Precision Livestock Farming: potential application for sheep systems in harsh environments

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LAY SUMMARY

Scottish hill sheep systems are comparable to other extensive sheep systems in harsh environments. They face difficulties such as low productivity, poor economic viability, labour availability and capability, and ensuring good animal welfare. They do however, play an important role for rural communities, environmental management, and production of sheepmeat and breeding animals. Exploring alternative approaches, such as Precision Livestock Farming (PLF), to overcome these difficulties is essential. PLF has been successfully applied to intensive systems but few examples exist for extensive systems.

Pregnancy supplementation and retention and culling decision making are key processes within hill sheep systems. How they occur can have major impacts on productivity and profitability of the system. Therefore, the aim of this thesis was to investigate and understand the capacity for application and potential impacts of PLF for hill sheep systems, when considered for two challenge areas: ewe pregnancy supplementation, and ewe retention and culling decision making.

Research was carried out on a hill sheep research farm, in the West Highlands of Scotland on a flock of 900 breeding ewes. Methods were applied and data collected from October 2013 to October 2016. Ewes were assigned to one of two management approaches. The first approach was a conventional one, where management decisions were carried out at a flock level, or without the assistance of Electronic Identification (EID) technology. The other approach was PLF, where management decisions were carried out at an individual animal level, assisted by EID and weighing technology.

A PLF approach was applied to allocate supplementary feed to pregnant hill ewes based on liveweight change. Inputs required (feed) and outputs (number of lambs born and liveweight of lambs) were similar between ewes allocated supplementation in the PLF approach and those allocated based on a stockperson's assessment of condition. However, the PLF approach successfully moved more individuals out of higher supplementation levels.

When considering retention and culling decision making of ewes, questionnaires carried out with stockpeople revealed many culling reasons were used. These were mostly based on the stockperson's opinion, and that little recorded information was used to inform decision making. Culling at a fixed age occurs on some hill sheep systems but this limits longevity. This thesis showed that ewes retained beyond a cull age were able to perform as well or better than younger ewes, and that a flock that did not cull based on age had the potential to improve profitability.

Comparison between individual ewes' performance, genetic and appearance attributes and their following year's performance, found that many common culling reasons (stockperson's opinion, number of lambs weaned, ewe age and ewe appearance) had little association with future performance. Conversely, promising attributes included liveweight, Body Condition Scores and liveweight change.

In conclusion, this thesis established that PLF can be applied to hill sheep systems using technology and individual sheep data to inform decision making, with the potential to improve productivity and profitability.

ABSTRACT

Scottish hill sheep systems are comparable to other extensive sheep systems in harsh environments around the world. They face a number of difficulties, including low productivity, poor economic viability, labour availability and capability, and ensuring good animal welfare. They do however, play an important role for rural communities, environmental management, and production of sheepmeat and breeding animals. Exploring alternative approaches, such as Precision Livestock Farming (PLF), to overcome these difficulties is essential. PLF has been successfully applied to intensive systems but few examples exist for extensive systems, such as hill sheep systems.

Pregnancy supplementation and retention and culling decision making are both key processes within hill sheep systems. How they occur can have major impacts on productivity and profitability of the system. Therefore, the aim of this thesis was to investigate and understand the capacity for application and potential impacts of PLF for hill sheep systems, when considered for two challenge areas: ewe pregnancy supplementation, and ewe retention and culling decision making.

This research was carried out on a 2,200 ha hill sheep research farm, in the West Highlands of Scotland. The majority of the land was unimproved hill pasture and around 230 ha of improved fields and semi-improved parks. Methods were applied and data collected from October 2013 to October 2016 from a long-term performance recorded research flock of 600 Scottish Blackface and 300 Lleyn breeding ewes. All 900 breeding ewes were assigned to one of two management approaches. The first approach was a conventional one, where management decisions were carried out at a flock level, or without the assistance of Electronic Identification (EID) technology, and was comparable to conventional hill sheep systems. The other approach was PLF, where management decisions were carried out at an individual animal level, assisted by EID and weighing technology.

A PLF approach was applied to allocate supplementation to pregnant hill ewes based on liveweight change. Inputs required (feed) and outputs (number of lambs born and liveweight of lambs) were similar between ewes allocated supplementation in the PLF approach and those allocated supplementation based on a stockperson’s assessment of their condition. However the PLF approach successfully moved more

individual ewes out of higher supplementation levels. This PLF supplementary approach could be consistently applied to any sheep system and constitutes a framework which can be easily modified and further developed. The work also demonstrated that liveweights could be collected quickly and reliably using automated weighing technology. Such technology and liveweight data are likely to be key for future developments of PLF approaches for hill sheep systems.

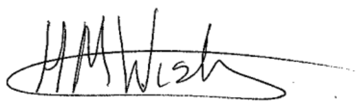
The second challenge targeted was retention and culling decision making of ewes from the breeding flock. Questionnaires carried out with stockpeople revealed many different reasons are used to make culling decisions. These reasons were mostly based on the stockperson's opinion and subjective assessment, and that little recorded information was used to inform decision making. Culling at a fixed age occurs on some hill sheep systems but this limits longevity and the associated benefits of increased longevity. Within the research flock, used in this thesis, the majority of ewes left the flock as a result of culling decisions and not because of death. However, findings showed that ewes retained beyond a standard cull age, were able to perform as well or better than younger ewes. A flock that did not cull based on age had the potential to improve profitability.

Comparison between individual ewes' performance, genetic and appearance attributes and their following year's performance, found that many common culling reasons (including stockpersons opinion, number of lambs previously weaned, ewe age and ewe appearance) had little association with future ewe performance. Conversely, promising attributes included liveweight, Body Condition Scores and liveweight change, all of which require data to be collected prior to any decision making. A PLF approach, that uses data collected about a ewe over its lifetime to make retention and culling decisions, has the potential to improve productivity and profitability of the system.

In conclusion, this thesis established that PLF can be applied to hill sheep systems using commercially available EID and automated weighing technology, as well as individual sheep data to inform decision making. Such application has the potential to improve productivity and profitability. For PLF to be widely adopted onto commercial sheep farms, further research will be required to demonstrate greater benefits to the system, including labour and welfare, and to better understand farmers' motivation towards uptake. Adoption of PLF approaches into hill sheep systems has the potential to benefit individual farms and the industry as a whole.

DECLARATION

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where stated otherwise, by reference or acknowledgment, the work presented is entirely my own.



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This PhD was funded by SRUC's Sponsored Education, for which I am grateful. Acknowledgement is also given to SRUC and Scottish Government's Rural & Environment Science & Analytical Services Division (RESAS) Strategic Research Programme, who funded the work I carried out at SRUC on the long-term recording of the Hill Sheep Breeding Project (where the majority of data originated from for this thesis).

Statistical assistance was gratefully received from Ian Nevison (Chapter 3) and Sarah Brocklehurst (Chapter 9). Ian assisted with the development of the delayed liveweight correction equation. Sarah assisted with a GenStat program that allow me to carry out the statistical analysis, and also spent time explaining ways to interpret the outputs, all of which was extremely helpful.

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Thank you to my family for the inspiration and motivation to carry out a PhD in agriculture. It is the huge respect and admiration I have for how hard you all work on the family farm that drives me to carry out research that, I hope, may one day assist in developing and improving livestock farming. Also, to all my family and friends for supporting me throughout and never getting bored of asking if I had finished yet! Thanks also to Simone for providing a final proof read of my manuscript.

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To all these amazing individuals, Thank you!

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ABBREVIATIONS

%Dev	Percentage Deviation
%SofS	Percentage Sum of Squares
3D	Three Dimensional
AC	Agreement Coefficient
Adj R^2	Adjusted R Squared
AHDB	Agriculture and Horticulture Development Board
ANOVA	Analysis of Variances
aWt1	Actual without delay liveweight
aWt2	Actual delayed liveweight
BCS	Body Condition Score
BioSS	Biomathematics & Statistics Scotland
BLUP	Best Linear Unbiased Prediction
CAP	Common Agricultural Policy
CON	Conventional
cPostWt	Mid-mating liveweight collected after delay, corrected to pre-gather liveweight
cPreWt	Pre-mating liveweight collected without delay, corrected to pre-gather liveweight
cWt1	Corrected aWt1 calculated from aWt2 using correction equation
Defra	Department for Environment Food and Rural Affairs
DM	Dry matter
DNA	Deoxyribonucleic acid
E-	Explanatory variables
E-all	Visual Appearance Assessment, Recorded Performance, and Estimated Breeding Values Explanatory variables
EBLEX	Agriculture and Horticulture Development Board (previously English Beef and Lamb Executive)
EBV	Estimated Breeding Value
E-EBV	Estimated Breeding Values Explanatory variables
EID	Electronic Identification
EMC	Ewe Marginal Contribution
ERA NET	European Research Area Network
E-RP	Recorded performance Explanatory variables
EU	European Union
E-VAA	Visual Appearance Assessment Explanatory variables
FAO	Food and Agriculture Organization of the United Nations

FAWC	Farm Animal Welfare Council
FMS	Farm Management Software
GLM	Generalised Linear Models
GPS	Global Positioning System
LF	Low Frequency
LFA	Less-Favoured Area
LM	Linear Models
ME	Metabolizable energy
MJ	Mega joule
MSE	Mean Squared Error
n	Sample size
NSA	National Sheep Association
PA	Precision Agriculture
PLF	Precision Livestock Farming
PostWt	Mid-mating liveweight collected after delay
PreWt	Pre-mating liveweight collected without delay
PY	Previous Year (year prior to stockdraw)
Q	Question from survey
QMS	Quality Meat Scotland
r	Pearson correlation coefficient
R-	Response variables
R-EMC	Ewe Marginal Contribution response variable
R-ES	Ewe survival at weaning response variables
RFID	Radio Frequency Identification
R-LmNo	Total number of lambs weaned response variable
R-LmWt	Total liveweight of lambs weaned response variable
ROC	Receiver Operating Characteristic
SAC	Scotland's Rural College (previously Scottish Agricultural College)
SD	Standard deviation
SE	Standard error
Sens	Sensitivity
Spec	Specificity
SRUC	Scotland's Rural College
SusSheP	Sustainable Sheep Production research project
TST	Targeted Selective Treatment
UHF	Ultra-High Frequency
UK	United Kingdom
VAA	Visual Appearance Assessment

CHAPTER 1: INTRODUCTION

Livestock are farmed on every continent in the world, apart from Antarctica. The characteristics, capabilities and constraints of livestock systems are the product of the physical, social and political environments in which they exist (Angus et al., 2009; Morris, 2017; Reed et al., 2009). All livestock systems have a number of globally important responsibilities, namely: resource production, to provide employment and to manage land (FAO, 2009; Godfray et al., 2010), which should be carried out in a way that the enterprises remain viable. However, such systems must consider resource use, animal welfare and environmental impact (Derner et al., 2017; Waterhouse, 1996).

Livestock systems are often found in environments unsuitable for other forms of agriculture or land use. These “harsher” conditions may relate to challenges in the landscape (steep or large areas of ground), climatic conditions (very wet, dry, cold, hot or windy) and resource availability, such as the growing environment for plants (not enough rain or water, poor soil structure or composition, short growing seasons, Kilgour et al., 2008; Ross et al., 2016). Sheep systems are most often found within these harsh environments, thriving in places where other livestock may have difficulties in surviving (Rossi, 2017; Zygoyiannis, 2006). An example of such a system is the Scottish hill sheep system, which has important roles for rural communities, environment management, and production of lamb meat and breeding animals (Royal Society of Edinburgh, 2008; Waterhouse, 1999). However, these hill systems also face a number of difficulties including low productivity, poor economic viability, labour availability and capability, and ensuring good animal welfare (Morgan-Davies et al., 2015; Renwick et al., 2008).

All livestock systems have evolved and adapted over time to benefit from advances in scientific knowledge and technology development (Burgess and Morris, 2009). Farming is currently going through a digital or technological revolution (Bronson and Knezevic, 2016; Gallardo and Sauer, 2018; King, 2017), with the increase in Precision Livestock Farming (PLF) approaches and technologies being part of this. PLF is an approach to managing livestock systems with the potential to improve productivity, economic viability, sustainability, welfare, and reduce labour (Banhazi et al., 2012b; Berckmans, 2017, 2004; Wathes et al., 2008). However, to date PLF research has largely focused on, and applied to, intensive livestock systems (Norton and Berckmans, 2017; van Hertem et al., 2016; Xin and Liu, 2017). Application to extensive systems, such as Scottish hill sheep systems, could provide a new approach to tackling the difficulties they face, as well as provide a model for other extensive sheep systems in harsh environments worldwide.

1.1 Thesis aim

The aim of this thesis is to investigate and understand the capacity for application and potential impacts of PLF for hill sheep systems, when considered for two challenge areas: ewe pregnancy supplementation, and ewe retention and culling decision making.

1.2 Thesis outline

This thesis is composed of ten chapters. The flow of information, data and findings between chapters can be seen in Figure 1.1.

Chapter 2 is a literature review that explores key points namely: the importance of Scottish hill sheep systems; the difficulties faced by these systems; definition of PLF as well as examples of previous applications; and what measures and technology are available and suitable for exploring PLF in hill sheep systems.

Chapter 3 describes the research settings, including the research hill sheep flock used for the majority of investigations and data collected in this thesis.

The next six chapters are separated into two parts, each addressing one of the two challenge areas.

1.2.1 PART 1 Challenge: Pregnancy supplementation

Part 1 considers the first challenge area of allocating pregnant ewes to supplementary feeding groups.

Chapter 4 determines how delayed weighing can alter the accuracy of liveweights and suggests methods of collection and processing, to ensure liveweights are reliable for PLF approaches.

Chapter 5 explores the feasibility, resources required and the impact on performance of a PLF compared to a conventional management approach for allocating supplementary feed to pregnant ewes, in hill sheep systems.

1.2.2 PART 2 Challenge: Retention and culling decision making

Part 2 concentrates on the second challenge of making ewe retention and culling decisions within hill sheep systems.

Chapter 6 identifies what current culling protocols are used on commercial sheep systems, including what information or technology are used to inform these decisions. This provides a record of what culling reasons could be considered in a PLF approach.

Chapter 7 provides an account of the possibility and implications of increasing Scottish Blackface ewes' longevity within hill sheep systems, where the flock had previously been culled at a fixed age. This provides information and knowledge on whether a PLF approach for making retention and culling decisions should consider the age of the ewe.

Chapter 8 aims to develop and test a tool which could be used to describe a ewe's appearance at stockdraw. This is to allow attributes to be quantified so they could be considered to inform a PLF approach to retention and culling decision making.

Chapter 9 uses findings from Chapters 6, 7 and 8 to explore the challenge of retention and culling decision making. It describes a method that could be used to develop a prediction model to inform a PLF approach for making retention and culling decisions and to identify potential predictor variables.

Finally, Chapter 10 considers the findings from all preceding chapters and discusses the possibility and potential impacts of applying PLF to hill sheep systems.

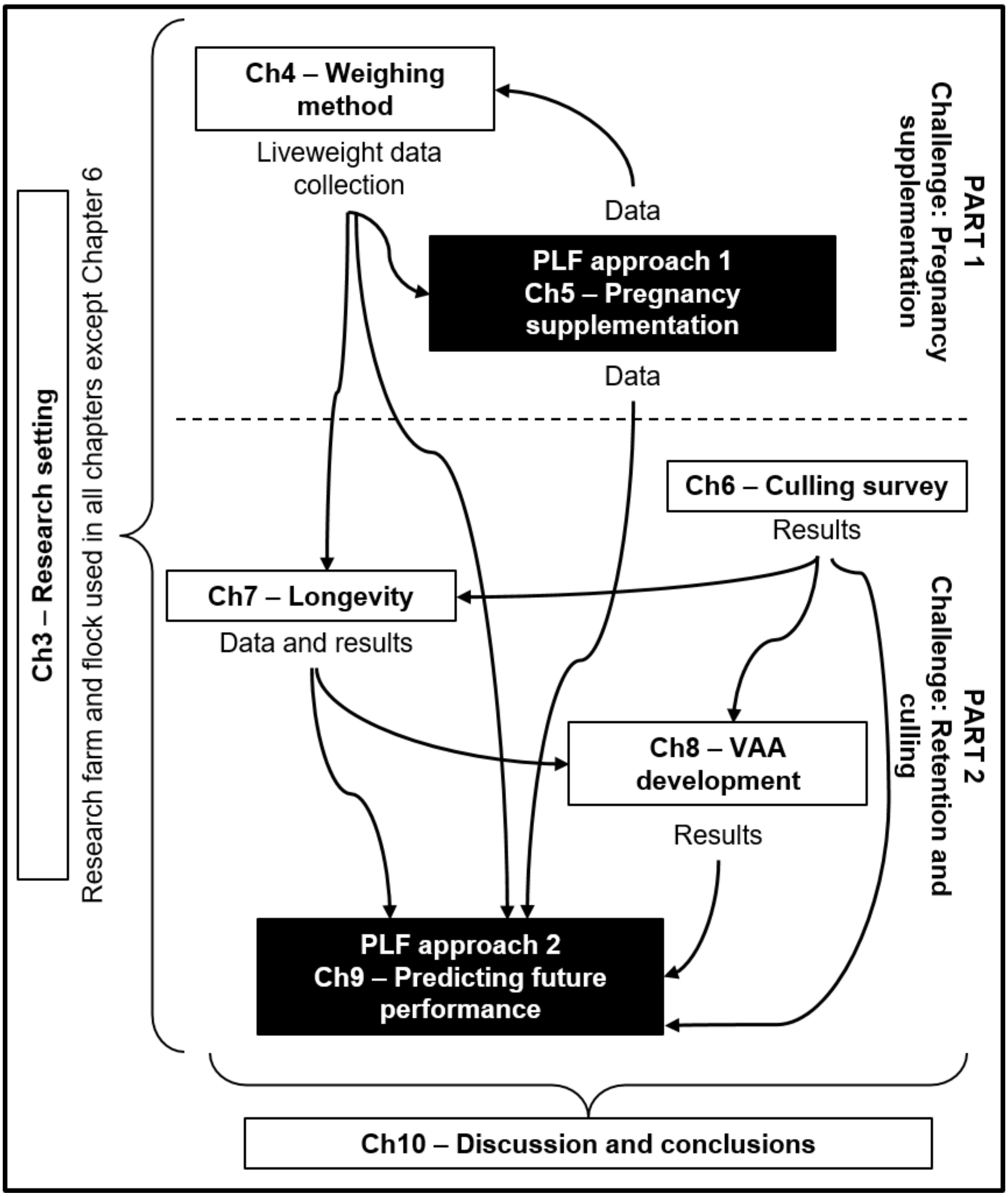


Figure 1.1 Thesis layout and how results and data from one chapter inform and are associated with other chapters.

1.3 Publications

Chapters 4 and 5 have been adapted from a published paper and conference proceeding, respectively. Initial stages of research for Chapters 4 and 9 were published as conference proceedings. These publications are:

Wishart, H., Morgan-Davies, C., Stott, A., Wilson, R., Waterhouse, T., 2017. Liveweight loss associated with handling and weighing of grazing sheep. Small Ruminant Research, 153, 163-170. [Chapter 4].

Wishart, H., Lambe, N., Morgan-Davies, C., Waterhouse, A., 2014. The effect of duration of removal from grazing on body weight in sheep measured with an automated weighing system, in: British Society of Animal Science. Nottingham, UK, p. 15. [Chapter 4].

Wishart, H., Morgan-Davies, C., Waterhouse, A., 2015. A PLF approach for allocating supplementary feed to pregnant ewes in an extensive hill sheep system, in: Proceedings of Precision Livestock Farming ’15. Milan, Italy, pp. 256-265. [Chapter 5].

Wishart, H., Lambe, N., Morgan-Davies, C., Waterhouse, A., 2016. Brief Communication: Which traits best predict ewe performance and survival the following year on a UK hill farm?, in: Proceedings of the New Zealand Society of Animal Production. Adelaide, Australia, pp. 159–162. [Chapter 9].

1.4 Research team publications

This PhD was carried out part-time over six years. During this time I held the position of research technician for the research flock on which this thesis research was applied. I was also involved in conference proceedings and peer-reviewed research papers published by colleagues in my research group. These included:

Kenyon, F., Morgan-Davies, C., Lambe, N.R., Wishart, H., Waterhouse, A., McBean, D., McCracken, D., 2017. The application of a weight-based targeted selective wormer treatment (TST) strategy on hill and upland sheep flocks, in: Advances in Animal Biosciences, Precision Management of Grassland and Grazing Livestock. Edinburgh, UK, p. 891.

Kenyon, F., Morgan-Davies, C., Lambe, N.R., Wishart, H., Waterhouse, A., McBean, D., McCracken, D., 2017. Application of weight-based targeted selective

anthelmintic treatment (TST) strategy on hill and upland sheep flocks, in: Proceedings of the 9th International Sheep Veterinary Congress. Harrogate, UK.

Morgan-Davies, C., Lambe, N., McLaren, A., Wishart, H., Waterhouse, A., McCracken, D., 2015. Labour profiles and Electronic Identification (EID) technology: assessing different management approaches on extensive sheep farming systems, in: Agro2015, 5th International Symposium for Farming Systems Design. Montpellier, France.

Morgan-Davies, C., Lambe, N., Wishart, H., Waterhouse, A., Kenyon, F., McBean, D., McCracken, D., 2018. Impacts of using a precision livestock system targeted approach in mountain sheep flocks. Livestock Science 208, 67–76. [Appendix 2].

Morgan-Davies, C., Lambe, N.R., Kenyon, F., McBean, D., Wishart, H., McCracken, D., 2016. Introducing a Targeted Selective Treatment worming approach on a hill farm using Electronic Identification of lambs, in: BSAS - Advances in Animal Biosciences - Animal Science for a Sustainable Future. Chester, UK.

Morgan-Davies, C., Lambe, N.R., Waterhouse, A., Kenyon, F., McBean, D., Wishart, H., McLaren, A., McCracken, D., 2017. Evaluating precision management of sheep in a hill farming system, in: Advances in Animal Biosciences, Precision Management of Grassland and Grazing Livestock. Edinburgh, UK, p. 892.

Morgan-Davies, C., Lambe, N.R., Wishart, H., Kenyon, F., McBean, D., Waterhouse, A., McLaren, A., Borthwick, F., McCracken, D., 2015. Integrating electronic identification in hill farming management, in: EAAP 66th Annual Meeting. Warsaw, Poland, p. 195.

Morgan-Davies, C., Wishart, H., 2015. Electronic Identification : Making the most out of compulsory tagging. SRUC Rural Policy Centre, Edinburgh.

Morgan-Davies, C., Wishart, H., Lambe, N., McLaren, A., Kenyon, F., McBean, D., Waterhouse, A., Umstätter, C., 2014. Improving efficiency in hill ewes for a better climate, in: McCracken, K. (Ed.), Delivering Multiple Benefits from Our Land: Sustainable Development in Practice. Edinburgh, UK, pp. 241–244.

Morgan-Davies, C., Wishart, H., Lambe, N.R., Kenyon, F., McBean, D., 2015. Integrating EID technology into hill sheep farming management, in: 4th Farm Animal Imaging Conference. Edinburgh, UK.

Morgan-Davies, C., Wishart, H., Lambe, N.R., Kenyon, F., McBean, D., Waterhouse, A., McCracken, D., 2015. EID and other Technological Advances in Small Ruminant Research. International Animal Health Journal 2, 64–66.

Umstätter, C., Morgan-Davies, C., Stevens [Wishart], H., Kenyon, F., McBean, D., Lambe, N., Waterhouse, A., 2013. Integrating Electronic Identification into Hill Sheep Management, in: Berckmans, D., Vandermeulen, J. (Eds.), Precision Livestock Farming ’13. Leuven, Belgium, pp. 412–420.

Wishart, H., Lambe, N., 2019. Variation in individual feed intake profiles recorded in group-housed lambs, in: British Society of Animal Science. Edinburgh, UK, p. 21.

CHAPTER 2: LITERATURE REVIEW

This literature review has three distinct sections. The first section presents Scottish hill sheep systems, how they compare to other sheep systems globally, their importance and the difficulties they face. One option for addressing these difficulties is through a PLF approach. The second section defines and characterises what PLF is and provides examples of where the approach has been researched and previously applied. The final section considers the feasibility of applying a PLF approach to two challenges of hill sheep systems, in order to address some of the difficulties faced. Potential measures and technology available for PLF application are also considered. The two challenges are only briefly presented; literature reviews on these topics are carried out in later chapters.

2.1 Scottish hill sheep systems

2.1.1 Characteristics

Sheep systems' characteristics differ globally in terms of flock size, breed, main production output (meat, milk, wool or live animals), and management practices, as a result of climate, environment and society (Dýrmundsson, 2006; Kilgour et al., 2008; Morris, 2017; Zygoyiannis, 2006). Even within the UK, three different types of systems are identifiable: hill, upland and lowland (Kilgour et al., 2008; Morris, 2017; Waterhouse, 1999). Scottish hill sheep systems are the focus of this thesis, however they share many common characteristics with other sheep systems, both within the UK and around the world.

2.1.1.1 Environment

2.1.1.1.1 *Climate*

There is an estimated worldwide population of 1.4 billion sheep (FAOSTAT, 2017). These sheep are found in production systems on all six of the habitable continents. The highest proportions of sheep are found in the temperate zones, specifically in parts of Europe, Asia, Australia, New Zealand and South America (Morris, 2017; Zygoyiannis, 2006). Scotland is within this temperate zone but has a strongly oceanic climate (wet and mild). Sheep systems found in similar climates include those in the North Atlantic region such as Norway, the Faroe Islands and Iceland (Ross et al., 2016). This climate is different to other countries within temperate zones, which tend to be drier and either hotter or colder.

2.1.1.1.2 *Landscape*

Livestock grazing is estimated to cover 26 % of the Earth's ice-free land surface (FAO, 2009), with the majority being cattle and sheep. In Scotland, 80 % of the total land area is classed as agricultural holdings (6.2 million hectares, The Scottish Government, 2018a). The majority (5.7 million hectares) is classified as Less-Favoured Areas (LFA – Article 2 of EU Council Directive No. 75/268/EEC), meaning land that "*has a natural disadvantage which makes agricultural production difficult"* (The Scottish Government, 2018a, p.3). Most of Scotland's LFA is on elevated upland or hill land, where hill sheep systems are found. This hill land provides a number of services and uses including: farming, forestry, energy production, sporting activities, nature conservation and for access and recreation (Morgan-Davies et al., 2015).

Other sheep systems that also utilise large areas of elevated hill land are found elsewhere in the UK (Lake District, Snowdonia), Ireland, Europe (Alps, Pyrenees), New Zealand, and many other mountain landscapes around the world (Morris, 2017; Ross et al., 2016; Waterhouse, 1999).

In Scottish hill sheep systems, ewes spend the majority of the year on hill pasture at low stocking rates (0.5-2 ewes per hectare) often on open hill land not separated with fences between neighbouring farms (Waterhouse, 1996). Common grazing (where the same land is co-grazed by sheep from different farms) happens in some areas of Scotland, as well as in Norway and Iceland (Ross et al., 2016). A flock of ewes will "heft", whereby the group will graze and stay on a particular area of the hill, their home-range (Morgan-Davies et al., 2016). These "hefted" or "bound" flocks are an important aspect of Scottish hill sheep systems. A hill sheep farm might have multiple flocks that graze different hefts on the same farm. The hefted flocks are preserved by retaining ewe lambs in the breeding flock with their dams so they can learn their area of hill to graze (Kilgour et al., 2008; Waterhouse, 1999).

2.1.1.1.3 *Natural grazing resource*

Quantity and quality of pasture available for hill sheep systems globally is typically poor. This is a result of the climate, soil type, and the geography of hill land which makes pasture improvements (such as fertilisation) challenging (Kilgour et al., 2008; Ross et al., 2016; Waterhouse, 1999). The Scottish climate results in a short growing season so quantity of fresh grass growth is limited to certain periods of the year. This is common in other countries in the North Atlantic region (Ross et al., 2016). Scottish hill sheep system pastures are also often found on acidic soils, with a range of native grasses and heathland plants (such as *Nardus stricta*), which are often of poor digestibility (Ross et al., 2016; Royal Society of Edinburgh, 2008; Waterhouse, 1999).

Sheep systems worldwide often graze on the poorest quality of land and pasture (Morris, 2017). If the land was more accessible and more productive it would likely be cultivated or used for more intensive livestock production. In these grazing environments, sheep have a number of advantages over cattle including: ability to forage and survive in places where cattle would struggle to perform well; better able to utilise water and nitrogen; produce wool as well as meat and milk; and being smaller in size means they are more agile in mountainous areas (Zygoyiannis, 2006).

Although the flat, dry, barren expanses of Australian sheep systems may appear different to Scottish hill sheep systems, they still suffer the same challenges of managing large areas of land and animals with insufficient natural resources available (Morris et al., 2012; Morris, 2017).

2.1.1.2 Sheep and flock

2.1.1.2.1 *Breed*

Sheep breeds vary widely between systems and locations worldwide. Hill systems within the UK are similar to Scottish hill sheep systems in many aspects; however, hill breeds vary between locations. In Scotland, the primary breed is the Scottish Blackface followed by the Cheviot, whereas in northern England and Wales, the Swaledale and Welsh Mountain are more prevalent, respectively (Pollott, 2012). In Ireland, Scottish Blackfaces and Cheviot are also important (Annett et al., 2011, 2010; Carson et al., 2001).

Across Britain the Scottish Blackface is the most abundant pure-bred breed, at 8.6 % of all ewes (Pollott, 2012). As with all hill breeds, Scottish Blackfaces are hardy, have a small mature size and produce lambs with lightweight carcasses when slaughtered (Morris, 2017). As with any hardy sheep breed worldwide, Scottish Blackfaces are suited to the harsh hill environments due to physical (wool characteristics), physiological (cold tolerance) and behavioural (grazing behaviour) adaptations (Waterhouse, 1999).

2.1.1.2.2 *Flock*

Flock size also varies greatly both within UK sheep systems and globally. Australia and New Zealand have the largest flocks, sometimes with thousands of animals (Morris, 2009). Scottish hill sheep systems are more comparable to flocks within Europe, that tend to have hundreds as opposed to thousands of animals (Dýrmundsson, 2006). Within Britain, Welsh sheep systems have the smallest flocks followed by the English then Scottish flocks (Waterhouse, 1999). There is an average of 200 breeding ewes per holding across Scotland (The Scottish Government, 2019), although this number is much higher for hill systems (Waterhouse, 1999).

Hill sheep systems are often closed flocks with females joining the flock as homebred "replacements" (Waterhouse, 1999). This is important for maintaining a hefted flock but also leads to higher health status as there is less risk for new or different diseases to be brought in (Kilgour et al., 2008). Rams are however often bought from other hill farms to ensure different genetics enter the flock and reduced risks from inbreeding.

2.1.1.2.3 *Production*

Globally three main types of sheep production systems have been identified: extensive production of wool and meat, intensive dairy production, and traditional pastoralism (Kilgour et al., 2008; Morris, 2017). Scottish hill sheep systems are considered extensive systems and will be focused upon. Extensive sheep systems are found around the world and differences between these, across the UK, New Zealand, Australia and Uruguay, were reviewed by Morris (2017). As well as producing meat and wool, Scottish hill sheep systems also provide breeding animals for use on other farms and systems. The importance of each of these products for Scottish hill sheep systems will be considered later.

Even within Scottish hill sheep systems, differences can be identified. The most traditional and widespread system type (and the focus of this thesis) is characterised by flocks that are hefted to the hill land where they spend the majority of the year unsupervised and movement of animals to upland systems occurs (Waterhouse, 1999). Alternative systems include those that have more productive or improved land and are able to produce and finish cross-bred animals. Hill sheep are also found in crofting systems, in the North-West Highlands and Islands of Scotland. These are small farming setups often carried out part-time and with small flocks (Kilgour et al., 2008).

2.1.1.3 Management practices

2.1.1.3.1 *Husbandry, handling and monitoring*

The typical production year for Scottish hill sheep systems starts in the late autumn/early winter when mating occurs, resulting in lambing in the spring (Figure 2.1). These timings are fixed as a result of the climate and when spring-grass becomes available (Morris, 2017; Waterhouse, 1999).

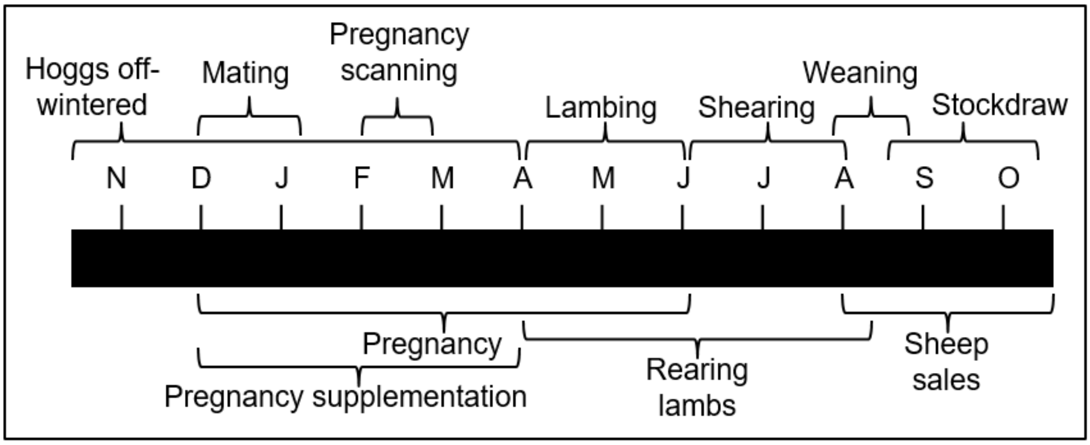


Figure 2.1 Events and processes of a standard Scottish hill sheep system production year.

Due to the extensive hill areas and low stocking density, little daily shepherding occurs. The animals are also largely unsupervised until key handling points (Waterhouse, 1999). The lack of frequent inspections and stress caused by occasional handling can compromise welfare (Goddard et al., 2006). Such welfare concerns are common with other extensive sheep systems (Kilgour et al., 2008; Morris, 2017) and shall be explored later.

Within UK hill sheep systems, females in their first year of production (known as “gimmers”) are typically mated for the first time at 1.5 years of age and lamb at 2 years of age (Kilgour et al., 2008). After lambs are weaned from their dam in late summer, but before mating, the flock is sorted through by a stockperson in a process referred to as “stockdraw”. During stockdraw, retention and culling decisions are made on which ewes should remain within the breeding flock (retained) and which should be sold, or moved to other types of sheep systems (culled). Within these hill sheep systems, ewes are often culled from the flock at a fixed age, typically after their fourth or fifth crop of lambs (Kilgour et al., 2008). If these ewes are still considered to be productive (“sound”) they are often referred to as “draft” ewes.

In geographical areas within the UK where hill sheep systems are prevalent, there are many specialist sales of breeding rams, draft ewes and spare female lambs (Kilgour et al., 2008; Waterhouse, 1999). These sales allow for genetics to be shared between farms and system types (Morris, 2017). Male hill lambs are also often sold in the autumn to upland and lowland systems to be fattened, or “finished” ready for slaughter (Waterhouse, 1999). This movement of animals between hill, upland and lowland areas is part of the UK stratified sheep industry, which is somewhat unique compared to any other sheep systems around the world (Kilgour et al., 2008; Morris, 2017; Waterhouse, 1999).

2.1.1.3.2 *Wintering*

Within Northern Europe, the extensive systems on marginal upland or hill/mountain land also vary between those that bring ewes inside during the winter (in Nordic and Alpine regions) and those where animals remain outside throughout winter months, such as Scottish hill sheep systems (Dýrmundsson, 2006; Ross et al., 2016; Waterhouse, 1999). For the latter case, supplementation is often provided, specifically for pregnant ewes, to overcome the poor quality of nutrition and quantity of grass available during the winter (Fthenakis et al., 2012; Henderson, 2002; Kilgour et al., 2008).

Another important characteristic of Scottish hill sheep systems, which is perhaps less common in other sheep systems, is that replacement ewe lambs are often “away-wintered” after weaning (Morris, 2017). They are moved to a farm on lower land with a greater quality and quantity of pasture availability during the winter. This not only ensures they have sufficient grazing during their first winter but also reduces the grazing pressure on the hill farm when grazing is already limited (Kilgour et al., 2008). Moving flocks to different pastures depending on season and time of year is carried out in other areas of the world but, in those transhumance systems, the stockpeople move with flocks (Waterhouse, 1999). Within the Scottish systems, while the replacement ewe lambs move to different areas, the responsibility of care often shifts to the stockperson on the relocated farm.

To conclude, although Scottish hill sheep systems are somewhat unique to any other sheep system globally, they do share many characteristics with many systems, particularly extensive ones. This makes Scottish hill sheep systems a suitable case study on which different management approaches could be trialled, while ensuring findings could be applicable to other systems.

2.1.2 The importance of Scottish hill sheep systems

This section aims to identify why and to what extent Scottish hill sheep systems are important. Four outputs and responsibilities of these systems are: production outputs; role within the UK’s stratified sheep industry; employment and income for rural areas; and management of the hill environment.

2.1.2.1 Production outputs

2.1.2.1.1 *Meat*

The three main production outputs from UK hill sheep systems are meat, wool and breeding animals. It is estimated that by 2050 the global human population will increase to 9.8 billion (UN DSA PD, 2017), with the demand for meat from livestock also expected to rise (FAO, 2009; Godfray et al., 2010). In 2018 poultry was the largest source of meat, producing 36.3 % of the world's meat, followed by pork (36 %) then beef (21.6 %), while sheep meat was the fourth largest source making up just 5 % of total world meat production (FAO, 2018a). Indeed, pigs and poultry are able to convert feed to muscle/meat with greater efficiency compared to ruminants (Derner et al., 2017; Morris, 2009). However, the advantage ruminants have over these systems is that they are able to utilise grasslands (unsuitable for cultivation) by converting grass into protein suitable for human consumption (Morris, 2009). Furthermore, sheep are able to thrive and produce meat in environments cattle would find challenging (as previously discussed).

While sheepmeat is of modest significance on the worldwide meat market, it is one of the most important products from sheep systems around the world. Indeed, world sheepmeat production was forecast to reach 15 million tonnes in 2018 (FAO, 2018a). China was forecast to be the largest producer (and importer) of sheepmeat in 2018, followed by Australia (FAO, 2018b). The UK was the sixth largest producer and third largest exporter of sheepmeat (Colby, 2015). Within the EU, the UK produced the largest proportion (39 %) of sheep and goat meat, followed by Spain (17 %), while Ireland produced the fifth largest (8 %, Rossi, 2017). In 2017, a total of 89,400 t of Scottish sheepmeat was exported, of which the majority (94 %) went to EU countries (QMS, 2018a). Furthermore Scotland produced enough sheepmeat for 191 % of the potential consumption in Scotland in 2017 (QMS, 2018a).

However, even though these figures suggest the importance of sheepmeat to Scotland, and while finished sheep and lamb contributed £209 m in 2017, this was only 7 % of Scotland's total agricultural output (with the 93 % remainder composed of: finished and store cattle at 22 %; other livestock and livestock products 28 %; and cereals, potatoes, horticulture, capital formation and other agricultural work 43 %, The Scottish Government, 2018b).

While it is not possible to determine the exact extent of sheepmeat produced from Scottish hill sheep systems, it is likely to be significant. In 2017 the Highlands and

Islands region, which has a large proportion of hill farms (Renwick et al., 2008), held the third largest proportion of the total 2.9 million head of breeding ewes across Scotland compared to any other region (13.6 %, QMS, 2018a). Furthermore, sheep production made up 20 % of the estimated output per hectare of the region, which was greater than any other region in Scotland (The Scottish Government, 2018b). Moreover, 21.9 % of slaughter lambs within the UK in 2012 were from pure-bred hill ewes but this proportion increased to 60.1 % when slaughter lambs from all hill ewes crossed with other breeds were also included (Pollott, 2012).

Sheepmeat from Scottish hill sheep systems also has the potential to be viewed as having added value compared to other sheep systems due to the production method. Extensively rearing animals on the hill is often viewed by consumers as providing higher standards of welfare, compared to other systems, by allowing animals to exhibit more natural behaviours (Derner et al., 2017; Goddard et al., 2006; Montossi et al., 2013). This is in spite of their welfare potentially being compromised by the harsh weather, limited grass and limited supervision of animals (Kilgour et al., 2008; Morris, 2017; Stott et al., 2012, 2005; Waterhouse, 1996).

Therefore, meat produced from Scottish hill sheep systems may appear modest both for Scotland's agricultural outputs and for national and worldwide meat markets. However, it is still important for its capacity to produce meat from the large areas of hill land unsuitable for other more intensive farming activities.

2.1.2.1.2 *Wool*

Historically wool was an important product globally, providing a key textile with which clothing could be made. Wool production was the main reason why sheep numbers increased within the UK and Scotland in the 19th century (Riddell and Walker, 2011). However, with development and popularity of modern textiles the importance of wool production significantly reduced. Nowadays, even within countries where wool production is considered important and profitable, such as Australia, Uruguay and New Zealand, there has been a change towards breeds suitable for both wool and meat production (Morris, 2017).

Even though wool production forms a source of income from hill sheep systems it is minimal, as demonstrated through the results of QMS's annual survey of profitability of Scottish cattle and sheep enterprises. Of the 22 LFA hill flocks included in the report the average income from wool was £ 1.50 per ewe which, when compared to lamb sales at £ 56.04 per ewe, accounts for very little income (QMS, 2018b).

2.1.2.1.3 *Breeding animals*

As well as meat, an important output from hill sheep systems is breeding animals; these support the stratified sheep industry seen in the UK.

2.1.2.2 Role within the UK's stratified sheep industry

The UK sheep industry has a stratified structure, which is based on the natural resources in different areas and movement of sheep between system types (Kilgour et al., 2008; Waterhouse, 1999, Figure 2.2).

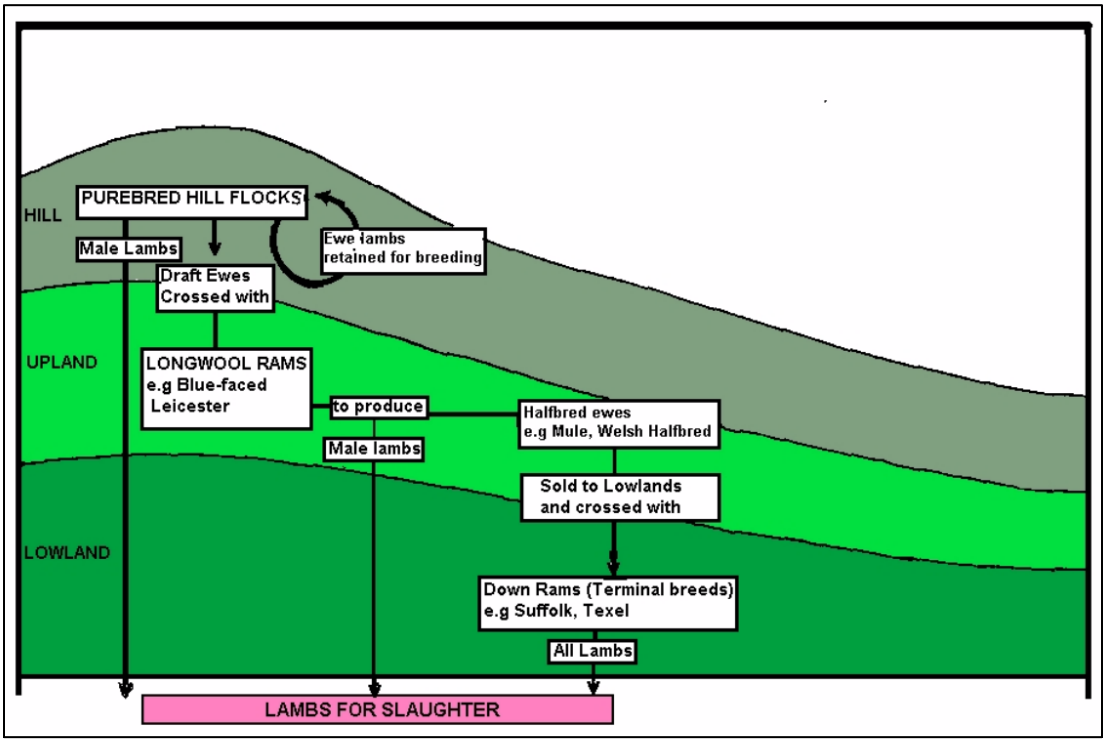


Figure 2.2 The stratified sheep breeding structure of the UK sheep industry (Waterhouse, 1999).

The movement of animals between these systems is well known (Kilgour et al., 2008; Morris, 2017; Rodriguez-Ledesma et al., 2011; Waterhouse, 1999). Spare pure-bred hill ewe lambs (not required for replacements of the hill sheep flock) and draft ewes move from hill systems to upland systems. Upland systems tend to be lower in altitude than hill types with better weather and improved grazing available, thereby resulting in better production outputs. Draft hill ewes that move to upland systems, can be bred from for a further one to three years, due in-part to these easier environmental conditions (Rodriguez-Ledesma et al., 2011). Hill ewes are crossed with longwool sires producing female offspring crosses called "Mules", which then move to lowland systems. These lowland systems have the best resources available in terms of pasture quality and quantity compared to the other two system types. Mules are bred with terminal sires to produce lambs for slaughter. Male lambs produced from all three system types, and female lambs from lowland systems, tend to be fattened and finished ready for slaughter on upland and lowland farms due to the improved nutrient resources available (Waterhouse, 1999).

Through this stratified system genetics are passed to different parts of the sheep industry. Therefore the genetic characteristics of the hill sheep population are very important. Crossing of hill ewes results in offspring with hybrid vigour (heterosis) and therefore higher output potential (Derner et al., 2017; NSA, 2016; Rodriguez-Ledesma et al., 2011).

While stratification is still believed to be prevalent particularly within Scotland's Highland and Island regions, which are predominately LFA hill farms (Rodriguez-Ledesma et al., 2011), there are indications that the structure is breaking down. In 1971 in Britain the ratio of sheep between a stratified to non-stratified breeding structure was 86:14 which changed to 71:29 in 2003 and by 2012 the ratio was almost equal at 55:45 (Pollott, 2012). However, this was determined from a report on the number of sheep within different breeds within Britain. Whether the stratification is breaking down or different breeds are being kept by different farms instead is unknown.

The stratified structure of the UK sheep industry breaking down could have economic implications for Scottish hill sheep systems, if there is less demand and market for animals from the hill systems (draft ewes, ewe lambs and male lambs for finishing). Another possible outcome is that older sound ewes, normally drafted from hill flocks after their fourth or fifth crop of lambs, may be retained longer within the flock. The possibility and potential impacts if this occurred are currently unknown.

2.1.2.3 Employment and income for rural areas

Hill sheep systems also provide important levels of employment and income in rural areas (Morgan-Davies et al., 2012). Although exact figures on people earning a living from hill sheep systems are challenging to determine, Scotland-wide agriculture figures provide a useful indication of the situation.

A Scottish Government publication, “Rural Scotland Key Facts 2015”, reported that agriculture, forestry, and fishing combined provided the largest source of private sector jobs (16 %) in remote rural areas and the second largest in accessible rural areas (12 %, The Scottish Government, 2015). In 2018, while 67,000 people in Scotland were employed in agriculture, this was only 2.5 % of all employed in all sectors, although this is higher than the UK total of 1.5 % (The Scottish Government, 2019). Interestingly, in 2015 only 37 % of people working on Scottish agricultural holdings were “working occupiers” (meaning a person that owned or rented a farm and worked on it) and only 14 % of working spouses were working full-time on farms (The Scottish Government, 2016a). The low rate of full-time employment suggests potential issues with the reliability and availability of jobs within Scottish agriculture as a whole. When considering hill sheep systems this situation is more striking, with 68 % LFA cattle and sheep holdings reported to have a standard labour requirement of less than one full-time equivalent (The Scottish Government, 2016a). This suggests that only a limited number of people are gaining full-time work from such farms.

