates, the second section presents research on flock-level factors that influence lamb production.

2.1.1. Research on factors that influence lamb growth rates

A variety of genetic, nutritional and disease factors have been reported to affect lamb growth. One of the most studied aspects has been the influence of breed and sire genetics and the growth rates and weight of crossbred animals. Historic studies have compared the growth rates and carcass quality of lambs descendant from popular sire breeds such the Suffolk and Texel (Kempster et al., 1987; Leymaster and Jenkins, 1993; Wolf et al., 1980) but more recent studies have also evaluated the influence of these sires on local breeds. For instance, the superior growth of sheep from composite breeds compared to purebred animals has been reported in a recent longitudinal study in Patagonia, where cross-bred lambs (sire breeds included Texel, Suffolk and Dorset) raised under an extensive system were found to have greater liveweight gains from birth to weaning compared to Corriedale pure-bred lambs (Elizalde et al., 2018). In a previous fully randomised study in Brazil, Dorper crossbred lambs exhibited a greater daily liveweight gain (223.8 g/day) than Santa Inês pure bred lambs (168.1 g/day) (Souza et al., 2016). In the UK, the effect of sire genotypes such as Texel, Blue-Faced Leicester and the hill breed Scottish Blackface have also been evaluated; the weight of lamb weaned per ewe was significantly higher with Blue-Faced Leicester and Texel compared to Blackface sires (Carson et al., 2000). It is now recognised that the use of a terminal sire (i.e. rams used for production of good conformation lambs for meat) can increase lamb productivity, although some researchers highlight the possible need of additional assistance at lambing due to the greater birth weights of these animals (Carson et al., 2000; Elizalde et al., 2018).

Another factor reported to affect growth rates is litter size. In a study in the United States of America, Dimsoski et al. (1999) compared the growth of singles and twin lambs reared in three sheep management systems with different lambing times. They noted that single-born lambs had higher daily growth rates than twins in the three systems evaluated (Dimsoski et al., 1999). This increased growth rate of singles compared to twins was also observed in a recent study in the Czech Republic; Ptáček et al. (2017) found that single lambs tended to have greater birth weights and increased growth rates traits compared to twins (Ptáček et al., 2017).

A gender effect has also been identified in research on lamb growth (Arnold and Meyer, 1988); with males reported to grow approximately 15% faster than females (Andrews and Ørskov, 1970). The increased growth rates of males compared to females has been confirmed in more recent studies (Green et al., 1998; Yilmaz et al., 2007)

Historic studies have also researched the role of dietary protein content on lamb liveweight gains and wool production (Andrews and Ørskov, 1970; Kellaway, 1973). In the nineteen seventies, Andrews et al. (1970) investigated the role of different protein concentration (from 10 to 20%) on the growth rate of lambs and observed that liveweight gains responded curvilinearly to increases in dietary protein concentration. They estimated that the optimum crude protein concentration for growth (established at feeding levels very close to ‘ad libitum’) varied according to lamb liveweight, being about 18, 15 and 13% at body weights of 20, 25, 30 and 35 kg respectively (Andrews and Ørskov, 1970). More recently, Jimenez et al. (2019) published a meta-analysis of 21 controlled studies investigating the effect of concentrate supplementation and production system on lamb growth rates and carcass quality in lambs reared under extensive systems in different countries. The researchers reported that lambs finished in a feedlot or with supplementation under extensive systems exhibited faster growth rates and produced heavier carcase weights compared to grazing lambs. However, a large variability in this effect was found, possibly due to the wide range of breeds, climatic conditions, animal age and management factors across the assessed studies (Jiménez et al., 2019). In summary, these studies suggested a positive influence of feeding concentrates to lamb growth, but variability in this effect was observed and no cost benefits were evaluated.

Comparatively few studies have considered the management of grazing areas in terms of composition and type of grazing and its influence on lamb growth rates. In relation to pasture composition, a study in the UK considered the effect of three different swards (red clover, lucerne and perineal grass) on lamb growth. In this study, 10 rams and 10 ewes were rotationally grazed from weaning to finishing; greater average growth rates were observed in the red clover sward (305 grams/day), followed by the lucerne sward (243 grams/days) and finally perennial ryegrass sward (184 grams/ day) (Fraser et al., 2004). According to the authors, red clover provided a greater protein supply to the animal (Fraser et al., 2004). The effects of type of grazing (permanent/rotational) on Merino ewe liveweight were recently evaluated in a study taking place in extensive pastures in Australia; a rotational system with 20 paddocks provided greater lamb weight gains compared to both a 4-paddock and a permanent grazing systems (Badgery et al., 2017). The effects of mixed grazing (simultaneous sheep and cattle grazing) were evaluated in a meta-analysis of 16 controlled studies (D'Alexis et al., 2014). Both ewes and lambs at different ages and stages of production cycle in mixed grazing systems demonstrated greater average daily weight gains than those in sheep-only systems, but variation depending on age and state was observed. Interestingly, differences between mixed cattle and sheep and cattle-only grazing were not significant suggesting that sheep possibly exploit joint grazing between the two species better than cattle. The authors noted that the ratio between the two species for positive gains was important, with a maximum threshold ratio of 5 sheep to 1 cow (D'Alexis et al., 2014), however no information on the interaction between stocking rates and proportion of sheep/cattle effects was provided in the study. In summary, these studies suggest that there is a beneficial effect of rotational grazing, mixed-grazing systems, and legume-based pastures, but no studies have investigated the simultaneous effects of these practices or controlled for other potential confounding factors on growth rates. The importance of grazing aspects on flock productivity were considered when designing the questionnaire in this thesis.

Further studies have evaluated the impact of disease on lamb growth rates. In relatively old experimental studies it has been noted that lambs experimentally infected with footrot or Trichostrongylus colubriformis endoparasites had lower average growth rates compared to a control group (Coop et al., 1984; Marshall et al., 1991). Other studies have observed and compared average differences in weights/growth rates of groups of lambs affected and unaffected with pneumonia (Alley, 1987; Jones et al., 1982), lameness (Wassink et al., 2010), orf (Lovatt et al., 2012) and endoparasites (Coop et al., 1982); however there has been limited exploration of the influence of disease on individual lamb growth rate. Only a few studies have prospectively followed cohorts of individual lambs in order to quantify the impact of disease cases on lamb growth e.g. diarrhoea (Green et al., 1998; Huntley et al., 2012), endoparasites (Broughan and Wall, 2007) and ewe mastitis (Grant et al., 2016). Therefore, there is limited robust evidence on the impact of endemic diseases on individual lamb growth rates in the UK. Moreover, many previous studies have examined one factor at a time, despite the fact that these effects tend to occur simultaneously, meaning that inevitable complex and confounding relationships can be missed. The few studies that have integrated some information on more than one factor have reported that there can be multiple simultaneous influences on lamb growth (Green et al., 1998; Huntley et al., 2012; Juengel et al., 2018). A longitudinal study published in 1998 was the first in sheep farming to account for the simultaneous impact of multiple factors on lamb growth and to disentangle their effects (Green et al., 1998). This remains the only example of a study that prospectively assessed the specific effect of lamb disease on lamb growth in UK flocks. The researchers reported that lambs with diarrhoea showed a loss of approximately 2kg compared to non-affected lambs. The study also provided important insights into the impact of other factors (age, litter size, sex, farm of origin). However, despite taking place in the UK and in principle being relevant to the current national sheep industry, the study was carried out in three intensively housed rearing systems. Such systems play a negligible role in the sheep industry today and there remains a very limited understanding of the important factors that affect lamb growth in commercial UK flocks kept under extensive conditions, which is currently the norm.

In summary, it can be concluded that whilst there are a variety of published studies that provide information on basic factors that influence lamb growth, such as breed, gender and nutrition, only one longitudinal study has attempted to evaluate more detailed reasons for temporal changes in growth. There are few UK studies on factors affecting lamb growth that relate closely to current production systems and in particular, the understanding of the impact of endemic disease on lamb growth is poor and represents an important knowledge gap for the industry.

2.1.2. Research on productivity; the number and value of lambs reared on farm

There is a marked absence in the literature of flock-based studies investigating factors influencing the production parameters of interest in this research, namely the number of lambs reared on farm or lamb financial value. A few studies evaluating production-related metrics at flock level have been published. These can be categorised into survey-based (i.e. using commercial farm data) and simulation model-based (parameterised using expert opinion or experimental data); these studies are reviewed below.

Within the studies based on real farm data, several have focused on the financial aspects and technical efficiency of dairy sheep flocks (Milán et al., 2014; Theodoridis et al., 2014; Toro-Mujica et al., 2011; Tzouramani et al., 2011). Despite providing detailed flock financial information, these studies are of little relevance to the research questions in this thesis because the dairy systems studied are very different to those of meat production in the UK, and factors affecting production of milk are likely to be different to those affecting production of meat.

A few studies have been conducted in Spain and Egypt that have examined financial data in flocks producing lamb for meat. In Spain, in the region of Castilla-León, the cost structure and the profitability of 20 farms rearing Assaf sheep (a dual-purpose breed) were analysed. The sources of income in these flocks included milk (78%), lambs (13%), culled ewes (0.5%), wool and manure (<1%) as well as the farm support payments from the common agricultural policy (7%). Feeding accounted for the greatest proportion of costs (61%) followed by labour (18%) and equipment maintenance and depreciation (8%). Interestingly 40% of farms were unable to cover all the costs and had negative balances (Milán et al., 2014) which is similar to the poor economic situation of some sheep enterprises observed in the UK (see Section 1.1.2.3.2). A previous study taking place in Catalonia, Spain, examined the financial records of 52 farms dedicated to production of meat from Ripollesa sheep (Milán et al., 2003). The authors reported that farm income was correlated with the number of sheep in the flock (r = 0.48) and that the most diversified farms were earning more income than those exclusively dealing with sheep (Milán et al., 2003). European subsides represented on average 27% of the total income (Milán et al., 2003); this again emphasises the importance of subsides for sheep farming in other Europe regions outside the UK. A further study in the Aragón region, Spain, analysed technical and economic data from 49 farms. The authors developed a production function and used feed costs, depreciation of capital and labour as explanatory variables (Pérez et al., 2007). Despite the large variability in the variables distribution, feed and labour costs represented the main expenses. Again, the average farm income from production was small, showing the great dependency of sheep farms on EU subsidies. The authors concluded that the best technical efficiency results were obtained by extreme farms; either extensive, low cost farms without housing and one lambing per year with alignment towards seasonal lamb prices, or well-managed, more intensive prolific farms (Pérez et al., 2007). This study lacked detailed information on management practices which makes it less relevant to the research in this thesis. Whilst these studies (Milán et al., 2014, 2003; Pérez et al., 2007) are useful from a contextual point of view and for understanding the main sources of incomes and costs of meat sheep farms in other regions of Europe, there is a clear absence of production based indicators and no study has collected detailed information on flock management practices.