A steady decline in full-time agricultural employment is seen across Scotland and particularly within the Highlands and Islands, where hill sheep systems are prevalent (Renwick et al., 2008; Thomson et al., 2011). The cause of this reduction was suggested by Thomson et al. (2011) as the result of full-time farming being unable to provide sufficient income. Indeed the 2016 Economics Report on Scottish Agriculture summarised that 84 % of farms in Scotland over 2014-15 were carrying out income generating diversified activities (The Scottish Government, 2016a), suggesting that alternatives to farming were being sought to provide sufficient income.

The poor employment and rural income supplied by hill sheep systems is exacerbated further when the impact on other businesses associated with the system is considered. The “Response from the hills” report (Thomson et al., 2011) concluded that the reduction in Scottish sheep flocks and beef herds had negatively impacted on other businesses, including: livestock suppliers, haulage companies, veterinarian practices, auction marts, and abattoirs.

To conclude, while hill sheep systems do provide employment within rural communities directly, and indirectly through associated businesses (Renwick et al., 2008; Thomson et al., 2011), there are challenges associated.

2.1.2.4 Management of the hill environment

2.1.2.4.1 *Biodiversity*

The interaction of hill sheep systems and biodiversity is usually discussed within research when grazing is increased or decreased (for example DeGabriel et al., 2011; Holland et al., 2008a; Pollock et al., 2013; Renwick et al., 2008). Historically Scottish hills and uplands have been considered to have been ‘over-grazed’ resulting in negative impacts on some elements of biodiversity, including the loss of *Calluna* heathland cover, reduction of lichen cover and restriction of native tree regeneration (Ross et al., 2016). In contrast, removing grazing of hill pasture altogether may also have negative impacts on biodiversity (Holland et al., 2008a; Ross et al., 2016).

Through carrying out field studies Pollock et al. (2013) found that reduction in grazing sheep numbers were associated with: increased deer numbers; increased abundancy of dwarf-shrub cover (heather, *Calluna vulgaris*); increased vegetation height; and decreased rough grasses and dead material (possibly a result of increased deer numbers). Increased deer numbers, as a result of decreased sheep grazing numbers, is viewed within literature as being a negative outcome for the environment (DeGabriel et al., 2011; Gilbert, 2010). As well as damaging heather and restricting plant diversity (DeGabriel et al., 2011), it has also been reported that increased deer numbers spread and increase the incidence of tick-borne diseases which can infect humans, mountain hares and grouse (Gilbert, 2010). However, deer presence is not necessarily believed to be detrimental to the hill environment. DeGabriel et al. (2011) suggested that mixed grazing (sheep and deer) can enhance habitat quality and maintain plant diversity. Management of sheep grazing is therefore an important element in the debate of hill use and its biodiversity.

2.1.2.4.2 *Landscape*

The uplands and hills of Scotland are not only used for production (livestock, timber and renewable energy) but also for recreational purposes (tourism, public access and hunting) as reviewed by Morgan-Davies et al. (2015). The “open landscape” that is seen as attractive is believed to be anthropogenic as a result of keeping and grazing livestock (Fenton, 2008; Gibon, 2005; Ross et al., 2016). Although there is an argument that grazing should be stopped to return the Scottish uplands to a more ‘natural’ image containing trees (Fenton, 2008). However, Fenton (2008) argued that the treeless landscape could actually be the result of non-human causes and therefore the current landscape could be more natural than many presume. Whatever the cause of the largely treeless landscape, The Royal Society of Edinburgh (2008) suggested that public opinion of the Scottish hills and islands is that managed hills for grazing is more desirable than an un-kept version.

This evidence suggests that hill sheep systems are important to the Scottish hill environment through maintaining current biodiversity and managing a landscape considered to be attractive.

2.1.3 Difficulties of hill sheep systems

Scottish hill sheep systems face a wide range of difficulties and threats to their operations, many of which are shared by other sheep systems around the world (Table 2.1). Four of these difficulties have been explored further in the following sections. Identifying and discussing difficulties for hill sheep systems is important in order to consider what improvements could be made.

Table 2.1 Difficulties faced by sheep systems (references specific to Scottish hill sheep systems in bold).

Difficulty	**References**
Low productivity	Morris, 2017; **Renwick et al., 2008; Waterhouse, 1996**
Poor economic viability	Morris, 2009; **Renwick et al., 2008**; Stott et al., 2012; **Waterhouse, 1999**
Labour availability and capability	Colby, 2015; Montossi et al., 2013; **Morgan-Davies et al., 2018; Renwick et al., 2008; Waterhouse, 1996**
Maintaining good animal welfare	**Goddard et al., 2006; Morgan-Davies et al., 2012**; Morris et al., 2012; Munoz et al., 2018; Stott et al., 2012; **Waterhouse, 1999**
Sustainability of system	Bernués, 2016; Bernués et al., 2011; Jones et al., 2013; Nguyen et al., 2013; Thompson, 2009; **Waterhouse, 1996**
Risk from predators	**Dýrmundsson, 2006**; Morris, 2017; **Renwick et al., 2008; Ross et al., 2016**
Disease outbreaks	Colby, 2015; **Renwick et al., 2008; Ross et al., 2016**
Market volatility	FAO, 2018a; Morris, 2009; **NFU, 2017**
Policy changes	**Angus et al., 2009; Hubbard et al., 2018; Renwick et al., 2008**
Influence of weather on performance	Henderson, 2002; **Jones et al., 2005; Sarout et al., 2018**
Conflict with other land users	**Angus et al., 2009**; Burgess and Morris, 2009; **Morgan-Davies et al., 2015**

2.1.3.1 Productivity

The Scottish Blackface is the most commonly used breed within Scottish hill sheep systems (Pollott, 2012). Previous research found that Scottish Blackface ewes can wean around 1.2 lambs per ewe mated (Annett et al., 2010; Carson et al., 2001). Industry reports present similar values of around 1 lamb reared per ewe mated (AHDB, 2015a; QMS, 2018b). QMS's reports on "Cattle and sheep enterprise profitability in Scotland" (2013; 2016; 2018b) showed that LFA sheep enterprises had a rearing rate of 0.9-1.2 lambs per ewe mated, which was lower than upland (~1.5) and lowland sheep systems (~1.6).

Low rearing values are in part caused by the high mortality rates of lambs within these hill sheep systems (Waterhouse, 1996). Research presenting lamb losses were summarised by Waterhouse (1996) and showed a range of 10-60 % lamb losses. While these values derive from over 20 year old research, similar losses are still quoted. AHDB (2015a) suggested that in a hill sheep system overall 14 % of lambs, identified through ultrasound scanning of ewes in mid-pregnancy, are lost by weaning or 11 % that are born are lost before weaning.

Causes, and therefore targets, to improve productivity (in terms of number of lambs reared) fall into three main categories: nutrition, genetics, and management (Henderson, 2002; Parker and Waterhouse, 1986; Sawalha et al., 2007; Waterhouse, 1996).

AHDB (and previously EBLEX) produced a series of advice manuals under their "Better Returns Programme" which aimed to provide advice to stockpeople on how to improve productivity (and thereby, returns) (AHDB, 2015a; EBLEX, 2014, 2008). Throughout these documents, emphasis was placed on providing sufficient nutrition to ensure the ewe was at the correct condition prior to mating, during mating, throughout pregnancy and while rearing lambs. Providing supplementary feed to pregnant ewes over the winter is one management method to fill the energy gap created from the poor quality pasture available (Henderson, 2002). The advantages of providing supplementary feeding are further realised when ewes are managed and fed according to the number of lambs carried. This is possible, and has been shown to be effective, by ultrasound scanning of ewes in mid-pregnancy (at around day 90 of pregnancy) allowing preferential management and feeding of ewes carrying more lambs (Parker and Waterhouse, 1986). Genetic selection is also an option to improve survival of Scottish Blackface lambs (Sawalha et al., 2007).

2.1.3.2 *Economic viability*

Poor economic viability associated with sheep systems is a difficulty seen worldwide (Morris, 2009). This is a result of low productivity, high production costs (such as feed and labour) and low income received from outputs. While there is a wealth of peer-reviewed literature that refers to poor economic viability associated with sheep production (Morgan-Davies et al., 2015; Morris, 2017, 2009; Stott et al., 2012), literature presenting actual values are more scarce and so grey literature must be considered.

Income of hill sheep systems derive largely from the number of animals sold at the end of the production year in the autumn. Lambs sold make up the largest proportion of this income and may be: finished lambs, sold straight for slaughter; store lambs, sold to be fattened or finished on another farm; or ewe lambs for breeding. A lesser amount comes from sale of draft ewes (SAC, 2016). As previously discussed, with low productivity, income from such sales will be limited by the number of animals produced.

Irrespective of the number of animals sold and the income generated from this, profitability is a result of the margin when the costs associated with production are taken into account. Furthermore even as stock prices have increased so too have production costs (Renwick et al., 2008). The costs associated with production are (according to AHDB, 2016):

- Variable costs: concentrates, forage, veterinary, bedding, other livestock costs.
- Fixed costs: paid labour, value of family unpaid labour, power and machinery costs, contractor costs, contractor charges, administration, property charges, land rent, depreciation (machinery and property).

To demonstrate the poor economic viability of hill sheep systems the QMS report on "Cattle and sheep enterprise profitability in Scotland" which used financial data from real farms can be considered (Figure 2.3). For 36 LFA hill flocks sampled the average net margin (considering outputs from lamb and wool sales minus variable and fixed costs) was -£ 19.07 (QMS, 2018b). Within this same report the margins of LFA upland ewe flocks and lowland ewe flocks was greater (for average flocks the net margin was £ 7.68 and £ 41.63, respectively). The difference in profitability appears to originate from upland and lowland flocks rearing more and heavier lambs which had a higher value than the hill flocks sampled. The average LFA hill flocks reared 102 lambs per 100 ewes which was 42 less lambs compared to LFA upland flocks and 59 less than lowland flocks and all lambs sold finished, as store or for breeding received lower values than the other two system types (between £ 9.72 to £ 25.20 less, QMS, 2018b).

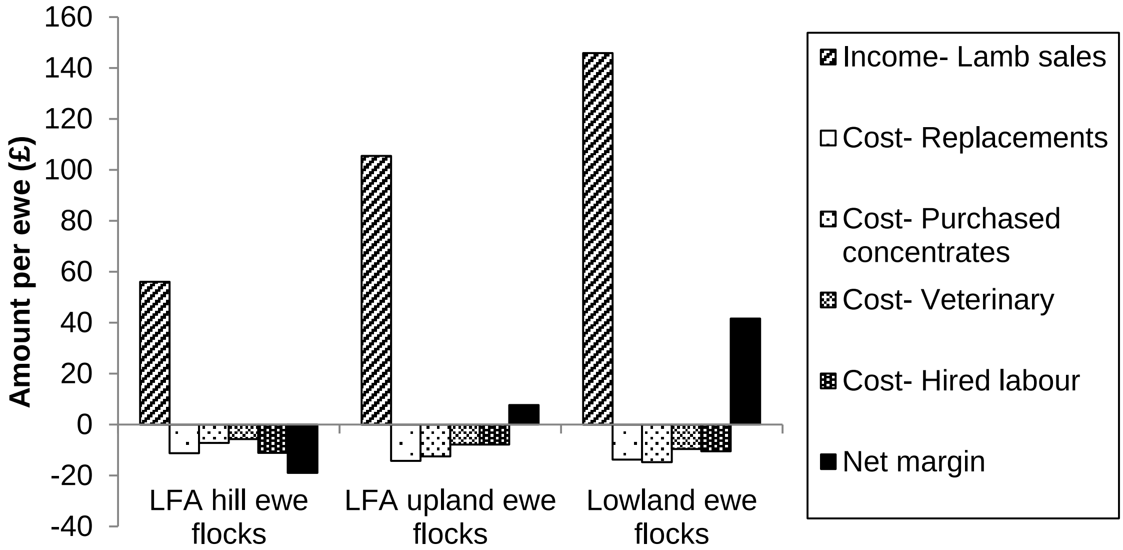


Figure 2.3 Average income and some costs per ewe for three Scottish sheep productions systems, including net margin (data from QMS, 2018b).

The four largest costs for hill sheep systems (Figure 2.3) were management of replacement ewe lambs, labour, concentrate feed and veterinary treatments (AHDB, 2016; QMS, 2018b). Methods to reduce costs have involved breeding and managing sheep differently, for example: so less concentrate feed is required (Bocquier and González-García, 2010; Richards et al., 2012), improved health so less veterinary treatments are required (Conington et al., 2008; Morgan-Davies et al., 2006), and improved system efficiency so less labour is required (Gallardo and Sauer, 2018; Richards et al., 2012).

Another issue affecting economic viability is the value of the product. However the relative value customers are willing to pay for meat in general has globally reduced (Angus et al., 2009; Herrero and Thornton, 2013; Montossi et al., 2013).

Therefore the economic viability of hill sheep systems is poor. In the UK, these systems currently heavily rely on government agricultural support payments (Renwick et al., 2008; Royal Society of Edinburgh, 2008). These have seen many changes over time, the details of which are beyond the scope of this thesis but are well published (Morgan-Davies et al., 2015; Riddell and Walker, 2011; Thomson et al., 2011; Tracy, 1989, 1976). Further changes to support and income are likely as a result of Brexit and it is expected that impacts will be financially unfavourable for UK sheep systems (Davis et al., 2017; Dwyer, 2018; Hubbard et al., 2018). Therefore hill sheep systems and research should strive to improve systems and to be profitable without reliance on subsidies in order to ensure their financial security.

This thesis seeks to address and potentially improve productivity and economic viability. However, labour and welfare are important factors, and are briefly presented.

2.1.3.3 Labour

Labour is closely associated with profitability, as it is one of the largest costs of the system. As previously explained, numbers of people employed within Scottish agriculture are limited and are reducing (Renwick et al., 2008; Royal Society of Edinburgh, 2008; The Scottish Government, 2019, 2015; Thomson et al., 2011). Labour reduction on hill sheep systems has been associated with reduction in hill sheep numbers. However, as Renwick et al. (2008) discussed, it is unknown whether sheep numbers have been reduced to limit farm labour costs, or whether it was due to a lack of skilled, experienced and capable workers required to manage a large flock.

The reduced capability of labour is partly associated with the ageing farming population, a trend reported worldwide (Defra, 2019; Montossi et al., 2013; Morris et al., 2012). In the UK alone, 36 % of those working in agriculture in 2018 were 65 years or older, while only 3 % were under 35 years old, and the median age in years had increased from 58 years old in 2003 to 60 in 2018 (Defra, 2019). A similar distribution and ageing is seen within Scotland (The Scottish Government, 2018a). A suggested cause is that the next generation often moves away from rural locations in search of better employment opportunities (Royal Society of Edinburgh, 2008).

An important implication is the relationship between labour availability and capability on extensive sheep systems, and the welfare of the animals (Goddard et al., 2006; Kirwan et al., 2009; Vosough Ahmadi et al., 2010; Waterhouse, 1996). If the number of sheep per stockperson increases, due to lack of available labour, then a larger number of sheep need to be monitored, therefore reducing the attention given to each animal (Waterhouse, 1996). Kirwan et al. (2009) summarised that "Quality of life" of hill sheep could be compromised by labour pressure. Although interestingly, Vosough Ahmadi et al. (2010) found that increased labour did not necessarily mean better welfare. Instead, the distribution of labour was more important.

2.1.3.4 Welfare

Animals in extensive systems are often thought as having good welfare (Ferguson et al., 2017; Goddard et al., 2006; Kilgour et al., 2008; Montossi et al., 2013). Indeed, grazing wide areas undisturbed by human interventions is seen as allowing normal behaviour to be expressed. "Freedom to express normal behaviour" is the fifth of the UK's Farm Animal Welfare Council's Five Freedoms, which are used to gauge welfare of livestock (FAWC, 2009). However, other factors of hill sheep systems have the potential to negatively impact on welfare if not appropriately managed. This is highlighted when considered against the four other Five Freedoms (as reviewed by Rutter, 2014):

- "Freedom from hunger and thirst": with pregnancy occurring over winter, when grazing quality is compromised, ewes may not receive sufficient nutrition and supplementation may be required (Dwyer, 2009; Kilgour et al., 2008).
- "Freedom from pain, injury and disease": ewes within extensive systems are often not frequently monitored and therefore any injury or disease may not be identified and treated quickly (Goddard et al., 2006; Morris et al., 2012; Waterhouse, 1996).
- "Freedom from discomfort": hill sheep remain outside throughout the year and are subjected to weather conditions often without artificial shelters so discomfort may result (Goddard et al., 2006; Richmond et al., 2017).
- "Freedom from fear and distress": ewes are not frequently handled so fear and distress are likely when this does occur and through gathering using dogs (Grandin, 2014; Hutson, 2014; Kilgour et al., 2008).

The Five Freedoms provide a useful framework to consider welfare of livestock, however a further development within this field of research is that of "a life worth living" (Wathes, 2010). Aside from these ethical considerations, welfare is also important as it is associated with productivity (Kilgour et al., 2008; Morgan-Davies et al., 2006; Morris et al., 2012) and profitability (Lawrence and Stott, 2009; Milne et al., 2008; Stott et al., 2005) of the system.

2.1.4 Reduction in sheep numbers

Difficulties faced by hill sheep systems have contributed to the long term trend seen in decreasing sheep numbers (Morris, 2017; Renwick et al., 2008). Changes in subsidies, accelerated the drop in hill sheep numbers which began in Scotland in 1999 (Morgan-Davies et al., 2012; Renwick et al., 2008; Riddell and Walker, 2011; The Scottish Government, 2016b). Sheep numbers (lambs and breeding ewes) have decreased from 8.2 million, in 2000, by 47 % to 5.7 million in 2018 (Figure 2.4, The Scottish Government, 2018a). It is believed downsizing and farmers leaving the industry have also contributed to the decrease (Renwick et al., 2008; Thomson et al., 2011). The reduction in sheep numbers has also been seen worldwide and has been attributed to the poor economic viability associated with the industry (Morris, 2009).

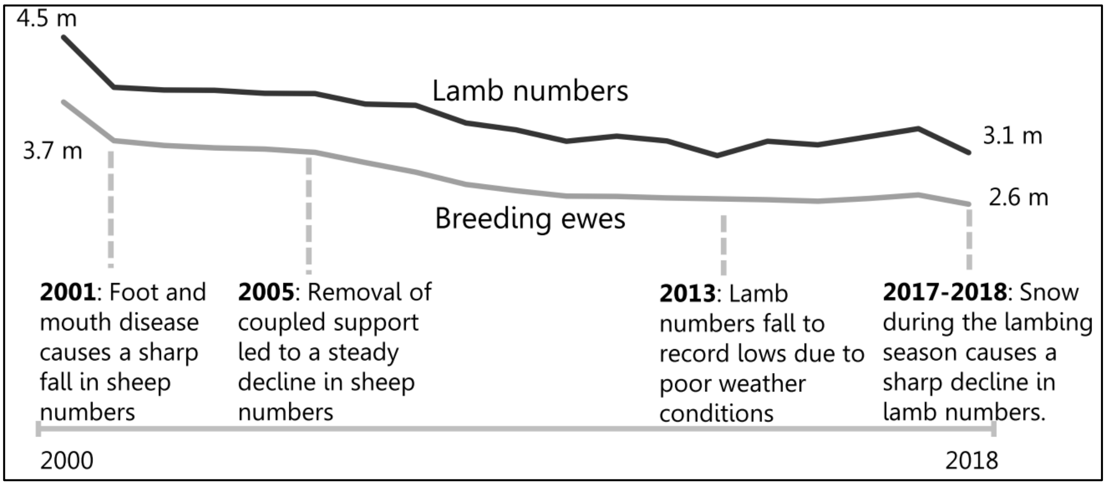


Figure 2.4 Sheep numbers in Scotland June 2000-2018 (million, from "Results from the June 2018 Scottish Agricultural Census", The Scottish Government, 2018a).

2.1.5 Conclusion

To conclude this section, Scottish hill sheep systems hold many similarities with other extensive systems around the world. The harsh environment in which Scottish hill sheep systems operate, is a combination of the wet and mild climate, vast areas of steep hill land, short growing seasons, and pastures of poor quality and quantity. Scottish hill sheep systems are however important for the role they play in: production outputs, specifically sheepmeat and breeding animals; the UK stratified sheep industry; social and economic aspects of rural communities; and management of land for biodiversity and landscape.

Nonetheless, Scottish hill sheep systems face a wide range of difficulties, such as low productivity, poor economic viability, animal welfare consideration and labour issues. The reduction in sheep numbers seen within Scotland demonstrates that these difficulties are already having negative impacts. Efforts need to be made to address these problems to safeguard the future of such systems. One possible approach is through implementing PLF.

2.2 Precision Livestock Farming (PLF)

The term Precision Agriculture (PA) was coined in response to the emergence of technology such as Global Positioning Systems (GPS) and Geographical Information Systems (Bramley, 2009). PA uses these technologies within arable systems to address the issue of variation occurring across one field and has been a recognised topic area for nearly 30 years (as reviewed by Bramley, 2009). More recently the basic principles of PA have been applied to livestock systems, referred to as PLF (Montossi et al., 2013; Scholten et al., 2013).

PLF is an approach to managing livestock systems with the objective to improve efficiency by some or all of the following: by improving productivity, economic viability, sustainability, welfare, and reducing labour (Banhazi et al., 2012b; Berckmans, 2017; Montossi et al., 2013). While this appears a clear objective of PLF, definitions within the literature regarding what a PLF approach actually is, are not consistent.

The term "Precision Livestock Farming" was first used by Berckmans in 2004, who stated that: PLF *"involves the measurements, predictions and data-analyses of animal variables. PLF offers totally new possibilities to collect and analyse data from farm animals in a continuous and fully automatic way"* (Berckmans, 2004, p.29). (Berckmans (2017, p.7) went further and stated that "*The aim of PLF is to manage individual animals by continuous real-time monitoring of health, welfare, production/reproduction, and environmental impact*".

However, variation in PLF definitions between authors and over-time is apparent; Wathes et al. (2008, p.2) included in their definition that PLF uses "*the principles and technology of process engineering*". Although the ideas of "continuous" and "real-time" are included in PLF definitions by many authors (Norton and Berckmans, 2017; Scholten et al., 2013; Van Hertem et al., 2016; Vranken and Berckmans, 2017; Xin and Liu, 2017), an international review of PLF by Banhazi et al. (2012b) made no direct mention of either term.

In Australia, the term Precision Sheep Management (PSM) was defined as "*a practical approach to managing sheep (sub) flocks to achieve increased profits*" (Richards et al., 2012, p.53). Morris et al. (2012) included the idea of individual animal management (or small groups) and the use of technology to improve management efficiency. Therefore "PSM" can be considered a type of "PLF" focused on sheep systems. The term “smart farming” is also used in the literature as a synonym of “PLF” (Morris et al., 2012).

This lack of consistency in definition is likely a result of different livestock systems being the focus for different researchers. When the focus of application of PLF is within very controlled intensive systems such as chicken, pig and dairy houses (Berckmans, 2017; van Hertem et al., 2016; Xin and Liu, 2017), having PLF approaches that operate in a “continuous” and “real-time” manner is reasonable and practical. However within extensive systems the definition and scope of possibilities change, as will be discussed.

2.2.1 Four key principles of PLF application

Although within the literature, PLF has had different definitions certain reoccurring themes were evident. As a result four common principles, irrespective of system (animal species or production intensity), have been identified and collated:

2.2.1.1 One: Scientific knowledge

PLF is a platform through which fundamental scientific understandings of livestock biology and production can be applied to a whole livestock system (Guarino et al., 2017; Mertens et al., 2011; Wathes et al., 2008). PLF applications are, therefore, founded on and developed with scientific knowledge. This ensures development of robust methods with increased chance of successful application within commercial settings.

2.2.1.2 Two: Measure, monitor and manage

A system can be monitored by collecting data (measures) at a precise and accurate level, suitable for the system, allowing for corrective action (management) to be provided in a timely manner. For instance, pig and poultry houses may be monitored by sensors within the environment, these ensure measures, such as temperature and humidity, are kept within chosen ranges to satisfy production requirements (Banhazi and Black, 2009; Fournel et al., 2017; van Hertem et al., 2016). Growth and production can also be measured, monitored and managed by weighing systems (Bowen et al., 2009; Jordan et al., 2006).

2.2.1.3 Three: Technology

The availability and development of technology has made PLF possible. Sensors and measuring devices can be used to collect data, which are then collated by software and presented, normally by computers (Defra, 2013; Voulodimos et al., 2010). Technology can also be used to improve processes, sometimes through automation, that reduce labour and make tasks possible (for example, Cronin et al., 2008; Morris et al., 2012). The importance of technology to the future of agriculture was recently highlighted by King (2017).

Technology use brings major advantages to PLF, including: greater accuracy in data collection and recording; ability to collect information about animals that was not previously possible (for example, thermal biometric changes, McManus et al., 2016); to reduce labour associated with a task (Morgan-Davies et al., 2018b); and allow automation of processes (Bowen et al., 2008; Dickinson et al., 2013; Richards and Atkins, 2007). The development of individual identification and computer assisted technology has facilitated the ability to collect and process vast amounts of information about farming systems quickly and efficiently without increased labour, making PLF possible (Banhazi et al., 2012b).

2.2.1.4 Four: Precision over variation

A key idea of PA is that variation exists across a field, and identifying the variation allows different management to be applied to different areas (Bramley, 2009). This is the basis for the final key principle; variation exists in any system either between animals or areas of the animal's environment (Black, 2014; Coates and Penning, 2000; Montossi et al., 2013; Wathes et al., 2008). This principle is relevant to the first three, which allow for variation to be identified and precise management exerted within the system. Depending on the system, the level of precision may be to provide the exact environmental conditions within animal houses (as demonstrated by Vranken and Berckmans, 2017; Xin and Liu, 2017) or for management to be applied on an individual animal basis (as demonstrated by Bowen et al., 2008; Richards and Atkins, 2007). Indeed, the idea that PLF could be applied on a per-animal basis was first identified by Berckmans (2004), describing animals as being Complex, Individual and Time-variant systems.

Large variations in production between individual sheep within the same flock have been reported (Richards et al., 2012; Rowe and Masters, 2005). Barge et al. (2013) explained that if animals can be identified and managed at an individual level, welfare and productivity could be improved. Therefore, animals can benefit from being within a group of animals yet be treated as individuals (Wathes et al., 2008).

Technology can be used to identify individuals within a flock or herd and allow management according to individual needs (Rossing, 1999). Therefore PLF approaches address variation within the system by allowing for precise measuring, monitoring and management.

2.2.2 Proposed PLF definition

Based on these identified four key principles of PLF application, an appropriate complete definition is proposed:

PLF is an approach to livestock system management which utilises four key principles: 1) exploitation of scientific knowledge about the system; 2) measurement, monitoring and management of the system; 3) appropriate use of technology; and 4) identifying and targeting variation within the system precisely. The goal of these four principles is to improve the efficiency of the livestock system by some, or all of the following: increasing productivity, economic viability, welfare, and reducing labour and environmental impact. The principles and goal to be achieved will depend on the characteristics of the livestock system including: species, intensity of system and main outputs.

2.2.3 PLF and sheep production

There are many published examples of PLF (Appendix 1), however the majority of these are from chicken, pig and dairy systems. These intensive systems have attracted the most attention and development for PLF (2012-2016 EU-PLF project, Berckmans and Guarino, 2017). The focus on these is arguably a result of the way these systems operate, animals are either handled regularly and frequently (for example dairy cattle are handled at least twice a day for milking) and/or systems are within controllable built environments, allowing for relatively easy implementation of PLF. However there are some examples where PLF approaches have been researched and applied to sheep systems. Five examples are reviewed below: two are well established within commercial sheep systems (pregnancy and litter size detection, and selection indices); and three are currently more within experimental settings (determining parentage, anthelmintic treatment and real-time monitoring).

2.2.3.1 Pregnancy and litter size detection

Although the term PLF was first used in 2004 (Berckmans, 2004), there are management practices carried out prior to this that could be considered a PLF approach. For example, in the 1980s ultrasonographic scanning of ewes was demonstrated to accurately assess the number of lambs being carried. This allowed for different management of ewes carrying different numbers of lambs (Logue et al., 1987; Parker and Waterhouse, 1986). The scientific knowledge, underpinning this example, is the knowledge that ewes carrying different numbers of lambs have different nutrient requirements, prenatal risks and post lambing nutrient requirements (Fthenakis et al., 2012; Henderson, 2002). Moving ewes carrying twins from hill grazing onto improved pastures and providing extra supplementary feeding has been reported to reduce lamb losses (Parker and Waterhouse, 1986; Waterhouse, 1996). This application is well understood and has been shown by Morgan-Davies et al. (2006) to be a common tool that has been adopted and used within UK hill sheep systems.

However, while being successful at identifying individual ewes carrying different numbers of lambs, this method of managing groups after scanning is still at a batch management basis and does not consider individual variation and needs within parity groups. Therefore a PLF approach that identified individual ewes with different needs within the same scan result could be beneficial. For example, Hinch and Brien (2014) demonstrated that insufficient nutrition during pregnancy resulted in below optimal birth weights of lambs, and contributed to higher losses of these lambs. Therefore, if individual pregnancy nutrient requirement can be realised, impacts could be, improved lamb and ewe performance and welfare, as well as a more productive and profitable system.

2.2.3.2 Selection indexes

Selective breeding, using measures such as Estimated Breeding Values (EBVs) and breeding indexes can be used to identify, select and breed from genetically superior animals. Such selection indexes use performance data from the individual animal and its relatives (Islam et al., 2012; Simm, 1998). Different methods have previously been used to produce EBVs but the preferred option is through the use of Best Linear Unbiased Prediction (BLUP), as originally presented by Henderson in 1949 (Henderson, 1975; Simm, 1998).

EBVs and breeding indexes are generated in the UK by Signet Breeding Services. A good definition for how selection indices are generated and what they mean is provided by Signet: "*Pedigree and performance data is analysed to calculate how much of each animal's performance is due to its breeding merit and how much is due to the environment in which it has been raised. This assessment of breeding* *potential is expressed as Estimated Breeding Values"* (Signet website, 2015). EBVs are generated at individual trait level however they can be combined to produce breeding indexes. EBVs and breeding indexes of individual animals can then be compared and genetically superior animals can be identified and bred from.

Using selection indexes to inform breeding decisions is an example of a PLF approach successfully applied within hill sheep systems (Conington et al., 2006; Lambe et al., 2014; McLaren et al., 2012). However, Conington et al. (2001) presented relatively low numbers of performance recorded hill flocks (those with selection indices) with proportionally less than 0.01 of lambs born per year recorded in hill sheep systems. There is no evidence that this low uptake of recording or use of selection indexes at flock or ram purchases has increased. Indeed for the 2016-2017 production year, Signet provided EBVs for only 12 Scottish Blackface flocks. It was estimated that in Britain only 3 % of Scottish Blackface producers were using rams with EBVs, although the author of the report suggested proportions might be underestimated as some producers did not know they had purchased rams with EBVs (Pollott, 2012).

Some specific reasons why hill sheep systems are not performance recorded have been suggested by Conington et al. (2001) as: the pedigree is difficult to record in the systems; stockpeople do not know the potential benefits of using genetic indexes; pure-bred hill breeds are still largely selected on aesthetic qualities which genetic indexes do not take into account; and a belief by stockpeople that the environment had a larger impact on hill sheep performance.

2.2.3.3 Determining parentage

Determining parentage (or pedigree) of individual sheep is another application for PLF. Knowing a sheep's pedigree is essential information for any selective breeding program, including using breeding indices, as discussed above (Kemmis et al., 2016; Morris et al., 2012; Voulodimos et al., 2010). The simplest method to determine maternal parentage is to record dam and lamb at birth. However, this can be very labour intensive (Richards et al., 2012) and can still result in 10.5 % of matches between ewe and lambs being incorrect, when compared to DNA analysis (Barnett et al., 1999). Moreover, the difficulties in recording ewe and lambs at birth are exacerbated when considered within hill sheep systems (Conington et al., 2001). In these conditions, ewes often lamb on the hill and it would be challenging and time consuming for a stockperson to monitor all animals daily in the vast area

(Waterhouse, 1996). As a result, lambs within these systems are often not seen for weeks after birth. Even if ewes were to be brought into improved fields to lamb there would still be a large labour requirement. Furthermore, mating often occurs on the hill pasture where multiple sires join the ewe flock, therefore paternal parentage is also challenging to determine.

Conington et al. (2001) suggested the physical difficulties of recording pedigree in extensive conditions may be one reason why genetic improvement has not occurred in hill flocks. An alternative is to use DNA analysis to match lambs to both dam and sire. This has clear advantages of improving accuracy (Barnett et al., 1999) and is able to determine both parents, without altering mating or lambing practices. However, it is relatively expensive and therefore an unpractical suggestion to most sheep systems (Kemmis et al., 2016; Richards et al., 2012).

Pedigree MatchMaker is a PLF solution for this problem by “Sheep CRC”, Australia’s Government funded research program (Kemmis et al., 2016). The method uses Radio Frequency Identification (RFID) readers and RFID ear tags to determine maternal parentage of lambs (Morris et al., 2012; Richards and Atkins, 2007). It requires ewes and lambs to pass by RFID readers multiple times which read and record the individual number stored on the ewe and lambs RFID ear tag (RFID technology will be discussed later). Software then analyses these data and determines parentage using the knowledge that lambs will be in closer proximity to their dam compared to other ewes. It has been shown to be effective at determining parentage within a commercial farm environment by Kemmis et al. (2016) who matched 84.5-93.3 % lambs to a ewe and, of these, 96-97 % were correct matches.

The Pedigree Matchmaker requires ewes and lambs to pass through gates, on which RFID readers are mounted, to reach water (and sometimes feed and hay) or between paddocks (Kemmis et al., 2016; Richards and Atkins, 2007). On a large area like a hill it could be challenging to set up gates where all ewes and lambs would pass through frequently. Indeed Richards and Atkins (2007) suggested that three to four weeks were required in order to get accurate matches, and this was in restricted paddocks. Therefore the extensive area of hill sheep systems adds extra complication for application of this PLF method with current technology.

An alternative option to determine maternal parentage without needing to fix readers to gates is via a commercial product called SmartShepherd. This involves attaching small Bluetooth devices to ewes and lambs within a group and the proximity between devices is recorded and analysed by software to determine maternal parentage (Sohi et al., 2017). While in the early stages of application, this appears a promising option for determining maternal parentage.

For determining paternal parentage the Alpha-Detector could be used (Alhamada et al., 2017, 2016). This operates by recording the date and IDs when a ram, wearing a harness containing an RFID reader, mounts a ewe with a transponder attached to her rump. Results from this technology to detect oestrus in ewes (Alhamada et al., 2016) and evaluate ram libido (Alhamada et al., 2017) appear promising initial steps in development.

To conclude, determining pedigree is still a challenging process but new technologies appear promising. Developing technologies for use within hill sheep systems warrant further investigation but are beyond the scope of this current thesis.

2.2.3.4 Anthelmintic treatment

Targeted Selective Treatment (TST) is a PLF method which has been applied to identify which individual lambs within a flock could benefit from anthelmintic treatment. The Happy Factor™ model developed by Greer et al. (2009) predicts liveweight gain of lambs taking into account grass availability. It has been successfully used to identify lambs within a sub-flock that could benefit from anthelmintic treatment and those that would not (Busin et al., 2013; Greer et al., 2009; Kenyon and Jackson, 2012), including in a Scottish hill sheep system (Morgan-Davies et al., 2018b, 2014; Umstätter et al., 2013).

Compared to a more traditional approach, where whole flock based anthelmintic treatments are applied, the TST approach has resulted in less anthelmintic medicine being used, and therefore less labour and lower costs, as well as similar liveweights of lambs reached (Busin et al., 2013; Morgan-Davies et al., 2018b, 2014). This TST method also tackles the issue of anthelmintic resistance in sheep gastrointestinal helminthic populations, in a refugia based approach (Besier et al., 2010; Greer et al., 2009). This is where a population of parasitic worms is left within the environment thereby diluting the resistant individuals and only the sheep suffering from their worm burden are therefore treated (Kenyon et al., 2009). The TST regime described here, while currently in experimental stages, shows potential for application on commercial farms (Busin et al., 2013; Greer et al., 2009; Kenyon and Jackson, 2012).

2.2.3.5 Real-time monitoring

There is also a range of on-animal sensors for sheep being developed, to measure location, movement, heart rate, chewing, oestrus, urine, contact, respiration and temperature (Fogarty et al., 2018). One area that has received much recent development is recording behaviour of sheep in extensive systems via tri-axial accelerometers (Decandia et al., 2018; Giovanetti et al., 2017; Grisot et al., 2018; Umstätter et al., 2008). The greatest advantage of such real-time monitoring technology is the potential to provide early warning systems for when measures (activity, Umstätter et al., 2008; body temperature and heart rate, Fuchs et al., n.d.) deviate from the expected. These sensors could also be accompanied by location technology (GPS) so the animals can be found (Fogarty et al., 2018). Such early warning systems have the potential to provide productivity, economic, welfare and labour advantages. However, the sensors are still largely in developmental stages and not currently available on commercial systems.

2.3 Applying PLF to hill sheep systems

2.3.1 Rationale for challenge areas

Banhazi and Black (2009 p.3) suggested that when developing a PLF approach for a system, there is a need to identify and target processes *"which if not carried out correctly, will have a major impact on either productivity or profitability of an enterprise"*. As well as this, welfare and labour should also be considered for hill sheep systems. As a result, the main processes within hill sheep systems can be presented in terms of their potential impacts on productivity, economic viability, welfare and labour. These have been collated and summarised in Table 2.2.

Two important hill sheep systems processes (referred to as challenges) were selected for PLF application within this thesis:

1) Pregnancy supplementation: allocating supplementary feeding to pregnant ewes.
2) Retention and culling decision making (Stockdraw): making decisions on whether to retain or cull ewes within/from the main breeding flock at stockdraw.

For reasons previously discussed, and those that will be explored in the following chapters, these two challenges were chosen given their importance to the whole system, especially when the processes involved are not carried out correctly. Supplementary concentrate feeding is a large cost to the farm (AHDB, 2016; QMS, 2018b) but essential during pregnancy to ensure success of raising lambs (Henderson, 2002). Therefore, correctly allocating supplementation is likely to have large impacts on productivity and profitability of the system.

The system is only as productive (and therefore profitable) as the individual ewes within the flock. Therefore ensuring retention and culling decision making is carried out correctly could have large impacts on productivity and profitability of the system.

A literature review for each challenge is carried out in the upcoming chapters. For PLF to be considered for the challenges suitable tools must first be identified. These include suitable animal measures for monitoring and management, and available technology for implementation.

Table 2.2 Hill sheep systems processes and their impacts on productivity, economic viability, sheep welfare and labour, as interpreted and summarised by the author.

Productivity	Economic viability	Welfare	Labour
Replacement ewe lambs off-wintered			
Quality of grazing at wintering impacts on replacement ewe lamb growth over first winter and so performance later in life.	Costs associated with off-wintering.	Improved plane of nutrition during first winter is better for survival and building up body reserves. May involve transport to and from wintering farm, which negatively impacts welfare.	Reduction of labour on home farm as less animals are present, although the work transfers to the off-wintering farm.
Mating			
Performance of both males and females influence potential lamb crop.	Costs associated with purchasing males for breeding.	Mating could result in offspring with improved genetics including ability to survive and thrive.	Labour involved in sorting ewes into mating groups and checking animals increases with the number of groups.
Pregnancy			
Success of pregnancy determines number of lambs born.	Number of lambs born ultimately influences number of lambs that will be available for sale at the end of the year.	Pregnancy requires appropriate husbandry to ensure welfare is not compromised.	Monitoring and managing ewes during pregnancy involves labour.
Pregnancy scanning			
Determining number of lambs being carried can allow different management to increase chance of lamb survival.	Costs associated with scanning.	Handling during pregnancy can cause stress. Welfare can be improved by using scanning results for ewe management.	Labour associated with scanning.
Pregnancy supplementation			
Providing supplementation influences ewe and lamb performance.	Supplementation provided can be a large expense.	Providing supplementation allows pregnant ewe nutritional requirement to be met.	Labour to provide supplementation is often required daily and increases with the number of groups to be fed.
Lambing			
Management of ewes and lambs at lambing can impact early lamb survival.	Number of lambs born ultimately influences number of lambs that will be available for sale at the end of the year.	Ewe and lamb well-being are affected by husbandry during lambing.	Lambing has a high labour requirement.

Continued

Table 2.2 Continued

Productivity	Economic viability	Welfare	Labour
Rearing lambs			
Management of ewes and lambs over lamb rearing can influence final lamb liveweight at weaning.	Final liveweight of lambs by weaning impacts sale opportunities.	Ewe's maternal ability (including ability to produce sufficient amounts of milk) can impact on the welfare of lambs.	Labour is involved in monitoring and managing ewe and lambs.
Shearing			
Ewe genetics influences the quantity and quality of ewe wool produced.	Costs associated with shearing and income from the sale of wool.	Handling associated with shearing ewes can cause stress and physical injury. Removal of fleece considered a benefit to ewe welfare.	Shearing has a high labour requirement.
Weaning			
When to wean lambs will impact ewe future performance by affecting the time to recover before the next mating.	Liveweight and condition of lambs at weaning will impact sale opportunities and prices received.	Weaning causes stress for ewes and lambs due to separation. The change in feed can also cause stress for lambs.	Labour is involved to wean and sort ewes and lambs.
Stockdraw			
Productivity of the flock is determined by individuals within it, so ewe retention decisions will impact on future flock performance.	Which ewes are culled will impact on income from their sales and also that from replacement ewe lambs.	Stockdraw is an opportunity to check all ewes and identify any problems that might impact on welfare.	Being thorough at stockdraw increases labour.
Sheep sales			
Impacts in flock performance from those animals retained.	Main income (aside from subsidies) generated from sheep sales.	Handling, transport and movement to new locations can cause stress for sheep.	Labour is affected by the number of sales and the distance to sales.
Veterinary treatments			
Providing veterinary treatments can positively impact the performance of treated animals.	Costs associated with treatments.	Appropriate and timely veterinary treatment can improve health and welfare.	Increased veterinary treatments increases labour.

2.3.2 Potential measures for monitoring and management

Measures which can be practically and reliably monitored and managed are a key part of PLF methodology (Berckmans, 2004; Vranken and Berckmans, 2017). For PLF approaches to be applied within hill sheep systems, suitable measures need to be identified. Intensive PLF systems may include measures of the housed environment (for example in van Hertem et al., 2016; Vranken and Berckmans, 2017; Wathes et al., 2008), however within extensive systems environmental measures (such as temperature and humidity) cannot often be managed. Although, measures of pasture quantity and quality within extensive systems (see examples in Coates and Penning, 2000) could be used within PLF methodology. Measures more appropriate for extensive systems are often collected directly from the animal, and could be physiological, behavioural or production based (Wathes et al., 2008).

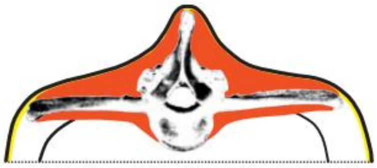
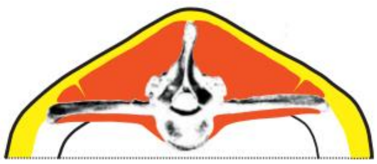
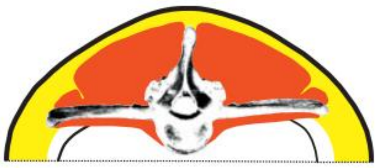
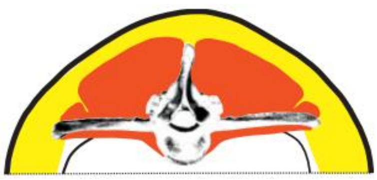
The measures used must not only be appropriate to the system but also address the aims of the PLF method (Banhazi et al., 2012a). Therefore, for the two challenge areas, measures of interest include: Body Condition Score (BSC), liveweight, and a range of production outputs. Other potentially useful PLF measures for hill sheep systems, which are not consider here, include: feed intake, location, movement, disease surveillance, and body temperature (Banhazi et al., 2012b; Pomar et al., 2011; Rutter, 2014; Wathes et al., 2008).

2.3.2.1 Body Condition Score (BCS)

A BCS is a biological measure, determined by a trained person through palpation of the anterior lumber vertebrae and recorded on a five point scale, for the amount of subcutaneous fat and muscle coverage (Table 2.3, Jefferies, 1961; Kenyon et al., 2014; Russel, 1984; Russel et al., 1969). Assessing BCS allows inference of how well an animal is performing, or likely to perform, to previous, current and future situations, and is believed to be a viable method of assessing a sheep’s energy status (Brown et al., 2015).

As well as being an important variable for research (as reviewed by Kenyon et al., 2014), scoring ewes is also promoted to stockpeople as a tool to guide decision making on farms (for example, AHDB, 2015a; EBLEX, 2014). However, condition scoring ewes is only useful if targets are identified and management decisions are made in response (Curnow et al., 2011). Kenyon et al. (2014) suggested the three key times to collect BCS were at weaning, mid-pregnancy and just before lambing, all of which allow for ewes below target BCS to be identified and managed appropriately.

Table 2.3 Description of Body Condition Scores (BCS) including illustration of the vertebra and ribs with approximate muscle (orange) and fat (yellow) distribution (from Kenyon et al., 2014 p.40, originally adapted from Jefferies, 1961; Russel, 1984; Russel et al., 1969).

BCS	Description	Illustration
1	The spinous processes are prominent and sharp. The transverse processes are also sharp, with fingers passing easily under the end of this process. The eye muscle areas are shallow with little to no fat cover.	
2	The spinous processes are smooth but still prominent. The individual processes can still be felt but only as fine corrugations. The transverse processes are smooth and rounded. However, it is still possible to pass the fingers under the ends of the processes with some pressure. The eye muscle areas are of moderate depth, but have sparse fat cover.	
3	The spinous processes are smooth and rounded, and individual bones can only be felt with some pressure applied. The transverse processes are also smooth and are well covered. Firm pressure is required to feel over the ends. Eye muscle area is full and covered by a moderate degree of fat.	
4	With pressure applied, the spinous processes can just be detected, although the ends of the transverse processes cannot. Eye muscle areas are full with a thick covering of fat.	
5	Even with firm pressure applied, the spinous processes cannot be detected. Due to a high level of fat adjacent to the spinous process, a depression directly above where the spinous processes would normally be felt may be present. It is not possible to detect the transverse processes. The eye muscle areas are very full with very thick fat cover. It is possible to have significant deposits of fat cover over the rump and tail.	

2.3.2.1.1 *BCS and performance*

Once identified, management for ewes below a target BCS could be undertaken to provide these ewes with a higher plane of nutrition. This could be via access to higher quality pasture or through providing supplementary feeding (EBLEX, 2008; Fthenakis et al., 2012). Effective management of ewe BCS is associated with improved: lamb survival from embryo to weaning; number of lambs conceived, born and weaned; liveweight of lambs from birth to weaning; ewe survival; and quantity and quality of milk produced (Gunn et al., 1969; Kenyon et al., 2014; Morgan-Davies et al., 2008; Russel, 1984). Even though the relationships between BCS and these production traits are often positive, a review by Kenyon et al. (2014) highlighted studies where findings varied and instead suggested relationships were more likely curvilinear and not linear.