In contrast to more financial-based research, a few studies have investigated relationships between management practices and production based indicators, although none used the production metrics of interest in this thesis. A relatively old study in Egypt investigated the relationship between flock management practices and both production and financial metrics (measured as "total liveweight of litter at 4 months per kg of breedable ewe" and "annual gross income per ewe lambing" respectively) (Galal et al., 1996). One hundred and ninety-one animals (crosses between Finnsheep and local breed) were given to 67 households to farm with the purpose of collecting performance data over time. The farm gross income sources comprised culled rams, ewes, wool and manure; this contrasts with the UK conditions where the main sources of income from production are lambs. The authors reported that feeding represented the main expense and that the sale of lambs accounted for approximately 70% of the gross income with no relationship with flock size, although larger flocks had poorer financial performance. The only factor significantly associated with increased gross income per ewe was the permanent availability of a ram compared to only intermittent availability (Galal et al., 1996); this is in contrast to the UK situation where rams are only added to the flock for a limited period of time. Furthermore, because flock management and production systems between the two countries are very dissimilar (i.e. different flock sizes, types of breeds used, and different climatic and geographical characteristics), direct inferences about the studied factors in the UK context are not possible. It is worthy of note that all studies collecting financial data identified feedstuff costs as the greatest expense, which suggests that nutrition and feeding management are areas of sheep farm production worth investigating.

Two additional studies have evaluated the relationships between management practices and flock based indicators in Australia and New Zealand, two countries that have a production system more similar to the UK than Mediterranean countries, in terms of breeds used and grassland availability. Townsley and Parker (1987) analysed data on management practices and production indicators (mean autumn liveweights of one and two year old ewes) of 30 farms from New Zealand, collected through interviews. The factors associated with increased autumn liveweight were the availability of summer water, weighing animals and the type of grazing system employed (Townsley and Parker, 1987). This was the first study to control for different sources of confounders and to investigate the simultaneous effect of different variables, by using a least squares regression model. In a further study in Australia, Denney et al. (1990) compared the total production of wool per hectare against several management practices; stocking rate was the most important factor explaining 61% of the variance between farms, and sheep bloodline and farm location accounted for 13% of the remaining variation (Denney et al., 1990). The fact that these flocks were focused on the production of wool hampers comparisons with UK meat producing farms, but the different components of flock management simultaneously investigated (stocking rates, nutrition, breed type) are interesting from a study design point of view. Despite these interesting findings, both studies are old, and neither focused on the outcomes of interest of this thesis, therefore they are of limited relevance to the current research.

More recently, two simulation models were used to predict the costs and net profit associated with specific sheep farm management scenarios (Bohan et al., 2018; Raineri et al., 2015) in Ireland and Brazilian sheep enterprises. Raineri et al. (2015) used the opinion of a panel of sheep farmers to estimate the detailed production costs of a hypothetical, representative sheep farm from Sao Paulo state; according to their model, feedstuffs were responsible for most of the production costs (Raineri et al., 2015) which aligns with previous research. Nevertheless, by focusing only on costs, this research omitted an important component of the enterprise economics which are returns from lamb production; moreover, the results of this study are less useful in a UK context because sheep production systems are very different in Brazil. This is not the case in Ireland which is a country with the similar conditions of production to the UK. Bohan et al. (2018) used a stochastic budgetary model to investigate the effect of three different stocking rates and two prolificacy values on the number of lambs weaned per hectare and net profit in Irish flocks. They reported that as the number of lambs weaned per hectare rose from 16 lambs/ha to 27 lambs/ha the carcass weight produced per hectare increased from 272 kg/ha to 474 kg/ha corresponding to an increase in net profit from €361/ha to €802/ha (Bohan et al., 2018). Although this type of model is useful to evaluate production scenarios in the event of changes in these two specific parameters, it provides no information about other factors that affect productivity. Furthermore, since it was parameterised with experimental data there are questions around the applicability of these results to real-world, commercial farms.

In summary, whilst a detailed financial analysis is useful for an assessment of the profitability of sheep farms in the long term, the lack of incorporation of management practices hampers a comparison of the effects of these practices on profitability and flock performance. The few studies that have collected data on management practices and production indicators have not investigated the production metrics of interest in this thesis and have been carried out outside the UK in different systems and climates meaning it is difficult to be certain of the applicability of results to UK flocks. However, the types of variables studied (related to husbandry, feeding, management of grassland and stocking rates) and the methods used (regression methods that account for the potential effect of confounders) are of interest to inform the design of the current research. This review highlights a substantial and important gap in our current knowledge about management factors that influence the number of lambs sold and the value of carcasses in commercial UK sheep farms.

2.1.3. The influence of farmer attitudes on flock productivity

It is known from other agricultural fields such as dairy or arable that farmer attitudes can have an impact of farm productivity. However no such study has investigated the role of sheep farmer attitudes and beliefs on the productivity of their enterprises to date. The integration of psychology and social theories in previous research in dairy and arable farming allowed the capture of non-tangible aspects related to farmer goals, attitudes and beliefs (Gasson, 1973; Willock et al., 1999c; Wilson et al., 2001), which were shown to be predictive of farm outputs and farm financial metrics such as gross margins or profit (Leary and Gate, 2017; Mäkinen, 2013; Nuthall, 1999; Rougoor et al., 2000). The influence of UK sheep farmer attitudes on enterprise performance remains unknown and is worthy of investigation.