2.3.2.1.2 *Subjectivity of BCSs*

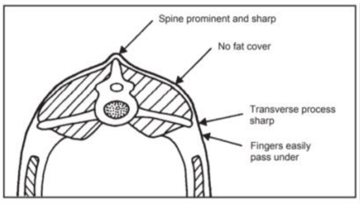
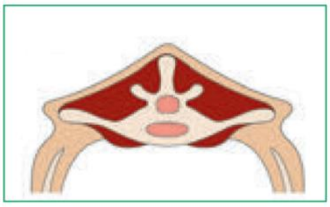
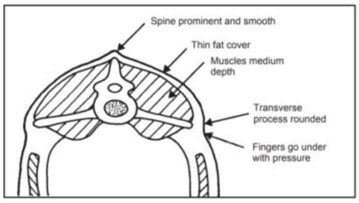
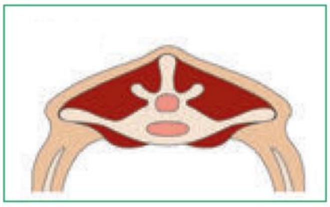
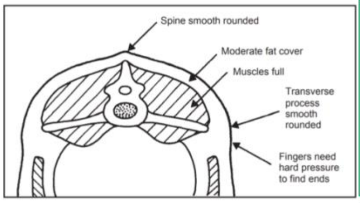
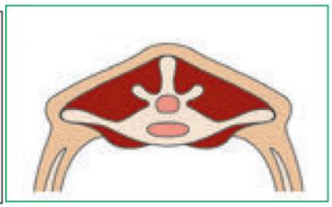
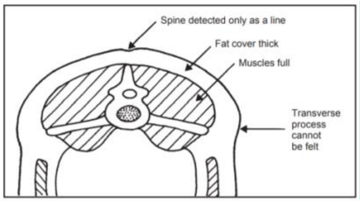
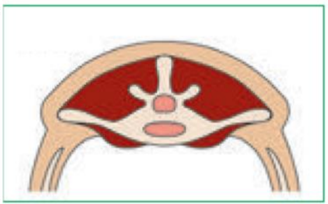
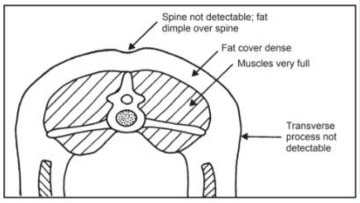
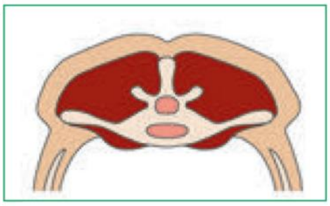
As well as BCS, another biological measure which is well used within research and in practice is liveweight (detailed discussion to follow). BCS has a major advantage over liveweight measures in that it is independent of: gut-fill; length and wetness of fleece; physiological state (for example pregnancy); and within and between breed differences of skeletal size (Brown et al., 2015; Jefferies, 1961; Kenyon et al., 2014; Russel et al., 1969).

Aside from these advantages over liveweight data, the subjectivity and reliability of BCSs is often considered within research (Kenyon et al., 2012; Phythian et al., 2012b). Some research has shown reliability to be good both between and within assessors (for example, Phythian et al., 2012b), while many other examples have not estimated reliability so highly (as reviewed by Kenyon et al., 2014).

The subjectivity of this measure can be demonstrated through considering pictorial examples available. Table 2.3 appears to be an accurate representation of the original written description of the different condition scores by Jefferies (1961) and Russel et al. (1969). However, Table 2.4 shows the variety of scoring charts available to research practitioners and stockpeople. Thompson and Meyer's (1994) diagram (Table 2.4) show very little difference between muscle depth at the different scores, while others appear very simplistic, for example that from Lifetime wool (2011), which may cause issues for those learning the practice. As well as requiring consistency in these diagrams, another method to improve reliability of scoring, is through training and re-calibration of scorers (as suggested by Phythian et al., 2012b). This re-calibration requires scorers to compare their BCS assessment, although this may be challenging for stockpeople working in isolation from other scorers.

An alternative for recording BCS is through automated optical measurements. Indeed systems using 3D cameras to automatically measure and record dairy cattle condition are now found in commercial automated milking systems (Halachmi et al., 2019; Spoliansky et al., 2016). Although in a recent review on sensors for PLF, which discussed automatic recording BCS for dairy cattle, no reference was made to a similar approach for sheep (Halachmi et al., 2019). Therefore, until new technology can be developed to accurately record BCS in sheep, human assessment seems the only option.

Table 2.4 Comparison of Body Condition Score (BCS) diagrams from three sources.

<table>
<tr><th>BCS</th><th>Thompson and Meyer (1994, p.2)</th><th>EBLEX (2014, p.3)</th><th>Lifetime wool (2011)</th></tr>
<tr><td>1</td><td>
</td><td></td><td></td></tr>
<tr><td>2</td><td>
</td><td></td><td></td></tr>
<tr><td>3</td><td>
</td><td></td><td></td></tr>
<tr><td>4</td><td>
</td><td></td><td></td></tr>
<tr><td>5</td><td>
</td><td></td><td></td></tr>
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2.3.2.1.3 *Suitability for PLF measure*

The purpose of reviewing literature on BCS is to evaluate the potential of being able to monitor and manage this measure within PLF approaches. Kenyon et al. (2014) suggested for BCSs to be useful they should be collected on an individual animal basis with individuals ideally being separated and given preferential feeding. This is an example of identifying the variation within the flock as well as managing animals individually; both important elements of PLF (Berckmans, 2004; Bramley, 2009). Also, as previously discussed, BCSs are associated with many productivity traits and therefore can be managed to influence these outcomes. Therefore BCSs should be considered as a potential measure for PLF application within hill sheep systems. However, the subjectivity of the measure must be considered.

2.3.2.2 Liveweight

This section is adapted from the introduction of Wishart et al. 2017 (presented in Chapter 4).

Liveweight is another potential biological measure for PLF methodology. Liveweights are indicative of an animal's current and changing physical state and measuring changes in liveweight is useful in assessing how an animal is responding to its current situation (Baker et al., 1947). As liveweight is affected by: growth, nutrition, health, stress, pregnancy, and genetics (Brown et al., 2015; Coates and Penning, 2000), research exploring these areas in sheep often use liveweight as an important variable. Liveweights are one of the most frequently utilised measurements in livestock research due to: ease of collection and understanding; comparability within and between animals; changes in response to a range of stimuli; flexibility of quantitative data produced for statistical analyses; and the potential application of methods for monitoring and managing liveweights on commercial farms (Brown et al., 2015; Coates and Penning, 2000).

Liveweight recording and associated management decisions have been identified as key elements for improving productivity and efficiency on commercial sheep farms in Australia and the UK (Brown et al., 2015; Young et al., 2011). Application within PLF approaches are being made possible through advances in commercially available weighing equipment (to be presented). RFID chips within each sheep ear tag and readers within the weigh-crate allow liveweights to be easily collected and utilised on an individual animal basis (Morgan-Davies and Wishart, 2015). It has also already been suggested as having the potential to allow new management systems to be developed using sheep liveweight to aid decision making (Brown et al., 2015).

Most research and commercial use of liveweight data involves making comparisons between liveweights at different time points within and between animals and groups.

To be able to produce reliable, comparable liveweights the variation and error associated with these data need to be understood and controlled.

Liveweight is a measure of body mass which is composed largely of muscle, fat, bone and organs. All of these have a relatively stable weight over a short period of time, such as a day, but alter over longer periods in response to environmental and biological conditions (Coates and Penning, 2000). Changes in weight of these components are of most interest within research and industry. However, body-water and the fluids and digesta of the gastrointestinal tract (known as gut-fill) also make up total body mass. Levels of these change over the day and result in fluctuations in liveweights being observed. While this is an issue with weighing all animals, gut-fill needs greater consideration with ruminants as the contents of the rumen can account for 10-23 % of total liveweight (Hughes, 1976).

Liveweights appear to be a potentially useful tool for PLF approaches however variation caused by gut-fill is an issue that requires further investigation (see Chapter 4).

2.3.2.3 Production outputs

BCS and liveweights are potentially useful PLF measures. However, they could also be considered production outputs if the aim of a system is to increase and/or reach a target liveweight or BCS (for example, within finishing systems). Indeed for intensive systems, production outputs are likely to focus more on growth (for example, Banhazi et al., 2012b) because the animals themselves are the output, therefore liveweight is a measure as well as an output. Although, production itself (such as producing and rearing young) is also suitable for PLF measures (Wathes et al., 2008). Production outputs of interest within PLF approaches for hill sheep systems are those often recorded as dependent and independent variables in research, and that stockpeople are often advised to monitor and manage (Table 2.5). These production outputs are also all economically important to the system (Mertens et al., 2011).

Table 2.5 Production outputs for sheep systems which have been used within research and applied settings.

Production outputs	**References, where production output was measured and/or managed**
Ovulation/ conception rate	Bruno-Galarraga et al., 2014; Coates and Penning, 2000; Kenyon et al., 2014
Ova/ embryo/ foetus number and mortality	Annett et al., 2011, 2010; Coates and Penning, 2000; EBLEX, 2008; Kenyon et al., 2014
Number of lambs born	Coates and Penning, 2000; EBLEX, 2008; Kenyon et al., 2014; Kern et al., 2010
Number of lambs per ewe at different handling points	EBLEX, 2008; Jordan et al., 2006; Kenyon et al., 2014; Young et al., 2011
Quantity and quality of milk	Coates and Penning, 2000; EBLEX, 2008; Galvani et al., 2014; Kenyon et al., 2014
Quantity and quality of fleece	Byrne et al., 2012; Coates and Penning, 2000; Mekkawy et al., 2009; Young et al., 2011
Lambing ease/ difficulty	Annett et al., 2011, 2010; Coates and Penning, 2000; EBLEX, 2008
Maternal behaviour	Alexander et al., 1993; Annett et al., 2011; Dwyer et al., 2003; EBLEX, 2008
Survival rate	Hickey, 1960; Kenyon et al., 2014; Morgan-Davies et al., 2008; Young et al., 2011
Presence and severity of disease	Annett et al., 2011; Conington et al., 2008; McLennan et al., 2016; Nugent and Jenkins, 1992
Ram fertility and libido	Coates and Penning, 2000; EBLEX, 2008; Kenyon et al., 2014
Ewes suitable to be retained within the flock	Annett et al., 2011; Borg et al., 2009a; Coates and Penning, 2000; McIntyre et al., 2012
Liveweight and liveweight change	Brown et al., 2015; Corner-Thomas et al., 2014; Young et al., 2011
BCS and BCS change	Annett et al., 2010; Corner-Thomas et al., 2015; Kenyon et al., 2014; Morgan-Davies et al., 2008

The raw production outputs can also be involved in calculations or manipulation to produce other outputs that could be used within PLF approaches, such as: producing EBVs (Conington et al., 2001; Lambe et al., 2008; McLaren et al., 2012); estimated or actual monetary values (AHDB, 2016; Young et al., 2011); and a ewe efficiency measure, such as dividing the total liveweight of lambs reared by the liveweight of ewes at mating (AHDB, 2016; Annett et al., 2010).

For production outputs, the frequency of monitoring within PLF approaches needs to be considered, with many claiming real-time continuous monitoring is required (Berckmans, 2004; Fournel et al., 2017; van Hertem et al., 2016). However, in agreement with the new definition provided (section 1.2.2), precision may occur through individual animal recording and not frequency or measuring. Therefore production outputs themselves are appropriate measures for PLF approaches (Wathes et al., 2008).

2.3.3 Available technology

For the measures to be useful for a PLF approach, their monitoring and management needs to be suitable for hill sheep systems. Previous research has highlighted that one of the barriers with applying PLF to farms is the availability of reliable and accurate technology (Berckmans, 2004) and utilising existing hardware and software should be considered (Banhazi et al., 2012a). With that in mind, approaches within this thesis will use technology that is already commercially available, and which will now be reviewed.

2.3.3.1 Identification

Marking animals as a type of identification has developed over time; previously identification was in the form of branding, ear notching or colouring animals, and was for management and to protect against theft (Landais, 2001). There are many different identification methods which have been used over the years for livestock, each with advantages and disadvantages (Table 2.6).

In the UK and Europe with outbreaks of infectious diseases (specifically bovine spongiform encephalopathy and foot and mouth disease) identification was considered essential to monitor animal movements (traceability), to protect against the spread of disease for both animal and human health (Eradus and Jansen, 1999; Morgan-Davies and Wishart, 2015; Ribó et al., 2001).

Within the European Union, a four year project (1998-2001) called IDEA (Identification électronique des animaux) explored introducing an electronic identification system (Ribó et al., 2001). Many countries now have their own system of traceability which includes animal identification, databases and information flow (as reviewed by Bai et al., 2017). Indeed, within the EU the current identification requirements for sheep and goats are effective by European Regulation 21/2004.

Of the examples of identification (from Table 2.6), RFID has been adopted by many countries for their traceability systems (Bai et al., 2017). Indeed identification of individual animals via RFID or Electronic Identification (EID) became compulsory within Scotland on the 31st December 2009 (The Scottish Government, 2010).

Table 2.6 Different forms of animal identification and evaluation for each.

Identification method	Advantages	Disadvantages	References
Low or no technology required			
Branding/tattoo, the horn or skin of the animal is marked	Low-cost Relatively simple to apply	Prone to errors Labour intensive to apply and read Can be easily altered Can cause the animal pain Horns can get lost	Awad, 2016; Bai et al., 2017
Ear shear/notching, ear cut in a pattern which can be read as a number	Low-cost Lasts throughout animal’s lifetime	Requires training in order to read Risk of ear tearing and then unreadable Can cause animal pain Limited amount of numbers which are identifiable	Awad, 2016; Bai et al., 2017
Ear tag, with number printed on	Low-cost Little distress caused to animal Easily removed	Prone to human-error when reading Could be lost Susceptible to fraud Application may cause infection	Awad, 2016; Bai et al., 2017
Electronic methods			
Barcode ear tags, printed bar code on the ear tag	Easy to read with barcode reader Low-cost Little distress caused to animal Easily removed	Could be lost Application may cause infection Requires line of sight	Awad, 2016; Bai et al., 2017; Ruiz-Garcia and Lunadei, 2011
RFID/EID ear tags, transponder is contained within a plastic ear tag which also has a printed number visible	Little distress caused to animal Easy to attach and remove Electronic read without animal contact or line of sight Electronic read tags quickly Electronic read tags accurately Read-write ability (UHF) Possibility of combining with sensors (UHF)	Could be lost Could be damaged and stop being electronic readable Could be tampered with Application may cause infection Need to be relatively close to animal to read (LF, within 20 cm) Security concerns if data stored on tag (UHF)	Awad, 2016; Eradus and Jansen, 1999; Morgan-Davies and Wishart, 2015; Ruiz-Garcia and Lunadei, 2011; Wheeler et al., 2012

Continued

Table 2.6 Continued

RFID/EID Bolus, inserted through the mouth and sits within the reticulum	Electronic read tags quickly Retention rate is high Electronic read tags accurately Cannot be tampered with	Could be lost Cannot see if animal has bolus Skilled person required to administer Risk of injury if administered incorrectly Risk of entering food chain	Awad, 2016; Cappai et al., 2014; Hentz et al., 2014; Morgan-Davies and Wishart, 2015
RFID implant, transponder is contained in a glass tube and injected under the skin	High level of reliability and security Electronic read tags quickly Electronic read tags accurately	Risk of entering food chain Risk of migrating from original implant site Skilled person required to administer Readability can be poor Cannot see if animal has implant	Awad, 2016; Bai et al., 2017
New emerging biometric methods (not yet commercially used)			
Muzzle print, either digital or ink print taken of unique groves of the muzzle (cattle)	Remains with the animal throughout its life Cannot be removed or altered High accuracy of identification	Challenging to collect accurately Labour intensive to collect and identify animal	Awad, 2016
DNA fingerprint, animals own DNA used to identify it	Possible to trace animal from farm to plate Remains with the animal throughout its life High identification accuracy Cannot be removed or altered	Expensive Labour intensive to collect and identify animal Require specialist equipment to identify animals so unlikely to have on farm application	Awad, 2016; Bai et al., 2017
Iris pattern, use unique pattern of the iris to identify animal	Cannot be removed or altered Remains with the animal throughout its life	Challenging to capture iris pattern accurately	Awad, 2016
Retina Vascular, scans the unique pattern of blood vessels on the retina	Remains with the animal throughout its life Cannot be removed or altered	Expensive Cannot use to identify a dead animal	Awad, 2016; Bai et al., 2017

RFID: Radio Frequency Identification; EID: Electronic Identification; UHF: Ultra-high frequency; LF: Low Frequency.

Within the UK, current legislation, as published on the UK Government website (UK Government, 2014), states that all adult sheep (over 12 months old or when they leave their farm of origin) must have two identifiers. These two identifiers must have the same unique 14 character individual identification number. One of the two identifiers must be in the form of an EID. These identifiers are normally ear tags but one could be a pastern (leg band), EID bolus or EID injectable. For lambs intended for slaughter, and less than 12 months old, only one identifier is required.

2.3.3.1.1 *Electronic identification development*

A collaboration of various research institutes around the world began RFID technology development at the beginning of the 1970s (Rossing, 1999). This first generation of RFID technology for livestock was a box attached to the animal on a collar (Eradus and Jansen, 1999). The second generation was a tiny electronic transponder (Eradus and Jansen, 1999) and it is this that is now used for individual identification of sheep and cattle within the EU (according to European Regulation 21/2004). RFID systems consist of a transponder which contains the individual identification number of the animal which can be retrieved and recorded on an RFID reader with the use of software (Awad, 2016; Barge et al., 2013). The RFID transponder is either packaged as an injectable glass tag put under the skin; in a bolus which sits in the reticulum of ruminants; or in an ear tag (Awad, 2016; Ruiz-Garcia and Lunadei, 2011).

Within the EU, low frequency RFID (referred to as EID) tags have to comply with ISO (International Organization for Standardization, numbers 11784 and 11785) standards, which includes numbering system (Ruiz-Garcia and Lunadei, 2011). All EID numbers start with a country code (826 for the UK) followed by a 0, then a six digit flock number and finally a five digit number which will be unique to individual animals on the same farm (Defra, 2013).

In order for EID to be useful, both on farm and within the supply chain, EID readers and software are required. Wireless electromagnetic fields created by readers are used to transfer/read the unique number from the transponder (Bai et al., 2017). Commercially available EID readers are either handheld sticks or panels (Morgan-Davies and Wishart, 2015). Panels are attached either to a race wall, to read tags as animals walk past or fitted within weigh-crates. Farm management software companies sell these readers to customers so information collected on farm can be uploaded into farm software packages stored on a computer, online or through mobile applications (Defra, 2013; Morgan-Davies and Wishart, 2015).

2.3.3.1.2 *Challenges and opportunities of EID*

When EID and associated technology (readers and farm management software), are used within applied settings, it can be an advantageous tool providing: improved identification of animals over visual tags; reduced labour costs; improved disease control and eradication; fraud control; provide a method to record parentage and breeding details; and allows improvement to farming systems (Barge et al., 2013; Morgan-Davies and Wishart, 2015; Rossing, 1999; Ruiz-Garcia and Lunadei, 2011). However some concerns over its use have been highlighted by research. For instance, there have been concerns over read rate (taking into account damage of transponder which inhibits reading) and retention of the tags (Barge et al., 2013; Cappai et al., 2014; Wheeler et al., 2012). Both elements are essential for an effective traceability system (Bai et al., 2017). In Scotland, the Scottish livestock traceability research team ("ScotEID", www.scoteid.com), which works closely with the Scottish Government, has researched tracking systems using EID. All their research has demonstrated that EID is an appropriate tool to use for traceability of sheep. However, it should be considered that tag readability both on farm and at abattoirs can also be reduced when readers are not installed or set up properly (Defra, 2013; Ruiz-Garcia and Lunadei, 2011).

For any advantages of EID to be realised on farm, extra EID equipment is required (for example, readers). Using EID and associated technology not only provides an effective way for farms to keep accurate records, such as medicinal treatments and movements, which they are required to keep (Defra, 2013), but also allows for individual animals and their performance to be monitored.

The current EID tags used in the UK operate at low frequency (LF) radio waves (125.0-134.5 kHz), with a relatively short read range (around 20 cm between tag and reader) and work passively, meaning information on them can only be read (Awad, 2016; Defra, 2013). The third generation known as ultra-high frequency (UHF) operate at 433 MHz, have a greater read range (typically 3 m) and a read/write ability (Ruiz-Garcia and Lunadei, 2011). Therefore information such as movement or health treatments can be written directly to the tag (Eradus and Jansen, 1999; Ruiz-Garcia and Lunadei, 2011). Future development of these RFID tags is to couple with sensor technology and provide the ability to record biological measures such as the animals' temperature (Eradus and Jansen, 1999; Ruiz-Garcia and Lunadei, 2011). While UHF tags are commercially available, uptake is still minimal and their use is not compulsory.

EID and associated technology (readers) are suitable for PLF approaches. This technology allows for individual animals to be identified and performance monitored at an individual level.

2.3.3.2 Weighing technology

As previously discussed, liveweight is a useful measure within PLF methodology, and weighing technology to collect liveweight data has developed over time.

2.3.3.2.1 *Digital and automated static weighing*

Typical livestock weighing equipment in the 1970s were mechanical scales with a lever support system where the indicator was a spring dial balance (Hirsch, 1985; Hughes and Garden, 1977). While these were a relatively simple design and construction, they required the stockperson to estimate the animal's liveweight from a needle that moved as the animal moved. Therefore, liveweight data was often inaccurate and data collection was time consuming (Hughes and Garden, 1977).

In the 1980s, Hirsch (1985) published results of an electronic digital indicator. The incorporated microprocessor received weight readings from load cells and through a damping algorithm was able to extract the average liveweight from an animal that was moving. Furthermore, the microprocessor also allowed for auto-taring after each animal, allowing for any dirt brought into, or left within, the weigh-crate by an animal to not be included in the recorded liveweight. Such a system allowed for a stable liveweight reading to be collected at the desired accuracy in the shortest possible time (Hirsch, 1985). The principles of this are still used within current commercial digital weigh-crates/weigh-heads.

There are many different commercial sheep weigh-crates on the market (Table 2.7). All types and models include three elements: a crate, in which the animal is held; weigh-cells or -bars, which are either compression cells positioned under the crate or expansion cells from which the crate hangs; and an indicator or weigh-head, which presents the liveweight. EID enabled weigh-crates also include: an EID antenna, EID reader and a weigh-head or separate device able to record both EID and weight record together. An EID enabled weigh-head is often more expensive than if a device such as a data logger, tablet or laptop were used (AHDB, 2015b).

The most advanced (and expensive) commercial weigh-crates also incorporate a number of automated pneumatic gates. These gates split (or draft) sheep in up to 5 different pens as they exit the weigh-crate (Table 2.7, Figure 2.5). Auto-drafting is controlled by a weigh-head into which the operator has set pre-defined sorting criteria, for example, based on liveweight, age, BCS or number of lambs being carried (AHDB, 2015b). In this way, EID tags and readers allow liveweights to be easily collected and utilised on an individual animal basis (Morgan-Davies and Wishart, 2015).

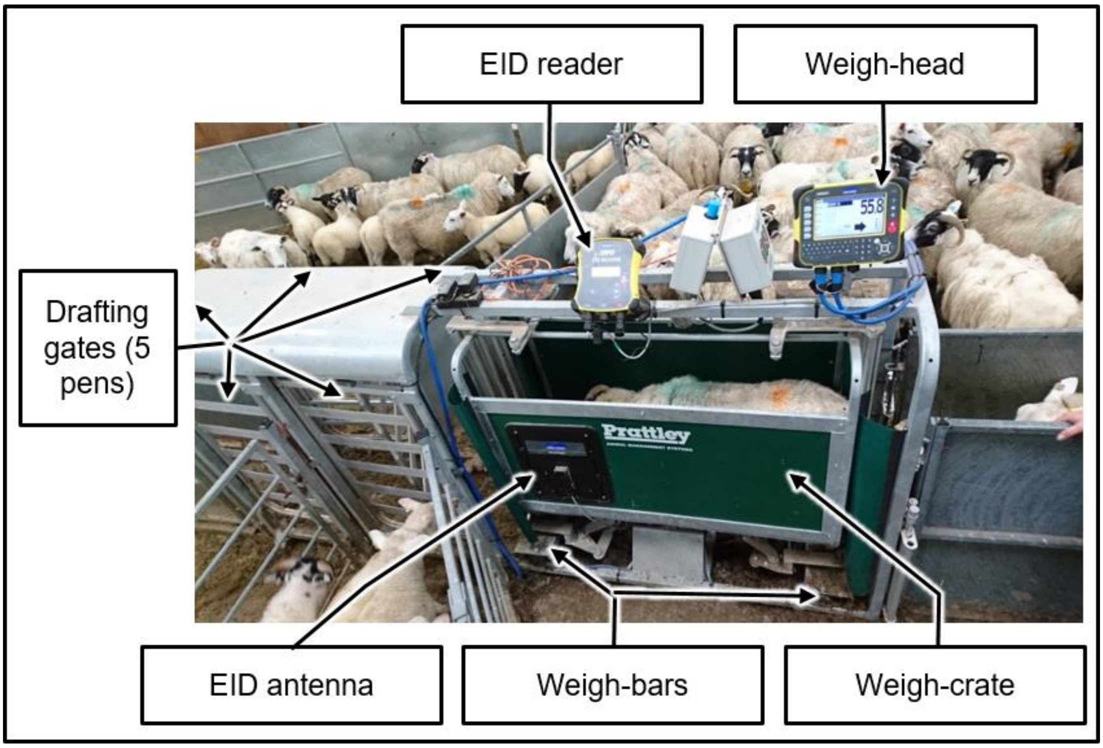


Figure 2.5 Example of automated weighing and drafting EID enabled weigh equipment.

EID enabled weighing technology (as presented) has been utilised to collect liveweight data in much research (Bowen et al., 2008; Galwey et al., 2013; Wilson et al., 2015). However, there is still little evidence that this technology is being adopted on-farms (Corner-Thomas et al., 2016; Rivallant et al., 2019). High cost of equipment is often cited in literature as a barrier to uptake (Lima et al., 2018; Morgan-Davies and Lambe, 2015; Rivallant et al., 2019). Therefore, EID enabled weighing technology use within PLF methodology seems appropriate, although cost needs to be considered.

Table 2.7 Commercial static sheep weigh-crates (including online prices as of 18th April 2019).

Manufacturer and model	Gates and drafting. Scales/weigh cells	Indicator/weigh-head	Built in EID reading	Price (ex VAT), website
IAE mechanical lamb weigher				
	Manual with no drafting Analog scales	Analog	None	£ 470.15 www.molevalleyfarmers.com
Ritchie digital lamb weigher				
	Manual with no drafting Digital scales	Battery operated	None	£ 843.00 www.ritchie-d.co.uk
FarmIT3000 weigh-crate				
	Manual 3 way drafting Digital load bars (Tru-Test MP600)	Digital weigh-head with automatic weight recording and other data entry capabilities (Tru-Test XR3000)	Built in antenna with reader transferring EID number directly to weigh-head (Agrident ASR EID Reader Module)	£ 1,300.00 www.boredersoftware.com (not including: EID reader, loadbars or weigh-head)

Continued

Table 2.7 Continued

Shearwell EID sheep management crate				
	Manual with no drafting Digital load bars (Te Pari 600mm Standard Load Bars)	Digital weigh-head with automatic weight recording and other data entry capabilities, sends data directly to handheld computer (Te Pari T10 weigh-head indicator, Shearwell Stock Recorder running FarmWorks software)	Built in antenna with reader transferring EID number to handheld computer (Shearwell Panel Antenna and Reader, Shearwell Stock Recorder running FarmWorks software)	£ 6,710.00 www.shearwell.co.uk
Prattley 3 way auto-drafter				
	Pneumatic 3 automated gates with 3 way drafting (controlled by weigh-head) Digital load bars (Tru-Test MP600)	Digital weigh-head with automatic weight recording and other data entry capabilities (Tru-Test XR5000)	Built in antenna with reader transferring EID number directly to weigh-head (Tru-Test EID antenna, Tru-Test XRP2 panel reader)	£ 9,495.00 www.tannertrading.co.uk (not including: EID antenna, reader or weigh-head)

Company details: IAE, Stoke-on-Trent, UK; Richie Agricultural, Forfar, UK; Border Software Ltd., Welshpool, UK; Shearwell Data Ltd., Wheddon Cross, UK; Prattley Industries Ltd, Temuka, New Zealand; Tru-Test, Datamars, Auckland, NZ; Te Pari Limited, Oamaru, NZ.

2.3.3.2.2 *Advances and developments in weighing technology*

The weighing technology discussed to this point is referred to as static weighing, where the animal is retained within the weigh-crate while weight data is recorded. A disadvantage is that all animals must be gathered into a single location to be weighed, which can impact reliability of liveweight data as a result of gut-fill loss (Coates and Penning, 2000; Hughes, 1976), as discussed (and will be investigated in Chapter 4). However, alternative weighing technologies have been developed.

Recent advances and developments in weighing technology have focussed on collecting liveweights frequently from livestock within their everyday environment (meaning within a shed or field). One developing methodology involves digital image analysis within buildings and pens to estimate cattle liveweights (for example, Tasdemir et al., 2011), although no similar examples could be found for sheep.

An in-field method of collecting liveweight data frequently from sheep is walk-over-weighing (Brown et al., 2014a, 2014b, 2012; González-García et al., 2018, 2017). This is where the individual sheep voluntarily walks through an EID weighing setup to reach a reward such as feed, water or alternative pasture. This is carried out within a field as part of the animal's everyday life and without stockpeople being present. Liveweight and EID number are automatically recorded as the animal walks over the weigh platform. Some research has queried the reliability of data generated from such setups (Brown et al., 2014a, 2014b), while other research groups have developed a novel gate setup for the system, slowing the movement of animals through, and demonstrated collection of reliable data (González-García et al., 2018). This walk-over-weighing technology is promising for future PLF methodology, however it is not currently commercially available within the UK and not used for research within this thesis.

2.3.3.3 Software and databases

Farm Management Software (FMS) (also referred to in the literature as Farm Management Information Systems, for example, Fountas et al., 2015, or Farm Management Systems, for example, Voulodimos et al., 2010) are commercially available and interesting for PLF. While it has been reported that FMS packages have been used for record-keeping since the 1970s (Fountas et al., 2015), they are now able to make use of the data collected from EID readers, data loggers, handheld computers, smart phones and weigh-heads. Indeed FMS have been highlighted as an important tool for EID use (Commission of the European

Communities, 2007; Henry et al., 2012). There are a huge number of FMSs commercially available; a recent article for crop production in the UK, US, Canada and Australia reviewed 141 relevant packages (Fountas et al., 2015). However, there are no published figures for the number of FMS packages that deal with livestock data. Although, within the UK there are a range of commercially available FMSs, including Farmplan (Ross-on-Wye, UK), Shearwell Data (Shearwell Data Ltd., Wheddon Cross, UK), FarmIT 3000 (Border Software Ltd., Welshpool, UK).

For sheep systems, these FMS are used to record movements, sales, medical treatments, pedigree, lambing records, carcass information, liveweight and BCS for individuals or groups (Defra, 2013). FMS also produce reports from the data entered. In this way, it is possible to see how FMS could be useful to monitor individual sheep and therefore provide information for PLF approaches, however they will not be considered further within this thesis.

2.4 Literature review conclusions

Scottish hill sheep systems are comparable to other extensive sheep systems in harsh environments around the world and can be used as a suitable case study. Hill sheep systems have important roles for rural communities, environmental management, and production of lamb meat and breeding animals. However, they face difficulties including: low productivity, poor economic viability, labour availability and capability, and ensuring good animal welfare. Exploring different approaches could address these difficulties; PLF is one such approach.

Terminology used to characterise and define PLF has previously been inconsistent. In response a new complete definition was formulated as follows: PLF is an approach to livestock system management which utilises four key principles: 1) exploitation of scientific knowledge about the system; 2) measurement, monitoring and management of the system; 3) appropriate use of technology; and 4) identifying and targeting variation within the system precisely. The goal of these four principles is to improve the efficiency of the livestock system by some, or all of the following: increasing productivity, economic viability, welfare, and reducing labour and environmental impact. The principles and goal to be achieved will depend on the characteristics of the livestock system including: species, intensity of system and main outputs.

PLF approaches have been successfully applied to intensive systems but there are limited examples of application to sheep systems. Application of PLF has the potential to improve difficulties faced by hill sheep systems and is an important area of research that, to date, has received limited exploration. This will be addressed within this thesis. When applying PLF to a system, identifying suitable processes to target is important. In this thesis, processes/challenges that will be considered for improvement have been identified as pregnancy supplementation, and retention and culling decision making. Potential measures and technology to be used to apply PLF approaches to these challenge areas were identified. Such measures include: liveweight, liveweight change, production outputs, and BCS. Commercially available technologies include EID and automated weighing and drafting technology.

In conclusion, this chapter has reviewed literature on hill sheep systems and PLF, as well as identifying gaps in the knowledge. This has provided the background and justification for exploring the aim of this thesis.

CHAPTER 3: RESEARCH SETTING

3.1 Research farm environment

Research for this thesis was carried out at Kirkton and Auchtertyre Farms which are part of the Scotland's Rural College (SRUC), Hill and Mountain Research Centre, in the West Highlands of Scotland. The land of the hill farm ranges between 180 to 1,034 m above sea level and has an annual rainfall of 2,500 mm.

Three pasture types are identifiable on the farm and are classified as: 1) improved fields, with good quality pasture, fertilised annually with the potential for silage making, at an altitude of around 180 m; 2) semi-improved parks, with partially improved semi-natural permanent grassland and wet heath, with an altitude of 180 to 230 m; and 3) unimproved hill, which is a mosaic of semi-natural permanent acid grasslands (*Nardus stricta*, *Agrostis* and *Festuca*), heath rush, sedge mire and wet heath, ranging in altitude from 230 to 1,034 m. The majority of the farm's 2,200 ha is unimproved hill pasture and around 230 ha is improved fields and semi-improved parks (Figure 3.1).

3.2 Research flock

For this thesis, methods were applied and data was collected from October 2013 to October 2016. During this period of study, the farm carried 1,200 hill ewes and 22 hill cattle. However, for the purpose of this thesis, it was the long-term performance recorded research flock of 900 breeding ewes which was of interest and whose data were used throughout.

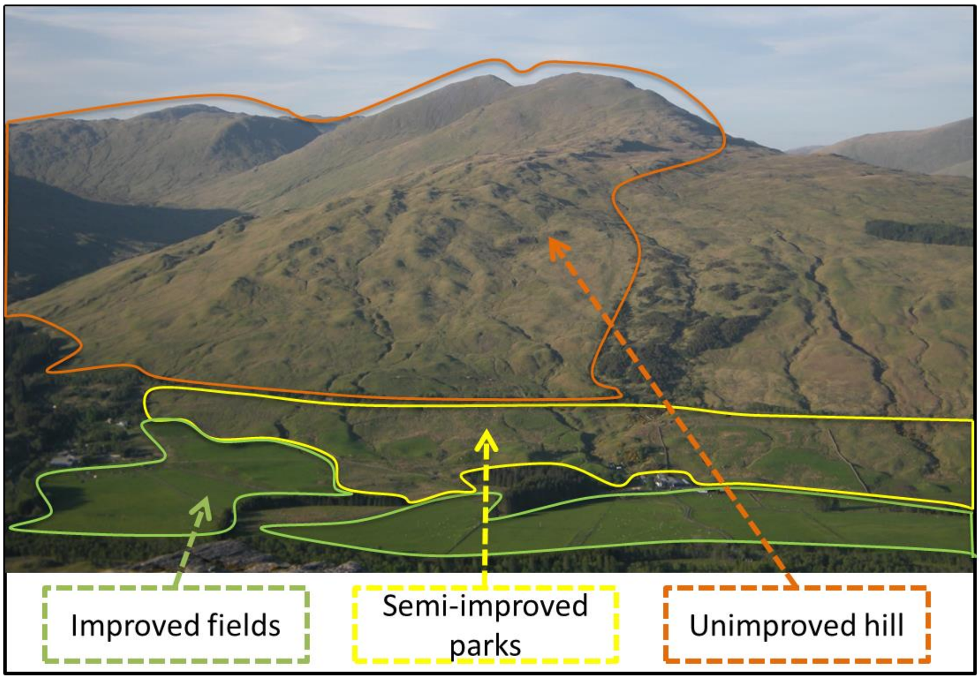


Figure 3.1 The research farm's pasture types (photo courtesy of Agathe Malzac)

All work involving animals was carried out in accordance with EU Directive 2010/63/EU and was approved by SRUC's Animal Welfare and Ethical Review Body. The research farm was typical of commercial Scottish hill farms in terms of environment, sheep breed and standard husbandry; although the research flock was handled and recorded more frequently at fixed points throughout the year (Figure 3.2).

3.2.1 Genetic lines of the research flock

The research flock was composed of three different genetic lines: Scottish Blackfaces with high EBVs; Scottish Blackfaces with average EBVs (Scottish Blackfaces had been performance recorded on the farm since 1996); and Lleyns with high EBVs (performance recorded since 2011). All EBVs were generated by Signet Breeding Services as part of their Sheepbreeder programme (Signet, 2015). Ewe lambs were selected to join the breeding ewe flock depending on their individual EBVs and the requirements of their line. Homebred or brought in rams were selected based on their EBVs and only mated with ewes of the same line. Further information on the different genetic lines can be found from Conington et al. (2006, 2001) and McLaren et al. (2012).

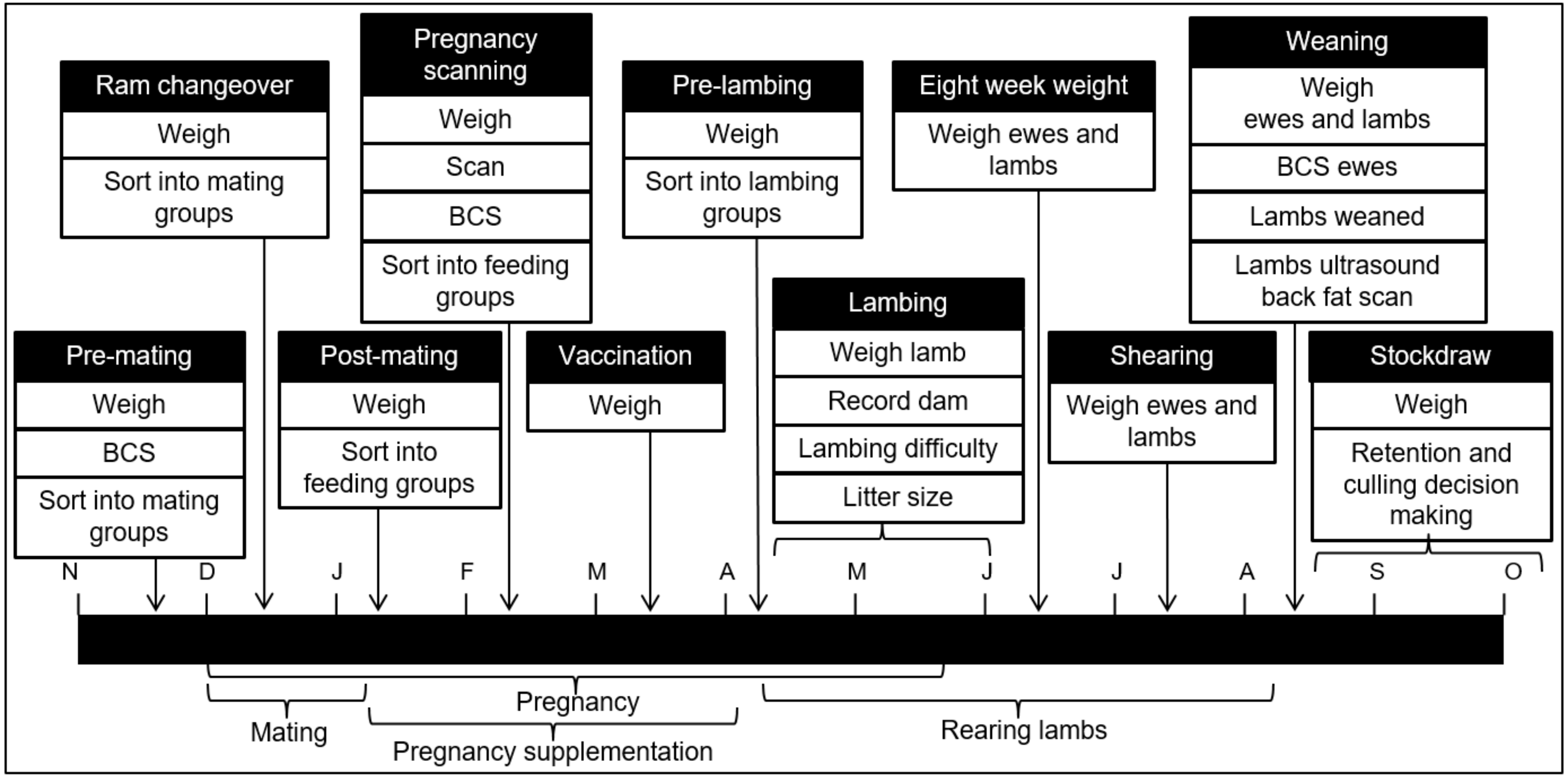


Figure 3.2 Production year of the research flock, showing ewe handling events (black boxes) and research tasks and data collected (white boxes). Handling events are marked when they typically occurred.

All tasks relate to the ewes of the flock unless specified.
Other husbandry tasks (including provision of standard medical treatment) and other research tasks also occurred at these handling events.
BCS: Body Condition Score; Pregnancy scanning/scan: ultrasound scanning to determine number of foetus being carried.

Sheep from the three lines were in mixed groups and managed together throughout the study period (apart from when separated into genetic line groups for mating). Data from all three genetic lines were used for this research and have been considered together. A thorough breed and line comparison, under the management approaches to be described, has been considered elsewhere (Zhou et al., 2017; Zhou, PhD thesis being completed).

3.2.2 Two management approaches

During the period of study, all 900 breeding ewes were assigned to one of two management approaches, which were balanced according to line, age, liveweight, litter size and sire (Table 3.1). The first approach was a conventional (CON) one, where management decisions were carried out at a flock level, or without the assistance of EID technology, and was comparable to conventional hill sheep systems. The other approach was PLF, where management decisions were carried out at an individual sheep level, assisted by EID technology.

Four processes through the year were affected by the different management approaches: pregnancy supplementation of ewes; retention and culling decision making at stockdraw of ewes; finishing of weaned male lambs; and anthelmintic treatment of lambs through the summer. Only the first two processes were explored within this thesis and the last was discussed elsewhere (Kenyon et al., 2017b; McBean et al., 2016; Morgan-Davies et al., 2018b). While different decisions were made based on the management approach the ewe belonged to, once decisions had been made, the ewes remained in mixed approach groups. Further details and comparisons between the approaches can be found from Morgan-Davies et al. (2018b, Appendix 2). EID and weighing facility

Table 3.1 Count of breeding ewes between genetic lines and management approaches.

Management approaches \ Genetic lines	Scottish Blackface control	Scottish Blackface selection	Lleyn
Conventional (CON)	150	150	150
Precision Livestock Farming (PLF)	150	150	150

3.3 EID and weighing setup

The following EID weighing setup was used to collect all liveweights discussed in all chapters of this thesis. A Prattley Auto Drafter (Prattley Industries, Temuka, New Zealand), with Tru-Test™ MP600 load bars and XR3000 weigh-head (Tru-Test Group, Auckland, New Zealand) recorded all sheep liveweight data automatically. All liveweight data was then downloaded onto a computer for analysis.

The weigh-head and weigh-bars collected liveweights at a resolution of 0.1 kg for weights between 0-50 kg; weights between 50-100 kg were recorded to 0.2 kg. The weigh-head was set to use the inbuilt system: Superdamp III (Sheep) (Tru-Test Group, Auckland, New Zealand). This used a damping algorithm to allow accurate liveweights to be collected from sheep in the weigh-crate standing still or moving, with the liveweight automatically recorded when within tolerance (Tru-Test XR3000, Tru-Test Group, Auckland, New Zealand).

The liveweights were recorded in the weigh-head against each ewe's unique identification number stored on their low frequency RFID, or EID, ear tag. This was read in the weigh-crate via an Allflex® RFID portal reader (Allflex Australia, Queensland, Australia). The EID tags used were either Ritchey™ RD2000 tags (Ritchey Ltd., County Durham, United Kingdom), Shearwell Data SET Tags (Shearwell Data Ltd., Somerset, United Kingdom) or Allflex® Button tags (Allflex UK Group Ltd, County Durham, United Kingdom). No difference in performance was seen between different EID tags.

The weighing setup also had the ability to automatically sort or draft (referred to as auto-draft) a group of ewes into smaller groups. The weigh-head could be programmed, creating drafting rules, for allocating ewes to one of five groups based on information stored in the weigh-head about each ewe (for example: breed, sex, age, management approach, genetic line), as well as new information collected as the ewe was weighed (for example: liveweight, liveweight change compared to a previous liveweight, BCS). When each ewe was weighed their EID, liveweight and extra information entered (such as BCS) was automatically recorded in the weigh-head. This data (and other information stored about the ewe) was then compared to the drafting rules and, according to that, the weigh-crate automatically opened the exit gates to allow ewes to enter one of five different pens.

PART 1

Challenge: allocating pregnant ewes to supplementary feeding groups within hill sheep systems

CHAPTER 4: LIVEWEIGHT LOSS ASSOCIATED WITH HANDLING AND WEIGHING OF GRAZING SHEEP

Liveweight data was identified in Chapter 2 as being a potentially useful measure for PLF approaches. The availability of technology for collection of liveweight data also appeared promising. However liveweight data is subject to short-term fluctuations. The aim of this chapter is to explore how reliable liveweight data are when collected in an applied setting, such as on research or commercial farms, particularly when delays in weighing occur, and how reliability could be improved.

This chapter is adapted from the following published paper:

Wishart, H., Morgan-Davies, C., Stott, A., Wilson, R., Waterhouse, T., 2017. Liveweight loss associated with handling and weighing of grazing sheep. Small Ruminant Research 153, 163-170.

Initial work was also presented as a conference proceedings:

Wishart, H., Lambe, N., Morgan-Davies, C., Waterhouse, A., 2014. The effect of duration of removal from grazing on body weight in sheep measured with an automated weighing system, in: British Society of Animal Science. Nottingham, UK. p. 15.

4.1 Introduction

Chapter 2 found that liveweights are used extensively throughout research due to their versatility in showing animal responses to a wide range of inputs (Baker et al., 1947; Brown et al., 2015; Coates and Penning, 2000). It has been suggested that liveweight, along with EID weighing technology, could be useful for PLF approaches (Brown et al., 2015; Morgan-Davies and Wishart, 2015; Young et al., 2011). However, a measure of liveweight is composed of many different factors, including gut-fill, which fluctuates and so impacts on liveweights (Hughes, 1976). Fluctuating liveweight causes concern for research requiring reliable liveweights. Short-term liveweight fluctuations in ruminants are affected by: feed and water consumption (Whiteman et al., 1954); time since last meal (Hughes, 1976); quality and quantity of feed available (Hughes and Harker, 1950); age and size of the animal (Lush et al., 1928); time of day relative to sunrise (Gregorini, 2012); ambient temperature (Lush et al., 1928); and individual differences in grazing behaviour (Hughes and Harker, 1950).

Robust methodology is required to reduce variation in liveweights between animals and weigh points to ensure liveweight data collected are comparable. This requirement becomes more essential as on-going improvements in weighing equipment, software and data management is resulting in liveweight data having greater use in research and management on farms (as will be demonstrated throughout this thesis). Methodologies to reduce variation include: fasting prior to weighing (Coates and Penning, 2000); standardising weighing procedure (Watson et al., 2013); taking an average of multiple liveweights across a number of successive days (Koch et al., 1958); weighing at a specific time relative to sunrise (Hughes and Harker, 1950); standardising feed before weighing (Meyer et al., 1960); increasing the number of animals (Hughes, 1976); and repetitions of the study (Lush et al., 1928). However, there is evidence that such methodologies to reduce variation are not being considered or used in research. To illustrate this I examined 35 recent peer-reviewed papers (from Small Ruminant Research 2014, all issues of volume 120) and revealed that of the 11 papers involving liveweights, only 2 clearly stated the method used to control liveweight variation.

Reasons why variation reduction methodology is not being followed may be that: broader methodology has not caught up with the improved weighing technology now available; people collecting liveweights are simply not aware of the problem; or such methodologies are not practical when liveweight collection (research or commercial) is carried out in farm situations.

Consideration of the on-farm situation raises concern that not only is variation in liveweight not being controlled but procedures in weighing could also be adding systematic error to the data. On a research or commercial farm, weighing of sheep is likely to occur alongside other husbandry or research procedures. On large farms, including hill sheep farms, many animals may be gathered from fields of varying distances to be handled and weighed on the same day. Inevitably, this results in delays, where groups of sheep are removed from pasture and then wait varying lengths of time, without access to food and water prior to weighing.

Delays in weighing leads to gut-fill weight loss, with previous literature reporting losses of 0.5 to 2 kg after six hours and 1 to 4 kg after 12 hours (Hughes, 1976). Indeed fasting (removal of feed and water) is well documented as a suitable method to reduce variation in liveweight, where feed and water are removed for fixed long periods of time prior to weighing (for example, Coates and Penning, 2000; Shrestha et al., 1991; Wilson et al., 2015). My review of the literature found that only research carried out by Wilson et al. (2015) considered the impact of removal of feed and water for less than six hours; however, this was with the focus of fasting to reduce variation in gut-fill between animals or weigh points. Adjustment of liveweights has previously been used as a method to reduce errors: by Scott (2011), via a moving average of mean liveweights; and by Kane et al. (1987), using assumptions of feed intake and quality. However, both these methods are unsuitable or challenging for single weighings in a grazing sheep system. No published studies were found that attempted to develop a correction equation for liveweights with a known short-term period of delay prior to weighing as a result of a gathering and handling procedure of six or less hours.

Additionally, research considering error in liveweight data often discusses it in relation to improving accuracy of the liveweight (Hughes and Harker, 1950; Hughes, 1976; Lush et al., 1928; Whiteman et al., 1954). The definition of *"accuracy refers to how well the observed value of a quantity agrees with the true value"* (Petrie and Watson, 2013). However given how many factors can impact on liveweight, it is challenging to define what the "correct" or "true" liveweight actually is. Reducing the factors impacting variability of liveweights (and so reducing error in liveweight) might instead be more relevant. Therefore the aim for collecting "reliable" liveweight may be more appropriate, where *"reliability reflects the amount of error, both random and systematic, inherent in any measurement. It encompasses repeatability, reproducibility, validity and stability"* (Petrie and Watson, 2013).

4.1.1 Aims of Chapter

The aims of this chapter are:

1) To determine the extent of liveweight loss in sheep, in a practical environment, as a result of delayed weighing over three and six hours.
2) To explore whether this information can be used to produce a methodology to reliably correct delayed liveweights across different situations.
3) To demonstrate the potential consequence of not correcting delayed liveweights.
4) To consider the suitability of utilising liveweights within PLF approaches applied to hill sheep systems.

4.2 Materials and Methods

This research was carried out in three stages, with the following objectives:

STAGE 1: Liveweight loss study. To quantify liveweight and liveweight loss over three and six hours delayed weighing within a handling facility and without access to feed or water. Then to use these findings to develop a correction equation for delayed liveweights.

STAGE 2: Validating process. To examine the precision and accuracy of the correction equation by using it on different sets of delayed liveweight data collected under a range of situations.

STAGE 3: Management simulation. To explore what impact delayed and corrected delayed liveweights could have when liveweight change is used to assign ewes to feeding levels.

All three stages of this research used the main research flock (described in Chapter 3) from which sheep and liveweight data were selected. All liveweight data were collected with the EID weighing facility described in Chapter 3.

4.2.1 STAGE 1: Liveweight loss study

4.2.1.1 Animals

For the liveweight loss study, 100 Scottish Blackface non-pregnant and non-lactating ewes (25 from each of four age groups; 1.5, 2.5, 3.5 and 4.5 years of age) were randomly selected and separated from the research flock grazing unimproved hill pasture. The 100 selected ewes were placed in a field of improved pasture overnight prior to the study on the following morning (6th November 2013).

4.2.1.2 Times and weighing

Three weigh sessions were started at 9 am, 12 pm and 3 pm; each weigh session involved weighing the 100 ewes three times (Table 4.1). Each time, or round, involved weighing all ewes once before moving on to the next round immediately after the last ewe exited the weigh-crate.

Table 4.1 Actual times for weighing sheep at three weigh sessions, with varying lengths of delay prior to weighing. Each weigh session comprised of weighing 100 ewes three times.

Weigh session	Approx. weigh time	Approx. hours delayed	Actual start time	Actual finish time of 3 rounds
1	9 am	0	08:59	09:43
2	12 pm	3	12:08	12:47
3	3 pm	6	15:04	15:45

A period of 30 minutes elapsed between sheep grazing being halted (by the stockperson and dog entering the field) and liveweight being collected from the first ewe entering the weigh-crate for the first weigh session. Between weigh sessions, ewes were housed indoors with no access to feed or water. The first liveweights collected (9 am, round 1 liveweights), are referred to as the "without delay" liveweights. The term "without delay" liveweight will be used throughout this chapter to describe any liveweight collected as soon as animals entered the handling facility; these may still contain some delay as a result of gathering from pasture. All other liveweights will be referred to as "delayed" liveweights.

During the day, between weigh sessions, BCSs (scored on a 5 point scale with quarter intervals, according to Russel et al., 1969) were collected. Three different experienced condition scorers assessed each ewe three times; resulting in nine scores per ewe. An average (mode) score per ewe was used in analysis.

4.2.1.3 Liveweight and liveweight change

The mean liveweight per ewe (from the three liveweights recorded per session) was used to provide the best estimate of liveweight at each weigh session. These were used to consider short-term liveweight change over three (9 am to 12 pm) and six (9 am to 3 pm) hours delay prior to weighing. These periods of delay are comparable to the length of handling operations on a farm. Gathering extensive hill grazing can take three hours (Stott et al., 2005), while six hours is a maximum length of time gathering and handling is likely to occur in one day. The mean liveweights at each weigh session were compared using a one-way Analysis of Variances (ANOVA) blocked for animal in GenStat 16th Edition (Payne et al., 2013).

Mean "without delay" liveweight (calculated from all three liveweights collected during the 9 am weigh session), BCS and age were all considered against the actual and the proportion of liveweight change over three and six hours delay. Correlation was used to explore mean "without delay" liveweight and one-way ANOVAs for BCS and age. Liveweight change over the first three hours (9 am to 12 pm) and the second three hours (12 pm to 3 pm) were compared via a paired t-test to determine whether rate of change was the same throughout the six hours delay period.

4.2.1.4 Delayed liveweight correction equation

All nine liveweights over the three weigh sessions were then used in the development of an equation to correct delayed liveweights. For this, liveweight loss over the whole six hour period was treated as linear. Using all nine liveweights per individual allowed for a greater number of data points in the analysis. The proportion of liveweight loss was analysed via a Linear Mixed Model in GenStat 16th Edition (Payne et al., 2013) to produce a regression equation (the correction equation). The fixed model included decimal hours delayed and the random model included the interaction between the individual sheep and decimal hours delayed. The proportion of liveweight loss was calculated from the "without delay" liveweight for all subsequent delayed liveweights (resulting in 800 data points). Decimal hours delayed since the "without delay" liveweight were calculated for each delayed liveweight as a result of time information automatically recorded by the weigh-head.

4.2.2 STAGE 2: Validating process

4.2.2.1 Dataset

The resulting correction equation from STAGE 1 was tested on a different dataset. This validation dataset contained 1,581 pairs of liveweights, from 20 groups of sheep. These were collected as part of the larger project being carried out on the research farm (as explained in Chapter 3), between and including January 2014 and June 2015. Each pair of liveweights was collected from the same sheep over the same day and with a known delay between the two liveweights. These data included sheep from outside the narrow range of conditions of the original liveweight loss study, and encompassed five different categories: breed, sex, stage of production, grazing location and hours delayed prior to weighing (Table 4.2).

Table 4.2 Description of validation dataset containing pairs of actual liveweights (aWt1, liveweight collected without delay and aWt2, delayed liveweight) collected from the same individual sheep on the same day with varying length of delay in weighing between the two, for different categories (SD in brackets).

Categories	***n***	**Mean aWt1 (kg)**	**Mean aWt2 (kg)**	**Mean Difference aWt2-aWt1 (kg)**	**Time range between aWt1-aWt2 (h)**
All	**1581**	**40.94 (10.56)**	**40.06 (10.35)**	**-0.88 (0.72)**	**0.3 - 4.9**
Stage of production					
Non-pregnant & non-lactating ewe	455	51.06 (5.91)	50.07 (5.93)	-0.99 (0.59)	2.3 - 4.9
Pregnant ewe	164	50.79 (6.25)	49.25 (6.20)	-1.55 (0.78)	2.2 - 3.65
Lactating ewe[a]	88	47.72 (5.67)	47.04 (5.73)	-0.68 (0.43)	0.85 - 2.62
Suckling lamb[b]	69	26.56 (3.89)	26.09 (3.69)	-0.48 (0.52)	1.28 - 4.72
Weaned lamb[c]	805	33.70 (5.81)	32.97 (5.62)	-0.73 (0.73)	0.3 - 4.72
Sex					
Female	1014	44.12 (11.38)	43.31 (11.04)	-0.81 (0.76)	0.3 - 4.9
Male (lambs only)	567	35.24 (5.36)	34.25 (5.28)	-0.99 (0.65)	0.38 - 4.72
Grazing location					
Improved field[d]	823	39.34 (8.35)	38.33 (8.29)	-1.01 (0.66)	0.38 - 4.72
Semi-improved park[e]	390	33.59 (9.23)	33.29 (9.09)	-0.3 (0.55)	0.3 - 4.57
Unimproved hill[f]	368	52.30 (6.40)	51.12 (6.43)	-1.18 (0.71)	2.2 - 4.9
Breed					
Scottish Blackface	623	39.21 (9.27)	38.32 (9.22)	-0.88 (0.67)	0.37 - 4.72
Lleyn	857	43.57 (10.70)	42.67 (10.40)	-0.9 (0.77)	0.3 - 4.9
Crossbred[g] (lambs only)	101	29.27 (5.57)	28.62 (5.24)	-0.65 (0.57)	1.28 - 4.72
Hours delayed prior to aWt1[h]					
0 to 1	658	41.31 (8.25)	40.28 (8.22)	-1.03 (0.62)	0.6 - 4.72
1 to 2	690	37.11 (10.65)	36.47 (10.4)	-0.64 (0.74)	0.3 - 4.9
2 to 3	233	51.22 (8.95)	50.08 (8.80)	-1.14 (0.75)	1.92 - 4.67

Continued

Table 4.2 Continued.

[a]ewes which had been with their lamb immediately before aWt1 but without contact with lamb between aWt1 and aWt2;
[b]lambs remained with their ewe between aWt1 and aWt2 and aged three to five months old;
[c]lambs aged four to six months old;
[d]good quality pasture, fertilised annually with the potential for silage making;
[e]partially improved semi-natural permanent grassland and wet heath;
[f]a mosaic of semi-natural permanent grassland and wet heath;
[g]crossbred lambs with dam of Scottish Blackface or Lleyn and opposite breed sire;
[h]estimated hours elapsed prior to aWt1 (from halting grazing to entering the weigh-crate).

The first of each pair of liveweights was an actual “without delay” liveweight (aWt1), collected as soon as the group of sheep entered the handling facility. The second was an actual “delayed” liveweight (aWt2), collected later the same day after varying lengths of delay within the handling facility, without access to feed and water. While this is secondary data, all liveweights (aWt1 and aWt2) were collected automatically with an individual time and date stamp; therefore the delay between liveweights could be accurately calculated.

Whilst the sheep were first weighed immediately after entry into the handling area, the groups used in the validation dataset came from grazing locations across the large research farm. They came from improved fields, semi-improved parks, and the unimproved hill (as described in Chapter 3).

The grazing locations had widely different gathering times compared to the liveweight loss study dataset. Therefore, two stockpersons and one technical staff, all of whom had experience of time taken to gather sheep from each field/location, were asked to estimate the normal gathering time. This was calculated from the moment grazing was halted (by the stockperson and dog entering the field) to the first of the group entering the weigh-crate. These estimates were used to determine the pre-gather time for each pair of liveweights. On average time elapsed was 1.21 h (SD 0.59) between pre-gather and aWt1. This length of delay prior to aWt1 was also used in analysis (Table 4.2).

4.2.2.1 Comparing corrected and uncorrected liveweights

The correction equation was used on aWt2 to generate a corrected version of aWt1 (cWt1) using the known length of delay between aWt1 and aWt2. In practice, to account for the varying lengths of delay prior to aWt1, the correction equation could be used to correct aWt2 to a pre-gather liveweight. However this pre-gather liveweight is not known so correction to the “without delay” liveweight (aWt1) allows the correction ability of the equation to be tested. This is possible as the equation treats liveweight loss as linear over this short-term period.

To explore whether cWt1 or aWt2 was a more accurate and precise estimate of aWt1, paired two-way t-tests were used to compare each with aWt1. The distribution of differences between these pairings of liveweights was also examined.

4.2.2.2 Category differences in correcting

To explore whether the correction equation had the same precision across a range of categories, a Linear Mixed Model in GenStat 16th Edition (Payne et al., 2013) was used on the difference between cWt1 and aWt1. The five different categories (listed in Table 4.2) were explored. Stage of production and grazing location were the only categories identified as being statistically significant and were included in the final fixed and random models. Predicted means were then generated to compare the different levels within each of these two categories.

4.2.3 STAGE 3: Management simulation

4.2.3.1 Dataset

A dataset was compiled to simulate the impact of assigning ewes to feeding levels based on liveweight change, comparing when actual delayed liveweights or corrected liveweights were used. This management example involves assigning feeding levels to pregnant ewes based on liveweight change over a period of two months. It was chosen as it is advised that pregnant ewes should be provided with supplementary feeding (for example, Fthenakis et al., 2012). Assigning individual ewes' feeding levels based on liveweight change over the first two months of pregnancy will be discussed in more detail in Chapter 5.

Actual "without delay" liveweights from 395 ewes for both systems and across breeds (Lleyn ewes, n = 239, were 1.5 to 7.5 years of age and Scottish Blackface ewes, n = 156, were 1.5 years of age) were collected from the research flock at pre-mating as soon as animals entered the handling facility (PreWt, November 2014). "Delayed" liveweights were also collected from the same animals two months later at post-mating after varying periods of time within the handling facility without access to feed and water (PostWt, January 2015). The correction equation was used on both sets of liveweights (PreWt and PostWt) to produce corrected pre-gather sets of liveweights (cPreWt and cPostWt, respectively). Time of pre-gather was calculated from the automatically recorded time stamp and the estimated time to gather each field (same method as previously explained in STAGE 2). Overall the average delay prior to weighing for PreWt was 2.6 h (SD 1.3) and for PostWt was 4.9 h (SD 1.3).

4.2.3.2 Assigning ewes to feeding levels

Ewes were assigned to feeding levels based on liveweight change between November and January (the period covering mating): low level feeding (LOW) for ewes that had put on liveweight; medium level feeding (MED) for ewes that had lost up to 5 % liveweight; and high level feeding (HIGH) for ewes that had lost over 5 % liveweight (method discussed in Chapter 5).

Two simulations were run with the data, to assign ewes to feeding levels, one using the actual collected “without delay” (PreWt) and “delayed” (PostWt) liveweights to determine liveweight change and the second using corrected versions of these liveweights (cPreWt and cPostWt). Counts of ewes assigned to each feeding level, based on these two alternative simulations, were compared via a Chi-squared test.

4.3 Results

4.3.1 STAGE 1: Liveweight loss study

4.3.1.1 Times and weighing

Each weigh session (where all 100 ewes were weighed three times) lasted 41.3 min (SD 2.5). The weighing rate, over all nine rounds was 7.5 s (SD 0.5) per ewe.

4.3.1.2 Liveweight and liveweight change

The analysis showed that ewes lost liveweight (P<0.001) over both three and six hours delayed prior to weighing (Figure 4.1). They lost 1.8 kg (SD 0.5) or 3.5 % (SD 0.8) liveweight and 2.9 kg (SD 0.6) or 5.6 % (SD 1.0) liveweight at three and six hour delays, respectively.

The mean "without delay" liveweight was found to be correlated (P<0.001) with actual liveweight change over three and six hour delays (r = -0.48 and -0.63, respectively), with heavier ewes losing more liveweight. However, there was a non-significant poor correlation between the mean "without delay" liveweight and proportion of liveweight change over both delay intervals (r= -0.05 and -0.18 for three and six hour delays, respectively). BCS did not impact on actual or proportion of liveweight change. However, age impacted at both three and six hour delay intervals for actual (P<0.001) and proportion (P<0.05) of liveweight change. The youngest ewes (aged 1.5 years old) lost less than all other age groups; they were also lighter than all other ages.

Over the first three hours (9 am to 12 pm) ewes lost more liveweight compared to the second three hours (12 pm to 3 pm) delayed (P<0.001, 1.8 kg compared to 1.1 kg liveweight lost, respectively).

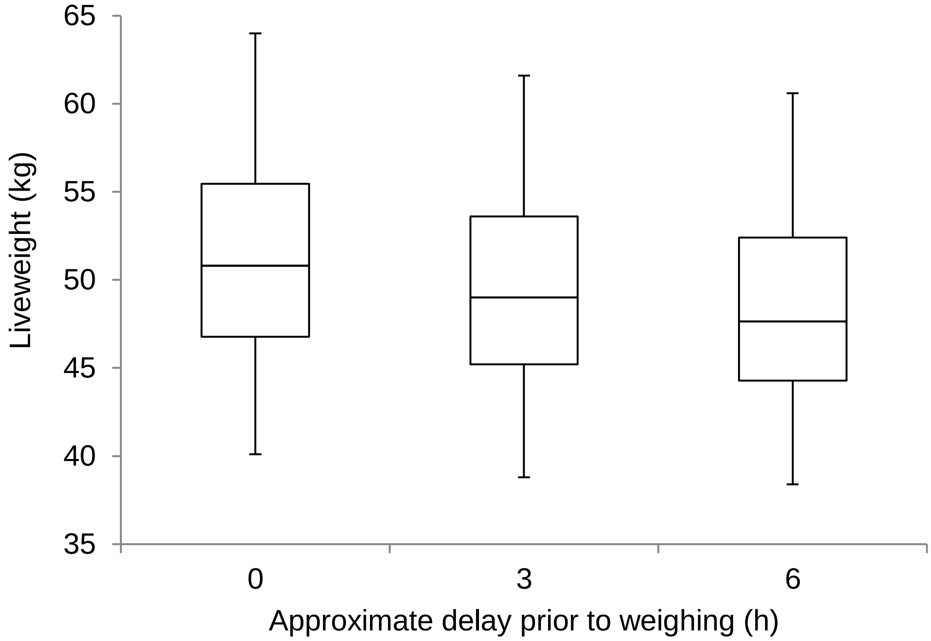


Figure 4.1 Liveweights at the three weigh sessions where 100 ewes were weighed three times per session with a time delay between sessions. Boxplot shows median, upper quartile, lower quartile (box) and range of liveweights (whiskers).

4.3.1.3 Delayed liveweight correction equation

The equation developed during STAGE 1, to correct delayed liveweights when length of delay is known (*P*<0.001), was:

$$y = 100\left(\frac{x}{\left(100 + (-0.9301\, t + 0.07106)\right)}\right)$$

Where:

y = corrected liveweight (kg)

x = actual delayed liveweight (kg)

t = time difference in decimal hours delayed

4.3.2 STAGE 2: Validating process

4.3.2.1 Comparing corrected and uncorrected liveweights

In comparing liveweights, aWt2 and cWt1 were both different to aWt1 (P<0.001). However, cWt1 was a more precise estimate of aWt1 compared to aWt2, demonstrated by 72 % of aWt1 liveweights being closer to cWt1 than to aWt2. Figure 4.2 illustrates how correction reduces the error that would occur if the delayed liveweight (aWt2) were used as the only liveweight for these sheep. Simplifying this data, the counts of sheep with a cWt1 that was: close to (-0.24 to 0.25 kg); higher than (>0.25 kg); or lower than (<-0.24 kg) aWt1, were very different (with a Chi-squared statistic of 1172.6, P<0.001) to the equivalent groupings of aWt2 to aWt1.

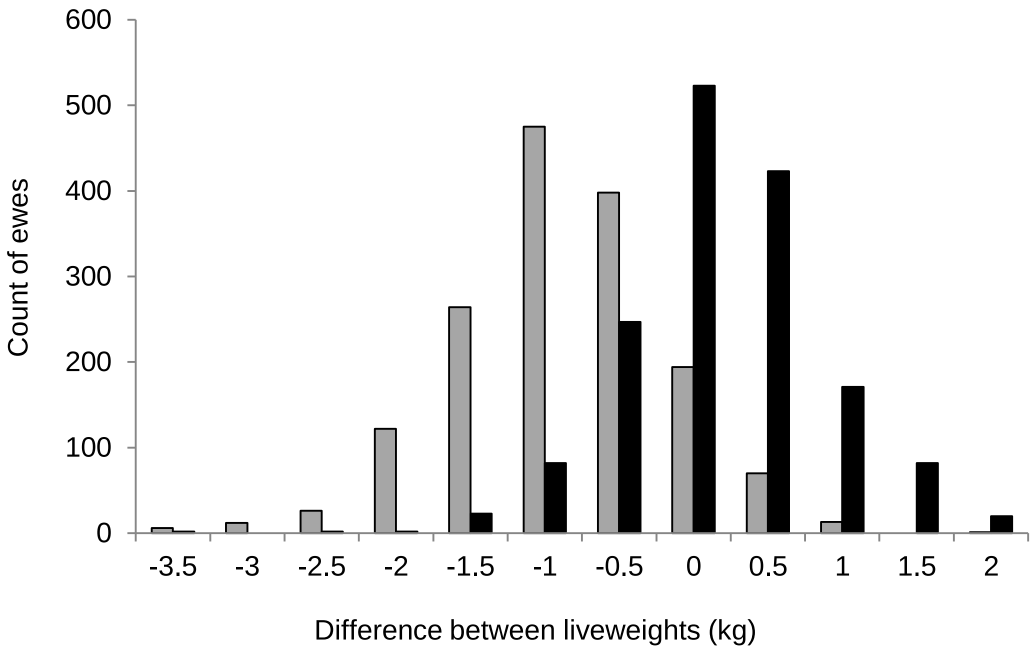


Figure 4.2 Distribution of difference between two sets of liveweights: 1) grey bars, actual delayed liveweight (aWt2) minus actual “without delay” liveweight (aWt1); and 2) black bars, corrected from aWt2 to the time of aWt1 (cWt1) minus aWt1. X-axis labelling is the mid-point of the group difference (meaning 0 kg means difference fell between -0.24 and +0.25 kg).

4.3.2.2 Category differences in correcting

Considering the ability of the correction equation to predict for different categories (listed in Table 4.2) of sheep revealed that out of the five originally explored (stage of production, sex, grazing location, breed and hours delayed prior to aWt1), only stage of production and grazing location had an impact (*P*<0.001) accounting for 24.6 % of variance. Of these categories, pregnant ewes, semi-improved park, and improved field had the best correction ability with the difference between predicted means cWt1 and aWt1 being within 0.4 kg (Figure 4.3).

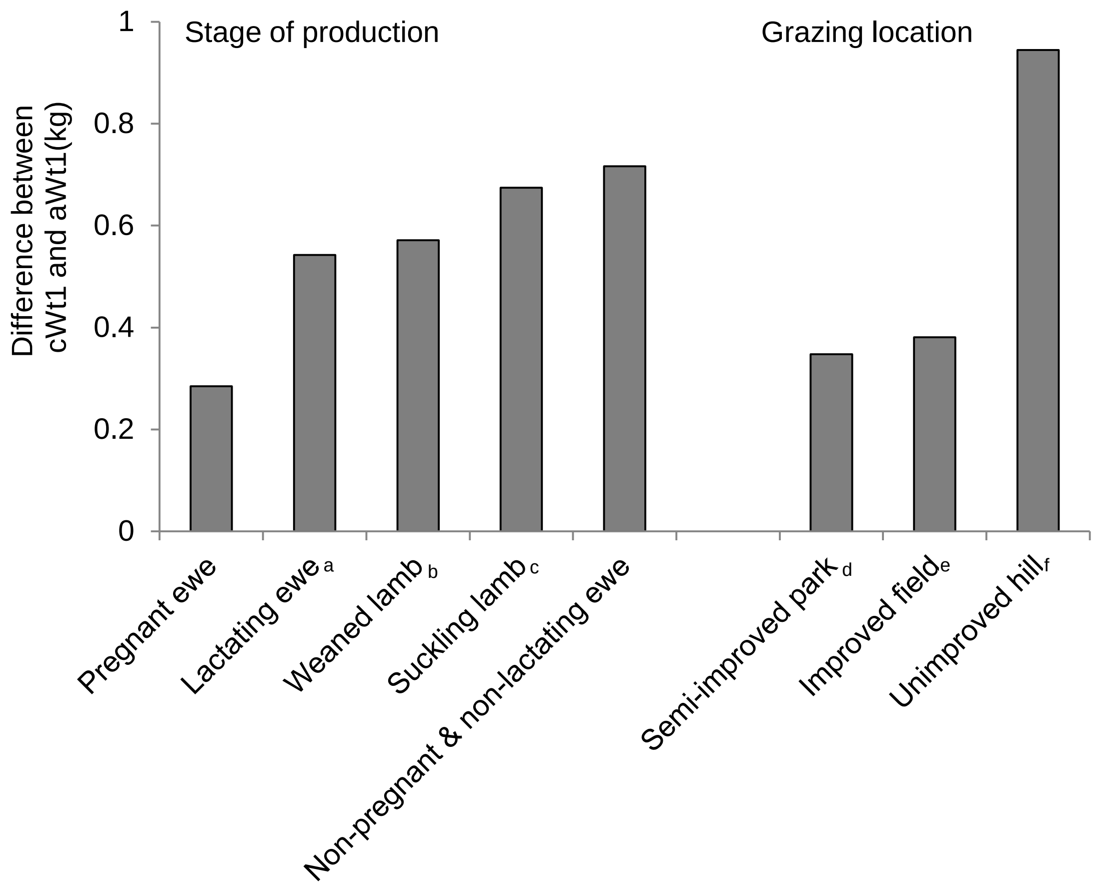


Figure 4.3 Difference (in absolute value) between a "without delay" liveweight collected as soon as the group entered handling facility (aWt1) and a delayed liveweight corrected to the time of aWt1 (cWt1), displayed as predicted means, for different categories.

[a]ewes which had been with their lamb immediately before aWt1 but were delayed without contact with lamb;
[b]lambs aged four to six months old;
[c]lambs remained with their ewe during delay and aged three to five months old;
[d]partially improved semi-natural permanent grassland and wet heath;
[e]good quality pasture, fertilised annually with the potential for silage making;
[f]a mosaic of semi-natural permanent grassland and wet heath.

4.3.3 STAGE 3: Management simulation

Comparing each actual delayed liveweight (PreWt and PostWt) to their respective corrected liveweight at pre-gather (cPreWt and cPostWt) showed a mean liveweight loss of 1.2 kg (SD 0.7) and 2.4 kg (SD 0.8) for PreWt and PostWt, respectively.

When corrected liveweights (cPreWt and cPostWt), rather than actual delayed liveweights (PreWt and PostWt), were used to determine liveweight change over the mating period, a different distribution of ewes to three feeding levels was seen (Figure 4.4), with a substantial proportion (24.3 %) of ewes being assigned to different management feeding levels (*P*<0.001).

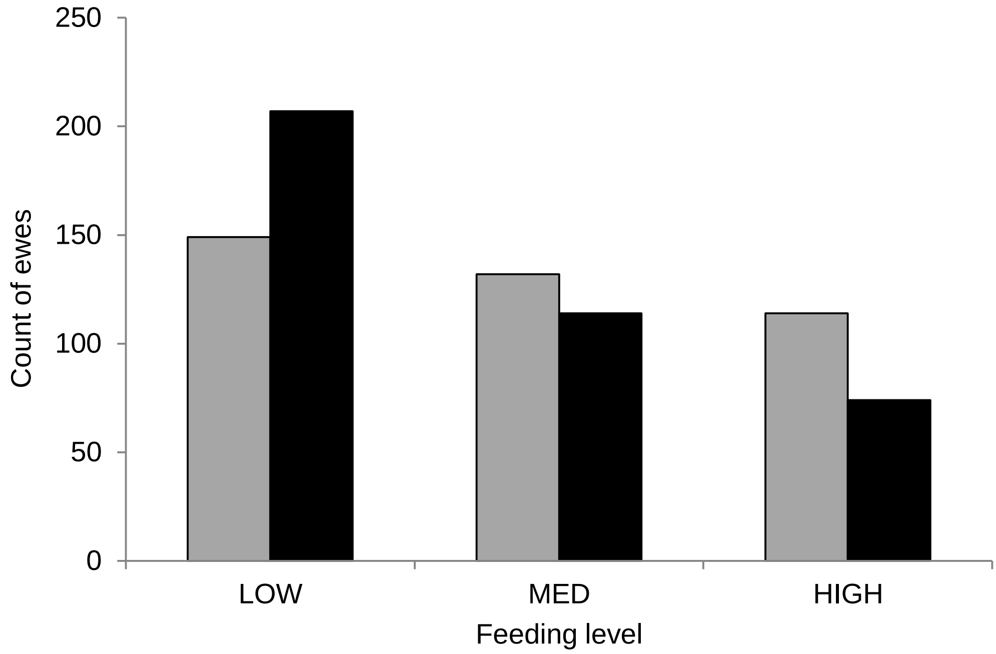


Figure 4.4 Number of ewes per feeding level based on the same decision rules but different liveweight calculations used to determine liveweight change between November and January. Three feeding levels available: LOW, ewes gained weight; MED, lost up to 5 % liveweight; and HIGH, lost over 5 % liveweight. Two different pairing of liveweights were used; delayed liveweights (PreWt and PostWt, grey bars), and corrected liveweights (cPreWt and cPostWt, black bars), where delayed liveweights were corrected to a pre-gather time point.

4.4 Discussion

4.4.1 STAGE 1: Liveweight loss study

The first stage of this research found that ewes lost a significant amount of liveweight after a delay of three and six hours within a handling facility. The magnitude of liveweight loss found is likely to impact on research findings and management decisions on-farm, unless it can be accounted for.

Although previous literature reported losses of 0.5 to 2 kg and 1 to 4 kg after six and 12 hours, respectively (as reviewed by Hughes, 1976), our study found greater losses. These losses were closer in agreement to findings by Wilson et al. (2015). The ewes in our study moved from poor quality unimproved hill pasture to improved field grazing the night before the liveweight loss study commenced. This allowed for near-by, easy access of the animals to commence work the following morning and is a typical management practice for any extensive sheep system. Change in pasture quality has been suggested to alter liveweight loss (Hughes and Harker, 1950). Therefore, while this change may result in higher liveweight loss compared to Hughes (1976), it is representative of a real-life situation.

It is interesting to note that ewes lost liveweight at a slightly higher rate over the first three hours compared to the second three hours, which is in agreement with previous research of liveweight loss (reviewed by Hughes, 1976). This could be explained by daily biological rhythms where the previous day's digesta is passed from the animal in the early morning (Whiteman et al., 1954) but could also simply be a result of diminishing returns. Both linear and non-linear correction equations were explored, as liveweight loss was not linear over the six hour period. However, a linear equation was ultimately used as it was both simpler to carry out and the alternatives provided no additional precision to the correction of delayed liveweights.

There was negative correlation between mean "without delay" liveweight and liveweight change, therefore heavier ewes lost more liveweight than lighter ewes. However, this was not to the same degree when liveweight loss was considered as a proportion of liveweight. The difference is explainable as larger animals would have a larger holding potential for water and digesta and therefore have a greater potential for loss. Nevertheless this appears to be at a similar rate of loss proportional to body size, which is why the correction equation uses proportion of liveweight.

This study demonstrated that liveweight data can be collected at a rate of 480 ewes per hour with modern weighing facilities using EID technology, making it an attractive option for collection of liveweights both for research and on farm. This increases the potential of managing sheep according to liveweight and liveweight change, such as for PLF approaches.

4.4.2 STAGE 2: Validating process

Weighing without any delay would clearly provide liveweights with the least error. However, when this is not possible the validating process demonstrated that the correction equation could be used to provide corrected liveweights (cWt1) that were a more accurate and precise estimation of an actual liveweight (aWt1) than a delayed actual liveweight (aWt2).

Given the wide range of factors, as well as period of delay, that can impact on gut-fill and short-term liveweight variation (as described in Coates and Penning, 2000; Hughes, 1976), it is encouraging that the correction equation worked well across the different categories of sheep. This is evidenced as breed, sex and hours delayed prior to aWt1 did not have a significant impact on the precision of correction, adding strength to the application potential of the equation.

The two categories that significantly impacted on precision of the equation were stage of production and grazing location. For these, corrected liveweights had a high level of precision for pregnant ewes and sheep previously grazing improved fields and semi-improved parks compared to all other stages of production and sheep from unimproved hill grazing. Pregnancy did not hamper the ability of the correction equation. Indeed, these ewes were all in mid-pregnancy, at around 90 days gestation, at which point the conceptus weight has very little impact on ewe liveweight (Henderson, 2002).

It is understandable that delayed liveweights of ewes from unimproved hill grazing corrected with a lower level of precision compared to improved fields and semi-improved parks given that sheep on hill grazing vary greatly in their time to gather (Morgan-Davies et al., 2006; Stott et al., 2005), adding to the variation on liveweight. However as hours delayed prior to aWt1 did not have a significant impact in the correction ability, it is considered that the grazing type was the most important factor. As previously mentioned, quality and quantity of pasture impact on liveweight variation (Hughes and Harker, 1950; Hughes, 1976) which may be contributing to the differences seen between sheep from different grazing types. Future research in the field of liveweight variation would benefit from collecting pasture data such as quality and quantity available. Also, having two categories (stage of production and grazing location) impacting on the correction ability of the equation suggests that alternative correction equations could be developed for different situations.

To be able to quantify the precision of the correction equation, as previously explained, the delayed liveweight (aWt2) was corrected back to the time of the actual “without delay” liveweight (aWt1) and not the time of pre-gather. This allowed for a comparison of cWt1 and aWt2 to a known liveweight (aWt1). Due to the distribution of ewes being gathered from fields of varying distances from the handling facility, different delays would already be impacting on the aWt1. The majority of aWt1 were collected within two hours of grazing being disturbed (85 % of 1,581 liveweight pairs). It is likely that as time elapsed, since gathering increased, the correction precision would change. In reality, to be able to produce comparable liveweights, the delay period caused by gathering should also be included in the hours delayed prior to weighing (as it was in the STAGE 3: Management simulation). Therefore the correction equation should be used to correct delayed liveweights to a pre-gather time point.

There were a small number of individual sheep within the validation dataset whose liveweights actually increased from aWt1 to aWt2, contradicting what would be expected. As no food or water would have been provided during this time, the increase is likely to be an impact of random error of weighing. The weigh equipment described in this research used a damping algorithm that allowed collection of the liveweight of a moving sheep. While this allows for some inaccuracy it is more accurate than using more traditional scales where the location of the needle needs to be read by eye (Hirsch, 1985). This may also explain the overestimation of the correction equation when comparing cWt1 to aWt1.

Overall, however, the comparison between corrected delayed and “without delay” liveweights highlights the reliability of the equation to correct delayed liveweights to a specific time point. There are no known published attempts of developing a correction equation for liveweights subjected to this short-term period of delay prior to weighing. Therefore, the success of this correction equation is important and could be useful to all practitioners collecting and utilising liveweights where delay is unavoidable.

4.4.3 STAGE 3: Management simulation

The final stage showed that when delayed liveweights were used, ewes appeared to lose more liveweight, which considerably altered the identity and number of ewes in each feeding level compared to if these liveweights had been corrected to a pre-gather liveweight. It should be noted that the pre-defined liveweight change boundaries for each feeding level constrains the example. Any alterations to these boundaries would impact on the number of ewes that would move from one feeding level to another. However it does serve to demonstrate that greater delay in weighing at PostWt (January) suggests a greater loss in liveweight, causing a higher proportion of ewes to be assigned to higher feeding levels. This in turn would increase the amount of feed provided, resulting in a significant cost to the farm that would not be required if more reliable (meaning corrected) liveweights had been used. A higher level of feed could also lead to over-supplementation with the risk of dystocia and lamb death.

The larger correction or error on January liveweights (PostWt), which were collected after delay compared to liveweights in November (PreWt) collected without delay, highlights the advantage of collecting without delay. Depending on the time delay associated with gathering, collecting liveweights without delay may be sufficient in reducing error, and a correction equation might not be required.

Within each handling, we know from the equipment time stamps that there is further variation in the delay between the first and last ewe weighed. Therefore if correction equations are not used, weighing as quickly as possible from the first to the last sheep, to reduce delay during the weighing session, is essential.

4.4.4 Wider implications of improved liveweight reliability

While feeding management has been explored by this research, there are other farm practices which could also benefit from correcting delayed liveweights: firstly, achieving a target carcass weight at the abattoir, by more accurately selecting finishing lambs to sell based on liveweight; secondly, producing more accurate EBVs when they are generated from liveweights; and thirdly, providing a more appropriate level of anthelmintic based on liveweight bands, as widely recommended as best practice (for example, Henderson, 2002).

Current advice for reducing liveweight variation in research includes increasing animal numbers (Hughes, 1976) and weighing multiple times (Koch et al., 1958).

However, correcting delayed liveweights may require fewer animals and weighings to reduce error and thereby follow the principles of the 3Rs (Replacement, Reduction and Refinement; Russell and Burch, 1959).

Finally, variation in liveweight may become less of a concern with the development of weighing technology that can collect liveweights in real-time, without extra handling or gut-fill issues, for instance walk-over-weighing (Brown et al., 2014b; González-García et al., 2018).

4.5 Conclusions

This chapter has shown that sheep lose a significant amount of liveweight over a short-term delay prior to weighing, as a result of practical handling operations. When this delay is uncontrollable, one method to improve reliability is by correcting delayed liveweights (via correction equations such as the one presented in this chapter). Alternatively, since the value of correction increases as the length of delay increases, collecting liveweights immediately (without delay) may be sufficient in producing reliable liveweights. Such approaches will reduce error in liveweights which, if used, can lead to incorrect conclusions in research and negative consequences for management practices of grazing sheep systems globally. Research papers should provide sufficient details of weighing procedures, particularly with respect to time delays between removal from feed and grazing, to actual weighing.

The equipment and procedure (of weighing without delay) has demonstrated that liveweight is a suitable measure to be used within PLF approaches. Therefore the PLF approaches, that this thesis will explore and develop, utilise liveweight data. Following the findings from this chapter, standardised procedures of liveweight collection were implemented onto the research farm, ensuring all liveweights were collected without delay as soon as ewes entered the handling facility. This ensured that all liveweight data used throughout this thesis (from November 2013 onwards) can be considered to be collected without delay.

CHAPTER 5: A PLF APPROACH FOR ALLOCATING SUPPLEMENTARY FEED TO PREGNANT EWES IN AN EXTENSIVE HILL SHEEP SYSTEM

Chapter 4 explored the importance of collecting liveweights without delay. It also introduced the concept of using EID weighing technology. The following chapter utilises the weighing technology to address the first challenge area of allocating supplementation to pregnant ewes.

This chapter is adapted from the conference proceedings:

Wishart, H., Morgan-Davies, C., Waterhouse, A. 2015. A PLF approach for allocating supplementary feed to pregnant ewes in an extensive hill sheep system, in: Proceedings of Precision Livestock Farming '15. Milan, Italy, pp. 256-265.

5.1 Introduction

A PLF approach of targeted supplementation during pregnancy is one method suggested to tackle the high production costs and low productivity difficulties seen in sheep industries around the world (Brown et al., 2015; Montossi et al., 2013; Rowe and Masters, 2005). However, it is yet to be explored for hill sheep systems.

5.1.1 Nutrition over pregnancy

The nutritional requirements over pregnancy, both maternal and foetal, and the effect of nutritional deficiencies, have been extensively researched for a wide range of animals, including sheep (Asmad et al., 2014; Fogarty et al., 1992; Fthenakis et al., 2012; Martin et al., 2004). Nutrition and body reserves of the ewe can impact on risks associated with pregnancy and lamb rearing. Such risks include: birth of small lambs, birth of premature lambs, reabsorption or abortion of foetus, low quality and quantity of colostrum and milk produced, and stillbirths (Fthenakis et al., 2012; Henderson, 2002; Morgan-Davies et al., 2008). If these effects occur at a flock level, the whole farm productivity and economic viability may be negatively affected.

In extensive sheep systems of North West Europe, much of the pregnancy period occurs during winter when grazing is of poor quality and often limited in quantity (Holland et al., 2008b). Furthermore, nutrient requirements to achieve a good outcome at lambing differ depending upon: ewe body size; body reserves; and number of lambs being carried (Fthenakis et al., 2012; Henderson, 2002; National Research Council, 2007). Providing supplementary concentrate feed provides a method to meet the gap between the nutrient requirement of the pregnant ewe and the nutrients available in the natural environment (Henderson, 2002).

5.1.2 Supplementation

Supplementary feeding, and the labour associated, present large costs to the farm business (Jordan et al., 2006; Rowe, 2004). Therefore, providing supplementation at the appropriate level for each sheep can reduce over- or under-feeding animals, and the associated costs to farm and productivity. This is the general principle of precision feeding (Rowe and Masters, 2005). When supplementation occurs in practice, flocks are divided into large sub-flocks or feeding groups where they may be offered supplementation once or twice daily, with a mean allocation per ewe. Research and industry literature highlight and promote the benefit of sub-dividing ewes into groups with similar nutritional requirements such as BCS (Corner-Thomas et al., 2015; EBLEX, 2008) and the number of lambs being carried (EBLEX, 2008; Foot et al., 1973; Jordan et al., 2006).

Instead of feeding at a group level, new methods to provide individual diet allowances within an extensive setting are being explored (for example, Bowen et al., 2009; Jordan et al., 2006; Rowe, 2004). However, considerable further development is required before they are available for general application on farm.

5.1.3 Measures to assess nutritional state

The two most common metrics used to assess current nutritional state for sheep are BCS and liveweight (Behrendt et al., 2011). BCSs provide a reliable measure of fat coverage and thus predicts overall body reserves and are not affected by sheep size or gut-fill; however it can be subjective and time-consuming to collect (as discussed in Chapter 2). Liveweight or liveweight change are more objective measures to identify if a ewe is maintaining, gaining or losing liveweight (Brown et al., 2015). Sheep liveweight and liveweight change have become more usable with EID, coupled with commercially available automatic weighing and drafting technology (as demonstrated in Chapter 4).

5.1.4 Pilot study

An early pilot study, into implementing a PLF approach to allocate supplementation to pregnant hill ewes, was carried out by the research group (see Umstätter et al., 2013). For this pilot, pregnant ewes were allocated supplementation during the period January 2013 to mid-April 2013, prior to the research presented in this chapter. Preliminary results of the pilot study suggested that supplementation could be assigned based on liveweight change, although the method of allocation was overly complex. The current chapter follows on from these initial findings by developing a simplified method of allocation with more thorough data analysis.

5.1.5 Aims of chapter

The aims of this chapter are to compare two different management approaches (introduced in Chapter 3) for allocating supplementation within a hill sheep system. The CON approach used body condition of ewes to allocate supplementation, while the PLF approach, utilised liveweight data and EID enabled weighing technology.

Specific aims of the chapter are:

1) To compare the difference of how the two approaches allocate ewes to supplementation levels.
2) To determine the difference in the amount of supplementation required by the two approaches.
3) To assess differences in liveweight and BCS profiles of ewes from the two approaches.
4) To evaluate the difference in performance of the ewes (including number and liveweight of lambs produced) from the two approaches.
5) To discuss the feasibility of implementing the two approaches on hill sheep systems.

5.2 Material and Methods

5.2.1 Protocol

The whole research flock of around 900 ewes (as described in Chapter 3) were allocated to pregnancy supplementation levels according to their management approach (CON or PLF). Two supplementary periods were considered within the same production year: mid-pregnancy supplementation (January 2014 to mid-February 2014) and late pregnancy supplementation (mid-February 2014 to April 2014, Figure 5.1). It is typical practice on sheep farms to change the supplementation protocol after pregnancy scanning to reflect the scanning results.

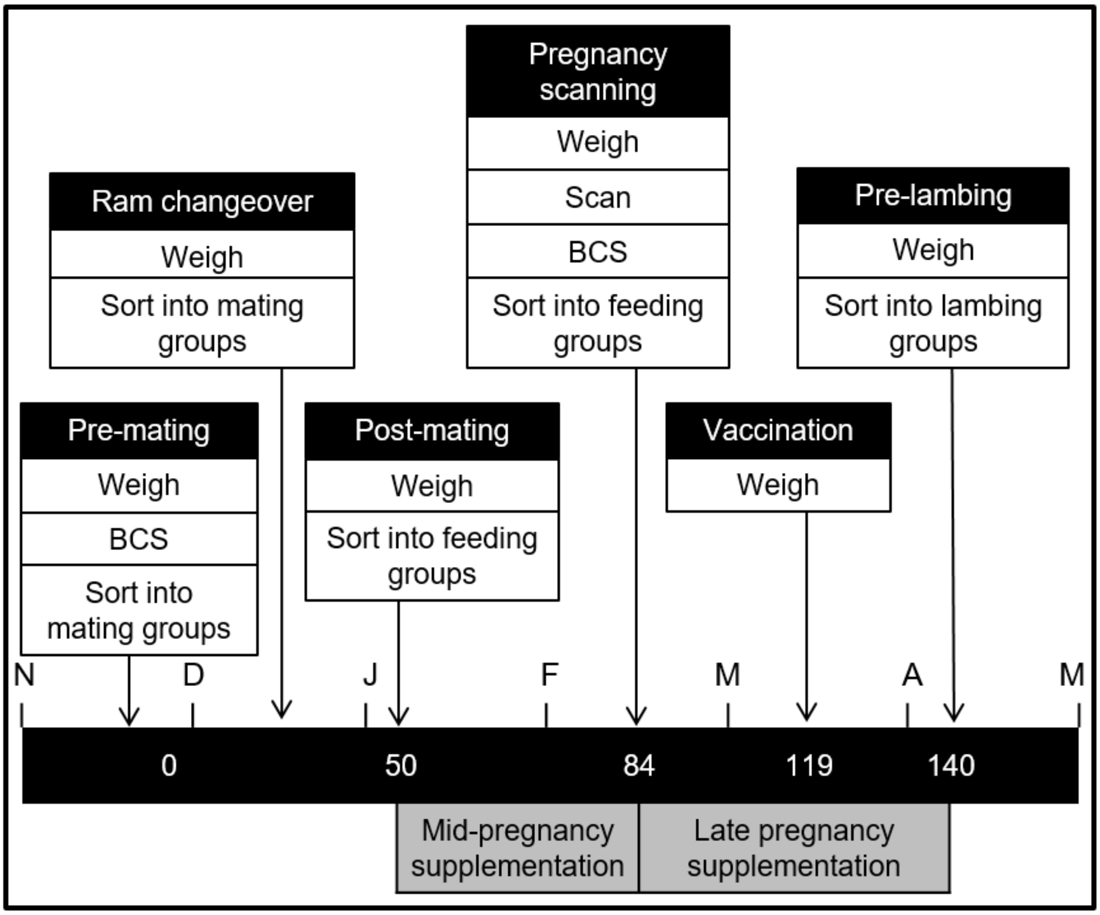


Figure 5.1 Timeline of when the two pregnancy supplementation periods (grey boxes) occurred in relation to handling events (black boxes; with tasks and data collected in white boxes) and the number of days of pregnancy (where day 0 is when the rams entered the mating groups).

On day 50 of pregnancy, at the post-mating handling event, and day 84, at the pregnancy scanning handling event, ewes were allocated into one of two types of supplementation: either “STANDARD” or “CORRECTIVE”, according to their management approach (Table 5.1). Day 84 allocation also took into account the number of foetal lambs that the ewe was carrying as measured by ultrasound pregnancy scanning.

A value of 5 % liveweight loss was used for PLF corrective feeding groups as this was the flock average amount lost recorded in previous years between pre-mating and pregnancy scanning.