2.2. Summary of knowledge gaps, objectives of the PhD and thesis structure

Despite the considerable size of the UK sheep industry, it is less profitable that other UK agricultural sectors and this raises the question about the economic sustainability of sheep farming over the long term. A greater financial resilience could be achieved by less reliance on farm support payments and maximisation of returns from lamb production. However factors and flock management strategies that maximise lamb production and lead to sheep enterprises being more productive are not yet understood. While past research has explored single genetic, nutrition and disease factors impacting sheep productivity, the variety of study contexts and the different productivity metrics assessed have hampered direct comparisons between study findings on the relative importance of the variables studied. In this context, the development of a productivity indicator that could be applied to a range of farms types regardless of the focus of production would be useful to facilitate comparisons.

To date, no comprehensive study has assessed the impact of a wide range of factors on UK sheep flock productivity. This presents an important knowledge gap and opportunity for research that would potentially benefit the UK sheep industry. Against this background, the objectives of this work were defined as follows.

2.3. Aims and objectives

The overall aim of this project was to address the lack of knowledge about factors influencing productivity on UK sheep farms, with a specific focus on the role of farm and farmer characteristics, flock management strategies and animal-related factors. The metrics of productivity of interest in this study were defined at individual level as 'lamb growth rate' and at flock level, as 'the number or value of lambs produced on farm'.

The first objective of this research was to use an observational, cross sectional study to collect information on a wide variety of factors to investigate their associations with the number of meat lambs produced on farm. An additional objective of this work was to define a comprehensive productivity metric based on abattoir data and lamb sales (representing the 'value of lambs produced on farm') that could be used to compare different farm types.

The second objective was to improve the understanding of disease and other animal-related factors on lamb growth rates. For this, a longitudinal study design was used.

Finally, given the importance of data collection and record-based decision making for more informed farm management, the third objective was to enhance the understanding on factors that influence the use of tools for recording on sheep farms, and to evaluate the impact of both farmer characteristics and attitudes towards flock recording technology.

3. Materials and methods

3.1. Publications

Four scientific papers have been produced from this research and these are provided in an Appendix to this report. The materials and methods used are described in detail in these publications, including all methodological steps and analytic techniques. An outline of the data sources used during the PhD are provided below.

3.2. The data

Five datasets were used in this study and a brief description of these is provided below.

1) A dataset was used that contained questionnaire responses from 746 sheep farmers alongside the number of lambs each farm sold to the abattoir during a one-year period. The target population in this study were commercial sheep farms with a history of close collaboration with a major British

food retailer that supplied lamb meat through two specified abattoirs. The questionnaire had been designed prior to the start of this PhD project and focused mainly on flock health and disease control practices carried out by the farmers between September 2015 and September 2016. A figure for the number of lambs sold by each farm was provided by the participating abattoirs. All data were given to the University of Nottingham in anonymised form in a spreadsheet format.

2) A dataset of detailed information from 408 sheep farmers on flock management, farm and farmer characteristics. The target population for this study was commercial sheep farms with a history of close collaboration with a major British food retailer that supplied lamb meat through two specified abattoirs. The data were collected through a questionnaire designed during the PhD and that requested information about flock management practices undertaken between Autumn 2016 and Autumn 2017. More granular abattoir data than that used in the previous study (including carcass weights and quality) was provided by the collaborating abattoirs. Unique, anonymous farm producer codes were used to link the questionnaire and abattoir data.

3) A dataset was obtained from a single sheep flock located in west Wales. The data comprised multiple measurements and observations taken from ewes (n = 559) and lambs (n = 808) by trained farm staff. Lambs were weighed repeatedly during their growth period (between 3 and 7 weighing points per lamb) and disease treatment records were obtained for both ewes and lambs. These data were collected between January and October 2017 and were provided to the University of Nottingham in a spreadsheet format.

4) A dataset containing 430 farmer responses to a questionnaire designed and administered prior to the start of this PhD (by Jasmeet Kaler and Orla Shortall). Given the importance of flock recording to the sheep industry, the purpose of this questionnaire was to explore the importance of farmer attitudes towards new flock recording technologies. The target population for this study were commercial sheep farms with a history of close collaboration with a major British food retailer that supplied lamb through one specified abattoir. The dataset contained information about the farmer and farm, basic husbandry practices and a section on opinions about technology (specifically animal electronic identification). The data were provided in a Stata file, with farm and farmer information anonymised.

5) A set of abattoir data used in this research were collected and collated by two abattoirs that supply meat to a major British food retailer. This information was included data on deadweight, weight condemned, carcass conformation, carcass fatness level classification and date of slaughter. The information on carcass conformation and quality was aligned with national lamb prices to estimate a financial income per farm.

Software

The analyses presented in this thesis were carried out in Stata version 14, RStudio-software version 1.1.463 and Mlwin version 3.02. Microsoft Excel was used to perform data collation throughout the thesis.

4. Results

The four scientific publications produced (see Appendix) provide a detailed description of all results from this PhD. A brief outline is provided here to give an overview of key results from the different components of the research.

4.1. Objective 1a:

To evaluate husbandry factors with an influence on productivity at flock level, with a special emphasis on disease control practices. 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 with the number of breeding ewes on farm to estimate flock productivity (number of lambs sold for meat per 100 ewes per farm per year). The 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 or 5 anthelmintic to ewes (as recommended by the Sustainable Control of Parasites in Sheep Initiative) during quarantining, had a greater flock productivity than farms not implementing these. Flocks with maternal breed types had higher productivity indexes compared with flocks with either pure hill or terminal breeds, and farms weighing lambs during lactation had greater productivity than those not weighing. Importantly, these actions were associated with other disease control practices, for example, treating individual lame ewes with an antibiotic injection, and carrying out faecal egg counts as well as weaning lambs between 13 and 15 weeks of age suggesting that an increase in productivity may be associated with the combined effect of these factors. This study provided new evidence on the positive relationship between sheep flock performance and disease control measures and demonstrated that lamb sales data can be used as a baseline source of information on flock performance and for farm benchmarking.