Table 5.1 Allocation criteria of ewes at days 50 and 84 of pregnancy to supplementation type (STANRDARD and CORRECTIVE) and supplementation level (LOW, MED and HIGH) according to management approach (CON: Conventional; or PLF: Precision Livestock Farming).

	STANDARD	**CORRECTIVE**	
	LOW	MED	HIGH
CON			
Stockperson-determined, based on ewe level of condition and fitness.	Ewe in good level of condition and fitness for current stage of pregnancy.	Ewe in less than ideal level of condition and fitness for current stage of pregnancy.	Ewe in very poor level of condition and fitness for current stage of pregnancy.
PLF			
EID weigh-crate and drafting determined, based on liveweight change.	Ewe maintained or gained liveweight since pre-mating.	Ewe lost up to 5 % liveweight since pre-mating.	Ewe lost over 5 % liveweight since pre-mating.

On days 50 and 84 all ewes (from both management approaches) were weighed. This liveweight data was collected using the same weighing facility and EID equipment as described in Chapter 3. Furthermore, liveweights were collected as soon as groups entered the handling facilities off pasture (in-line with recommendations from Chapter 4).

PLF and CON ewes were in mixed groups when weighed. During weighing, the weigh-head was programmed to auto-draft (sort) PLF ewes into their correct supplementation level by comparing their current liveweight to their pre-mating liveweight (according to Table 5.1). The weigh-head also identified and separated/draft all CON ewes into a separate pen. In small lots the CON ewes were then allocated to supplementation levels by two or more stockpeople moving through the group placing their hand on each ewe's back (on the lumber region) to assess condition (Figure 5.2). CON ewes that stockpeople felt were in a "less than ideal level of condition" or "very poor level of condition" (according to Table 5.1) were physically handled to move them into separate pens.

For both approaches, the labour required to allocate ewes into supplementation levels was also recorded. However, the analysis of these data was led by a colleague and are not part of this thesis (results published in Morgan-Davies et al., 2018b, Appendix 2).

Figure 5.2 Procedure carried out to allocate ewes in the conventional (CON) management approach to pregnancy supplementation level.

5.2.2 Supplementation

The STANDARD type of supplementation aimed to provide enough supplementary feed to maintain current body reserves (supplementation level: "LOW"). The aim of the CORRECTIVE types of supplementation (of which there were two levels: "MED" and "HIGH") were to provide extra supplementary feed to improve the body reserves of ewes judged to have below optimum nutritional outcomes at that handling point. Each ewe was then classified according to the two supplementation types they were allocated Figure 5.3).

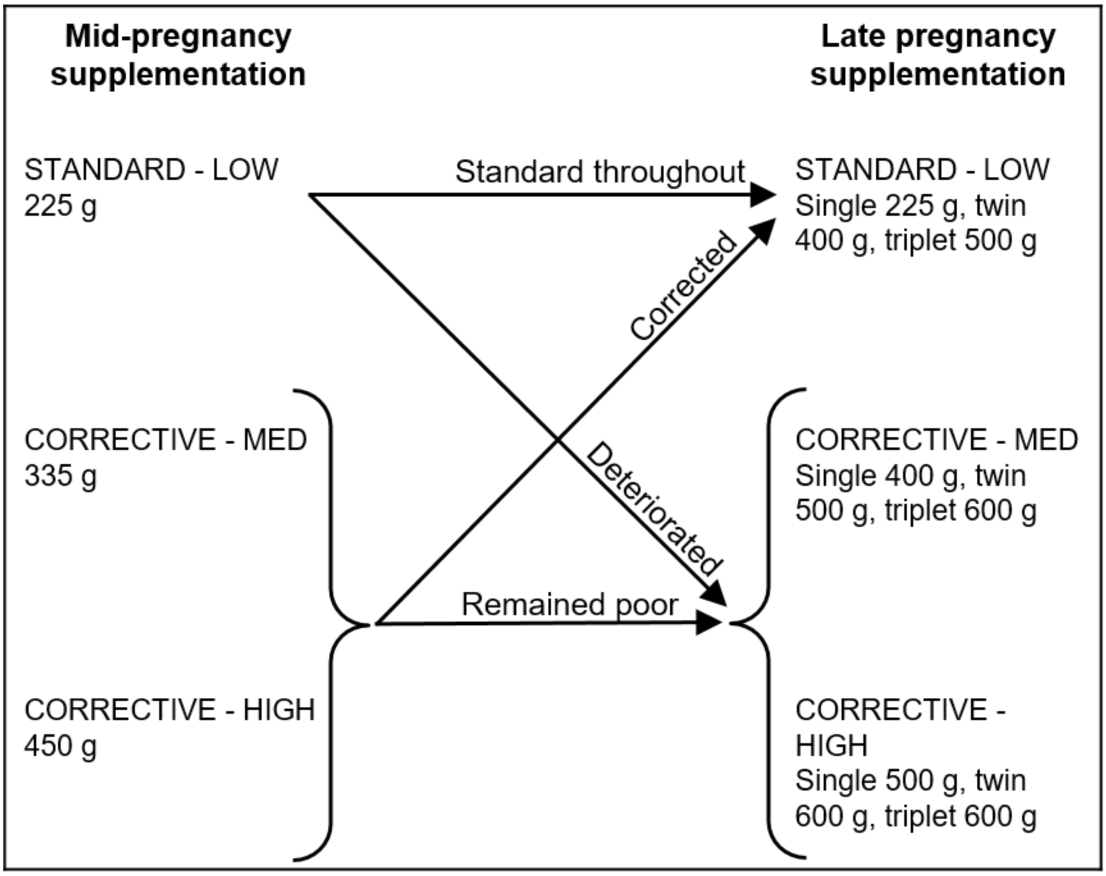


Figure 5.3 Supplementation types and levels available during the two periods of pregnancy supplementation, including the daily amount of concentrate provided per ewe. Classification (on arrows) describes how ewes moved between supplementation types."STANDARD": type of supplementation aimed to provide enough supplementary feed to maintain current body reserves; "CORRECTIVE": type of supplementation aimed to provide extra supplementary feed to improve the body reserves of ewes judged to have below optimum nutritional outcomes.

Once ewes were allocated to their individual supplementation levels, CON and PLF ewes at the same levels were combined into the same physical feeding groups. Where required, groups of ewes at the same mid-pregnancy supplementation level were randomly split into different feeding groups to accommodate the grazing locations. Gimmers (ewes in their first year of production) were in separate groups to the rest of the ewes to allow easier monitoring to ensure all were feeding. When groups were split, numbers of CON and PLF ewes within each group remained equal. For late pregnancy supplementation, ewes at the same supplementation level (such as MED singles and LOW twins, both on 400 g of supplement per ewe per day) were combined into the same feeding group.

Feeding groups with a LOW supplementation level tended to be allocated to graze on poorer pasture (such as the unimproved hill) compared to feeding groups at MED and HIGH supplementation levels, which grazed semi-improved parks and improved fields.

The supplementary concentrate feed used was Harbro Super Ewe Rolls 18, with a dry matter (DM) content of 855.4 g/kg, metabolizable energy (ME) of 11.8 MJ/kg DM and crude protein of 191 g/kg DM (SAC, Animal feed report, Appendix 3). Hay was also provided at the discretion of the farm staff when grass availability restricted grazing.

5.2.3 Statistical analysis

While the procedure described in section 5.2.2 was carried out on the entire flock, only ewes scanned in lamb were selected for analysis here, resulting in 665 ewe records (Table 5.2). All statistical analyses were carried out in GenStat 16th Edition (Payne et al., 2013).

Table 5.2 Count of ewe records available for analysis by breed and management approach (CON: conventional; PLF: Precision Livestock Farming).

	Scottish Blackface	Lleyn	Total
CON	197	129	**326**
PLF	212	127	**339**
Total	**409**	**256**	**665**

Counts of ewes in each class were statistically compared and analysed by Chi-squared tests. ANOVA and Chi-squared tests were used appropriately to compare the two management approaches for: amount of supplementary feed provided; ewe liveweight, at pre-mating, post-mating, scanning, vaccination and pre-lambing; BCS, at pre-mating and scanning; total number of lambs scanned and born; and lamb birth and eight week liveweight. Lamb liveweights were only considered to eight weeks of ages, to indicate the impact ewe supplementation could have on lamb performance.

Other factors that could affect allocation decisions and group performance include (but are not limited to): ewe breed, genetic line and age. However, only management approach, classification group and supplementation level were focused on at this stage of analysis.

5.3 Results

5.3.1 Allocation distribution

More CON ewes entered mid-pregnancy CORRECTIVE supplementation compared to PLF (44 % to 33 %, respectively *P*<0.01, Figure 5.4). The PLF approach was significantly more successful in moving ewes out of CORRECTIVE mid-pregnancy supplementation and into STANDARD late pregnancy supplementation (52 % of the PLF ewes moved, “Corrected”, compared to 25 % of CON, *P*<0.001, Figure 5.5).

The rest of the ewe classes (which were first assigned to STANDARD mid-pregnancy supplementation) remained in similar numbers in both management approaches. As such, the majority were “Standard throughout” and so remained in STANDARD supplementation (73 % of CON versus 72 % PLF); and the rest changed to CORRECTIVE supplementation (“Deteriorated”, 27 % of CON versus 28 % of PLF).

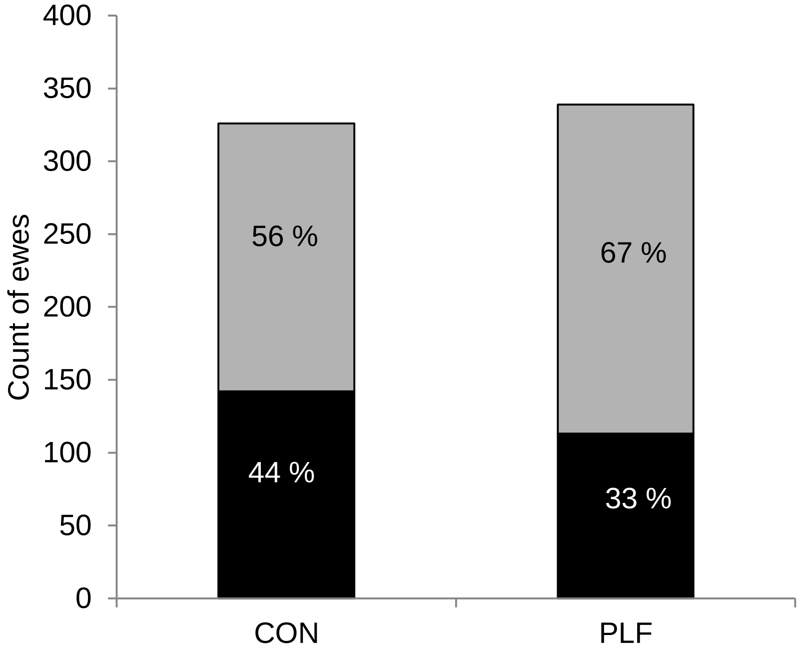


Figure 5.4 Count of all ewes which were allocated into CORRECTIVE (black) and STANDARD (grey) supplementation, on day 50 of pregnancy for mid-pregnancy supplementation, according to management approach criteria (PLF: Precision Livestock Farm; CON: Conventional). Percentages shown are as a proportion of the approach.

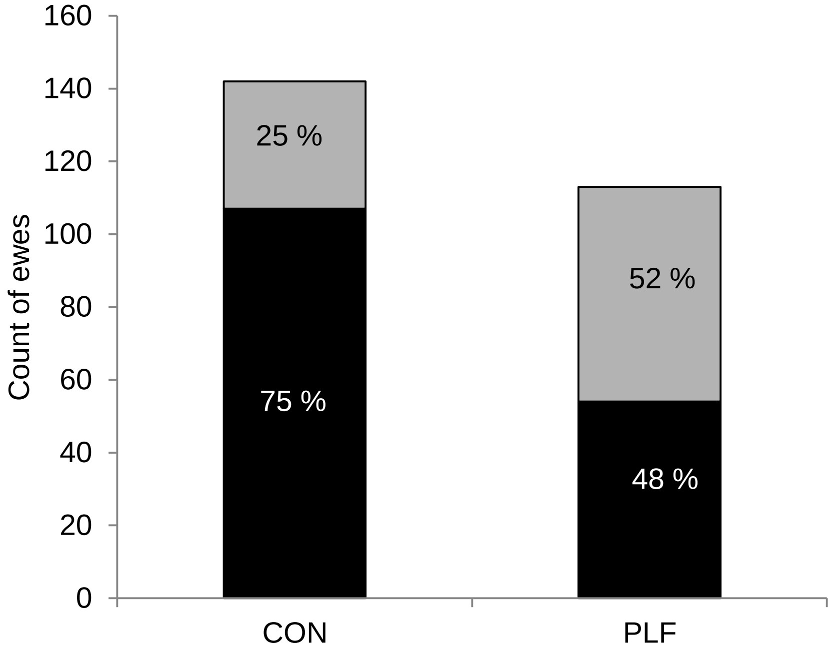


Figure 5.5 Count of all ewes which entered CORRECTIVE supplementation at day 50 of pregnancy and which, at day 84, either stayed in CORRECTIVE ("Remained poor", black) or moved to STANDARD ("Corrected", grey) supplementation, according to management approach criteria (PLF: Precision Livestock Farming; CON: Conventional). Percentages shown are a proportion of the approach.

5.3.2 Supplementation

The actual amount of concentrate provided per ewe per day was close to the planned amounts (Table 5.3). Due to a high number of ewes within LOW and MED levels in mid-pregnancy supplementation, both were split into 4 feeding groups.

Ewes allocated to LOW supplementation level during mid-pregnancy were grazed on the unimproved hill pasture. However, within this group, there were 38 PLF ewes that the Farm Manager had welfare concerns, as they appeared to be at a lower BCS compared to the rest of the group. Therefore, they were separated and placed within an improved field of similar grazing quality to the hill pasture. In this way they were still managed according to the protocol, receiving the same LOW level of supplementation. However, they could be more closely monitored than if they had been on the hill, to ensure their welfare did not deteriorate. This action allowed their data to still be comparable; whereas the alternative was to move them to a higher supplementation level, which would have resulted in their data being removed from analysis. The welfare of these 38 did not deteriorate and they were managed with the rest of the flock when allocated into their late pregnancy supplementation.

Table 5.3 Number of groups and supplementary feed rate provided during the two supplementation periods.

		Number of groups	Feeding (g/day/ewe)	
			Planned	**Actual**
Mid-pregnancy supplementation				
STANDARD	LOW	4	225	224-237
CORRECTIVE	MED	4	335	333-337
	HIGH	1	450	447
Late pregnancy supplementation				
STANDARD	LOW singles	1	225	232
	LOW twins	1	400	401
	LOW triplets	1[a]	500	500
CORRECTIVE	MED singles	1	400	401
	HIGH singles	1[a]	500	500
	MED twins	1[a]	500	500
	HIGH twins	1[b]	600	611
	MED triplets	1[b]	600	611
	HIGH triplets	1[b]	600	611

STANDARD: type of supplementation aimed to provide enough supplementary feed to maintain current body reserves (supplementation level: "LOW");
CORRECTIVE: type of supplementation (supplementation levels: MED and HIGH) aimed to provide extra supplementation to improve body reserves of ewes judged to have below optimum nutritional outcomes.
[ab]same letter indicates where ewes at different supplementation allocation were combined into the same feeding group as they had the same supplementation level.

Overall the total amount of supplementation for both approaches was similar (CON at 9,304.9 kg and PLF at 9,424.8 kg) and there was no difference in average amount per ewe (CON 28.6 kg SD 6.42 and PLF 27.8 kg SD 6.47, P=0.14, Figure 5.6).

The number of ewes in CORRECTIVE supplementation in mid-pregnancy was affected by the management approach and supplementation level (P<0.01), where more PLF ewes were allocated to a HIGH level of supplementation (36 %) compared to CON ewes (14 %).

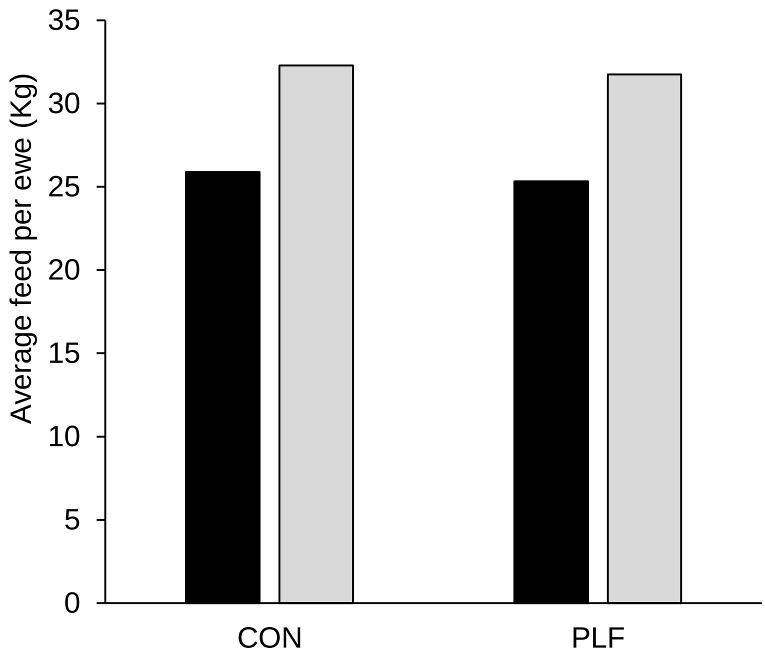


Figure 5.6 Amount of supplementary concentrate feed provided per ewe over mid- and late pregnancy combined (day 50 to 140 of pregnancy) where ewes were allocated to groups based on management approach criteria (PLF: Precision Livestock Farming; CON: Conventional) for ewes carrying single (black bars) or twin lambs (grey bars).

Distribution of counts of ewes to different supplementation levels were affected by management approach and scanning result (Figure 5.7, results not presented for 12 ewes scanned with triplets). The distribution of ewes scanned with single lambs, in late pregnancy was not significantly affected by supplementation type or approach (P=0.08). However, the distribution of ewes scanned with single lambs, that received CORRECTIVE type supplementation, was affected by approach and supplementation level (P<0.001), where more PLF were allocated to the HIGH level (39 %) compared to CON (8 %). Distribution of ewes scanned with twin lambs, was affected by supplementation type and approach (P<0.01), where more PLF ewes entered STANDARD supplementation (70 %) compared to CON (50 %). Of those within CORRECTIVE supplementation, there was no difference between counts of ewes at different levels (MED and HIGH) or approach (P=0.84).

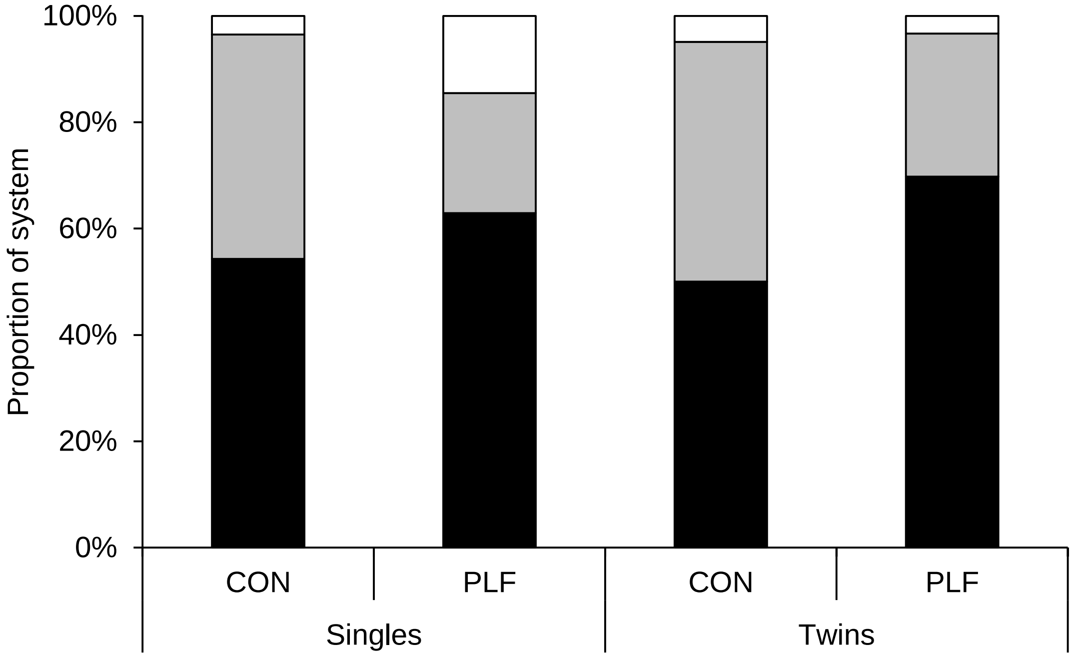


Figure 5.7 Distribution of ewes to different supplementation levels over late pregnancy (day 84 to 140 of pregnancy) as a proportion of each management approach by pregnancy ultrasound scan result. Where allocation to supplementation was based on management approach criteria (PLF: Precision Livestock Farming; CON: Conventional). Different supplementation levels: LOW (black bars, 225 g concentrate feed per ewe per day for ewes scanned carrying single lambs and 400 g for twins), MED (grey bars, 400 g for singles and 500 g for twins) and HIGH (white bars, 500 g for singles and 600 g for twins).

5.3.3 Liveweight and BCS

Average liveweight and BCS profiles appeared different between the two approaches (Figure 5.8). However, average liveweights at any single handling point were not significantly different between approaches (*P*>0.05). Average BCS at pre-mating was significantly higher for CON (2.91) compared to PLF (2.82, *P*<0.001). Within CON, liveweights were significantly different between classes at each handling point (*P*<0.05). CON BCS at the two handling points of premating and scanning were also significantly different (*P*<0.05) between classes (Chi-squared value = 75.17, df =12 and Chi-squared value = 57.15, df =9, respectively). For PLF, the only significant differences between classes were for liveweight at pre-mating, scanning and pre-lambing (*P*<0.05) and BCS at pre-mating (*P*<0.05, Chi-squared value = 21.54, df = 12). Liveweight distribution did not alter between approach or handling point (Figure 5.9).

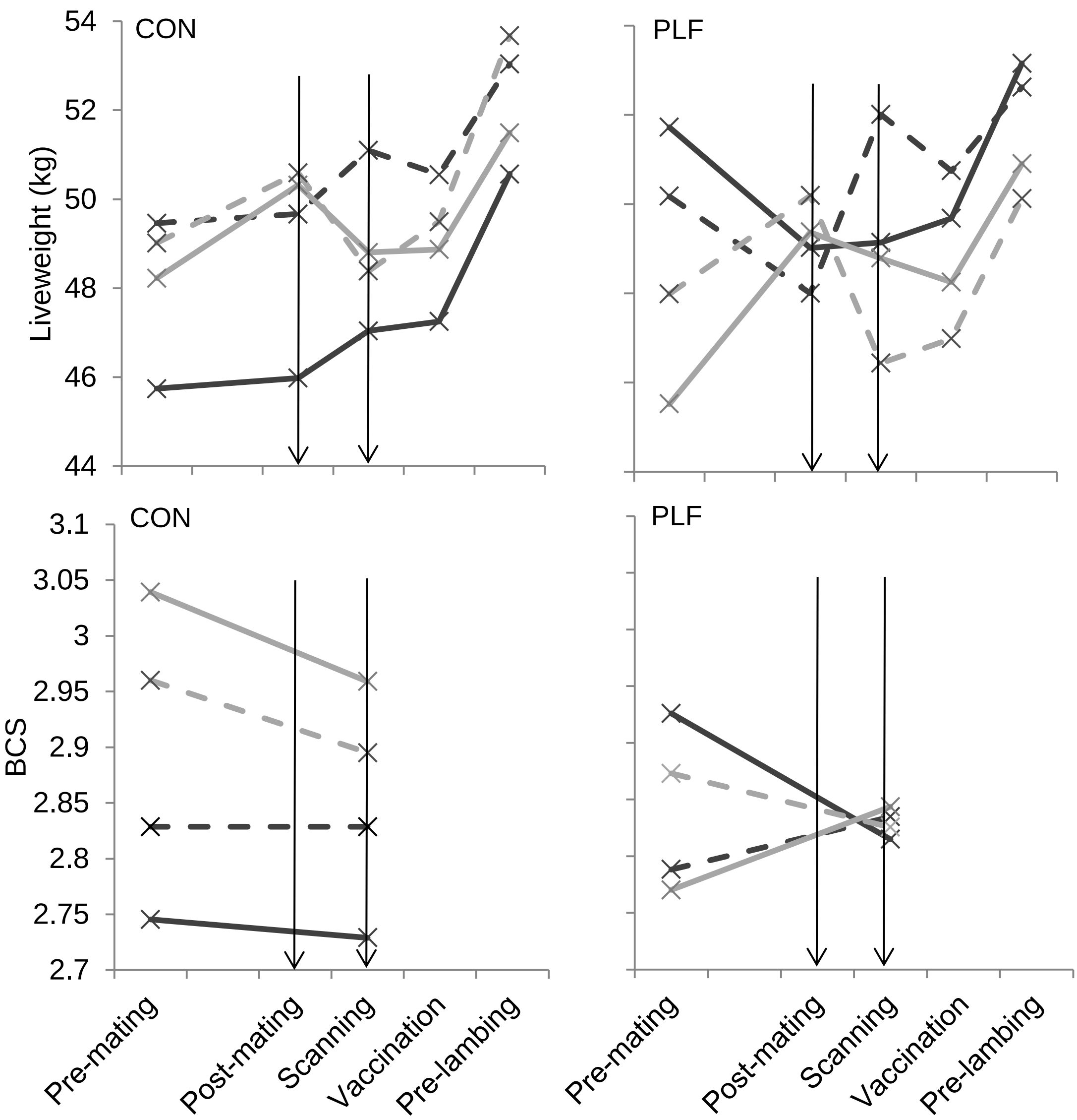


Figure 5.8 Liveweights and Body Condition Score (BCS) for Conventional (CON) and Precision Livestock Farming (PLF) management approaches for allocating ewes to CORRECTIVE or STANDARD supplementation at post-mating and pregnancy scanning (indicated by arrows). Ewes were classed according to their own approach criteria of allocation into mid-pregnancy and late pregnancy supplementation groups, as: “Corrected”, moved from CORRECTIVE in mid-pregnancy supplementation to STANDARD in late pregnancy supplementation ( ); “Remained poor”, remained in CORRECTIVE ( ); “Standard throughout”, remained in STANDARD ( ); and “Deteriorated”, moved from STANDARD to CORRECTIVE ( ).

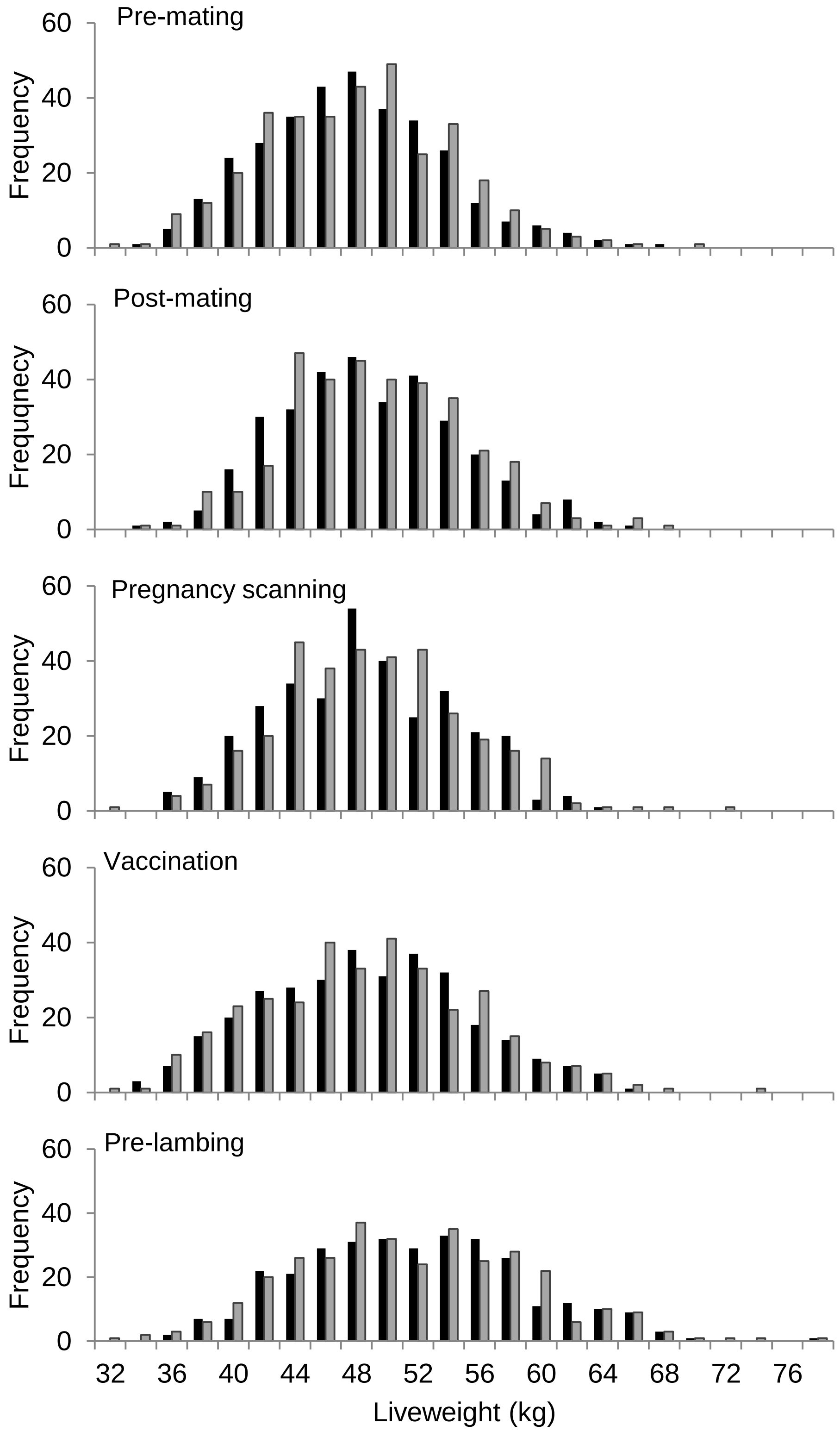


Figure 5.9 Frequency distribution of ewe liveweight at different handling points, when ewes were allocated pregnancy supplementation based on management approach criteria (CON: Conventional, stockperson based decision making, black bars; and PLF: Precision Livestock Farming, based on liveweight change, grey bars).

5.3.4 Production

There were no significant differences between the two management approaches in terms of: number of lambs scanned and born; lamb birth liveweight; and lamb eight week liveweight (Table 5.4).

Table 5.4 Production values for ewes allocated pregnancy supplementation based on management approach criteria (SD in brackets).

	CON	**PLF**	*P*-value[a]
Across approach			
Lambs scanned per 100 ewes	141	139	0.71[b]
Lambs born per 100 ewes	132	130	0.88[b]
Average per ewe			
Total lamb birth liveweight (kg)	5.3 (1.86)	5.2 (1.91)	0.57
Average lamb birth liveweight (kg)	3.8 (0.85)	3.8 (0.87)	0.54
Total lamb eight week liveweight (kg)	26 (10.48)	25.7 (10.74)	0.70
Average lamb eight week liveweight (kg)	18.5 (3.32)	18.4 (3.52)	0.62

PLF: Precision Livestock Farm, approach criteria based on percentage of liveweight change; CON: Conventional, approach criteria based on the stockperson's assessment of ewe condition).
[a]*P*-values show significance when the two approaches are compared;
[b]*P*-values for Chi-squared test on the count of ewes at each litter size and approach.

5.4 Discussion

5.4.1 Allocation and supplementation

The use of the EID enabled weigh-crate and auto-drafting equipment allowed for weighing and sorting PLF ewes into supplementation levels based on percentage of liveweight change since pre-mating. The PLF approach was more successful at moving ewes out of CORRECTIVE supplementation than the CON approach. However, supplementary feed provided was equal across approaches. This was a result of the PLF approach moving more ewes into the highest supplementary level of feeding. Therefore neither management approach required greater investment of supplementation to implement.

5.4.2 Liveweight and BCS

The liveweight profiles of different classes of PLF ewes were largely the product of the supplementation level they were allocated to. Liveweight averages were however different to that of CON ewes. The changes in liveweight between the two allocation points demonstrate how the supplementation impacted. Average liveweight and BCS for each class of PLF ewes narrowed between pre-mating and scanning (for BCS) and to pre-lambing (for liveweight, in all classification excluding the "Deteriorated" class); this suggests that the PLF approach had reduced the range between extreme animals ensuring greater conformity across the flock. However, when distributions of ewe liveweights across the flock at each handling point were considered, no difference was seen between approaches.

5.4.3 Production

The lack of significant difference between management approaches for: number of lambs scanned and born per ewe; lamb birth liveweight; and lamb eight week liveweight, was interesting. The result may be an effect of both management approaches being capable at allocating ewes to appropriate supplementation with successful outcomes. It may also be that the overall nutrition available and provided (from concentrate supplementation, supplementary hay, and grass) far exceeded nutritional requirements. A lack of difference in performance between feeding approaches was also found by Corner-Thomas et al. (2015) when comparing the effect of feeding different levels of supplementation to ewes.

5.4.4 Evaluation of the PLF approach

The lack of differences found between approaches could be considered a limitation of this research, although there are a number of points to consider. Firstly, the requirements (feed) and outputs (performance) were similar for both approaches which is a promising start in developing a new PLF approach.

The CON system was termed "conventional"; however, arguably it was more sophisticated than often occurs on commercial hill sheep systems, where only a proportion of stockpeople will handle and sort their ewes into feeding groups (McBean et al., 2016). Assessing current nutritional state of a ewe by considering condition of each ewe in the flock is in itself a precise methodology (Kenyon et al., 2014). An alternative could have been to compare the PLF approach to an approach where ewes remain in a single feeding group or only split on pregnancy scan result.

The CON approach relies on the ability of the stockperson to assess ewe condition. Furthermore, the presence of the author to record the sorting decisions may have resulted in a higher level of diligence from stockpeople in assessing ewes than would normally occur on farm. In contrast, the PLF approach is based on the objective, quantifiable measure of liveweight loss. Therefore, it would be expected that the PLF approach is likely to have more repeatable and consistent results. The PLF method also does not require a skilled stockperson able to assess condition effectively. Work carried out in parallel to this thesis found that labour input was lower for the PLF approach compared to the CON for allocating supplementation (10 s per ewe per person compared to 18 s, respectively, Morgan-Davies et al., 2018b, Appendix 2). Therefore the reduced labour required by the PLF approach increases its potential use within hill sheep systems, given the labour availability and capability difficulties faced by such systems (Colby, 2015; Montossi et al., 2013; Morgan-Davies et al., 2018b; Renwick et al., 2008; Waterhouse, 1996).

Another potential benefit of the PLF approach over the CON is improved welfare. Handling can cause stress in livestock (Grandin, 2007) so improving methods and reducing handling times should improve welfare. While no specific welfare measurements were made through this study, the author observed that the sheep appeared calmer and less stressed when walking through the weigh-crate, used in the PLF approach, compared to when physically handled for the CON approach. Further research would be required to explore the welfare implications of both approaches.

Two different breeds of ewes were included within the dataset of this chapter (Scottish Blackface and Lleyn). Initially it had been considered that performance of the two breeds could be compared. However, given the lack of difference observed between the two approaches, it did not seem appropriate to add further complexity to analyses. Both breeds were retained within the dataset to increase the number of records available for analysis and ewes of both breed were distributed throughout the different supplementation levels. In contrast to this, it is acknowledged that breed is likely to impact on performance differences (Al-Nakib et al., 1997; Annett et al., 2011, 2010; Dickerson and Glimp, 1975). However, Hocking Edwards et al. (2018) found that while absolute measures of ewes (such as liveweight) may vary between breeds the biological principles and effects are the same. Therefore considering the two breeds together within this chapter appeared reasonable.

5.4.5 PLF approach development

Given the different elements of the PLF approach and how it is carried out there are many possibilities for development which could have positive impacts. The aspects that could be altered include: different liveweight change cut-offs for each level of supplementation; different levels of supplementation; and consideration of BCS to allow for ewes in a poorer condition to gain more, and those at a higher condition to lose more, before preferential supplementation is provided. The final option is believed to be a useful addition to the approach and recognises the importance of BCS for productivity (EBLEX, 2008; Fthenakis et al., 2012; Kenyon et al., 2014).

Indeed, following the research carried out for this thesis, in subsequent production years, new reference liveweights have been incorporated into the method to allocate ewes to pregnancy supplementation across the whole flock. These reference liveweights were calculated by correcting individual ewes' pre-mating liveweight to a flock average BCS. The corrected pre-mating liveweights were then reduced by a proportion of liveweight loss from pre-mating to early pregnancy and pre-mating to pregnancy scanning. This produced individual ewe reference liveweights at early pregnancy and pregnancy scanning handling points, respectively. Results from this altered approach have yet to be analysed.

In other literature real-time and continuous monitoring and management has been suggested PLF approaches (Berckmans and Guarino, 2017; Scholten et al., 2013; van Hertem et al., 2016). However, within this chapter, monitoring and management decisions are only carried out at two points through pregnancy, where ewes are allocated to their supplementation level. Bowen et al. (2009, 2008) demonstrated that supplementation could be allocated to ewes using automated drafting within a field. Further, research using walk-over-weighing (as previously presented in Chapter 2) has demonstrated that regular in-field weighing is possible and can generate reliable liveweight data (Brown et al., 2014b, 2014a; González-García et al., 2018). With these technologies it could be possible to monitor liveweights and make supplementation decisions frequently for individuals within a grazing group.

5.4.6 Application potential

This PLF approach of allocating ewes into supplementation groups has been presented to stockpeople at farm open days. Personal communications with the practitioners suggested opinions were largely positive, appreciating the potential benefits of utilising EID and associated technology to allocate ewes into groups based on liveweight change. However concern arose over: the complexity of the PLF allocation criteria; the cost of the equipment; and technical capability required to operate. The latter two points have been echoed in other research exploring the uptake of EID driven methods within the sheep industry (Brown et al., 2015; Jordan et al., 2006). Concerns over technology costs and training to allow uptake, need to be addressed in order to ensure that the application and benefit of any PLF approach are realised. PLF uptake potential will be considered in Chapter 10.

For such an approach of pregnancy supplementation to be applicable on commercial hill sheep systems, it would be necessary to have access to EID enabled weighing equipment and handle ewes at three time points: pre-mating, post-mating and at pregnancy scanning. If handling and weighing at these points do not occur, adoption of the PLF approach could create extra handling and labour. Therefore, the benefits need to be demonstrated to outweigh these extra costs. This is challenging given that the benefits (of reduced cost of feed and increased lamb production) of carrying out the approach were not confirmed within this chapter. For hill sheep systems that have access to EID weighing technology and frequently weigh ewes, the PLF approach would be straight-forward to implement. Furthermore, for systems that do sort ewes into supplementary groups by handling and assessing condition, adoption of such an approach would likely reduce labour. Therefore the adoption potential of this PLF approach is likely to be dependent on the resources available and procedures already carried out on an individual farm.

5.5 Conclusions

This research has demonstrated the possibility to manage the nutrition of pregnant ewes in a precise manner in an extensive hill sheep system using a PLF approach. Automatic EID enabled weighing and drafting crates were efficient at segregating large flocks.

Allocating ewes to pregnancy supplementation based on proportion of liveweight change was more effective at moving ewes out of corrective supplementation, compared to an allocation based on stockpersons' subjective assessment of nutritional need. Furthermore, this trial suggested that a liveweight-based PLF approach was efficient at managing body reserves to reduce business risks associated with both low and high body reserves during pregnancy and at lambing.

The PLF approach had similar input (feed) requirements and ewes produced similar outputs (number of lambs scanned and born, and liveweight of lambs at birth and at eight weeks old) compared to ewes managed using an assessment of condition. Although parallel research found that the PLF approach required less labour than the CON approach of allocation (Morgan-Davies et al., 2018b, Appendix 2). From observations the PLF approach has the potential to provide a method of handling and sorting ewes that promote good welfare. Furthermore, the PLF approach is arguably more repeatable given that decisions were based on objective liveweight changes compared to the subjective criteria of the CON approach of allocation.

Although promising, the current PLF method of allocation requires a degree of simplification for ease of further analysis and potential use on commercial hill farms. The variation in body reserves at pre-mating also needs to be further considered as another criterion for ewe supplementation allocation.

PART 2

Challenge: making retention and culling decisions for ewes in a hill sheep system at stockdraw

CHAPTER 6: CURRENT CULLING PROTOCOLS WITHIN THE UK SHEEP INDUSTRY

Chapters 4 and 5 addressed the first challenge identified in Chapter 2 of allocating pregnancy supplementation. These previous chapters found that EID and weighing technology could be used to allocate supplementation to pregnant ewes by utilising liveweight data. Part 2 explores how individual data and information could be used in a PLF approach to inform retention and culling decision making at stockdraw of ewes within a breeding flock.

This chapter aims to understand the reasons stockpeople use when making ewe culling decisions. This is important to know to inform research within the following chapters and provide industry context.

6.1 Introduction

"Culling" is the process by which ewes are removed from the flock by a stockperson. Culling is ultimately an economic decision (EBLEX, 2014; Fetrow et al., 2006; Groenendaal and Galligan, 2005; Monti et al., 1999; Richards et al., 2013, 2012), where the stockperson believes that returns from the sale of a ewe will be greater than if the ewe were to be retained within the flock and sold at a later date. This decision is also made while considering whether a replacement taking the ewe's place in the flock would be of greater benefit than if the ewe were retained and the replacement sold instead (Essl, 1998; Nugent and Jenkins, 1993).

As well as the associated economic factors, retention and culling decisions also have an important impact on, and association with, longevity (Kern et al., 2010; Mekkawy et al., 2009), genetic potential (Monti et al., 1999; Nugent and Jenkins, 1993; Richards et al., 2012), performance (Monti et al., 1999; Nugent and Jenkins, 1993; Richards et al., 2013) and welfare (McGregor, 2011) of the flock. Longevity (meaning the length of productive life), and associations with culling decisions, will be considered in detail in Chapter 7.

For the purpose of this thesis, "culling" refers only to ewes sold from the flock and does not include those that leave due to death. Further, for simplicity, "cull" also describes ewes sold from the flock that were still considered "sound" (meaning still productive and suitable for breeding), these are often referred to as "draft" or "cast" ewes (for example in Kilgour et al., 2008; Rodriguez-Ledesma et al., 2011; Waterhouse, 1999).

6.1.1 Culling reasons

Culling reasons are an important element of livestock culling and retention research. Within dairy research, culling reasons are often classified as: "voluntary", such as low milk production, and "involuntary" such as death, illness or infertility (Berry et al., 2005; Lehenbauer and Oltjen, 1998; Monti et al., 1999). However, these terms are more relevant to the dairy industry as production (of milk) can be regularly monitored. Alternative terms suggested by Fetrow et al. (2006) for dairy cattle are more appropriate for sheep, and are: "biological/forced" reasons, including when an animal dies or is infertile, and "economic" reasons which would be used when it is believed by the stockperson that selling the animal and having a replacement would be more productive and so more economically viable. However, for the purpose of this chapter culling reasons have not been classified in this way because specific cull reasons are of greater interest.

Given the importance of culling, it is surprising that the literature states decisions are often carried out based on the stockpersons' intuition of the best animals to cull (for sheep, McGregor, 2011; and dairy, Berry et al., 2005; Groenendaal and Galligan, 2005; Kelleher et al., 2015; Lehenbauer and Oltjen, 1998). Research that explored culling and longevity in sheep has reported a wide range of culling reasons used within study flocks (Table 6.1).

Table 6.1 Reasons reported in research that have been used to cull ewes.

Cull reasons	References
Reproductive	
Barren (failure to conceive)	Annett et al., 2011; Mekkawy et al., 2009; Nugent and Jenkins, 1993
Poor mothering ability (maternal instinct, not enough milk)	Annett et al., 2011; Nugent and Jenkins, 1993
Lambing difficulty	Annett et al., 2011
Abortion	Annett et al., 2011
Prolapse	Annett et al., 2011; Mekkawy et al., 2009
Physical	
Poor body condition	Annett et al., 2011; Mekkawy et al., 2009
Mouth condition (missing teeth, poor bite position)	Annett et al., 2011; Kilgour et al., 2008; McGregor, 2011; Mekkawy et al., 2009
Udder problems (poor teat conformation, mastitis)	Annett et al., 2011; Kilgour et al., 2008; Mekkawy et al., 2009; Nugent and Jenkins, 1993
Foot/leg problems (lameness)	Annett et al., 2011; Mekkawy et al., 2009; Nugent and Jenkins, 1993
Other	
Age	Kilgour et al., 2008; Nugent and Jenkins, 1993
Disease	Nugent and Jenkins, 1993

Cull reasons reported in research (Table 6.1) are similar to those found in industry advice. Published advice for stockpeople stating what criteria should be used to cull ewes from the flock classified cull reasons into three groups: "poor performance", "structural integrity" and "disease", as well as advised how to identify different age groups to allow culling on age to occur (EBLEX, 2014).

The majority of literature that presented culling reasons were from research and experimental farms (Mekkawy et al., 2009). Culling reasons on research farms may be influenced by project requirements and therefore may not be the same as commercial farms. Annett et al. (2011, 2010) is one source that reported culling reasons from commercial sheep farms, however the study was limited to six hill farms. Therefore to be able to research retention and culling decisions, understanding the current culling practices on commercial systems is important. Furthermore, knowledge on current culling practices is scarce, including what variation in culling decisions exists between farms and whether it is affected by flock type (meaning, hill, upland and lowland systems) or by production aims. Hill sheep systems are associated with producing store lambs and ewes suitable for further breeding, while upland and lowland systems are associated with producing finished lambs for slaughter (Kilgour et al., 2008; Waterhouse, 1999). It could be that as different flock types aim to produce different types of animals, then different cull reasons would be used.

It has been suggested that culling decision making is a management process that would benefit from a more precise, data driven approach (meaning a PLF approach, Richards et al., 2013, 2012). For this to occur, detailed records of ewes need to be kept to inform decision making. However, the current methods that stockpeople are using to make culling decisions are also unknown.

6.1.2 Aims of chapter

The aims of this chapter are:

1) To find out what cull reasons, are used on commercial farms within the UK sheep industry, to remove ewes from the breeding flock.
2) To identify whether there are any differences in culling practices between flock types or the type of animals being produced.
3) To discover what information and data collection methods are being used by stockpeople to inform culling decision making.

Understanding current culling practices will inform further research within this thesis and is also important for the consideration of a PLF approach for making retention and culling decisions.

6.2 Materials and Methods

6.2.1 Questionnaire

A questionnaire was developed to collect reasons why stockpeople decide to cull ewes from the breeding flock. The draft questionnaire was trialled on experienced stockpeople and knowledgeable research staff, to improve clarity of questions and identify any gaps in questions and options available. The final version was composed of eight main questions (Figure 6.1). The first four questions collected information about the respondents' sheep system (Q1, Q2 and Q3) and when ewe culling decisions were made (Q4). The next two questions were concerned with the reasons that the respondent used to cull a ewe from the main breeding flock (Q5) and which were considered important culling reasons (Q6). Question 7 collected information on what information and tools respondents used to inform ewe culling decisions. The final question (Q8) allowed for any other comments on ewe culling to be made.

The questionnaire was completed via two methods. Firstly, a face-to-face paper version was carried out by the author or one of three other research staff (all of whom were knowledgeable about the topic area). This was implemented at two commercial sheep shows (NSA Highland Sheep 31st May 2017 in Strathpeffer, Ross-shire; and NSA North Sheep 7th June 2017 in Tow Law, County Durham); via opportune sampling of visitors to the SRUC stand. Prior to commencing the questions, it was first established that the respondent had experience of making culling-decisions on a particular sheep flock.