4.2. Objective 1b:

To investigate additional factors related to flock nutrition, grassland management and animal selection with a relationship to flock productivity, defined in this case as financial lamb-derived revenue. From a population of 830 sheep farms, 408 farmers completed a detailed online questionnaire comprising over 300 variables. Total lamb-derived revenue was calculated for each farm which included the use of detailed abattoir information on carcass weight and conformation. The median flock size was 560 ewes and median land size 265 acres. The median revenue per acre from lambs sold during the study period (2017) was £197 (IQR=120-296) and median revenue per ewe £95 (IQR=72-123). A robust analytic approach using regularised (elastic net) regression with bootstrapping was implemented to account for multicollinearity in the data and to reduce the likelihood of model over-fitting. To provide model inference and allow ranking of variables in terms of relevance for follow up intervention studies, both covariate stability and coefficient distributions were evaluated. Factors with high stability and a relatively large positive association with revenue per acre were; increased stocking rate, fertilizer being used on most of the grazing land, the use of rotational grazing, decreased proportion of ewes with prolapses, separation of lame sheep from the rest of the flock, selecting ewes for culling based on prolapses and infertility, conducting body condition scoring of at least the majority of ewes in the flock at lambing, early lactation or weaning, increased farmer education and farmers with a positive business attitude. Additional factors with a high stability and relatively large associations with increased revenue per ewe were; never trimming diseased feet of lame ewes and keeping good farm records. This appears was the first study in animal health epidemiology to use bootstrapped regularised regression to evaluate a wide dataset to provide a ranking of the importance of explanatory covariates. From a wide dataset, this enabled identification of a relatively small set of variables with a potentially large influence on lamb-derived revenue which can be considered prime candidates for future intervention studies.

4.3. Objective 2:

To gain a better understanding of the role of lamb and ewe factors on lamb growth, with a special emphasis on the impact of disease cases. The primary aim of this study was to use longitudinal data to quantify the simultaneous effects of multiple ewe and lamb factors on lamb growth rate; a secondary aim was to evaluate model structures that specifically account for lamb grouping effects during the growth period and compare these to classical hierarchical growth rate models. A total of 4172 weight recordings from 805 lambs and data on disease events were collected over a 6-month period from a commercial pedigree sheep flock. Three mixed model structures were compared, hierarchical, cross classified and multiple membership, and final estimates determined within a Bayesian framework. The multiple membership structure provided the best model fit and was used for final inference; taking account of the effect of lamb grouping over time provided the best estimates of lamb growth rate. Ewe lameness and mastitis cases had a deleterious impact on lamb growth. Lambs from ewes identified with mastitis during lactation were on average 3.0 kg lighter during the four month growth period than lambs from unaffected ewes. Lambs from ewes that were not lame during pregnancy were 3.0 kg heavier at eight weeks of age than lambs from ewes with a least one lameness case during the same period. Lambs from ewes lame either during the first 4 weeks or between 4-8 weeks of a lamb’s life (but not lame during pregnancy) were also significantly heavier at 56 days of age, than lambs reared by ewes that were lame during pregnancy (2.8 and 3.3 kg respectively). Cases of pneumonia and bacterial arthritis in lambs had a significant negative impact on lamb growth with affected lambs being on average 5.5 kg and 2.2 kg less than non-affected lambs respectively after the disease event. Prior to a case of lameness or pneumonia, lambs were significantly heavier than unaffected lambs suggesting a possible trade-off between growth and immune function. Overall, the study provided evidence that a combination of ewe and lamb characteristics and disease events play an important role in determining lamb growth rate and that heavier lambs may be more susceptible to disease.

4.4. Objective 3:

To enhance the understanding on factors that influence the use of tools for recording of animal information on sheep farms, and to evaluate the impact of both farmer characteristics and attitudes towards flock recording technology. The results of the first studies in this thesis indicated that farmers with greater levels of flock productivity were carrying out more recording practices. The fact that individual electronic identification is mandatory in all adult sheep presents a great opportunity for more frequent and accurate recording on farms. The use of technologies such as Electronic Identification (EID) aid recording of individual animal specific information, but anecdotal evidence suggests they are not widely used. The aim of this study was to assess uptake of EID technology, and explore drivers and barriers of adoption of related tools among English and Welsh farmers, including the influence of farmer attitudes and demographic factors on the uptake decision. In this context, farm beliefs and management practices associated with adoption of this technology were investigated via a questionnaire. A total of 2000 questionnaires were sent, with a response rate of 22%. Among the respondents, 87 had adopted EID tools for recording flock information, 97 intended to adopt it in the future, and 222 had neither adopted it, nor intended adopting it. Exploratory factor analysis (EFA) and multivariable logistic regression modelling were used to identify farmer beliefs and management practices significantly associated with the adoption of EID technology. Exploratory Factor Analysis identified three factors expressing farmer's beliefs – usefulness and practicality, and external pressure and negative feelings. These results suggest that farmer beliefs play a significant role in technology uptake. Interestingly, non-adopters of technology were more likely than adopters to believe that 'government pressurise farmers to adopt technology'. In contrast, adopters were significantly more likely than non-adopters to see EID as practical and useful. Farmers with higher information technologies literacy and intending to intensify production in the future were significantly more likely to adopt EID technology. Importantly, flocks managed with EID tools had significantly lower farmer- reported flock lameness levels. These findings bring insights on the dynamics of adoption of EID tools and suggest that communicating evidence of the positive effects EID tools on flock performance and strengthening farmer's capability in use of technology are likely to enhance the uptake of this technology in sheep farms.

5. Discussion

The primary aim of this work was to address this substantial knowledge gap through the analysis of sheep production data, collected both at farm and at animal level, in order to generate a deeper understanding of these aspects. Four scientific publications have been produced and a detailed discussion of each objective is provided in these papers (see Appendix). Further discussion is provided below to draw out key themes and areas of relevance to the industry.

Two notable themes appeared several times during this research; lameness and recording keeping practices. Possible reasons for this are discussed below. The effect of grassland management on productivity was found to have a large effect and its importance in the productivity models means that this aspect deserves further attention and is also discussed below.

5.1. Importance of lameness to sheep farm productivity

The results presented in this thesis are the first to provide a detailed understanding of the impact of lameness on productivity at lamb level (i.e. lamb growth) and the first to estimate the impact of lameness management practices on flock level productivity (i.e. numbers and value of lamb produced). The only previous UK study reporting the impact of lameness on flock productivity had used solely the number of days to finish in affected and unaffected animals in a single flock (Wassink et al., 2010), and the research did not account for other possible confounding effects. The fact that several variables related to lameness prevalence and management were important predictors in several different models of sheep productivity may reflect the prevalence or severity of this disease. In this research, records of lesions or diagnoses of lameness were not available and therefore differentiation of the type of lameness was not possible. It is possible that variation may exist in terms of the impact on productivity of the different types or causes of lameness in relation to the types of management practices applied. It should be acknowledged that results in this thesis represent average effects across the different types of lameness that would have been present in the study farms.

Regardless of the cause, lameness remains an important condition on sheep farms, although research suggests that lameness prevalence has been decreasing in England from 11% in 2003 to 5% in 2013 (Winter et al., 2015). These estimates suggest that the target proposed by the Farm Animal Welfare Council, which recommended that the prevalence of sheep lameness should decrease to 5% by 2016 (FAWC, 2011), was met. The observed reduction is likely to be partly a consequence of a communication strategy run by the Agriculture and Horticulture Development Board focused on key areas of lameness control and prevention (‘5-point plan’) (AHDB, 2015). Interestingly the results of this thesis align with previous research that suggested that the best approaches for lameness control were to avoid foot trimming and to carry out individual ewe treatment with parenteral antibiotic (Kaler et al., 2010; Winter et al., 2015); it was found that farmers that undertook these practices had greater flock productivity.

While much lameness research has been carried out from a ‘sheep welfare’ and disease dynamics perspective, research investigating the costs associated with lameness control has been limited and this has resulted in a poor understanding on the economic aspects of the condition. A suggestion for future work is to build on the research carried out this thesis, which identified a strong positive association between implementation of best lameness management practices and financial returns, and add an assessment of the associated costs of lameness control. A complete economic assessment of lameness control may be useful to stimulate behaviour change and enhance lameness prevention strategies in the segment of the farmer population that greatly values financial aspects when making decisions (Willock et al., 1999a).

5.2. Importance of grassland management to sheep farm productivity

Practices related to grassland management had a relatively large effect size in the flock productivity models and are therefore potentially of great importance in determining flock productivity as measured by lamb-derived income. Interestingly, however, there was a relatively small of uptake of low cost grassland intensification practices by the farmers (e.g. only 50% of the farmers were rotationally grazing sheep). This raises questions as to why a greater number of farmers are not implementing such practices, and suggests that further research could focus on the farmer barriers and motivators for implementation of such strategies. It is possible that farm environmental considerations are playing a role in their decisions, which may explain why farmers do not manage grassland more intensively, but this is uncertain. Alternatively, it could be that there is little recognition of the importance of grassland management in terms of provision of optimal nutrition and health. Better grassland management is also likely to have a positive impact on decreasing nutritional diseases such as pregnancy toxaemia and could improve ewe body condition scores as well as enhancing lamb growth rates. Whilst previous research has assessed the relationships between rotational grazing and endoparasite burden in adult sheep and weaned lambs (Burke et al., 2009; Colvin et al., 2008), to date no research has assessed the impact of other grassland management practices such as fertiliser use, on sheep nutrition-related conditions such as pregnancy toxaemia or low weight gains. In fact, fertiliser use and soil research was the second most voted topic by New Zealand sheep farmers on the perceived most important areas for future research (Greer et al., 2015). A better understanding and communication of the exact value and cost benefit of improved grassland management, could contribute to greater farmer uptake of such practices and improved profitability across the sheep sector.

5.3. Importance of record-keeping to sheep farm productivity

A link between record-keeping and improved flock productivity was observed during the research and a detailed investigation of reasons for the uptake of technology for record-keeping was undertaken. This research is the first to report that sheep farmers who keep records and base decisions on data have greater flock productivity than those who do not, and this aligns with previous evidence from the cattle sector (Solano et al., 2006). Although, by integrating variables to capture farmer attitudes, this thesis has contributed to a better understanding of the uptake of record-keeping technology, there remains a poor understanding of which specific records farmers find most useful and how these records actually influence decision making. Further research to explore these areas would be beneficial to the industry and could include which records are of particular use in different systems (e.g. production of pedigree breeding animals, intensive lowland production of lambs for meat) and the extent to which flock size influences the types or methods of record-keeping needed within these systems. A deeper understanding of these aspects could help to maximise uptake of existing record keeping tools, such as those promoted by AHDB (https://ahdb.org.uk/knowledge-library/flock-notebook).