Secondly, in order to increase respondent numbers, the questionnaire was made available on-line (hosted by SurveyMonkey.com) between Sunday 18th June 2017 and Friday 30th June 2017. This was promoted via SRUC Hill and Mountain Research Centre's Twitter and Facebook pages, which were both known to have followers involved in sheep production. The on-line version included an additional first question which asked whether the respondent had "detailed knowledge of the culling protocol applied to a flock of ewes"; failure to answer this positively resulted in the questionnaire being terminated. All data recorded was anonymous with no identifying information recorded. A total of 115 responses to the questionnaire were collected (NSA Highland Sheep = 20, NSA North Sheep = 30 and online = 65).

Ewe culling protocol

SRUC SusSheP SheepNet

Q1. What best describes your flock?

hill☐ upland☐ lowland☐

Q2 What breeds do you have in your ewe flock?

sheep breed: ______________________

Q3. What are the main sheep being sold from the flock? *(tick all that apply)*

slaughter/finishing lambs☐ ewe lambs/gimmers for breeding ☐

store lambs☐ unsound ewes (unsuitable for breeding) ☐

breeding rams☐ sound ewes (suitable for breeding)☐

Other:____

Q4. When do you carry out your main stockdraw (when ewe culling decisions are made)?_____________

Q5. Would you cull a ewe (from the main breeding flock) for any of these reasons?

(tick all that apply, add comments if needed)

Q5.1 reached a specific age	☐	*what age in years at stockdraw:*
Q5.2 over or undershot jaw	☐	
Q5.3 missing teeth	☐	*how many teeth missing:*
Q5.4 other mouth abnormalities	☐	*what:*
Q5.5 bad legs and/or bad feet	☐	
Q5.6 udder and/or teats the wrong size	☐	
Q5.7 overall structure (how ewe put together)	☐	
Q5.8 does not meet breed or flock standards	☐	
Q5.9 the wrong size	☐	*if on a specific weight, what is it:*
Q5.10 not thriving ("a poor do-er")	☐	
Q5.11 poor body condition	☐	

Q5.12 failure to get pregnant	☐	*how many times:*
Q5.13 got pregnant but no live lamb born	☐	*how many times:*
Q5.14 lamb born but failed to raise to wean	☐	*how many times:*
Q5.15 lambing difficulty	☐	*what:*
Q5.16 bad mothering ability	☐	
Q5.17 prolapse	☐	
Q5.18 mastitis	☐	
Q5.19 other specific disease(s)	☐	*what:*
Q5.20 EBVs	☐	
Q5.21 bad attitude and/or behaviour	☐	
Q5.22 Other:		

Q6. In your ewe flock what are the 3 most important things that would make you cull a ewe?

(list in order of importance)

1)____

2)____

3)____

Q7. What do you base your ewe culling decisions on? *(tick all that apply)*

visual appearance of ewe☐ paper records (e.g. in a diary) ☐ own PC recording system☐

remembering performance/problems ☐ EID assisted (readers etc.) ☐ farm management software☐

physical marks/tags on ewe☐ Other:_______________________________________

Q8. Any other comments on ewe culling protocol? (continue on back of sheet if needed)

____

Thank you!

Figure 6.1 Questionnaire on culling practices of ewes from the breeding flock (question numbering added to allow easier referencing within this chapter).

6.2.2 Data cleaning

All questionnaires that were carried out face-to-face were completed, however 11 online questionnaires were started but not finished and so were removed from the final analysis. This resulted in 104 complete questionnaires for analysis.

A number of responses to questions were altered to make them comparable. These changes included:

- Three respondents selected multiple options for their flock type (Q1). Their answer was changed the single more extreme type (so if respondents selected “hill” and “upland”, then “hill” was used).
- To answer what “age in years at stockdraw” a ewe would be culled at (Q5.1), some respondents put the crop number instead of age. It was presumed that the first crop of lambs a ewe will have is when they are two years old therefore all crop numbers were increased by one to make an estimated age in years.
- A number of questions asked for a specific value to be given, such as: Q5.1 “what age in years at stockdraw”; Q.5.3 “how many teeth missing”; or for Q5.12, Q5.13 and Q5.14 the number of times an event occurred before culling. Instead of putting a single value some respondents put a range or two options (for example, “4 to 5” or “4 or 5”). In these situations the most extreme value was selected, which was the lowest value quoted.
- Question 6 asked for “the 3 most important things that would make you cull a ewe”, these answers were screened across all respondents and a condensed list of reasons was created to aggregate responses (Appendix 4).

There were 29 responses for Question 8, which asked for “any other comments on ewe culling protocol”. While these comments were reviewed and considered, they were generally broad and vague without obvious benefit to this analysis so have been ignored.

6.2.3 Data analysis

Responses to multiple choice answers were presented in the form of bar graphs. Chi-squared tests were carried out on counts, where appropriate, to investigate whether flock type was important.

Question 6 asked respondents to specify the three most important reasons to cull a ewe, listed in order of importance. The answers were assigned a score with the first (most important) reason getting three points, two for the second and one for the third. An accumulated score per reason could then be calculated.

Question 7 asked respondents to select the information sources they use to base their culling decision on. The listed options were used to cluster respondents into two groups for comparison, depending on whether they used recorded information to make culling decisions or not. The two groups were either “No records” (for respondents that only selected options: “visual appearance of ewe”, “remembering performance/problems” and “physical marks/tags on ewes”) or “Records” (for respondents that selected any options: “paper records”, “EID assisted”, “own PC recording system” and “farm management software”). When “other” responses where provided they were included within the most relevant classification.

6.3 Results

6.3.1 Sheep systems represented (Q1, Q2, Q3 and Q4)

Out of all 104 respondents, 31 (29 %) were for hill flocks, 34 (33 %) for upland and 39 (38 %) for lowland (according to answers from Q1). A total of 33 different pure-bred ewe breeds were recorded across all respondents (Q2) and 59 respondents (57 %) had mules or cross-bred ewes (respondents were able to answer with multiple different sheep breeds). The Scottish Blackface was the pure breed that appeared the most times across any flock type (n = 19) followed by Texel (n = 14), Cheviot (n = 13), Swaledale (n = 12) and Suffolk (n = 12). All other pure breeds appeared less than 10 times each. There was a significant difference of the top five pure breeds, between flock type (Chi-squared test, P<0.001, Figure 6.2).

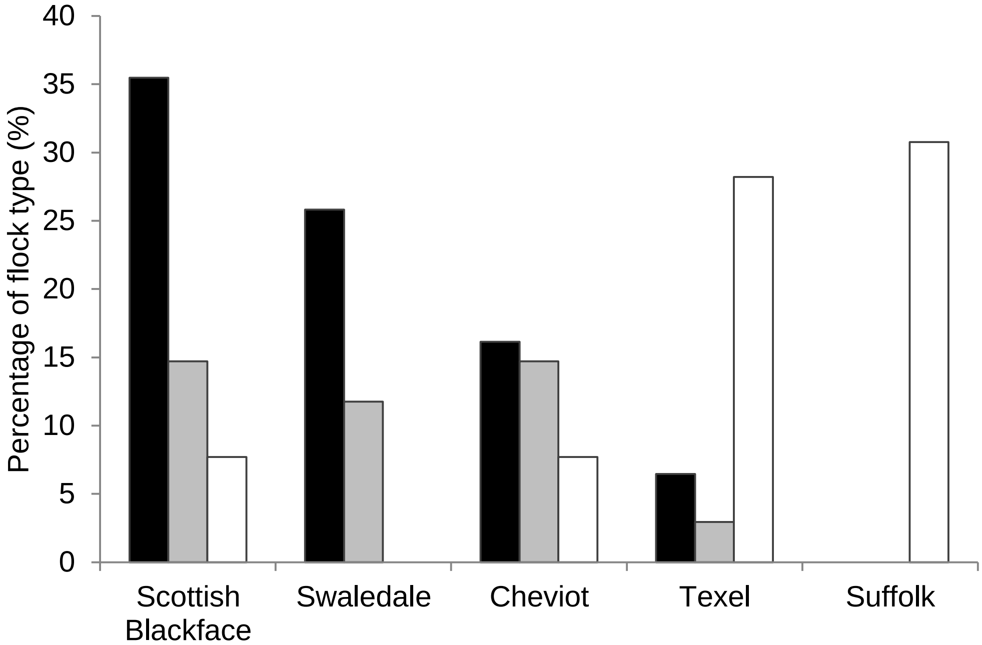


Figure 6.2 Five pure breeds of sheep recorded the most as being within respondent's ewe flocks, presented as a percentage of flock type (hill, black bars; upland, grey and lowland, white; from Question 2).

On average respondents selected three main types of sheep sold from the flock (Q3). There was a significant impact of flock type on the numbers selling sound ewes (P<0.05) and slaughter (finishing) lambs (P<0.05, Figure 6.3). Counts of respondents that sold different types of ewes (sound or unsound) from the flock varied across flock type (Table 6.2, P<0.05). The biggest difference was that 48 % of hill flock respondents reported that they sold sound ewes as a main type of sheep, compared to only 18 % of upland and 10 % of lowland flock respondents. Across all respondents, 33 % did not select “sound” or “unsound” ewe options.

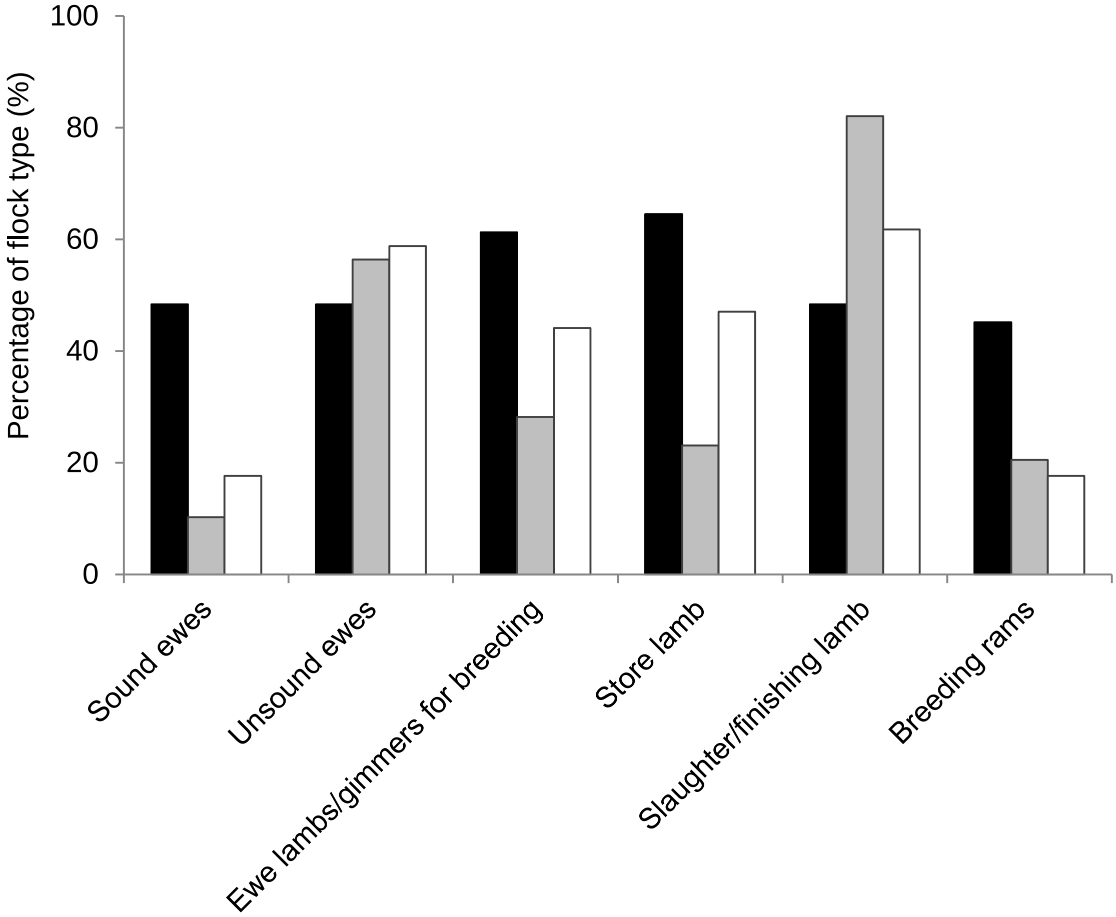


Figure 6.3 The main type of sheep sold, presented as a percentage of flock type (hill, black bars; upland, grey; and lowland, white; from Question 3).

Table 6.2 Count of respondents that selected different types of ewes sold from the flock, for each flock type (from Question 3 asking for the “main type of sheep sold from the flock”; percentage of farm type in brackets).

Ewes sold	**Hill**	**Upland**	**Lowland**	**Total**
Sound and unsound	6 (19.4)	3 (8.8)	3 (7.7)	12 (11.5)
Sound	9 (29.0)	3 (8.8)	1 (2.6)	13 (12.5)
Total selling sound ewes	*15 (48.4)*	*6 (17.6)*	*4 (10.3)*	*25 (24.0)*
Unsound	9 (29.0)	17 (50.0)	19 (48.7)	45 (43.3)
No ewes	7 (22.6)	11 (32.4)	16 (41.0)	34 (32.7)

A total of 85 (82 %) of respondents stated they carried out their main stockdraw during autumn (Q4, which included responses: “August”, “September” or “October”) or after weaning and before mating. For the remaining 19 respondents stockdraw was indicated to be earlier in the year and three responded that culling decisions were made throughout the year.

6.3.2 Cull reasons (Q5)

Of the 22 different potential cull reasons, provided in Question 5 (including an “other” option), on average respondents selected 12 reasons (Figure 6.4). There was no significant influence of flock type for decision to cull on each cull reason.

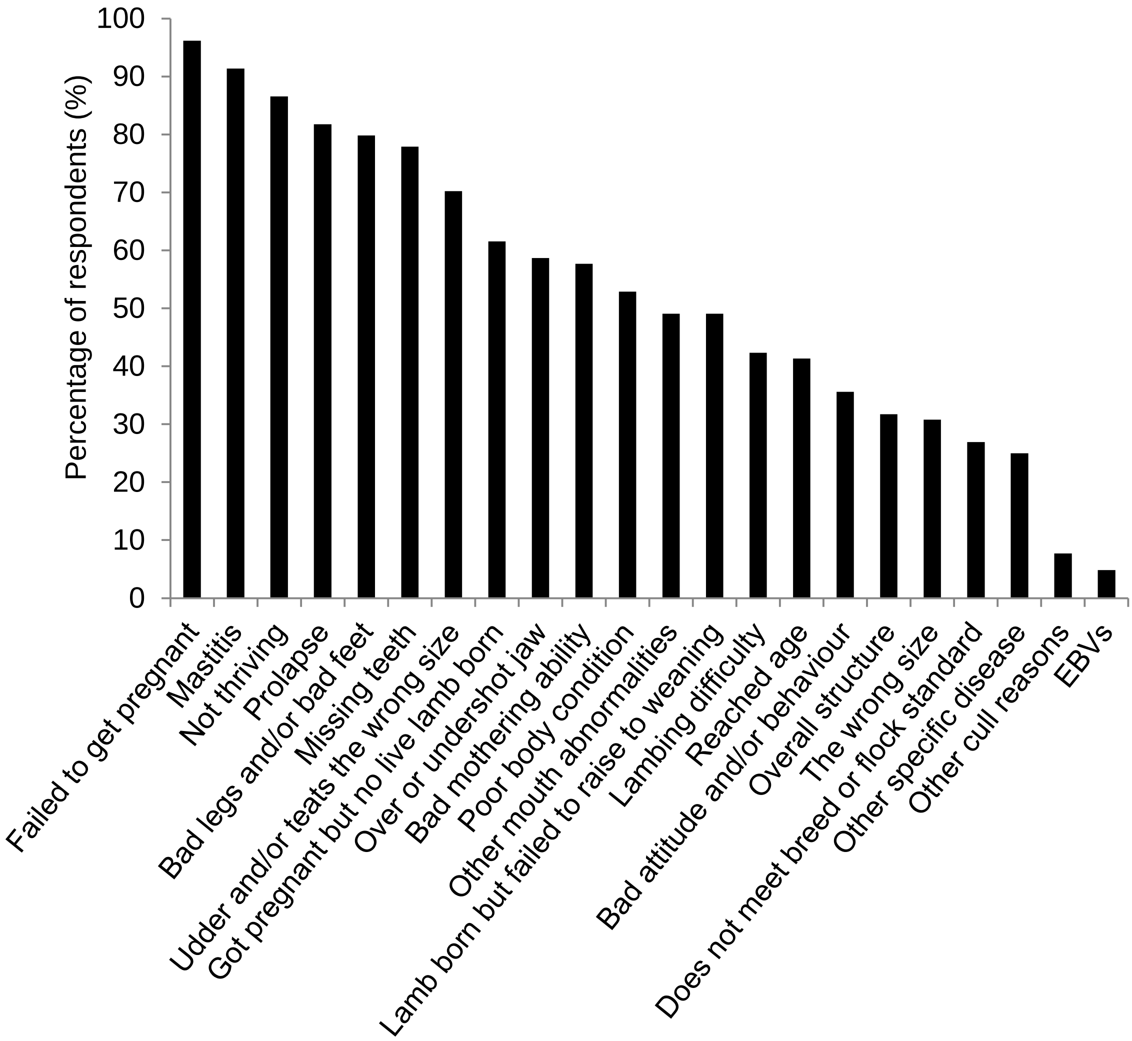


Figure 6.4 Reasons used by respondents to cull a ewe from the main breeding flock (from Question 5).

“Failure to get pregnant” (Q5.12) was the most selected reason for which respondents would cull a ewe (selected by 96 % of respondents). Of those that chose this option, 64 % provided details of how many times a ewe failed to get pregnant before it would be culled; 51 % stated the first time this occurred and 41 % after the second time. However, many commented that younger animals got a second chance whereas older ewes did not. A similar response was also given for the number of times a ewe was allowed to get “pregnant but no live lamb born” (Q5.13) and to have a “lamb born but failed to raise to wean” (Q5.14) prior to culling.

While some diseases or specific health issues were specified as cull reasons (for example, Q5.17 “prolapse” and Q5.18 “mastitis”), when asked if they culled on “other specific disease(s)” (Q5.19) 26 respondents (25 %) selected that they did and 21 provided details of diseases. These diseases included: footrot (n = 7), fluke (n = 1), Johne’s (n = 1), pneumonia (n = 1), scab (n = 1) and Schmallenberg (n = 1).

There were 81 respondents (78 %) who selected “missing teeth” (Q5.3) as a reason to cull a ewe, with 64 specifying the minimum number of missing teeth to decide to cull. Thirty-seven respondents said they culled ewes if they were missing one tooth. However, three respondents specified that all eight teeth had to be missing before the decision to cull was made (one for a hill flock and two for upland flocks).

Under half (41 %) of all respondents said they culled ewes from the flock based on age (Q5.1, Figure 6.5). The highest proportion of respondents from any one flock type to cull on age was those from hill flocks (at 55 %) followed by lowland (41 %) and finally upland (29 %). When only respondents that sold “sound ewes” (from Q3) were considered, the difference to cull on age between flock types was significant (P<0.05). For hill flocks that sold sound ewes (48 % of all hill flocks), 73 % culled on age, compared to 3 % of all upland and lowland flocks combined.

Amongst the respondents that culled on age, 37 (hill = 15, upland = 10, lowland = 12) provided the age in years at which ewes were culled from the flock. Across all flock types, the most common age (38 %) at which ewes were culled was six years at stockdraw. Hill flocks tended to cull at younger ages than other flock types (Figure 6.6).

Of the “other” cull reasons (Q5.22) provided by 11 respondents, all could have been included within one of the listed cull reasons: “bad legs and/or bad feet” (n = 4), “does not meet breed or flock standards” (n = 2) and “bad mothering ability” (n = 5).

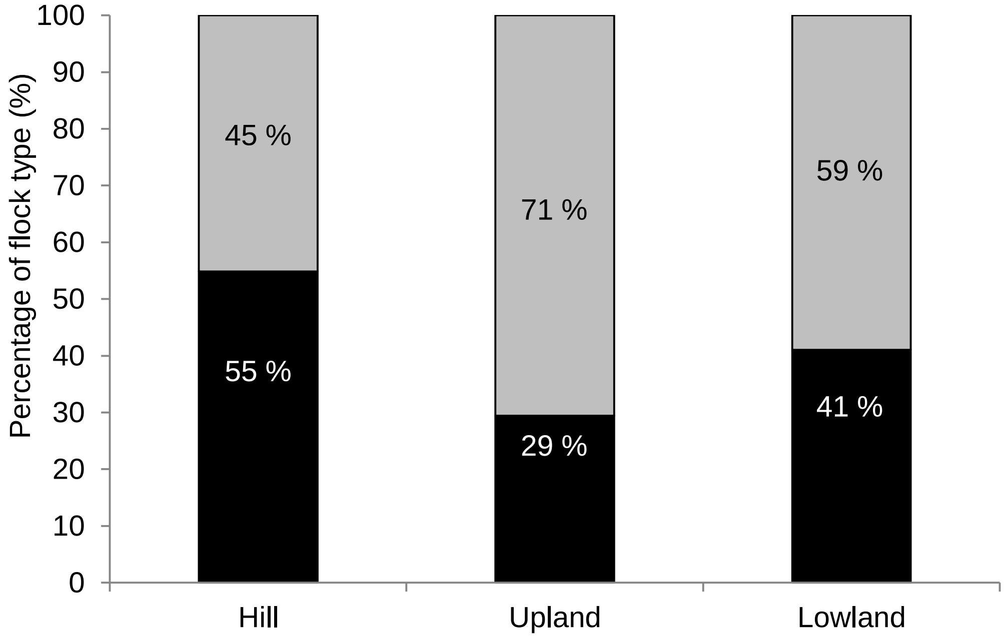


Figure 6.5 Percentage of respondents by flock type to cull ewes from the main breeding flock at a specific age (black, and those that did not in grey, from Question 5.1).

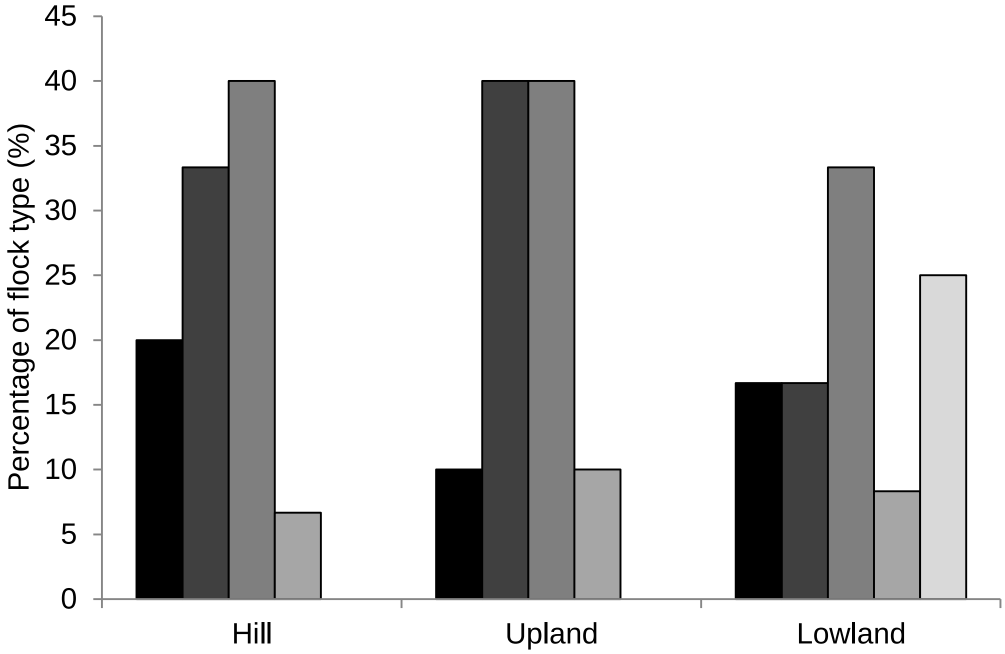


Figure 6.6 Age at which ewes were culled, presented as a percentage of respondents that culled on age by flock type (■ 4, ■ 5, ■ 6, ■ 7 and □ 8 years old at stockdraw, from Question 5.1).

6.3.3 Most important cull reasons (Q6)

When respondents were provided with an open-ended question to provide their own "most important" cull reasons (Q6), "Poor mouth" received the highest accumulated score (Figure 6.7). Nine respondents included "age" in their top three reasons (hill = 2, upland = 5 and lowland = 2).

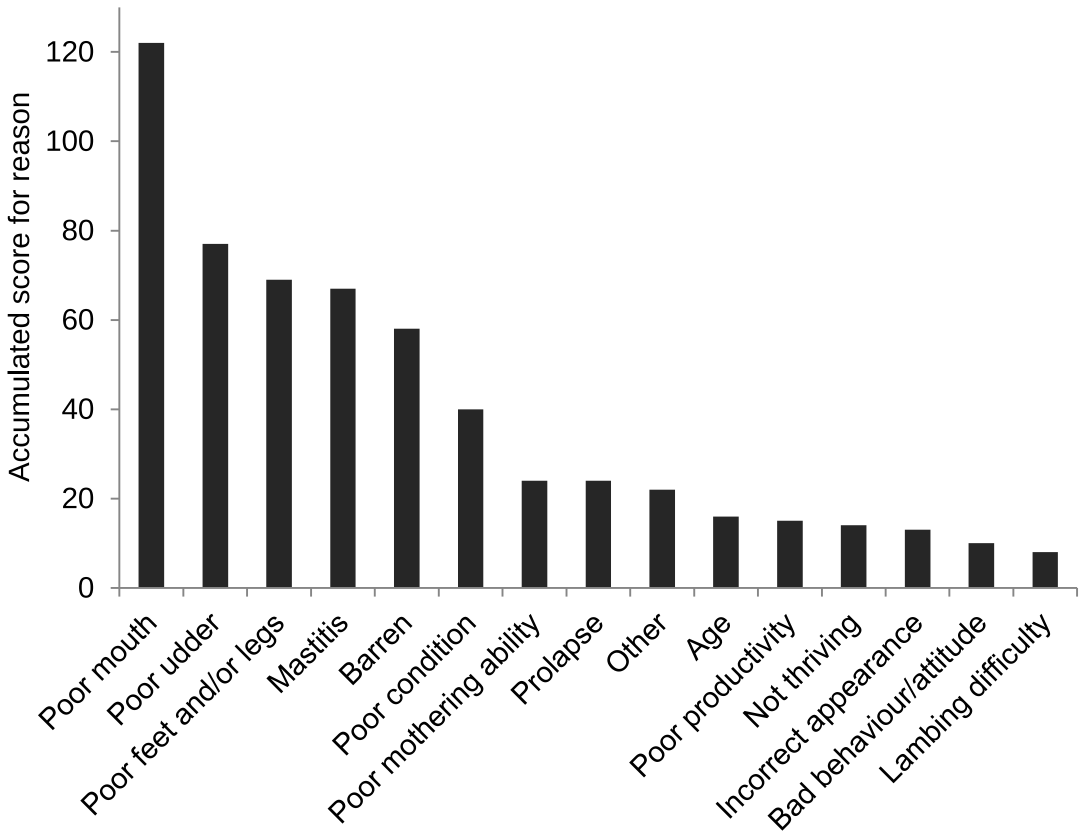


Figure 6.7 Accumulated score for the most important cull reason as specified by respondents (from Question 6).

6.3.4 Basis of culling decisions (Q7)

When respondents were asked what information source was used to base culling decisions on (Q7), on average 2 options were selected from the list provided (Figure 6.8). Six respondents did not select any option (hill = 3, upland = 1, lowland = 2). The top three options chosen were: "physical marks/tags on ewe" (65 % of respondents), "remembering performance/problems" (53 %) and "visual appearance of ewe" (45 %). Two respondents specified other methods used to make culling decisions, which were use of a mobile phone to record, and moving ewes to cull to a different grazing location. Across all options there was no significant difference between flock type and information source selected (from Chi-squared tests).

When responses were classified according to whether records were used to base culling decisions on, an equal percentage of respondents did not use any recording methods (“No records”, 47 %) compared to those that did (“Records”, 47 %, with the remaining 6% not selecting any of the options provided). Once the “no responses” were removed, Chi-squared tests showed that flock type did have an effect on whether or not the respondents used recording methods ($P<0.05$). Respondents of hill flocks had the lowest percentage of using “Records” (39 %), followed by lowland (46 %) and finally upland (56 %).

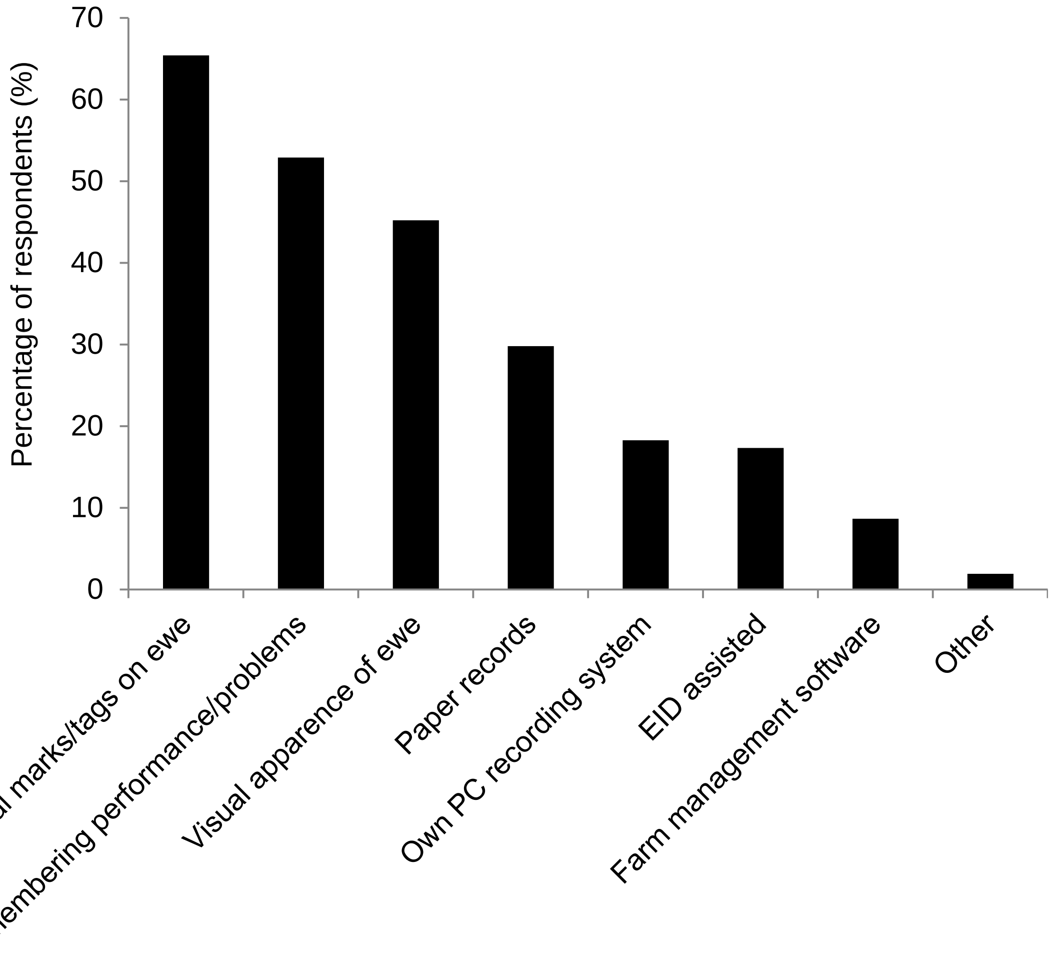


Figure 6.8 Basis of respondents culling decisions (from Question 7).

6.4 Discussion

The results of the questionnaire revealed that respondents use a wide range of reasons to cull ewes from the main breeding flock (Q5). Individual respondents selected, on average, twelve cull reasons from the pre-defined list. Different respondents selected different cull reasons but this was not associated with flock type, suggesting that factors other than flock type were impacting on culling decisions.

The 21 predefined cull reasons (Q5) were shown to be an exhaustive list of possible cull reasons used by respondents. Indeed, all the “other” cull reasons provided (Q5.22) could have been included under another reason from the predefined list. Furthermore, all responses to the open-ended question on “most important cull reasons” (Q6) were included in the 21 pre-defined list of reasons. Therefore, this complete list of possible cull reasons could be used in future culling and longevity based research and will also be useful for the following chapters of this thesis.

6.4.1 Main cull reasons

“Failure to get pregnant” (Q5.12) was the cull reason chosen by the most respondents (96 %). This reason can be considered to be analogous to the “barren” category of responses when respondents were asked for the three most important cull reasons (Q6). However, “barren” only received the fifth highest accumulated score from this latter open-ended question (Q6). This suggests that while the majority of respondents would cull based on a ewe’s reproductive ability (such as “failure to get pregnant” and “barren”), other reasons were seen as more important.

From the open-ended question of the “most important cull reasons” (Q6), “poor mouth” received the highest accumulated score. Furthermore, “Missing teeth” (from Q5, which would be considered a “poor mouth” from Q6) was the sixth most selected reason on the predefined list of 21 cull reasons and was selected by a high proportion of respondents (78 %).

While previous research comparing differences in culling protocols between stockpersons cannot be found, culling and longevity research often report the death and cull reasons of ewes under investigation and can used for comparison to the current findings. Annett et al. (2011) reported that “barren” was the most common reason Scottish Blackface and Scottish Blackface cross-bred ewes were culled from six commercial study farms in Northern Ireland. This was followed by “udder problems" and then "teeth condition". Similar common cull reasons were presented by Mekkawy et al. (2009), who also specified "udder condition" as the most common cull reason for younger Scottish Blackface mules and "teeth/mouth condition" for older ewes. "Barren" was not often reported (by Mekkawy et al., 2009) but this may have been a result of their culling protocol which allowed ewes to fail to conceive a lamb in two consecutive years prior to culling.

Previous research that reported common cull reasons (for example, Annett et al., 2011; Mekkawy et al., 2009) agreed with the most prevalent reasons provided by respondents in this questionnaire and also those that were considered the most important. Therefore the three cull reasons, of greatest interest for this thesis, are "failure to get pregnant" (or being barren), "poor mouth condition" and "poor udder condition". However, this does not mean that using these cull reasons will be successful at identifying unproductive ewes (meaning those that do not raise a lamb to weaning) within the flock.

"Failure to get pregnant" was seen as both an important cull reason (Q6) and occurred frequently within flocks (Q5). However research using culling ewe simulations based on non-conception concluded that culling based on first occurrence of non-conception is unlikely to be the most efficient management tool (Nugent and Jenkins, 1993). These authors suggested other factors that should be considered alongside non-conception, which included the ewes' genetic potential for reproduction and the current market value. The number of comments provided by respondents suggested that they were not making culling decisions based on one reason but considered many other factors. For example, for "failure to get pregnant" (Q5.12) comments provided in answer to "how many times" often included consideration of the ewe age as well, with younger ewes being given a second chance.

It appears logical that mouth condition should feature as an important culling reason. A ewe missing teeth will have problems to graze efficiently, resulting in loss of liveweight in late pregnancy and poor milk production culminating in poor growth rates of lambs (Sykes et al., 1974). However, there seemed to be no consistency in how many teeth lost constituted a poor mouth, with respondents often specifying a range in number of teeth lost. An in depth review of the association between incisors and performance in sheep was provided by McGregor (2011). Within the review, the author concluded that while longevity in sheep is reduced as a result of incisor wear and loss, culling practices that simply select ewes on a specific age, as an indicator of when incisor condition is likely to deteriorate, is inappropriate.

6.4.2 Culling decisions and age of ewes

It was initially surprising that a low number of respondents (only 41 %), selected age as a cull reason, as it is often stated that hill ewes are culled from the flock after their fourth or fifth crop of lambs (McGregor, 2011; Waterhouse, 1996). Moreover, livestock auction markets still hold annual sales of aged sound ewes, suggesting some ewes are still being culled based on age. One reason for the low response rate for “age” as a factor may have been because the term “cull” was associated by respondents to ewes no longer suitable for breeding whereas ewes that are sold on age may still be productive.

Interestingly, when narrowing the analysis to cover only respondents that reported selling sound ewes, 73 % of hill flocks selected “age” as a cull reason (compared to only 3 % of upland and lowland flocks combined). The remaining 27 % did not specify how they selected their sound ewes for sale. Irrespective of this, these sound ewes may still be sold during special sales for aged ewes and brought by upland flocks. Overall, 68 % of hill flock respondents said they either sold sound ewes (Q3) and/or culled on age (Q5.1), which far exceeded the proportion from upland (41 %) or lowland flocks (48 %).

Therefore it seems that (within hill flocks at least) age is still an important reason to cull ewes from a flock. Such a practice supports the stratified UK sheep industry, with older but still productive ewes moving from hill to upland or lowland systems (Pollott, 2012; Rodriguez-Ledesma et al., 2011; Waterhouse, 1999). Even though culling on age is seen as an economic decision (Fetrow et al., 2006; Groenendaal and Galligan, 2005; Monti et al., 1999; Richards et al., 2013), the practice could disadvantage the overall fitness of the hill flock. Flock fitness could be restricted by removing older ewes that are still productive and potentially of superior genetics (demonstrated by reaching an old age and not needing to be culled sooner), compared to younger ewe replacements with unknown performance potential. Moreover, it has been demonstrated that ewes can still be productive beyond a standard cull age of around six years old (Dickerson and Glimp, 1975; Notter, 2000; Qureshi et al., 1997; Sawalha et al., 2007). Greater consideration of ewe age and longevity associated with performance is carried out in Chapter 7.

There were 34 respondents (33 %) that appeared not to sell any “sound” or “unsound” ewes from the flock (Q3). However, all of these respondents selected multiple reasons to cull ewes (Q5). It could be that respondents forgot to report their ewe sales or that the wording of questions 3 and 5 was ambiguous. Question 3 asked “What are the main sheep being sold from the flock?” If respondents did not consider their ewe sales to be the “main” type of animals leaving the flock they may not have selected it. Furthermore, it could also be that while ewes were not “sold” from the flock, they may still have been culled “from the main breeding flock” (as worded in Question 5), and moved to a different flock or enterprise on the same farm. As a result, it was difficult to find out exactly what happened to ewes from these flocks.

6.4.3 Differences between flock types

The differences seen between flock types were as expected. More respondents from hill flocks stated they produced sound ewes and store lambs compared to those from upland and lowland flocks, more of which produced finished lambs. This is in agreement with what previous literature had reported was produced from each flock type (Kilgour et al., 2008; Waterhouse, 1999).

The breeds were also appropriate for the flock type reported; hill breeds (such as Scottish Blackface and Swaledale) were reported more often from respondents of hill flocks, and high productive breeds (such as Texels and Suffolks) from lowland flocks. Again this demonstrates that the stratified sheep industry (as described by Pollott, 2012; Rodriguez-Ledesma et al., 2011; Soffe, 2003) still exists. It is also interesting that, while there were a large number of pure-bred breeds represented from the different flocks, the Scottish Blackface was the most prevalent. This could be a result of the location in which some surveys were carried out. The NSA Highland Sheep (in Strathpeffer, Ross-shire) could have had farmers from a high proportion of farms with Scottish Blackface flocks. However, Scottish Blackfaces being so prevalent within the sampled farms is in agreement with a report that presented the breed structure in Britain, which found the Scottish Blackface to be the most prevalent pure-bred breed (making up 8.6 % of all ewes, or 1.3 million, in 2012, Pollott, 2012).

6.4.4 Decision making tools

There were very few respondents that used electronic technology to record and base culling decisions upon (Q8: “own PC recording system” selected by 18 % of respondents, “EID assisted” by 17 % and “farm management software” by 9 %). This is unsurprising given the low levels of stockpeople estimated to be using EID and associated technology to make management decisions within commercial sheep farms of England and Wales (as reported by Lima et al., 2018). Furthermore, only around half (47 %) of all respondents reported that they used any sort of records (paper or electronic) to inform culling decisions (where options selected were classified as “Records”). This reduced further when only hill flocks were considered (39 %).

As previously stated, culling a ewe that “failed to get pregnant” was the most selected culling reason (Q5). Given the low proportion of stockpeople using recording methods, it is likely that this decision to cull was made as a result of ultrasound scanning of ewes. This would occur where ewes were either being immediately separated for sale or marked (with colour spray or paint) so they were known later in the year (therefore providing “Physical marks/tags on ewe” to inform decision making).

The lack of more advanced recording equipment could be the reason why culling according to EBVs was not reported more highly. Indeed, for the cull reason of “ewe had a live lamb but failed to raise to weaning” one respondent, who did not cull for this reason, provided the comment of “do not know who they are”. Had EID based recording been used (to identify ewes to their lambs at lambing time and then identifying which lambs were present at weaning), this information could have been available. Richards et al. (2012) suggested that identifying and culling individual ewes which were unproductive, instead of by age, was one potential application of a Precision Sheep Management approach (which is analogous to PLF). Therefore if PLF tools could be utilised to collect ewe information during the year, this could result in different cull reasons being used. The following chapters will aim to explore what these different culling reasons may be.

6.5 Conclusions

Within the UK sheep industry there is a wide range of culling reasons used by individual stockpeople to remove ewes from the breeding flock. The most common cull reasons included those that related to reproduction ability and physical condition of the mouth and udder. Culling ewes on age was more prevalent in hill flocks, when sound ewes were sold from the flock. This is an economic decision associated with the stratification of the sheep industry. However, removing sound ewes at a specific age may disadvantage the flock by not retaining within it those genetically superior animals. The impacts of retaining these older ewes within the flock will be explored in the following chapter.

Decisions to cull ewes were mainly made from information immediately available to the stockperson such as: the appearance of the ewe, remembering ewe performance, and visual marks or tags on the ewe. Fewer hill flocks used records to base culling decisions on, compared to both other flock types. This provides justification for exploring a PLF approach for making retention and culling decisions as currently informed decision making does not occur.

This chapter has provided evidence for many attributes that are currently used to make retention and culling decisions. These attributes will be explored in the following chapters, by comparing their relationships to future performance and considering whether they should be used to inform retention and culling decisions.

CHAPTER 7: RELATIONSHIPS BETWEEN EWE AGE CULLING PROTOCOLS AND EWE PERFORMANCE, FLOCK STRUCTURE, FINANCIAL OUTCOMES, AND LONGEVITY

The previous chapter demonstrated that there are many reasons why ewes are culled from a flock. Several reasons were subjective and it is uncertain how effective these reasons are at identifying and removing unproductive ewes from the flock. Developing a PLF approach to identify ewes which will be productive the following year and thereby inform culling decisions will be discussed in later chapters. However, one culling reason given by a high proportion of respondents, for hill sheep systems, was culling at a fixed age. Therefore, this chapter aims to understand the relationship of ewe age with performance, flock structure, financial outcomes and longevity. Findings will inform whether age should be considered in the development of a PLF retention and culling approach.

7.1 Introduction

7.1.1 Culling on age

Culling ewes from the breeding flock at a fixed age is a practice that has been reported to occur in sheep systems within the UK and around the world (Annett et al., 2010; Hickey, 1960; Kilgour et al., 2008; McGregor, 2011; Waterhouse, 1999). The typical age to cull ewes from Scottish hill sheep systems is 5.5 to 6.5 years old, after their fourth or fifth crop of lambs (Kilgour et al., 2008; McGregor, 2011; Rodriguez-Ledesma et al., 2011; Waterhouse, 1999). Indeed, results from Chapter 6 showed that this practice still happens.

Culling on age occurs for two main reasons; firstly it is considered an "economic" cull reason (as discussed in Chapter 6 and by Fetrow et al., 2006). As a result of the stratified nature of the UK sheep industry, there is a market demand for aged sound hill ewes (often referred to as "draft" ewes) from upland sheep systems in order to breed from (Rodriguez-Ledesma et al., 2011; Waterhouse, 1999).

Secondly, culling on age is believed to remove older ewes from the flock before their health and fertility deteriorate, to the point where their welfare and productivity are impaired, both of which disadvantaging the sheep system (as discussed by Hickey, 1960; McGregor, 2011). However, expected performance of an older ewe also needs to be considered against the expected performance of a younger replacement ewe, if the former were to be culled.

7.1.2 Culling and longevity

Conversely, culling on age means that longevity of ewes is restricted. Restricting longevity is important to consider given the advantages that increased longevity can provide. In order to discuss these advantages it is first useful to understand what the term "longevity" means. While there is a large amount of literature on longevity in cattle (but less so for sheep), there seems to be little consistency in the terminology surrounding it. For example "length of productive life", is often used as a measure of longevity (for example, Getachew et al., 2015; Kern et al., 2010; Mekkawy et al., 2009; Vollema and Groen, 1998), meaning the time from the first lambing to death (Ducrocq, 1994). However, this has also been called "herd life" (Vollema and Groen, 1998), "number of parities" (Essl, 1998), or "productive longevity" (Abdelqader et al., 2012). "Productive life" has also been used by Borg et al. (2009a) as a measure of longevity and is described as: the age of the ewe in years at her last lambing.

Sometimes “longevity” and “lifetime performance” are used for different things, for example: “…*which could benefit their longevity and lifetime performance*” (Annett et al., 2011), while Mekkawy et al. (2009) used them interchangeably: “*Longevity, or length of productive life of a ewe, is a trait*…”

The terms “true longevity” and “functional longevity” have also been used (Ducrocq, 1994; López de Maturana et al., 2007). “Functional longevity” means the ability to delay culling for reasons such as sterility, lameness, mastitis or other diseases (Berry et al., 2005; Ducrocq, 1994; López de Maturana et al., 2007), and ”true longevity” meaning “*longevity as actually observed, i.e. mainly dependent on productivity*” (according to Ducrocq, 1994).

The wide range of terms used have often been in relation to dairy cattle, highlighting that a lot of previous longevity and culling research was concerned with dairy systems. In this thesis the term “longevity” will be used to describe the length of a ewe’s life within the primary breeding flock, ending when the animal either dies or is culled (therefore leaving the flock).

7.1.3 Importance of longevity

Increased longevity has been reported as having three important positive impacts to the livestock system, in terms of: productivity (Annett et al., 2011, 2010; Borg et al., 2009a; Mekkawy et al., 2009), profitability (Essl, 1998; Kilgour et al., 2008; McGregor, 2011) and environmental impact (Beauchemin et al., 2011; Jones et al., 2013; Nguyen et al., 2013).

Firstly, longevity can be an indicator of biological fitness and of genetic superiority, therefore, retaining ewes with greater longevity has the potential to improve fitness of the whole flock overtime (Annett et al., 2011; Borg et al., 2009b; Kelleher et al., 2015; Mekkawy et al., 2009; Nugent and Jenkins, 1993).

Moreover, research suggests that peak age of productivity in ewes may actually be older than a typical cull age of 5.5 or 6.5 years old (Dickerson and Glimp, 1975; McGregor, 2011; Mullaney and Brown, 1969; Notter, 2000). However, differences between ages and performance are known to vary between breeds (Annett et al., 2011; Dickerson and Glimp, 1975; Kern et al., 2010; Notter, 2000). Only two papers found focused on performance of Scottish Blackface ewes at different ages (Annett et al., 2011, 2010). Although, while Annett’s group used a large dataset across a number of farms, the oldest ewes included were only 5.5 years old at mating. The data collected was also on commercial farms that had their own culling protocols. Aside from these studies, no data has been published on the productivity of Scottish Blackface ewes beyond the cull age of 5.5 or 6.5 years old. Therefore, it is uncertain as to what extent Scottish Blackface ewes could be productive beyond this age.

The second reported advantage of increased longevity is the impact on replacement management and associated finances (Essl, 1998; Kilgour et al., 2008; McGregor, 2011; Waterhouse, 1999). Within hill sheep systems, young hill ewes (known as "replacements") typically join the main breeding flock at the age of 1.5 years old, and have their first lamb aged two. Therefore after being weaned at around 4 months old, these replacements are unproductive animals on the farm for over a year (not producing any lambs, Kilgour et al., 2008; Waterhouse, 1999). They still, however, require resource inputs including feed and medicine, and compete with productive ewes for grazing resources. Typically these replacements are "off-wintered", meaning they spend their first winter on another farm, on higher quality grazing than the hill farm. If they remain on farm they may instead be housed and/or provided with supplementary feed, potentially increasing costs. Providing correct nutrition during this first winter is important as it can impact on performance throughout the rest of the replacement's productive life (Gunn, 1977).

If ewes remain in the breeding flock for longer, fewer replacements are needed. This allows for more lambs to be sold and reduces the costs of managing replacements, all of which has financial benefits that are not realised if ewes are culled on age (as discussed by Essl, 1998 for dairy cattle and McGregor, 2011 in relation to sheep). To the author's knowledge, the level of financial gain from not culling on age, and so retaining ewes longer, has not previously been reported.

Thirdly, increasing longevity has been associated with reduced environmental impact, and therefore improved sustainability of the system (EBLEX, 2009). This is largely due to a more productive system with fewer unproductive replacement animals within the flock, therefore reducing the amount of Greenhouse Gas emissions per kilogram of meat produced. However, although literature has reported that improving flock longevity would be an effective tool in Greenhouse Gas mitigation; farmers believe it is impractical to achieve (Jones et al., 2013). Furthermore, at farm level, Greenhouse Gas models for cattle showed limited positive impacts on emissions when increasing longevity (Beauchemin et al., 2011; Nguyen et al., 2013). No similar research could be found for sheep. While the issue of longevity and environmental impact is worth noting, it is beyond the scope of this chapter and so will not be considered further.

7.1.4 Methods to improve longevity

If culling on age is restricting longevity, the advantages of increased longevity may not be realised. Potential methods to improve longevity are consequently important to consider. Increasing longevity of ewes could be done by two methods: 1) by considering the animal, through genetic analysis and selection; and 2) by considering the management, through retention and culling decisions.

The first of these approaches tries to find genetic indicators of ewes with increased longevity (for example, Borg et al., 2009a; Mekkawy et al., 2009; Sewalem et al., 2008). However, genetically identifying the longevity traits is proving challenging, due to the huge number of factors that can impact on longevity. Literature has reported that longevity is a low to medium heritable trait (Borg et al., 2009a; Mekkawy et al., 2009). Mekkawy et al. (2009) found moderate heritability of longevity at 0.27 which may have been a result of closely controlled experimental farms and through the use of cross-bred mules. Likewise, the analogous measure of "stayability", as used by Borg et al. (2009a), found heritability was estimated at only 0.00 to 0.09.

The alternative approach for increasing longevity is to alter management through changing culling and retention protocols. To date, there is no literature documenting what impact occurs when culling on age in hill sheep systems is stopped.

It is known that longevity and survival in sheep are affected by many factors, including breed (Annett et al., 2011; Dickerson and Glimp, 1975; Kern et al., 2010; Notter, 2000), number of lambings (Abdelqader et al., 2012; Kern et al., 2010), lambing interval (Abdelqader et al., 2012), age (Abdelqader et al., 2012; Annett et al., 2011), age at first lambing (Kern et al., 2010), body condition (Annett et al., 2011; Morgan-Davies et al., 2008), flock or farm (Abdelqader et al., 2012; Kern et al., 2010), and type of lambing (Abdelqader et al., 2012). It is therefore unlikely that all ewes reach the end of their productive life at the same age. This variation between ewes' individual longevity potential makes retention and culling decision making a likely candidate for a PLF approach (as suggested by Richards et al., 2012). This application will be considered in Chapters 8 and 9.

7.1.5 Aims of chapter

The purpose of this chapter is to provide an account of the possibility and implications of increasing Scottish Blackface ewes' longevity within a hill sheep system, where the flock had previously been culled at a fixed age. This will provide insight into whether culling on age is a benefit or a limitation for hill sheep systems. The results will also inform whether culling on age should be considered when developing a PLF approach for retention and culling decision making (Chapter 9).

The four aims of this chapter are:

1) To present the relationships between ewe age and survival and productivity, in a flock where culling at a fixed age was stopped.
2) To compare the performance between ewes that survived different amount of years within the breeding flock, for a single cohort of ewes all born in the same year.
3) To explore how altering age culling rules may impact on flock structure and longevity.
4) To present the financial implications between a flock with a fixed cull age to a flock without a fixed cull age.

7.2 Materials and Methods

7.2.1 Flock culling protocol

Within the research flock (described in Chapter 3), Scottish Blackface ewes, in the PLF approach, were culled (removed from the breeding flock) according to a list of pre-defined culling reasons (the culling protocol, Table 7.1). The culling protocol was established to identify ewes which were either no longer productive or were at a higher welfare risk if retained. All final decisions to cull ewes were made by the same stockperson (the Flock Manager) for all data presented in this thesis.

Table 7.1 Ewe culling protocol applied to the research flock.

Cull reason	Number of occurrences before cull	Time point when culled from the flock
Diseased or physical injury which impedes mobility and/or would jeopardise the highest standards of animal welfare	Once	As soon as possible after identification
Below Body Condition Score 2 at mating, with the anticipation that the ewe may not survive the winter without severe hardship	Once	Prior to mating (November)
Ultrasound pregnancy scanned not in lamb	Twice	After pregnancy scanning (February) or at stockdraw
Ultrasound pregnancy scanned in lamb but then failed to lamb	Twice	At stockdraw
Lambing prolapse (vaginal or uterine)	Once	At stockdraw
Knowingly aborted or had stillborn lambs	Twice	At stockdraw
Required any assistance to lamb	Twice	At stockdraw
Rejected own lamb	Twice	At stockdraw
Mastitis (any severity)	Once	At stockdraw
Less than four fixed incisors in the centre of the mouth (“broken mouth”)	Once	At stockdraw
Incisors are forward (overshot) or back (undershot) from the dental pad	Once	At stockdraw

The culling protocol originally included culling on age where any ewe aged over 5.5 years old was culled at stockdraw. The 2011 production year (referred to here as year 1, ran from November 2011 to October 2012) was the first year where culling on age did not occur at the end of the year. From stockdraw 2012 onwards, ewes remained in the flock as long as they did not meet any cull reason outlined in Table 7.1, irrespective of age. As a result, the flock age structure changed from four breeding ewe age groups in year 1 (at mating in 2011) to six breeding ewe age groups by year 4 (2014, Table 7.2). A total of 506 individual ewes appeared across these four years, they moved into the next age group the following production year (starting in November) if they survived and did not require culling.

To address the four aims of this chapter, five different sections of work were required. Each used different datasets, the details of which are shown in Table 7.3.

Table 7.2 Counts of ewes in each age group at mating (in November) across four years, when culling at 5.5 years old was stopped at the end of year 1 (percentage of flock in brackets).

Age group at mating (in years)	**Production year**			
	Year 1, 2011	**Year 2, 2012**	**Year 3, 2013**	**Year 4, 2014**
1.5	88 (31.0)	66 (23.2)	76 (26.9)	79 (27.5)
2.5	80 (28.3)	81 (28.5)	58 (20.5)	68 (23.7)
3.5	69 (24.4)	71 (25)	73 (25.8)	52 (18.1)
4.5	46 (16.3)	49 (17.3)	54 (19.1)	50 (17.4)
5.5	0 (0)	17 (6)	18 (6.4)	29 (10.1)
6.5	0 (0)	0 (0)	4 (1.4)	8 (2.8)
7.5	0 (0)	0 (0)	0 (0)	1 (0.3)
Total count:	283	284	283	287

Table 7.3 Data used for each of the four sections of work within this chapter.

Section	**Data used**
1: Performance and ewe age	Research flock data from production year 4 (November 2014 to October 2015).
2: Longevity and performance within age cohort	Research flock data (November 2010 to August 2015) of one age cohort of ewes (born in 2009).
3: Actual flock structure and cull age change	Research flock data from production years 1 (November 2011 to October 2012) and 4 (November 2014 to October 2015).
4: Modelled flock structure and cull age change	Modelled dataset based on research flock data from years 1 (November 2011 to October 2012) and 4 (November 2014 to October 2015)
5: Financial implications of a changed flock structure	Two modelled flocks (one with a cull age and one without) based on data from production year 4 (November 2014 to October 2015).

7.2.2 SECTION 1: Performance and ewe age

To consider the relationship between performance and ewe age, performance values were compared between different age groups within production year 4. Ewes with unreliable or incorrect data through the year were removed from the dataset, leaving records for 274 ewes. Using multiple years' worth of data was rejected as ewes appeared across several years and one year's performance data may not be independent from the following or previous year.

To have sufficient numbers within each age group for comparison and statistical analysis, age groups "5.5", "6.5" and "7.5" were combined to form a single age group of "5.5 and over".

Performance values of ewes compared between age groups included: survival; number of lambs pregnancy scanned, born and weaned; liveweight of lambs weaned; liveweight; BCS; number of individual antibiotic health treatments; and amount of supplementary feeding provided over pregnancy.

Ewe survival was recorded at weaning and after stockdraw. "Survived to weaning" referred to ewes which did not die or go missing from mating (in November) to the following weaning (in August). "Survived stockdraw" referred to ewes which were not culled at the end of the production year and so remained in the main breeding flock for the following production year.

The amount of supplementary feed provided was only considered over pregnancy (post-mating in January to pre-lambing in April) because levels of feed were more standardised across the flock for the rest of the year. An approach similar to that explained in Chapter 5 was used to allocate ewes to supplementation level. Individual feed was calculated from total feed provided to the group, presuming all individuals consumed equal amounts.

Where appropriate, ANOVA and Chi-squared tests were carried out in R (R Core Team, 2018) to determine whether production values between age groups were significantly different. For continuous variables, where a significant difference was found between groups, Tukey's Honest Significant Difference (HSD) was used for multiple pairwise-comparisons between group means, to determine where statistically significant differences occurred (Petrie and Watson, 2013).

7.2.3 SECTION 2: Longevity and performance within age cohort

There was potential for a large survival bias (meaning only considering the ewes that survived and ignoring those that did not) associated with data from ewes in the older age groups. A dataset was compiled to explore whether ewes that survived within the flock to older ages were different to others in their age cohort (meaning ewes all born in the same year) that did not survive in the flock as long. Lifetime performance data was compiled from ewes that were born in 2009 (this is the age cohort for ewes in age group 5.5 in production year 4, 2014 data). All ewes first joined the breeding flock in November 2010 (their first breeding year, aged 1.5 years old) and had the potential to have their first lamb in April 2011. Ewes survived in the flock if they did not die and were not culled. Data for this cohort of ewes were considered over five production years (from November 2010 to October 2015). Ewes within this age cohort were classified according to the number of years they survived in the breeding flock. Lifetime performance data (liveweights, BCSs, number of lambs weaned and total liveweight of lambs weaned) across the five production years were compared between ewes who survived different amount of years within the breeding flock.

Statistical analysis using ANOVAs and Chi-squared tests were carried out in a similar manner to that described in SECTION 1.

7.2.4 SECTION 3: Actual flock structure and cull age change

To consider how flock structure had altered by removal of a cull age, the distributions of ewes across ages within the flock were compared between production year 1 (2011 data) and year 4 (2014 data).

7.2.5 SECTION 4: Modelled flock structure and cull age change

Modelled data was used to consider the longer term implications on flock structure when the age at which ewes were culled from the flock was extended, and when percentage of loss from each age group remained constant between production years.

7.2.5.1 Determining a stable flock structure

To explore this, while limiting other factors that could confound results, a stable flock structure of a four age group flock was required. A “stable flock structure” meant that the distribution of the flock across each age group was the same from one production year to the next, after the percentage of loss had been removed.

However, distribution of the flock across age groups within a single production year differed. "Percentage of loss" meant the percentage of an age group that would not join the next age group in the following production year, as a result of death (including missing presumed dead) and culling.

To create a stable flock structure, the actual distribution of the research flock across four age groups in production year 1 (2011 data), was initially used. Actual percentage of loss from this data was also used to identify the percentage of each age group that would not join the next age group of the next production year. These values were then calculated over a number of iterations until the flock structure became stable, which occurred in the 53rd iteration (Table 7.4). Each iteration represented a single production year. The only percentage of loss value used not calculated from the actual data was for age group 4.5 years old at mating. This age groups' percentage of loss was set to 100 %, in order to mimic a four age group flock. Apart from iteration 1, the percentage of the flock that was in age group 1.5 years old was calculated as the difference between the total of all three other age groups from 100.

Table 7.4 Percentage of each age group calculated over different iterations until flock structure became stable. The percentage of loss assigned to each age group when they move into the next age group of the following iteration, is also shown.

		Age group at mating (in years)			
		1.5[a]	**2.5**	**3.5**	**4.5**
Percentage of loss assigned to each age group (%)		4.5	11.3	15.3	100
Iteration	1	31.0	28.3	24.4	16.3
	2	24.6	29.6	25.1	20.7
	3	29.0	23.5	26.3	21.3
	4	29.2	27.7	20.9	22.2
	5	29.9	27.9	24.5	17.7
	…				
	53	28.4	27.1	24.1	20.4
	54	28.4	27.1	24.1	20.4
	55	28.4	27.1	24.1	20.4

Iteration 1 and the percentage of loss assigned to each age group were actual values of the research flock recorded in production year 1 (2011 data, apart from age group 4.5 which was set to 100 % loss of age group).
[a]Apart from iteration 1 (where actual year 1, 2011, data was used), values for age group 1.5 were calculated as the amount required to make the percentage across all age groups equal 100.

7.2.5.2 Modelling a change in cull age

The resulting stable flock structure was then used, as the distribution across age groups, for the starting flock in run 1 of a model to determine how structure would alter when age at which ewes were culled changed. Each run represented a single production year. For this model the percentage of loss used for age groups 1.5 to 3.5 were the actual percentage loss recorded in production year 1 (2011 data). For 4.5 to 6.5 age groups the actual percentage loss recorded in production year 4 (2014 data) were used (Table 7.5). A loss of 100 % was set for age group 4.5 in the first three runs (years) of the model and then for age group 7.5. The age group at which all ewes were culled from the flock changed in run (year) 3 of the model from 4.5 to 7.5 years old. A maximum age of 7.5 years old was used as this was the oldest age in production year 4 (2014 data) and so no actual percentage of loss amounts were available.

From this model, the percentage of the flock aged “5.5 and over” at mating and the number of replacements (aged 1.5 entering the breeding flock for the first time) were compared across advancing runs (years) of the model.

7.2.6 SECTION 5: Financial implications of a changed flock structure

Using production year 4 (2014) data, two flocks of 100 ewes each were modelled: 1) a “4 age group” flock, which used data just from ewes aged 1.5 to 4.5 years old at mating; and 2) a “no age limit” flock, which used data from the entire flock (aged 1.5 to 7.5 years old at mating). Production values were calculated for both flocks and monetary values (in Table 7.6) were used to generate financial margins at a flock level. Sensitivity analysis was carried out on the incoming and outgoing values, as well as on the numbers of animals produced and sold by each flock.

Actual flock production values (from 2014 data) were used where possible. However, the numbers of male and female lambs weaned were calculated simply as half the total number of lambs weaned per flock (which was rounded up to an even number to allow for an even split between both sexes).

The number of replacements was calculated as the number of animals required to keep the total number of ewes in the flock the same (meaning at 100). As such, it was the same amount as the total number of ewes that left the flock during the year.

Table 7.5 Percentage of loss (to mimic deaths and culls) for each age group applied for each model run. The distribution of the flock in run 1 of the model is also shown.

	Age group at mating (in years)						
	1.5[a]	**2.5[a]**	**3.5[a]**	**4.5[b]**	**5.5[b]**	**6.5[b]**	**7.5**
Distribution of the flock in run 1 of model (% of flock)[c]	28.4	27.1	24.1	20.4			
Run[d] of model 1	4.5	11.3	15.3	100	NA	NA	NA
2	↓	↓	↓	↓			
3	↓	↓	↓				
4	↓	↓	↓	55.6	59.3	NA	NA
5	↓	↓	↓	↓	↓	62.5	NA
6	↓	↓	↓	↓	↓	↓	100
7	↓	↓	↓	↓	↓	↓	↓
8	↓	↓	↓	↓	↓	↓	↓
9	↓	↓	↓	↓	↓	↓	↓
10	↓	↓	↓	↓	↓	↓	↓
11	↓	↓	↓	↓	↓	↓	↓
12	↓	↓	↓	↓	↓	↓	↓
13	↓	↓	↓	↓	↓	↓	↓
14	↓	↓	↓	↓	↓	↓	↓
15	↓	↓	↓	↓	↓	↓	↓
16	↓	↓	↓	↓	↓	↓	↓

[a]Percentage of loss used for age groups 1.5 to 3.5 are the actual percentage loss recorded in production year 1 (2011 data);
[b]Percentage of loss used for age groups 4.5 to 6.5 are actual percentage loss recorded in production year 4 (2014 data);
[c]flock distribution in run 1 of the model is stable flock structure calculated in section 7.2.5.1;
[d]Each run of the model represented a single production year.

Table 7.6 Monetary values used to compare margins of two different flocks with different age structures.

	Value	Details
Income		
Unsound ewe sale price	£ 32.78	per ewe[a]
Sound ewe sale price	£ 68.00	per ewe[b]
Male store lamb sale price	£ 45.00	per lamb[b]
Ewe lamb sale price	£ 74.00	per lamb[b]
Outgoing		
Cost to remove dead	£ 22.20	per ewe[cd]
Supplementation	£ 0.22	per kg of feed[b]
Antibiotic treatment cost	£ 1.50	per treatment[c]
Replacement management cost	£ 18.02	per lamb[b]

[a]average actual amounts received by SRUC Kirkton Farm for sale of Scottish Blackface ewes sold at United Auctions Stirling in September and October in 2014, 2015 and 2016;
[b]values taken from SAC Farm Management Handbook 2016/17;
[c]values are actual amounts paid closest to 2nd December 2016 by SRUC Kirkton Farm;
[d]cost of ewe deaths derives from the carcass requiring collection by the knackery.

7.3 Results

7.3.1 SECTION 1: Performance and ewe age

Counts of ewes that “survived to weaning” were similar across all ages (Figure 7.1, P=0.13) however “survived stockdraw” was significantly associated with age (P<0.001), decreasing as age increased. Over half (61 %) of the “5.5 and over” age group were culled at stockdraw, compared to just 4 % of 1.5 years old group. Across all ages, the flocks mortality rate was 5 % (did not survive to weaning): 8 were found dead and 6 were missing presumed dead. A total of 60 ewes were culled from the flock for 5 reasons from the culling protocol (Table 7.7).

In all age groups, the number of lambs per 100 ewes decreased, from those ultrasound scanned (in February), born (in April), and weaned (in August, Figure 7.2). Out of the ewes that were scanned in lamb, those “5.5 and over” carried more multiple lambs (63.6 %) compared to all other age groups combined (56.5 %, P<0.05).

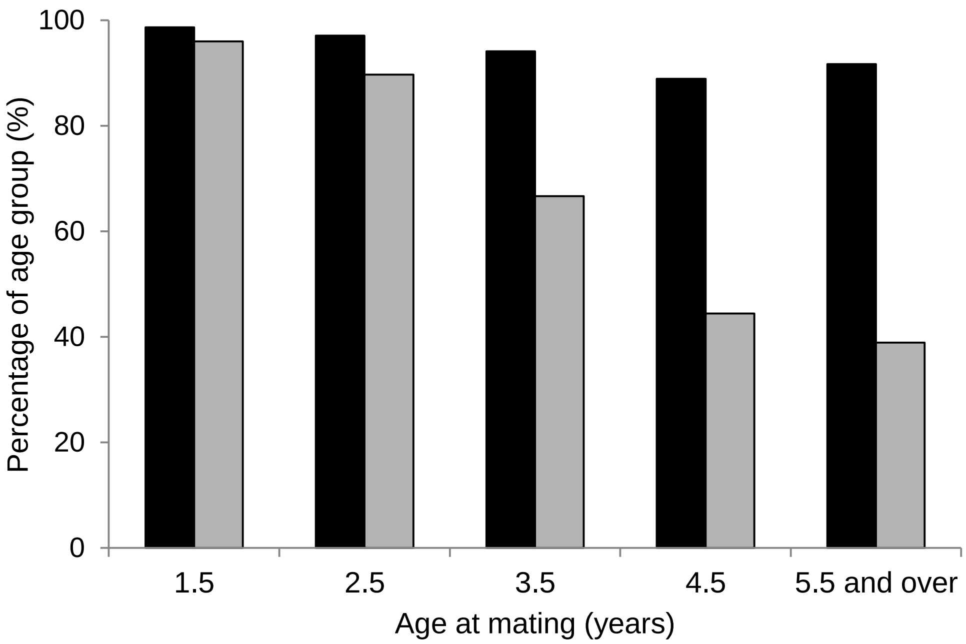


Figure 7.1 Ewe survival in different age groups for: “survived to weaning” (occurring in August, black) for ewes which did not die or go missing (presumed dead) over the production year; and “survived stockdraw” (carried out between August and October, grey) for those that did not meet any predefined culling rules and were retained within the flock.

Table 7.7 Reasons why ewes, from different age groups were culled from the flock (shown as counts of ewes, with percentage of total age group in brackets).

	Age at mating (years)				
	1.5	**2.5**	**3.5**	**4.5**	**5.5 and over**
Diseased or physical injury which impedes mobility and/or would jeopardise the highest standards of animal welfare	2 (2.7)	1 (1.5)	0 (0)	0 (0)	0 (0)
Ultrasound pregnancy scanned not in lamb (twice)	0 (0)	3 (4.4)	2 (3.9)	1 (2.2)	0 (0)
Mastitis (any severity)	0 (0)	1 (1.5)	1 (2)	1 (2.2)	2 (5.6)
Does not have a minimum of four fixed incisors in the centre of the mouth	0 (0)	0 (0)	8 (15.7)	17 (37.8)	13 (36.1)
Incisors forward (overshot) or back (undershot) from the dental pad	0 (0)	0 (0)	3 (5.9)	1 (2.2)	4 (11.1)

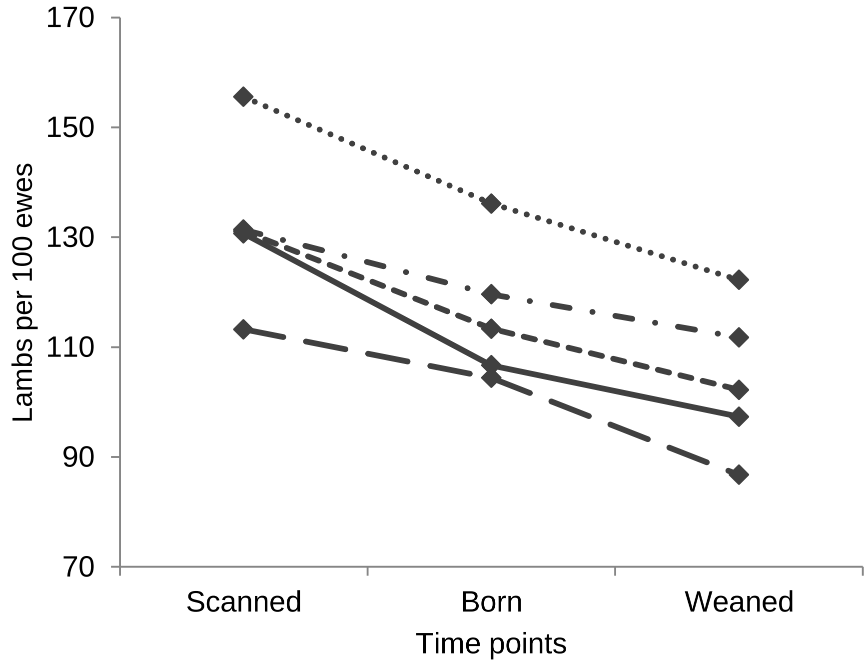


Figure 7.2 Number of lambs pregnancy scanned (by ultrasound in February), born (in April) and weaned (in August) per 100 ewes, for ewe age groups: 1.5 (—◆—), 2.5 (—◆ –), 3.5 (– ◆ –), 4.5 (- -◆- -) and 5.5 and over (···◆··) years old at mating.

There was no difference in counts between litter size and age group (when “5.5 and over” was compared to all other age groups combined) for lambs born (*P*=0.06) and lambs weaned (*P*=0.15). The percentage of ewes without lambs was slightly lower (but not significantly so) for the “5.5 and over” age group when compared to all other age groups combined; for scanning (8.3 % for “5.5 and over” compared to 12.6 % for rest, *P*=0.47), born (13.9 % compared to 19.7 %, *P*=0.41) and weaned (19.4 % compared to 26.8 %, *P*=0.35).

Average liveweight of lambs weaned and total liveweight of lamb weaned was unaffected by age group (*P*=0.18, Figure 7.3 and *P*=0.07 Figure 7.4, respectively).

Ewe liveweight increased as age increased (Figure 7.5, *P*<0.001). The 1.5 and 2.5 year old ewes had significantly lower liveweights than the 3.5, 4.5 and “5.5 and over” year old ewes (*P*<0.001). There was no significant difference between liveweights at the two handling points (at pre-mating compared to weaning).

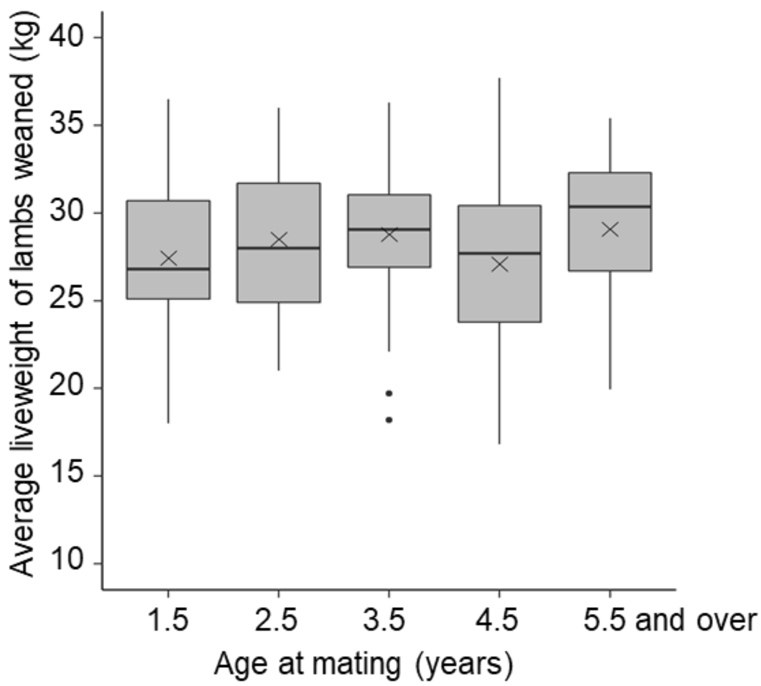


Figure 7.3 Average liveweight of lambs weaned for different age groups of ewes. Boxplot where: box shows median, upper quartile and lower quartile; whiskers shows range of liveweights; dots shows outliers; and cross shows the mean.

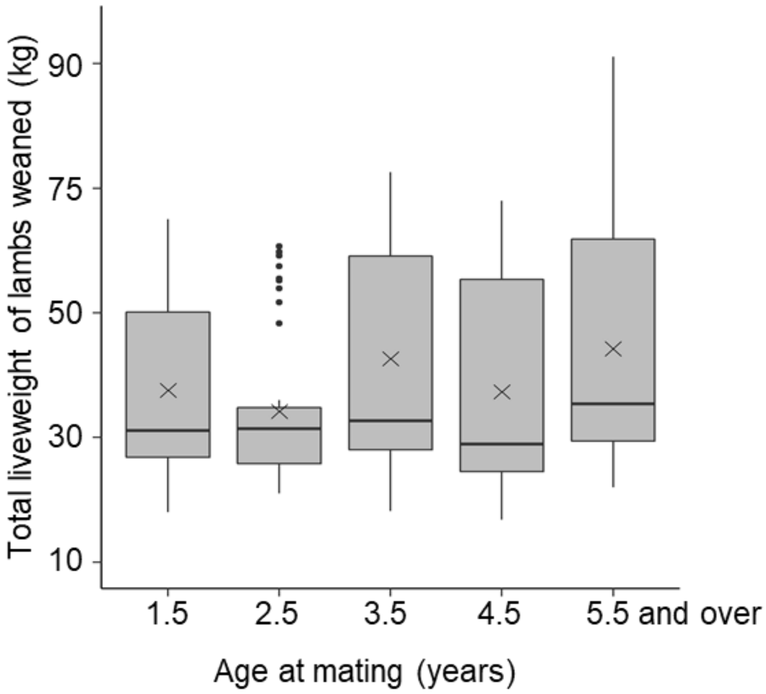


Figure 7.4 Total liveweight of lambs weaned per ewe for different ewe age groups. Boxplot where: box shows median, upper quartile and lower quartile; whiskers shows range of liveweights; dots shows outliers; and cross shows the mean.

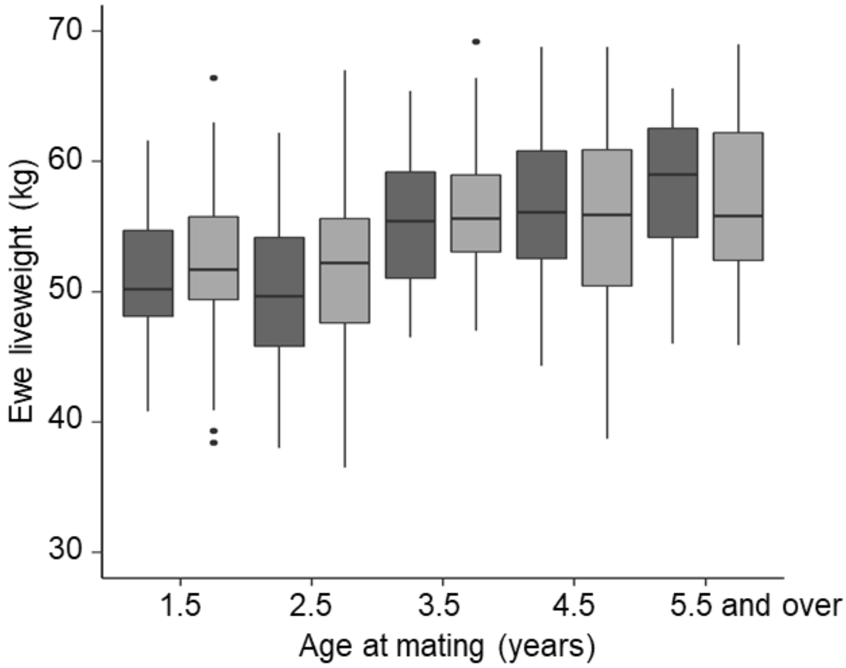


Figure 7.5 Average liveweight of ewes in different age groups at pre-mating (in November, dark grey) and at the following weaning (in August, light grey). Boxplot where: box shows median, upper quartile and lower quartile; whiskers shows range of liveweights; dots shows outliers; and cross shows the mean.

The distribution of ewes between age and BCS at pre-mating was significantly different (*P*<0.001) but not for BCS at weaning (*P*=0.2, Figure 7.6). At pre-mating, 1.5 year old ewes had the highest BCS, while the other age groups were similar.

Out of all the ewes, 7 % required at least one individual antibiotic treatment throughout the year. As age increased so did the percentage of age group to be treated (Figure 7.7), although counts were very low and the difference was not significant (*P*=0.26).

There was a significant difference in the average amount of supplementation provided over pregnancy (post-mating in January to pre-lambing in April) per ewe, between the 1.5 and 2.5 year old ewes (*P*<0.01), but not between any other age groups (Figure 7.8).

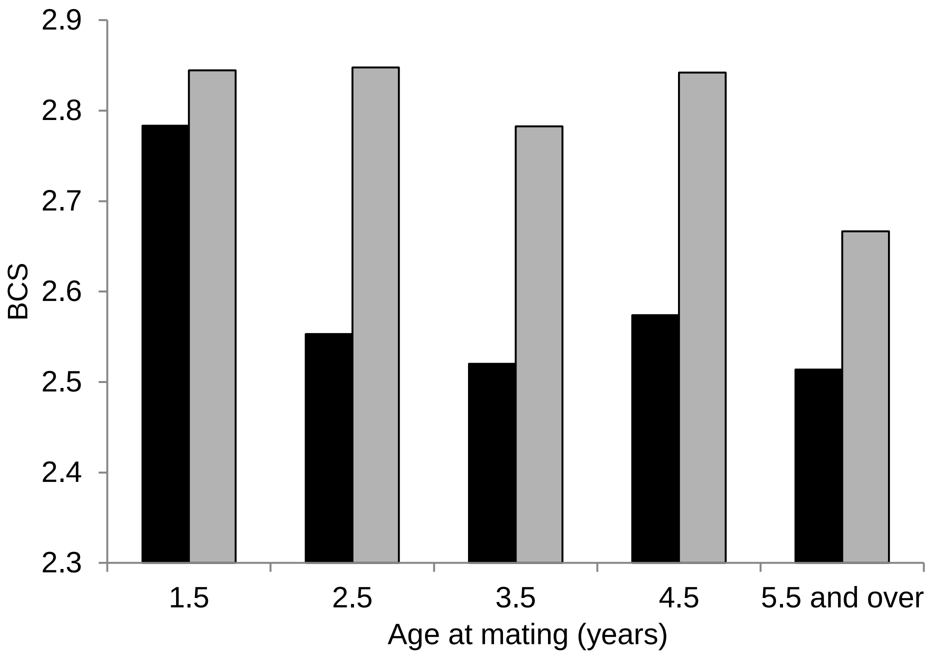


Figure 7.6 Average Body Condition Score (BCS) of ewes in different age groups at pre-mating (in November, black) and at the following weaning (in August, grey).

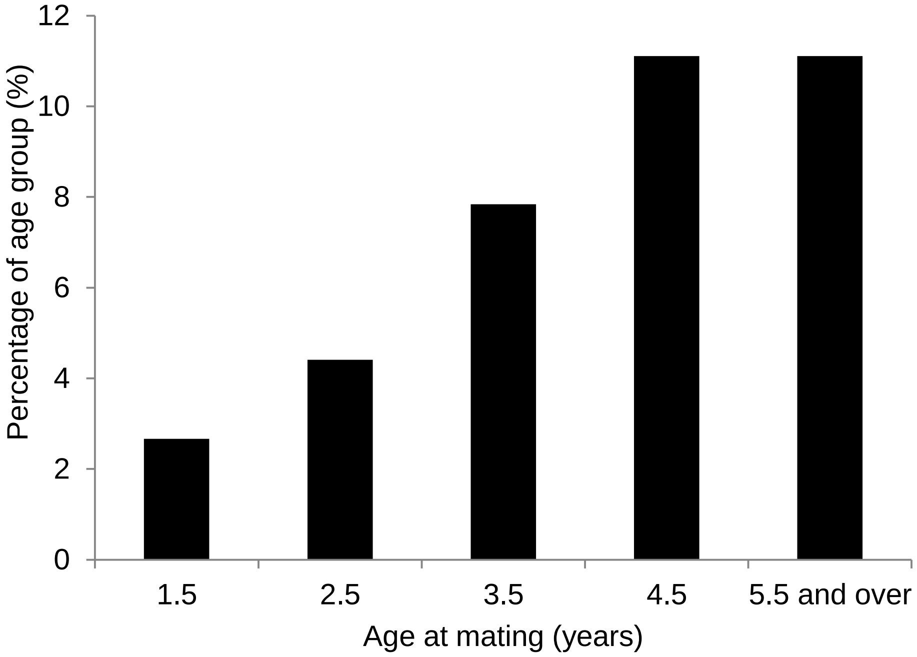


Figure 7.7 Percentage of age group that received 1 or more individual antibiotic treatment through the production year.

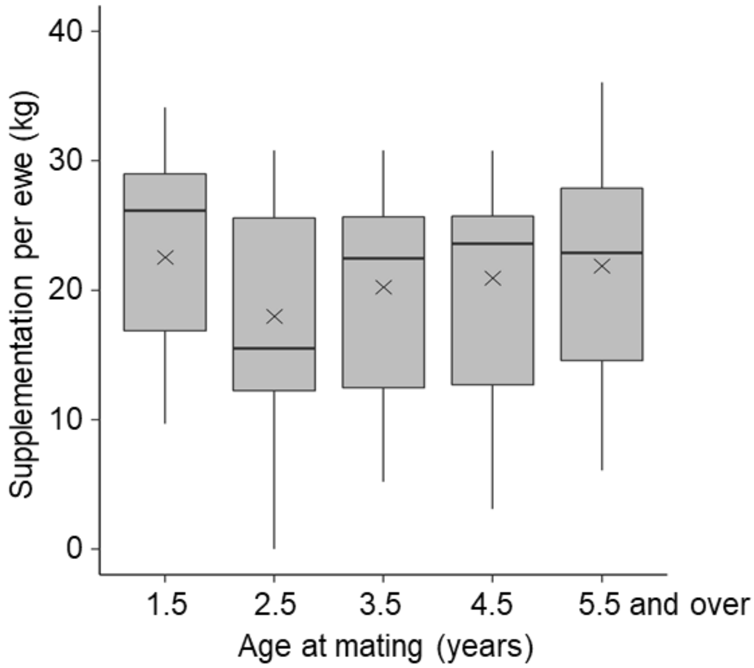


Figure 7.8 Average supplementation provided per ewe between post-mating (in January) and pre-lambing (in April), for different age groups of ewes. Boxplot where: box shows median, upper quartile and lower quartile; whiskers shows range of liveweights; dots shows outliers; and cross shows the mean.

7.3.2 SECTION 2: Longevity and performance within age cohort

From the range of performance values considered within the 2009 born cohort of ewes, only number of lambs weaned per 100 ewes and total liveweight of lambs weaned had a significant relationship between ewes that survived different amount of years within the breeding flock for some production years (Table 7.8).

Table 7.8 Performance values across five years of production (2010 to 2014) for ewes that survived different amount of years within the breeding flock, where all ewes were from the same single age cohort (born in 2009).

		Years survived in breeding flock				
		1	2	3	4	5
1st production year, 2010	Pre-mating liveweight	46.58	46.63	47.00	46.76	46.05
	Pre-mating BCS	2.88	2.93	2.88	2.90	2.91
	Lambs weaned per 100 ewes**	30.77	95.83	111.54	85.37	100.00
	Total liveweight of lambs weaned**	8.08[a]	24.37[ab]	31.79[b]	22.86[b]	26.85[b]
	Weaning liveweight	49.83	53.75	52.23	52.99	51.28
	Weaning BCS	2.67	2.94	2.83	2.87	2.89
2nd production, year, 2011	Pre-mating liveweight		52.50	50.58	51.51	51.22
	Pre-mating BCS		2.87	2.80	2.81	2.81
	Lambs weaned per 100 ewes %*		69.57	111.54	118.99	96.55
	Total liveweight of lambs weaned**		14.24[a]	32.00[b]	31.44[b]	26.86[ab]
	Weaning liveweight		53.75	52.64	51.68	52.60
	Weaning BCS		2.73	2.80	2.75	2.85
3rd production year, 2012	Pre-mating liveweight			54.02	54.69	55.86
	Pre-mating BCS			2.71	2.76	2.83
	Lambs weaned per 100 ewes **			96.15	116.05	127.59
	Total liveweight of lambs weaned			25.12	30.88	36.30
	Weaning liveweight			55.84	54.31	55.56
	Weaning BCS			2.74	2.71	2.76
4th production year, 2013	Pre-mating liveweight				49.62	51.64
	Pre-mating BCS				2.71	2.80
	Lambs weaned per 100 ewes				101.25	120.69
	Total liveweight of lambs weaned				28.00	35.88
	Weaning liveweight				58.01	59.12
	Weaning BCS				2.67	2.64
5th production year, 2014	Pre-mating liveweight					58.16
	Pre-mating BCS					2.53
	Lambs weaned per 100 ewes					124.14
	Total liveweight of lambs weaned					36.86
	Weaning liveweight					56.98
	Weaning BCS					2.71

Significant difference of average values between ewes that survived different amount of years, shown, where: *P<0.05, **P<0.01.
Different superscript letters in a row indicate a significant difference between different "years survived in the breeding flock".

7.3.3 SECTION 3: Actual flock structure and cull age change

In production year 1 (2011 data), when a four age group flock structure was in place, the highest percentage of animals in the flock was in the first age group (1.5 years old at mating at 31 %), whilst the lowest percentage (16.3 %) was in the fourth age group (4.5 years old). After four years of no age limit culling, the flock age structure had altered (Figure 7.9) and there were additional age groups of 5.5, 6.5 and 7.5. The percentage of younger ewes in the flock (aged 1.5 years) was also lower (at 27.5 %) and those in age groups 5.5 and over made up 13.2 % of the flock.

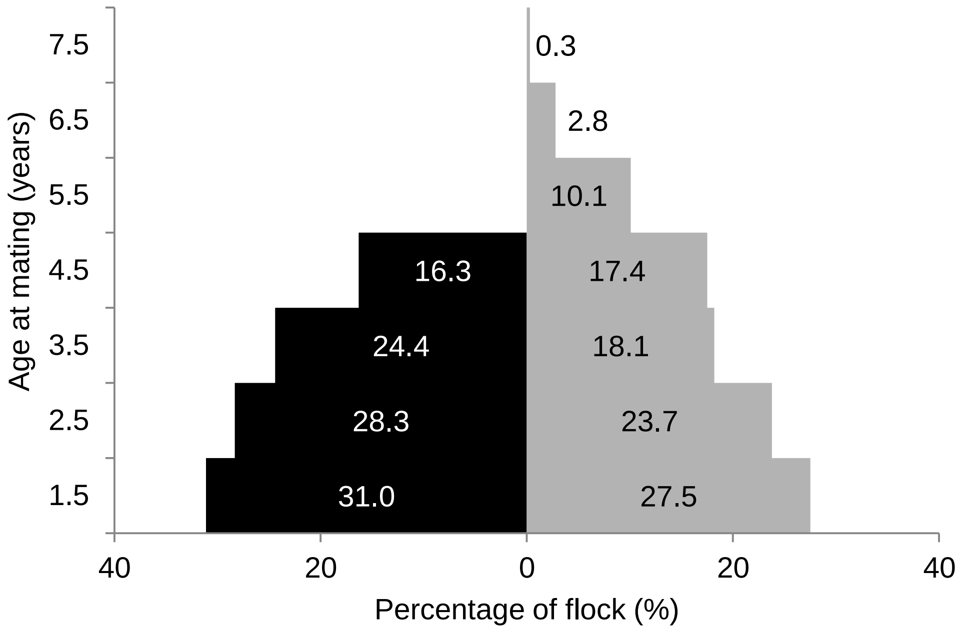


Figure 7.9 Flock distribution when a four age group structure was in place (year 1, black bars) and after four years of not culling at a fixed age (year 4, grey bars, percentage of flock in each age group shown on bars).

7.3.4 SECTION 4: Modelled flock structure and cull age change

Flock structure fluctuated over 13 runs of the model after the culling age of 5.5 was removed from the modelled flock (Figure 7.10). Replacements (ewes aged 1.5 years old at mating) reduced from 28.4 % to 24.9 % of the flock after culling age was removed, while ewes aged “5.5 and over” increased from 0 % to 12.4 % of the flock.

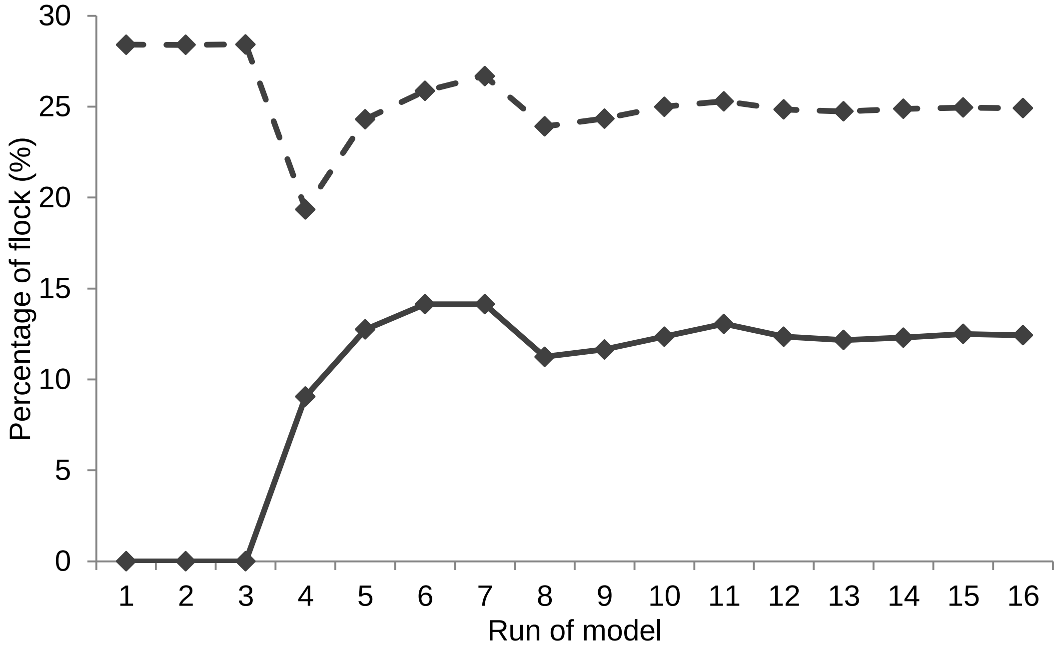


Figure 7.10 The modelled percentage of a flock made up of ewes “5.5 and over” years old at mating (solid line) and replacements (ewes aged 1.5 years old at mating, dashed line), when the reason to cull ewes at 5.5 years old was removed in run 3 (where each run represents one production year).

7.3.5 SECTION 5: Financial implications of a changed flock structure

Two flocks modelled using 2014 production data resulted in a margin of £ 9.20 (per 100 ewes) greater for the “No age limit” flock, compared to the “4 age group” flock (Table 7.9). The “4 age group” flock obtained £ 544.00 more income than the “No age limit” flock for the sale of sound ewes, whilst the “No age limit” flock received more income from the sale of: unsound ewes (£ 163.90 more), ewe lambs (£ 296.00), and male lambs (£ 45.00).

Sensitivity analyses of monetary values showed changes in the sale price of ewes and lambs impacted on flock margins (Table 7.10). A 10 % increase in unsound ewe sale price (from £ 32.78 to £ 36.06) resulted in a 1.9 % margin increase (or £ 72.12 gain) for the “No age limit” flock, compared to just a 1.5 % margin increase (or £ 55.73 gain) for the “4 age group” flock. The unsound ewe sale price needed to decrease by 5.6 % (from £ 32.78 to £ 30.16) before the “4 age group” flock had the greatest margin.

A 10 % increase in sound ewe sale price increased the “4 age group” flock margin by 1.5 % (or £ 54.40 gain). An increase of 1.2 % (from £ 68.00 to £ 69.15) was required for the “4 age group” flock margin to be greater than the “No age limit” flock margin. Decreasing ewe lamb sale price by 3.1 % (from £ 74.00 to £ 71.70) resulted in the “4 age group” flock having a greater margin. Whereas a 10 % increase in replacement management costs resulted in a 1.4 % margin loss (or a cost of £ 54.06) for the “4 age group” flock.

The number of ewes sold and number of lambs weaned impacted on the overall margin of the two flocks (Table 7.11). Increasing the number of unsound ewes sold by 1 resulted in a 1.6 % margin decrease (or £ 59.24 loss) for both flocks. Increasing lamb weaned numbers by 2 (meaning 1 extra male and 1 extra female lamb), resulted in a 3.2 % margin increase (or £ 119.00 gain) for both flocks.

Table 7.9 Financial comparison between two modelled flocks (of 100 ewes each) with different age structures.