The use of EID in the UK has huge potential benefits, not only at farm level, but also for monitoring national trends. Sheep are the only species where use of individual electronic identification is mandatory in the UK and this could pose a huge opportunity for data collection on farm, data integration and communication at a central level for monitoring of national trends. Interesting areas to follow up from a health and production point of view would be monitoring of lamb growth and disease rates, but at present the use of this technology is only mandatory for animals older than one year (e.g. lambs not intended for slaughter) so its use on these aspects is currently limited. Other barriers for uptake of this technology and its use for the provision of a holistic monitoring platform were identified, such as the difficulty with the technicalities of the technology (i.e. integration with other systems on farm) and the perception that the technology is not trustworthy. It is likely these barriers would need to be addressed by the industry or government prior to the expansion of this technology for further use. It is possible that the work around minimization of such barriers could be useful for future integration of other agricultural precision tools on farms.

5.4. Limitations of this research and additional thoughts on causality

It is important to acknowledge two overarching limitations encountered during the PhD. These were the type and amount of data available for the research and the lack of financial figures to estimate the costs associated with the implementation of specific farm strategies and practices; these are discussed further below.

The lack of data available in the sheep farming sector means that robust indicators of industry performance or representative figures on the characteristics of sheep enterprises are missing.

While this can be stimulating from a research and investigation point of view, it also results in a lack of data for use in research or for comparison between research studies. The types of study used (cross-sectional) allowed an estimate of the relative importance of specified factors on flock productivity, but causality should be inferred with great caution from cross-sectional studies. Indeed, causal inference in observational epidemiology is problematic and it is suggested that evidence for a causal effect should be based on a series of guidelines such as those defined by the epidemiologist and statistician Bradford Hill in the nineteen sixties; 'strength, consistency, specificity, temporality, biological gradient, plausibility, coherence, experiment and analogy' (Hill, 1965). It can be argued that three of these criteria – consistency, plausibility and coherence - apply to several findings of this thesis, especially those related with flock health and nutrition. Although the evidence produced for causal inference is limited in this research, it is important to consider possible and plausible causal pathways (Pearl and Mackenzie, 2018) because this may influence the types of follow up studies undertaken. Consideration of causal pathways highlights the possible routes for particular factors having a causal effect and also identifies pathways that are unclear and that therefore represent areas where more research may be appropriate. A schematic representation of hypothesised causal pathways arising from this research is provided in Figure 1 This illustrates that many of the factors identified as associated with sheep farm productivity (e.g. grazing- or health-related factors) have a hypothesised causal effect by ultimately increasing available nutrient supply to lambs which would increase growth rates. It is also evident that casual pathways for other factors are less intuitive. Factors such as body condition scoring, farmer attitude and flock recording are unlikely to have a direct causal effect on productivity and understanding their mediating influences (e.g exactly how body condition scoring information is used to improve productivity or exactly how farmers use flock records to change decisions or practices to improve productivity) would be of substantial use in terms of implementing changes on farm. Whilst it is acknowledged that these possible causal pathways are entirely hypothetical (Figure 1), such hypotheses are useful to generate subsequent research questions which can confirm or refute the pathways proposed.

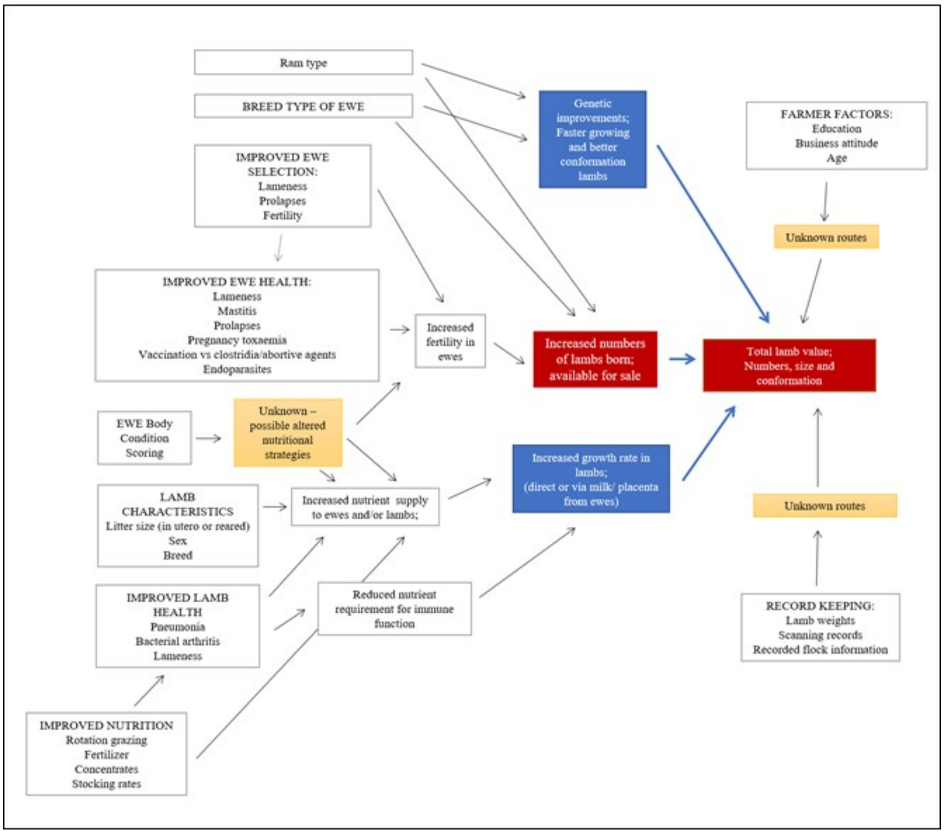

Figure 1. Hypothesis for possible causal pathways between the outcomes of interest (marked in red) and the variables found important in this thesis. The yellow squares represent the areas where there is no clear, straightforward path for the underlying biological processes and routes of causation.

It is also important to recognise the limitations but also the value of cross-sectional studies, especially in early stages of research. In the current thesis, such approaches allowed the identification of a set of candidate variables that can be followed up in future intervention studies.

The second main limitation of this thesis was the lack of information on the costs associated with the implementation of the management practices identified as beneficial. Results of this research demonstrate there is a clear relationship between specific factors and farm productivity, but the missing information on costs means that their medium and long term cost-benefit remains unclear. A future intervention study encompassing a smaller number of farms but focusing on detailed economic assessment of farms implementing a selection of these identified practices would allow the cost-benefit relationships of such practices to be established.

5.5. Potential future research areas

This thesis has focused on specific sheep farm populations of interest (those with available data) and therefore information on and inferences applicable to the whole UK sheep sector are missing. An overlap between the populations studied in this thesis (e.g. commercial sheep farms supplying lambs directly to an abattoir) and the whole UK sheep farm population undoubtedly exists, but it was not possible to measure the extent to which the samples used in this research reflects the wider UK population. Future research would ideally target the whole UK sheep population and also gather information on key performance indicators that would be useful for monitoring temporal trends in the sector. Other parameters of interest for further follow-up include changes in farmer demographics, shifts in production specialisation and intensification levels, and penetration of certain management practices in the sheep farming industry.

While several examples of future intervention studies have been given throughout this thesis, those focusing on practices with little cost but apparent great benefit should be given priority. Results from this thesis suggest intervention studies should mainly focus the impact of rotational grazing, the consequences of fertiliser application, and stocking rates, the relative possible decrease of concentrate dependence, methods to ensure lameness prevalence is low and methods to collect and use data in a commercial setting to optimise decision-making.

6. Industry messages

This thesis has contributed to an improved understanding of the associations between sheep productivity and specific factors and management strategies in UK commercial sheep farms selling the whole, or part, of the lamb crop for meat directly to an abattoir. In this research, different metrics of sheep productivity were used (i.e. number of lambs sold for meat per ewe per year per farm; financial return from lamb sales per year per farm; lamb weight), allowing the identification of factors with a relationship with productivity at flock and at lamb levels. The results of this research have highlighted the importance of the integrated management of health and nutrition of a sheep flock, with disease control practices being identified as important throughout this thesis. Grassland management practices also appeared to play a key role in productivity, but these were evaluated only in one of the studies in this research, and therefore a detailed assessment of these relationships is suggested for future research. Interestingly, flock size had no clear relationship with flock productivity, indicating that both small and large farms can have high levels of productivity. Importantly, this research resulted in the identification of a set of management strategies with a positive relationship with productivity that are likely to be implementable on most of sheep farms, and the incorporation of other less mutable factors, such as type of breed used, farm location or farmer demographic aspects, aided explaining variability between enterprises. One implementable practice in most of the flocks is the collection of more frequent and accurate flock records; it was interesting to observe that an association between better recording practices and greater productivity was present throughout this thesis. This work also suggested that farmer attitudes appear to have a role in driving productivity, and also as motivators and barriers for adoption of agricultural precision tools. Finally, this thesis provided information on the impact of disease in ewes and lambs on lamb growth, which may be useful to prioritise the diseases to control with the greatest impact on lamb production.

In summary, this work has made a significant contribution to the expansion of current knowledge of factors influencing the productivity of UK commercial sheep farms. It is hoped that the identification of such factors will ultimately be helpful to improve the economic sustainability of sheep flocks in the UK and worldwide.

7. References

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8. Appendix: Publications from the PhD

Lima, E., Green, M., Lovatt, F., Davies, P., King, L., Kaler, J. Use of bootstrapped, regularised regression to identify factors associated with lamb-derived revenue on commercial sheep farms (2020) Preventive Veterinary Medicine, 174, art. no. 104851. DOI: 10.1016/j.prevetmed.2019.104851

Lima, E., Lovatt, F., Green, M., Roden, J., Davies, P., Kaler, J. Sustainable lamb production: Evaluation of factors affecting lamb growth using hierarchical, cross classified and multiple memberships models (2020) Preventive Veterinary Medicine, 174, art. no. 104822. DOI: 10.1016/j.prevetmed.2019.104822

Lima, E., Lovatt, F., Davies, P., Kaler, J. Using lamb sales data to investigate associations between implementation of disease preventive practices and sheep flock performance (2019) Animal, 13 (11), pp. 2630-2638.DOI: 10.1017/S1751731119001058

Lima, E., Hopkins, T., Gurney, E., Shortall, O., Lovatt, F., Davies, P., Williamson, G., Kaler, J. Drivers for precision livestock technology adoption: A study of factors associated with adoption of electronic identification technology by commercial sheep farmers in England and Wales (2018) PLoS ONE, 13 (1), art. no. e0190489, DOI: 10.1371/journal.pone.0190489