	Flock structure	
	4 age group	**No age limit**
Production values		
Number of ewes at the start of the year	100	100
Number of ewes died[a]	3	3
Number of ewes missing[a]	2	2
Number of unsound ewes sold[a]	17	22
Number of sound ewes sold[a]	8	0
Number of ewes to survive to pre-mating[b]	70	73
Number of replacements required[b]	30	27
Number of lambs weaned[ac]	100	102
Number of male lambs weaned[bc]	50	51
Number of ewe lambs weaned[bc]	50	51
Number of ewe lambs to sell[bd]	20	24
Amount of concentrate feed given (kg)[a]	2039.8	2059.2
Amount of individual treatments given[a]	8	9
Income		
Unsound ewes sold @ £32.78 each	£ 557.26	£ 721.16
Sound ewes sold @ £68.00 each	£ 544.00	£ 0.00
Male stored lambs sold @ £45 each	£ 2,250.00	£ 2,295.00
Ewe lambs sold @ £74 each	£ 1,480.00	£ 1,776.00
Outgoing		
Remove dead @ £22.20 each	-£ 66.60	-£ 66.60
Supplementation @ £0.22 per kg	-£ 448.76	-£ 453.02
Antibiotic treatments @ £1.50 each	-£ 12.00	-£ 13.50
Replacement management @ £18.02 each	-£ 540.60	-£ 486.54
Margin	**£ 3,763.30**	**£ 3,772.50**

[a]values used were actual percentages from production year 4 (2014) data;
[b]values were calculated from other values in this table;
[c]actual weaning values used but rounded to even number to split evenly between sexes;
[d]number of ewe lambs to sell after accounting for the replacements to be kept.

Table 7.10 Sensitivity analysis of values when comparing two different flock structures (“4 age group” and “No age limit”, both flocks of 100 ewes). Shaded rows show where the “4 age group” flock had a greater margin compared to the “No age limit” flock.

			Income/outgoing from group		**Change from flock standard margin[a]**		**Percentage change from standard margin (%)[a]**		**Difference in Margin between "No age limit" and "4 age group"**
		Amount each	**4 age group**	**No age limit**	**4 age group**	**No age limit**	**4 age group**	**No age limit**	
Unsound ewe sale price	+10 %	£ 36.06	£ 612.99	£ 793.28	£ 55.73	£ 72.12	1.48	1.91	£ 25.59
	+5 %	£ 34.42	£ 585.12	£ 757.22	£ 27.86	£ 36.06	0.74	0.96	£ 17.40
	+1 %	£ 33.11	£ 562.83	£ 728.37	£ 5.57	£ 7.21	0.15	0.19	£ 10.84
	Standard	**£ 32.78**	**£ 557.26**	**£ 721.16**	**£ 0.00**	**£ 0.00**	**0.00**	**0.00**	**£ 9.20**
	-1 %	£ 32.45	£ 551.69	£ 713.95	-£ 5.57	-£ 7.21	-0.15	-0.19	£ 7.56
	-5 %	£ 31.14	£ 529.40	£ 685.10	-£ 27.86	-£ 36.06	-0.74	-0.96	£ 1.01
	-10 %	£ 29.50	£ 501.53	£ 649.04	-£ 55.73	-£ 72.12	-1.48	-1.91	-£ 7.19
Sound ewe sale price	+10 %	£ 74.80	£ 598.40	£ -	£ 54.40	£ -	1.45	0.00	-£ 45.20
	+5 %	£ 71.40	£ 571.20	£ -	£ 27.20	£ -	0.72	0.00	-£ 18.00
	+1 %	£ 68.68	£ 549.44	£ -	£ 5.44	£ -	0.14	0.00	£ 3.76
	Standard	**£ 68.00**	**£ 544.00**	**£ -**	**£ 0.00**	**£ -**	**0.00**	**0.00**	**£ 9.20**
	-1 %	£ 67.32	£ 538.56	£ -	-£ 5.44	£ -	-0.14	0.00	£ 14.64
	-5 %	£ 64.60	£ 516.80	£ -	-£ 27.20	£ -	-0.72	0.00	£ 36.40
	-10 %	£ 61.20	£ 489.60	£ -	-£ 54.40	£ -	-1.45	0.00	£ 63.60
Ewe lamb sale price	+10 %	£ 81.40	£ 1,628.00	£ 1,953.60	£ 148.00	£177.60	3.93	4.71	£ 38.80
	+5 %	£ 77.70	£ 1,554.00	£ 1,864.80	£ 74.00	£ 88.80	1.97	2.35	£ 24.00
	+1 %	£ 74.74	£ 1,494.80	£ 1,793.76	£ 14.80	£ 17.76	0.39	0.47	£ 12.16
	Standard	**£ 74.00**	**£ 1,480.00**	**£ 1,776.00**	**£ 0.00**	**£ 0.00**	**0.00**	**0.00**	**£ 9.20**
	-1 %	£ 73.26	£ 1,465.20	£ 1,758.24	-£ 14.80	-£ 17.76	-0.39	-0.47	£ 6.24
	-5 %	£ 70.30	£ 1,406.00	£ 1,687.20	-£ 74.00	-£ 88.80	-1.97	-2.35	-£ 5.60
	-10 %	£ 66.60	£ 1,332.00	£ 1,598.40	-£ 148.00	-£177.60	-3.93	-4.71	-£ 20.40

Continued

Table 7.10 Continued.

Cost of replacement management	+10 %	£ 19.82	-£ 594.66	-£ 535.19	-£ 54.06	-£ 48.65	-1.44	-1.29	£ 14.61
	+5 %	£ 18.92	-£ 567.63	-£ 510.87	-£ 27.03	-£ 24.33	-0.72	-0.64	£ 11.91
	+1 %	£ 18.20	-£ 546.01	-£ 491.41	-£ 5.41	-£ 4.87	-0.14	-0.13	£ 9.74
	Standard	**£ 18.02**	**-£ 540.60**	**-£ 486.54**	**£ 0.00**	**£ 0.00**	**0.00**	**0.00**	**£ 9.20**
	-1 %	£ 17.84	-£ 535.19	-£ 481.67	£ 5.41	£ 4.87	0.14	0.13	£ 8.66
	-5 %	£ 17.12	-£ 513.57	-£ 462.21	£ 27.03	£ 24.33	0.72	0.64	£ 6.50
	-10 %	£ 16.22	-£ 486.54	-£ 437.89	£ 54.06	£ 48.65	1.44	1.29	£ 3.80

[a]Standard margin for the two flocks (as shown in Table 7.9) was: “4 age group” at £ 3,763.30, and “No age limit” at £ 3,772.50.

Table 7.11 Sensitivity analysis of number of sheep when comparing two different flock structures ("4 age group" and "No age limit", both flocks of 100 ewes). Shaded rows show where the "4 age group" flock had a greater margin compared to the "No age limit" flock.

		Count of sheep		**Income from group**		**Change from flock standard margin[a]**		**Percentage change from flock standard margin (%)[a]**		**Difference in Margin between "No age limit" and "4 age group"**
		4 age group	**No age limit**	**4 age group**	**No age limit**	**4 age group**	**No age limit**	**4 age group**	**No age limit**	
Number of unsound ewes to sell	+10 ewes	27	32	£ 885.06	£ 1,048.96	-£ 592.40	-£ 592.40	-15.74	-15.70	£ 9.20
	+5 ewes	22	27	£ 721.16	£ 885.06	-£ 296.20	-£ 296.20	-7.87	-7.85	£ 9.20
	+1 ewe	18	23	£ 590.04	£ 753.94	-£ 59.24	-£ 59.24	-1.57	-1.57	£ 9.20
	Standard	**17**	**22**	**£ 557.26**	**£ 721.16**	**£ 0.00**	**£ 0.00**	**0.00**	**0.00**	**£ 9.20**
	-1 ewe	16	21	£ 524.48	£ 688.38	£ 59.24	£ 59.24	1.57	1.57	£ 9.20
	-5 ewes	12	17	£ 393.36	£ 557.26	£ 296.20	£ 296.20	7.87	7.85	£ 9.20
	-10 ewes	7	12	£ 229.46	£ 393.36	£ 592.40	£ 592.40	15.74	15.70	£ 9.20
Number of sound ewes to sell	+10 ewes	18	0	£ 1,224.00	£ -	-£ 240.20	£ -	-6.38	0.00	£ 249.40
	+5 ewes	13	0	£ 884.00	£ -	-£ 120.10	£ -	-3.19	0.00	£ 129.30
	+1 ewe	9	0	£ 612.00	£ -	-£ 24.02	£ -	-0.64	0.00	£ 33.22
	Standard	**8**	**0**	**£ 544.00**	**£ -**	**£ 0.00**	**£ -**	**0.00**	**0.00**	**£ 9.20**
	-1 ewe	7	0	£ 476.00	£ -	£ 24.02	£ -	0.64	0.00	-£ 14.82
	-5 ewes	3	0	£ 204.00	£ -	£ 120.10	£ -	3.19	0.00	-£ 110.90
	-8 ewes	0	0	£ -	£ -	£ 192.16	£ -	5.11	0.00	-£ 182.96

Continued

Table 7.11 Continued.

				Income from ewe lamb sales							
Number of lambs weaned	+10 lambs	110	112	£ 1,850.00	£ 2,146.00	£ 595.00	£ 595.00	15.81	15.77	£ 9.20
	+6 lambs	106	108	£ 1,702.00	£ 1,998.00	£ 357.00	£ 357.00	9.49	9.46	£ 9.20
	+2 lambs	102	104	£ 1,554.00	£ 1,850.00	£ 119.00	£ 119.00	3.16	3.15	£ 9.20
	Standard	**100**	**102**	**£ 1,480.00**	**£ 1,776.00**	**£ 0.00**	**£ 0.00**	**0.00**	**0.00**	**£ 9.20**
	-2 lambs	98	100	£ 1,406.00	£ 1,702.00	-£ 119.00	-£ 119.00	-3.16	-3.15	£ 9.20
	-6 lambs	94	96	£ 1,258.00	£ 1,554.00	-£ 357.00	-£ 357.00	-9.49	-9.46	£ 9.20
	-10 lambs	90	92	£ 1,110.00	£ 1,406.00	-£ 595.00	-£ 595.00	-15.81	-15.77	£ 9.20

[a]Standard margin for the two flocks (as shown in Table 7.9) was: “4 age group” at £ 3,763.30, and “No age limit” at £ 3,772.50.

7.4 Discussion

7.4.1 SECTION 1: Performance and ewe age

The research flock data showed that, when culling no longer occurred at 5.5 years old, ewes retained were still able to survive and performed as well or better than ewes from younger age groups. This suggests that culling at a fixed age is not appropriate for identifying and removing unproductive ewes from the flock. Although, the issue of low numbers of ewes in the older age groups needs to be addressed (discussion to follow).

7.4.1.1 Survival and culling

Survival from mating to weaning was similar across all age groups, including the "5.5 and over" group. Overall mortality rate for the flock was 5 % (ewes recorded dead or missing presumed dead) and 8 % for ewes "5.5 and over". This latter value of mortality is higher than values reported in some literature for the same age group of ewes. Mekkawy et al. (2009) reported 1.5 % of 5.5 year old mules died, while in other research 8 % is much lower. For example research by Hickey (1960) reported 21 % death rate for 5.5 year old New Zealand cross ewes. This value of 21 % seems surprisingly high and may be the result of different management practices or other unknown factors. Mortality within this chapter is closer in agreement to those for a traditionally managed hill flock of Scottish Blackface ewes in similar conditions, which was reported at between 7 - 12 % over four years of production (Morgan-Davies et al., 2008).

Annett et al. (2011) found that (over a five year study period) more ewes left the flock as a result of death (33.5 %) compared to being culled (25.6 %). This is in contrast with the findings of the current chapter that found more ewes left as a result of culling instead of death.

For both research and commercial flocks it is challenging to determine whether recorded mortality and culling rates are a true reflection of a flock's survival (and so longevity) potential, or whether they are a result of management practices. Studies carried out on wild unmanaged populations of sheep can instead provide a useful comparison. Such a population is the Soay sheep found on St Kilda Islands off the north-west coast of Scotland, which were first researched in 1955 and then more regularly since 1985 (Clutton-Brock and Pemberton, 2004).

Within the Soay sheep population, many individuals over 10 years old had been recorded as surviving and producing lambs (Catchpole et al., 2000; Hayward et al., 2013; Tavecchia et al., 2005). Furthermore, findings published for this population showed a sharp increase and then a gradual decrease in survival and production as ewe age advanced (Hayward et al., 2013; Nussey et al., 2011; Tavecchia et al., 2005). Within the current chapter not only did more ewes leave the flock as a result of culling decisions rather than death (and missing), more older ewes were culled compared to the younger age groups ($P<0.001$, 61 % of "5.5 and over" age group culled at stockdraw compared to 4 % of 1.5 years old group). This rapid decrease of ewe numbers at older ages ("5.5 and over") contrasts with the gradual decrease seen within Soay sheep. Therefore, culling on-farm does not appear to follow the same natural trends of losses seen in wild populations.

The difference in losses could suggest that longevity on farm is being restricted by the culling protocol, with management decisions removing too many ewes from the flock. Although, there are different selection pressures on the Soay sheep population compared to commercially farmed Scottish Blackfaces. Wild populations could have a selection pressure for longevity while the Scottish Blackface has been selected on other factors that could reduce longevity potential. A larger number of years of data would provide clarity and certainty on this finding.

7.4.1.2 Cull reasons

There appeared to be differences in culling reasons between age groups (although numbers were too sparse to carry out statistical analyses). No ewes aged 2.5 years or under were culled as a result of poor mouth condition but numbers culled for this reason increased as age increased. Culling older ewes for poor mouths is an observation that has been reported in previous research (Annett et al., 2011; McGregor, 2011; McLaren et al., 2019; Mekkawy et al., 2009).

7.4.1.3 Lamb production and ewe liveweights and BCSs

Productivity of older ewes ("5.5 and over") appeared to be comparable or superior compared to all other age groups of ewes. Number of lambs produced at different stages through the year (scanned, born and weaned) increased as ewe age increased. Prolificacy increasing with age has been demonstrated in other studies (Annett et al., 2011; Dickerson and Glimp, 1975; Hickey, 1960; Mullaney and Brown, 1969; Notter, 2000). This is an interesting result as it means more lambs from older ewes are available for selection. If longevity is an indicator of biological fitness and genetic superiority (Annett et al., 2011; Borg et al., 2009b; Kelleher et al., 2015; Mekkawy et al., 2009; Nugent and Jenkins, 1993), genetic improvements could be made at a greater rate throughout the flock, than if only selecting offspring from younger ewes.

While, in this study, prolificacy increased with age, it is likely that there would be a decline in prolificacy as age increased further. Indeed, Mullaney and Brown (1969), suggested that prolificacy declined beyond the age of 7 years old, for Merino, Polwarth and Corriedale ewes in Australia. Previous research found that liveweight of lambs increased with ewe age (Annett et al., 2011; Mullaney and Brown, 1969). While there appeared to be an increase in the mean value of average liveweight of lamb weaned and total liveweight of lambs weaned from ewes “5.5 and over” compared to younger ewes, these results were not significant (P=0.18 and P=0.07, respectively). Mysterud et al. (2002) found that within domesticated free-ranging Dala sheep in Norway, ewes aged 3 and 4 years old had the heaviest lambs but those aged 4 and 5 had the biggest litters. After this age, lamb liveweight and litter size decreased but only gradually. It is therefore surprising that more obvious differences between ages of ewes were not found within this chapter.

Previous research has shown that ewe liveweight and BCS decline in older ewes (Annett et al., 2010; Borg et al., 2009b). While no significant decline in ewe liveweight and BCS was found for older ages (“5.5 and over”) in this chapter, the data did show a slight decline. With a greater number of years of data, or ewes retained to greater ages, this decline may be more obvious. Interestingly Nussey et al. (2011) found that Soay sheep average ewe liveweights increased dramatically in the first four years of life, then levelled off and only declined within the two years prior to death. Again, larger numbers of ewes at the older ages would be required to explore whether similar patterns would be seen for Scottish Blackfaces.

7.4.1.4 Antibiotic treatments and feed

The results suggested that older ewes (“5.5 and over”) had similar or greater production outputs than other age groups; however, results on inputs required across ages were not so clear. Although there did appear to be some increase in antibiotic treatments and in the amount of feed with increased age, no significant differences were identified. Therefore, it cannot be confirmed whether older ewes required greater input. Furthermore, no literature could be found suggesting that older ewes need greater inputs. Therefore, this is a potential area for future research.

A reason why ewes are culled on age is a result of welfare concerns. Removing all ewes at a fixed age before welfare is compromised may be a preferable option than retaining ewes within the flock and risking welfare deteriorating prior to ewes being identified and culled (as discussed by Hickey, 1960; McGregor, 2011). Results within this chapter do not support this concern. Production and survival of older ewes within this research are comparable to younger animals, suggesting that welfare had not been compromised. However, to provide assurance that this is the case it would be useful and worthwhile for future research to specifically consider the welfare of these older ewes.

7.4.2 SECTION 2: Longevity and performance within age cohort

On the whole, performance values demonstrated that older ewes were similar or superior to younger age groups (SECTION 1). However there were low numbers of these older ewes. To consider the survival bias of data from older age groups, one age cohort performance was considered throughout their life. The ewes that survived into their fifth breeding year showed little sign of superiority to other ewes within their age cohort that left the flock in earlier years. The only difference seen between groups was the number and liveweights of lambs produced in some production years but this was often only significant for ewes in their last year present in the flock. Furthermore, these ewes may have been culled as a result of the low productivity in that year. Therefore, results in SECTION 1 from older age groups can be considered comparable to other age groups of ewes out with their age cohort, reducing concerns for survival bias.

7.4.3 SECTION 3: Actual flock structure and cull age change

Altering culling rules to no longer cull at a fixed age (of 5.5 years old) increased longevity within the research flock. This was demonstrated by three results: 1) from production year 1 (2011) to year 4 (2014) the maximum age group in the flock increased from 4.5 to 7.5 years old at mating; 2) the average age of ewes within the flock increased from 2.8 (in year 1) to 3.2 years old at mating (in year 4); and 3) by year 4 ewes aged 5.5 years and over made up 13.3 % of the flock.

Although 7.5 years old was the oldest age reached by ewes within the flock, over time, higher numbers of ewes could reach this age group or older. Indeed Mullaney and Brown (1969) and Hickey (1960) reported ewes at greater ages within their data: 8.5 years old at mating for Merino ewes within Australian flocks; and 11.5 years old for cross-bred ewes within New Zealand flocks, respectively. Furthermore, with Soay sheep still being productive beyond the age of 10 years old (Catchpole et al., 2000; Hayward et al., 2013; Tavecchia et al., 2005), there is potential for Scottish Blackfaces to be able to wean lambs to greater ages. However, Mysterud et al. (2002) reported that reproductive senescence (process of ageing and slowing of reproductive ability) occurs earlier in life for highly domesticated sheep breeds compared to breeds such as Soay.

7.4.4 SECTION 4: Modelled flock structure and cull age change

Compared to the restricted results provided from the research flock, the modelled flock allowed for a more controlled and longer term consideration of how flock structure may continue altering over time. As with the research flock, the model showed a quick reaction to the change in culling rules with a sudden drop in 1.5 year old ewes and increase in older ewes. Another decrease in both groups' numbers was observed 4 years after the culling rule change (at year 8 of the model). This drop occurred where the first affected age group of 1.5 year olds (in year 4) reached the "5.5 and over" age group, this pattern was apparent again after another four years. While large fluctuations in flock age structure reduced after just five years from the change in cull age, small fluctuations in values occurred for 13 years.

Such fluctuations could have been limited if replacements entering the flock remained constant when the change in culling rule occurred, therefore causing overall flock size to increase. However, desire to maintain flock size was considered to be more realistic to hill system situations. No literature could be found to compare how long fluctuations in structure may occur for after removing such a culling rule. Therefore, the results of this research provide new knowledge on the long term effect of changing culling age on flock structure.

Overall replacement ewes (at 1.5 years of age) reduced from 28.4 % of the flock prior to rule change to 24.9 % of the flock. This 12.3 % decline in the modelled flock was similar to the 11.3 % age group decline observed in the research flock just 3 years after a change in culling rule. This occurred even though the 1.5 years old age group in the actual flock started and ended at a higher percentage of the flock (31.0 % in year 1, 2011 and 27.5 % in year 4, 2014) compared to the modelled flock. The 12.3 % decline in replacements required is a substantial amount for large flocks, and is comparable to other published figures. For instance, Hickey (1960) reported that 15 % fewer replacements were required by advancing cull age by just one year. However, that research was focussed on New Zealand cross-bred ewes. Nevertheless, reducing replacement rates would likely affect the overall economic viability of the flock, as demonstrated in SECTION 5.

7.4.5 SECTION 5: Financial implications of a changed flock structure

Results showed that a flock which did not cull on age generated a £ 9.20 per 100 ewe greater margin over a year of production, compared to a flock culled at 5.5 years old. The greatest financial differences between the two flocks came from the sales of sound ewes, unsound ewes and ewe lambs, together with the cost of replacement management. This is in agreement with other research stating that financial gains are possible when longevity is increased as a result of fewer replacements required and, therefore, more younger females to sell (both for dairy: Essl, 1998; Groenendaal and Galligan, 2005; and sheep research: McGregor, 2011). These results are, however, somewhat limited as they only consider one year of production and used many cost and value assumptions. Sensitivity analysis provided greater insight into the impact that fluctuations in values could have on economic outcomes.

7.4.5.1 Sensitivity analysis

Sensitivity analyses showed that margins of the two flocks were very susceptible to small changes both in prices and in number of animals in each group. Changes in the sale price of unsound ewes had a larger impact on the “No age limit” flock margin compared to the “4 age group” flock. This is because the “No age limit” flock had more unsound ewes to sell (the reverse is true for the sale price of sound ewes). Likewise changing ewe lamb sale price had a greater impact on the “No age limit” flock margin, as a result of that flock having more ewe lambs to sell. Furthermore, the “4 age group” flock was more sensitive to the replacement management price, due to keeping more replacements.

The number of ewes sold and number of lambs weaned impacted on the overall margin of the two flocks. Any increase in the number of unsound (for both flocks) or sound ewes (for “4 age group” flock) sold resulted in a decrease in the flock’s margin. Changing the numbers of unsound and sound ewes to sell not only impacted on the total sale price for that ewe sale group but also on the income from ewe lamb sales and the replacement management costs (results not shown). This was because as more unsound or sound ewes were sold more replacements were required and so fewer ewe lambs were available to sell.

7.4.5.2 Management control and economic impacts

Market prices can alter greatly within and between years but, as demonstrated, small changes can have a large impact on the flock margin. Therefore, while prices cannot be controlled, making management decisions of when to sell particular groups of animals in response to when market values are favourable would be financially beneficial (as suggested by EBLEX, 2014). Compared to market prices, the stockperson has more control over the number of animals in each category. Changing culling management clearly affects the numbers of sound and unsound ewes for sale but other management changes could be considered, such as practices that increase weaning rate (thereby increasing number of lambs to sell) or breeding ewes with greater longevity resulting in fewer unsound ewes to sell.

While not culling on age appeared to have financial benefits for this research flock, it is unclear of the financial impact that would occur if this practice were adopted across the industry. Hill sheep systems culling on age is an essential part for the UK stratified sheep industry as it allows the movement of animals, and therefore genetics, from hill systems to upland systems (Kilgour et al., 2008; Waterhouse, 1999; as discussed in Chapter 2). If all hill sheep systems changed their culling protocols and retained old ewes as long as possible there would be fewer cull ewes to move to upland systems and more ewe lambs to sell.

In this scenario, ewe lamb numbers at market could drastically increase and sound ewe numbers decrease, therefore likely reducing ewe lamb sale price but increasing sound ewe price. It would be interesting to consider the financial implications of this change not just to hill sheep systems but also to upland sheep systems, which may potentially change from buying old ewes to young ewes. While these young ewes would potentially need a year before they could be bred from, they would have the potential of more breeding years compared to cull ewes. Thereby, at an industry level, this change would not only increase longevity of ewes within hill sheep systems but also the longevity of hill animals within upland flocks. This increase in longevity could therefore also have the potential to improve the environmental impact of the industry (as discussed in EBLEX, 2009). It should be noted, however, this is largely hypothetical without further research to provide insights into potential scenarios and likely outcomes.

7.4.6 Research limitations, improvements and strengths

7.4.6.1 Limitations and improvements

This is the first time that increasing hill sheep longevity has been considered in response to changing age culling management alone. While being an important first step, there are a number of limitations to the study design that, if improved, could result in greater scientific findings.

Firstly, the length of study time was restricted to just four years. While this is a similar length of time to other culling and longevity studies (5 years for Annett et al., 2011, and Hickey, 1960; and 4 years for Kern et al., 2010), greater lengths of time are advantageous to see long term effects (45 years for Borg et al., 2009a; and 11 for Mekkawy et al., 2009). Longitudinal studies required for longevity based research are challenging but are important and worthwhile (for example those on Soay sheep, Clutton-Brock and Pemberton, 2004). The Australian Merino Lifetime Productivity Project, as an example, aims to run over 10 years, between 2015 to 2025 (The Merino Lifetime Productivity Project, 2019). Since the 2014 production year the research flock has continued to be culled according to the culling protocol (Table 7.1) and not culled based on age. The longer this practice is continued within the research flock the greater amount of longitudinal data available, which could further research and understanding on longevity.

Secondly, results from previous research that covered shorter periods of time were strengthened by increasing the number of farms and data records used. For example Annett et al. (2011) included 1,143 animal records from 6 farms and Kern et al. (2010) used data from 5,191 ewes from 236 breeding farms. The current study was restricted to one farm and one flock of 506 ewes. However, this number is believed to be sufficient for the types of preliminary observations made of the data and this research area.

Thirdly, culling had a far greater impact over ewe survival within the flock compared to mortality; however these decisions were carried out by a stockperson and their subjective opinion on how well a ewe met the culling protocol. To truly consider the longevity potential of ewes, all ewes should remain within the flock until death, however the clear welfare and ethical concerns make this option more challenging.

Furthermore, no previous literature has been found that carried out such a research protocol on commercial or research farms.

7.4.6.2 Strength of research

Given the large effect culling decisions had over ewes remaining within the flock, it is surprising that previous culling and longevity research had no or limited control and recording of culling decisions (Annett et al., 2011; Borg et al., 2009a; Kern et al., 2010). An example of this was Kern et al. (2010), who used large amounts of data but was only able to calculate the date ewes left the flock when no further data recording occurred. Indeed, they also had no access to whether ewes had died, been culled or any details on culling management. This lack of control or knowledge of culling protocols is echoed in other research (for example in Annett et al., 2011; Borg et al., 2009a). The most detailed research found was from Mekkawy et al. (2009); where all culling and death reasons and when they occurred were recorded. However, they simply stated that ewes were "culled for normal husbandry reasons" but again provided no details of what these were or how and who carried out culling decisions.

Therefore, strength of the current research comes from being able to report all details and to control culling with a defined culling protocol. Although some reasons of the culling protocol were subjective, effort was made to make them as objective as possible. This meant that ewes may have been retained within the flock that otherwise might have been culled if the stockperson had used only their opinion for which to cull. Even with a protocol, the reliability of this research is dependent on the ability of the stockperson to make culling decisions. A suggested improvement would be to develop a more data driven method of making culling decisions, an idea that is important for PLF approaches. This will be explored in the following chapters.

A potential reason why culling on age has persisted within hill sheep systems could be due to the lack of other information to inform culling decisions. As demonstrated in Chapter 6, few stockpeople recorded information on ewes to inform culling decisions therefore current appearance of the ewe is all they had to inform culling decisions. Some cull reasons used within the research flock rely on recorded information and so would not be available if no data is recorded (for example, ewes were culled if they failed to be ultrasound scanned pregnant two years in a row, Table 7.1). Whereas, age of ewe can be relatively easy to identify, either through presence and loss of teeth (McGregor, 2011) or through physical management marks, such as using different colour ear tags for different age groups (as suggested by EBLEX, 2014). In this way stockpeople have used the information they have available to them, in the absence of any other more sophisticated methods. A PLF approach could instead be used to inform culling and retention decisions (as suggested by Richards et al., 2012). Such an approach could use individually collected ewe data, where EID and associated technology could be used to facilitate data recording. With more individual information available about the ewe, group based decision making such as culling on age would be less viable.

7.5 Conclusions

This chapter showed that Scottish Blackface ewes retained beyond a standard cull age of 5.5 years old can survive and still be productive within a hill sheep system. Production from ewes aged 5.5 years old and over was similar or better than the younger ewe age groups within the flock. Ewes that survived within the flock, to greater ages, were not significantly different to others within their birth cohort that left the flock in earlier years. The change in culling protocol, from removal at 5.5 years old to no age limit, resulted in increased longevity of ewes within the flock and a change in flock age structure. Additionally, there were financial benefits from a flock with no age limit. Therefore, based on these results, culling on age within a hill sheep system seems unjustified and retaining ewes beyond the cull age could result in more productive and economically viable flocks.

Decisions made at stockdraw removed more ewes from the flock than ewe mortality during the year, therefore it is important that these decisions are as effective as possible, and identify unproductive ewes to cull. Applying a PLF approach to this decision making therefore has the potential to have a large impact on which ewes leave the flock.

The second half of this thesis considers how a PLF approach could be used to inform retention and culling decisions. Chapter 6 found that stockpeople cull ewes from their flock based on age. However, in this chapter, the potential productive and financial benefits of retaining older ewes within the flock have been demonstrated. Hence, a PLF approach should not cull ewes based on age. Instead, such an approach should aim to identify and retain the more productive ewes within the flock, while identifying and culling the unproductive ones, based on data and not subjective assessments. This will be considered in the following chapters.

CHAPTER 8: DEVELOPMENT AND RELIABILITY TESTING OF A VISUAL APPEARANCE ASSESSMENT TO DESCRIBE EWE APPEARANCE AT STOCKDRAW

Chapter 6 identified that stockpeople often use visual appearance of ewes upon which to make culling decisions, such as the current condition of a ewe's mouth and udder. This thesis aims to consider whether these attributes are able to predict future performance and so inform a PLF approach for making retention and culling decisions. However, in order to do this a visual scoring system first needed to be established to collect the information about the condition and appearance of the ewe. The aim of this chapter is to describe and evaluate a scoring system to collect visual attributes at stockdraw.

8.1 Introduction

8.1.1 Visual assessments

Visual assessments, using scales and scores to classify attributes, have been developed and used in much sheep-based research (de La Fuente et al., 1996; Kaler et al., 2009; Lovatt, 2010; Phythian et al., 2019, 2012a; Richmond et al., 2017; Russel et al., 1969). These allow information on sheep to be collected when there may not be a more quantitative method available or appropriate to use. Such assessments are made through a rater, assessor, judge, observer or examiner assigning a score based on their subjective opinion of how well the sheep's current appearance fits within the written descriptions of a scale or range of scores. In this way, subjective qualitative information can be collected that aims to be reliable, reproducible and therefore comparable between animals and different situations.

The many examples of visual assessments used in sheep-based research appear to focus around different areas of interest including: behaviour (for example, Qualitative Behavioural Assessments, QBA, Phythian et al., 2013), welfare (McLennan et al., 2016; Phythian et al., 2019, 2012a; Richmond et al., 2017), disease (for example, foot integrity and footrot, Foddai et al., 2012; lameness, Kaler et al., 2009; and veterinary examinations reviewed by Lovatt, 2010) and production (for example, udder conformation, de La Fuente et al., 1996). Research by Mekkawy et al. (2009) involved measuring a list of subjective traits once for ewes prior to their first mating and once for the ewes' lambs, for considering heritability of these traits. While Mekkawy et al. (2009) did consider the appearance of the ewe around stockdraw time, the traits were only measured once in their life and not for the purpose of making annual retention and culling decisions. Indeed, no visual assessments could be found within the literature which focused on classifying the appearance of the ewe with any relevance to making annual retention and culling decisions.

8.1.2 Attributes considered at stockdraw

From research reviewed (Berry et al., 2005; Lehenbauer and Oltjen, 1998; McGregor, 2011) and results of Chapter 6, it is evident that stockpeople make retention and culling decisions largely based on the appearance of the ewe at stockdraw. Stockpeople seem to take into account a range of different attributes about the ewe including mouth, feet and udder condition. However within each attribute, it is logical that there would be a range from "perfect" or "ideal" condition down to a level at which the animal is not retained for future breeding (and so the decision to cull is made). Collecting such attribute information at stockdraw could provide research with greater understanding of each attribute and how they may individually (or as a suite) be used when investigating future performance predictions.

8.1.3 Reliability testing

When developing visual assessments, reproducibility (or reliability) of data produced needs to be considered. Reproducibility is important to remove any bias that may occur, ensuring that results are comparable between animals and different situations. This is usually achieved through inter- and intra-rater reliability testing (as demonstrated in Foddai et al., 2012; Kaler et al., 2009; Phythian et al., 2013, 2012a).

The visual assessment, described within this chapter, was used on the research flock over two years with data used in analyses in Chapter 9. All assessment scores on the research flock were carried out by one stockperson (the “Flock Manager”). Therefore it is important that the current chapter determines the reliability of these scores, by inter- and intra-rater reliability testing. This not only allows reliability of flock scores used within the next chapter to be determined, it also identifies how well the Flock Manager compares with a wider population of raters.

8.1.4 Aims of chapter

The aims of this chapter are:

1) To present a scoring system that collects information on all visual appearance attributes considered by stockpeople when making retention and culling decisions at stockdraw.
2) To determine how reliably each attribute can be collected both between and within raters.
3) To consider whether the rater’s previous stockdraw experience affects the reproducibility of results from the scoring system.
4) To determine how the Flock Manager’s scores compare with a wider population of raters.

8.2 Materials and Methods

8.2.1 Developing a Visual Appearance Assessment

A Visual Appearance Assessment (VAA) was devised to qualify and quantify the current condition of a ewe at stockdraw. This was made up of 16 visual attributes grouped into four key areas for consideration: “Structural soundness”; “Mouth condition”; “Udder condition” and “Breed characteristics” (Table 8.1). The attributes were selected and defined through discussions with researchers and stockpeople (including the Flock Manager), all of whom had knowledge and experience of what visual factors are considered at stockdraw to make retention and culling decisions. Many of these attributes were also identified by respondents to the questionnaire in Chapter 6, as being used to make culling decisions.

For each attribute a scoring system was determined, which used published systems where available and suitable. A scoring system for lameness (available from Kaler et al. 2009) was rejected for inclusion in the VAA because it was more detailed than believed required; it suggested assessors should be trained prior to use, and there were few cases of lameness within the research flock. Instead, the simplified “Legs and motion” attribute was used. The mouth condition attributes “Jaw position”, “Tooth angle” and “Tooth length”, used a scoring system developed by van Heelsum et al. (2006). “Udder condition” attributes were selected and simplified from those suggested in De La Fuente et al. (1996).

In the majority of cases, the attributes were restricted to three possible scores; all defined in a descriptive manner to reduce confusion and to ensure assessment of each ewe would be as time efficient as possible. Attributes with more than three possible scores were either published scoring systems (“Jaw position”, “Tooth angle” and “Tooth length”) or where a range of scores were more appropriate (“Teeth present” and “Retention decision”).

Table 8.1 Visual Appearance Assessment (VAA).

	Attribute	Score	Description
Structural soundness	Size	1	Smaller than ideal
		2	Ideal
		3	Bigger than ideal
	Flatness of back	1	Very saddled back
		2	Slightly saddled back
		3	Flat level back
	Soundness of feet	1	Any foot not sound
		2	All feet sound
	Legs and motion	1	Any problem e.g. hooked legs, post leg etc.
		2	Less than ideal
		3	Ideal, straight legs
Mouth condition	Teeth present	0 to 8	Number of sound incisor teeth present
	Jaw position[a]	-5 to 5	-5: lower jaw 5mm back from upper jaw to 5: lower jaw 5mm in front of upper jaw
	Tooth angle[a]	-3 to 3	−3: incisor teeth 45° forward from lower jaw to 3: 45° back; ideal position is at right angle with lower jaw
	Tooth length[a]	-2 to 2	−2: very short to 2: very long
Udder condition	Teat size	1	Smaller than ideal
		2	Ideal
		3	Larger than ideal
	Udder attachment	1	Poorly attached, hanging
		2	Reasonable attached
		3	Well attached, close to body
	Udder damage	1	Abnormalities or blind both sides or damaged any side
		2	Abnormalities or blind one side
		3	Sound
Breed characteristics	Face colour	1	Lots of white coverage
		2	A little bit of white coverage
		3	Mostly black with grey nose
	Face shape	1	North type
		2	Between the two types
		3	South type
	Fleece colour	1	Lots of brown patches
		2	A few brown patches
		3	All white
	Fleece length	1	Very woolly
		2	A bit woolly
		3	Short tight wool
	Retention decision	1 to 5	1: would definitely sell to 5: would definitely keep

[a]scored according to van Heelsum et al (2006).

8.2.1.1 Breed characteristics

Van Heelsum et al. (2006) and Mekkawy et al. (2009) also used breed type traits. However, “Breed characteristic” attributes more relevant to the Scottish Blackface breed were developed for the VAA. Ewes were scored for “Face type”, “Face colour”, “Fleece colour” and “Fleece length”. For “Face type”, Scottish Blackfaces are characterised as “North type” (or “Perth type”) and “South type” (or “Lanark type”). The “South type” has thicker horns, which are closer to the face, with a shorter face and flatter nose compared to the “North type” (Blackface Sheep Breeders Association, 2016). Breed characteristics were included because the visual appearance of Scottish Blackfaces is widely believed, by the farming community, to be important and therefore could impact the price received at market. The breed characteristics could therefore impact culling decisions but are unlikely to have any bearing on the ewes’ current health and welfare, and future performance.

8.2.1.2 “Retention decision”

The attribute “Retention decision” was included as a five point scale. This allowed the rater to give an overall indication of their opinion on whether the ewe should be retained or not (where the scale was 1 = “Would definitely sell” to 5 = “Would definitely keep”), irrespective of how well the ewe had scored in all other attributes.

8.2.2 Carrying out the VAA

The VAA was carried out on all ewes within the research flock over three years. The data collected is used within this chapter and Chapter 9 (Figure 8.1). Five different analyses are presented in this chapter:

ANALYSIS 1: Inter-rater reliability.
ANALYSIS 2: Intra-rater reliability of test-raters.
ANALYSIS 3: Intra-rater reliability of the Flock Manager.
ANALYSIS 4: Flock Manager comparison with test-raters.
ANALYSIS 5: Test-rater’s opinion of the VAA attributes.

Analyses 1 to 4 are all reliability analyses (to be discussed) and use VAA data. Analysis 5 uses data collected via a questionnaire about the VAA. Analyses 1, 2, and 4 all use data collected from three VAA reliability testing days, whilst analysis 3 data was collected during the research flock’s 2014 stockdraw.

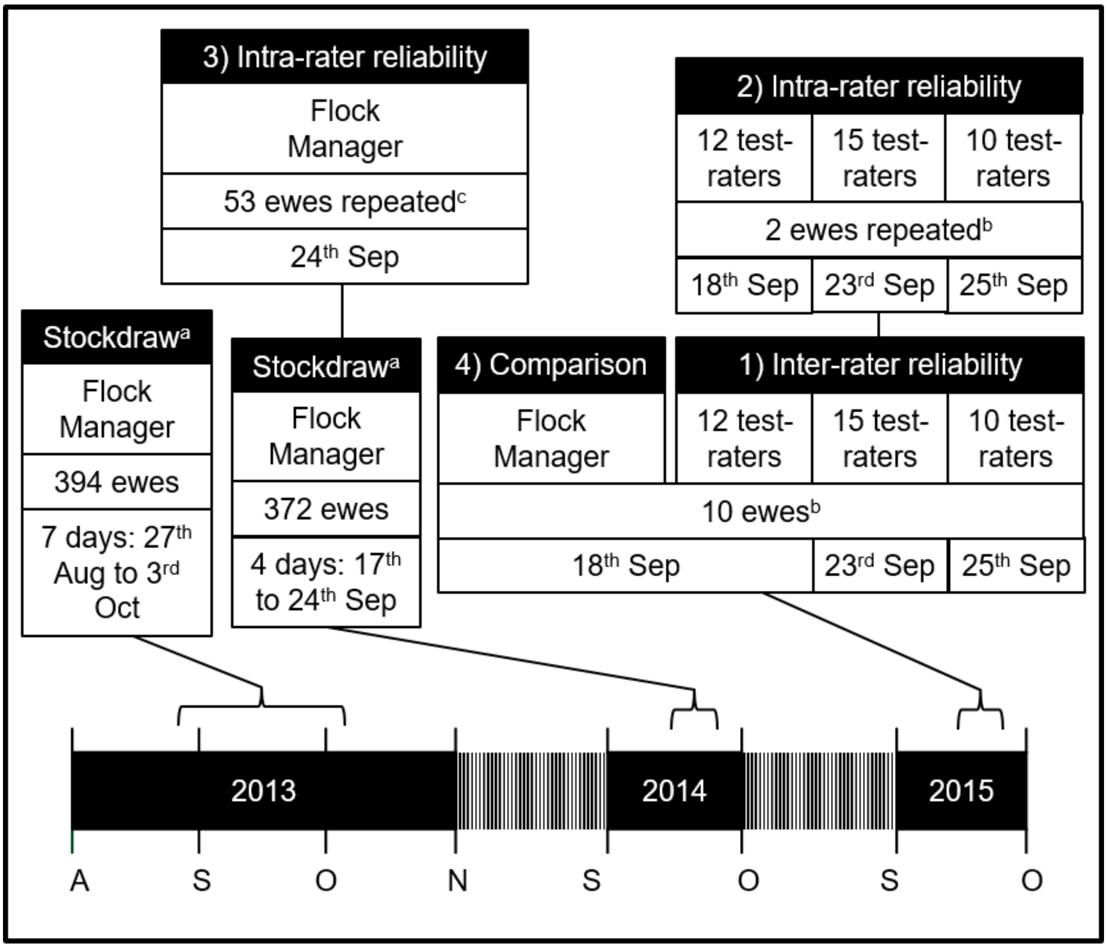


Figure 8.1 Timeline for when the Visual Appearance Assessment (VAA) was carried out on the research flock. The four analyses carried out in this chapter are numbered. The raters involved in the analysis as well as the number of ewes and the dates scoring occurred are also shown.

[a]data used in Chapter 9;
[b]same 10 ewes used for all groups of raters;
[c]53 ewes came from a group of 444 scored on the day, some of which do not appear in Chapter 9 dataset.

8.2.3 VAA reliability testing days

In total, 38 raters were used to test the reliability of the VAA scores; 37 “test-raters” and the Flock Manager. The 37 test-raters were volunteers from three separate visiting groups to the research farm and each group carried out VAA scoring on three different reliability testing days. The three groups of test-raters were: 1) SRUC’s Kirkton and Auchtertyre Farm Advisory Group on 18th September 2015 (12 test-raters); 2) SRUC’s Animal Science students on 23rd September 2015 (15 test-raters); and 3) SRUC’s Agriculture students on 25th September 2015 (10 test-raters). This allowed a range of raters to be represented, and included professionals, stockpeople, others involved in the farming industry, and lay people.

On each of the three VAA reliability testing days, the process was first explained to the group and then each test-rater was provided with, and asked to review, a written list of instructions and explanation (Appendix 5). Each test-rater completed a questionnaire prior to VAA scoring, which collected details on the test-rater's current role and experience of working with sheep and making retention and culling decisions (Appendix 6). Amongst the 37 test-raters there were three agricultural consultants; two agriculture researchers; 10 agricultural students; 16 animal science students; four farmers/ owners/ tenants/ farm managers; and two shepherds/ stockpeople. The test-raters were informed that by completing the questionnaires and VAA scoring, they gave consent for their results to be used. No personal information was collected, so test-raters could not be individually identified.

8.2.4 Agreement analysis

Chance-corrected agreement coefficients (AC) were used in agreement analyses to test VAA reproducibility for analyses 1 to 4. These take account of any agreement between raters which may have happened by chance and are therefore more robust and appropriate than simple percentage agreements (Gwet, 2014).

To test agreement between raters various methods were considered. Cohen's Kappa (Cohen, 1960), and the weighted version (Cohen, 1986), were rejected for use with this data due to limitations known as the kappa paradoxes (Feinstein and Cicchetti, 1990; Gwet, 2014; Marasini et al., 2016; Wongpakaran et al., 2013). Also, Cohen's Kappa is only appropriate for up to two raters. Therefore other AC calculation methods were considered. Gwet's AC1 and AC2 (Gwet, 2008) were selected for use. These ACs from Gwet (2008), while not being widely used, have been demonstrated to be superior to Cohen's Kappa (Gwet, 2014; Wongpakaran et al., 2013) and are able to generate ACs for multiple raters (Gwet, 2014). These ACs are expressed on a scale of 0 to 1 where 1 signifies complete agreement. Through considering and testing different ACs, Gwet's AC2 appeared to be the most appropriate to use. It also gave an AC closest to the actual percentage of agreement and identified significant ACs for all attributes at $P<0.05$.

All VAA attributes were on ordinal scales so percentage agreement and Gwet's AC2, both with ordinal weighting, were used for all agreement analyses. Percentage agreement considers actual agreement and partial agreement (when scores are near on the score scale but not identical) as a proportion of total scores. Gwet's AC2 is then the chance-corrected version of the percentage agreement. All agreement analyses were carried out in R (R Core Team, 2018) using functions by Gwet (2008, accessed from Advanced Analytics, 2010). In order to interpret the level of agreement from Gwet's AC values, Altman's Kappa Benchmark Scale (Altman, 1991) was used (Table 8.2).

Table 8.2 Altman's Kappa Benchmark Scale (Altman, 1991).

Agreement Coefficient	**Strength of Agreement**
< 0.20	Poor
0.21 to 0.40	Fair
0.41 to 0.60	Moderate
0.61 to 0.80	Good
0.81 to 1.00	Very good

To improve readability, the Materials and Methods then Results sections for each of the following five analyses are presented in turn. The Discussion section then covers all five analyses.

8.3 ANALYSIS 1: Inter-rater reliability

8.3.1 ANALYSIS 1: Materials and Methods

Ten Scottish Blackface ewes were selected from the flock to be scored with the VAA by all 37 test-raters. The same 10 ewes were used on all three of the VAA reliability testing days. The 10 ewes were chosen from the flock with the only requirement being that at least one ewe from each age group (2.5 to 7.5 years old at scoring) should be included. Each test-rater had direct access to each ewe and recorded the results themselves on an individual scoring form per ewe (Appendix 7). One ewe at-a-time was separated from the group of 10 and held in a gripping race (Conveyor, DM Handling Systems, Falkirk, UK) for the whole group of test-raters to each score at the same time. After scoring, the ewe was released into a pen outside the shed where scoring was taking place. The only score from the VAA (Table 8.1) that was not on the test-raters scoring form was "soundness of feet" due to the impracticality of doing this score in the restricted area in which scoring took place.

During the reliability testing days, test-raters provided an individual score for each of the eight incisor teeth. The number of teeth that received scores of "sound adult tooth present" and "sound lamb tooth present" were later counted to make the "Teeth present" score per ewe per test-rater. A "sound" tooth was one that was not loose or missing.

The "Udder damage" score was determined after scoring from test-raters provided a score for both halves of the udder and any abnormalities or damage present.

As a result of the "Information about VAA test-raters questionnaire" (Appendix 6) test-raters results were grouped according to their retention and culling decision making experience as: "Selectors", "Advisors" and "Lay People" (Table 8.3). Agreement of scoring between test-raters within each of these groups was analysed (via Gwet's AC2) to evaluate the inter-rater reliability. Chi-squared tests were carried out on counts of scores to determine where differences in distributions existed.

The written list of instructions for test-rates (Appendix 5) stated that "If you do not feel you have the expertise to assign a score (such as face shape), just leave blank". Those "missing" scores remained in the dataset during analysis. However "Face shape" was removed during agreement analysis for Advisors and Lay People due to the lack of scores recorded. Only 43 "Face shape" scores were recorded from these two groups out of a possible total of 270 scores (10 ewes scored by 27 Advisor and Lay People).

Table 8.3 Groupings of test-raters based on retention and culling decision experience, identified in answer to the question: “In your lifetime what is the highest level of responsibility you have had with selecting which ewes are kept in a flock for the following year”.

Test-rater group	**Experience (answers from questionnaire)**	**Number of raters**
Lay People	Not involved with deciding ewes to keep	15
Advisors	Advice which sheep to keep but others make the final decision	12
Selectors	Solely responsible or take advice from others but make the final decision	10

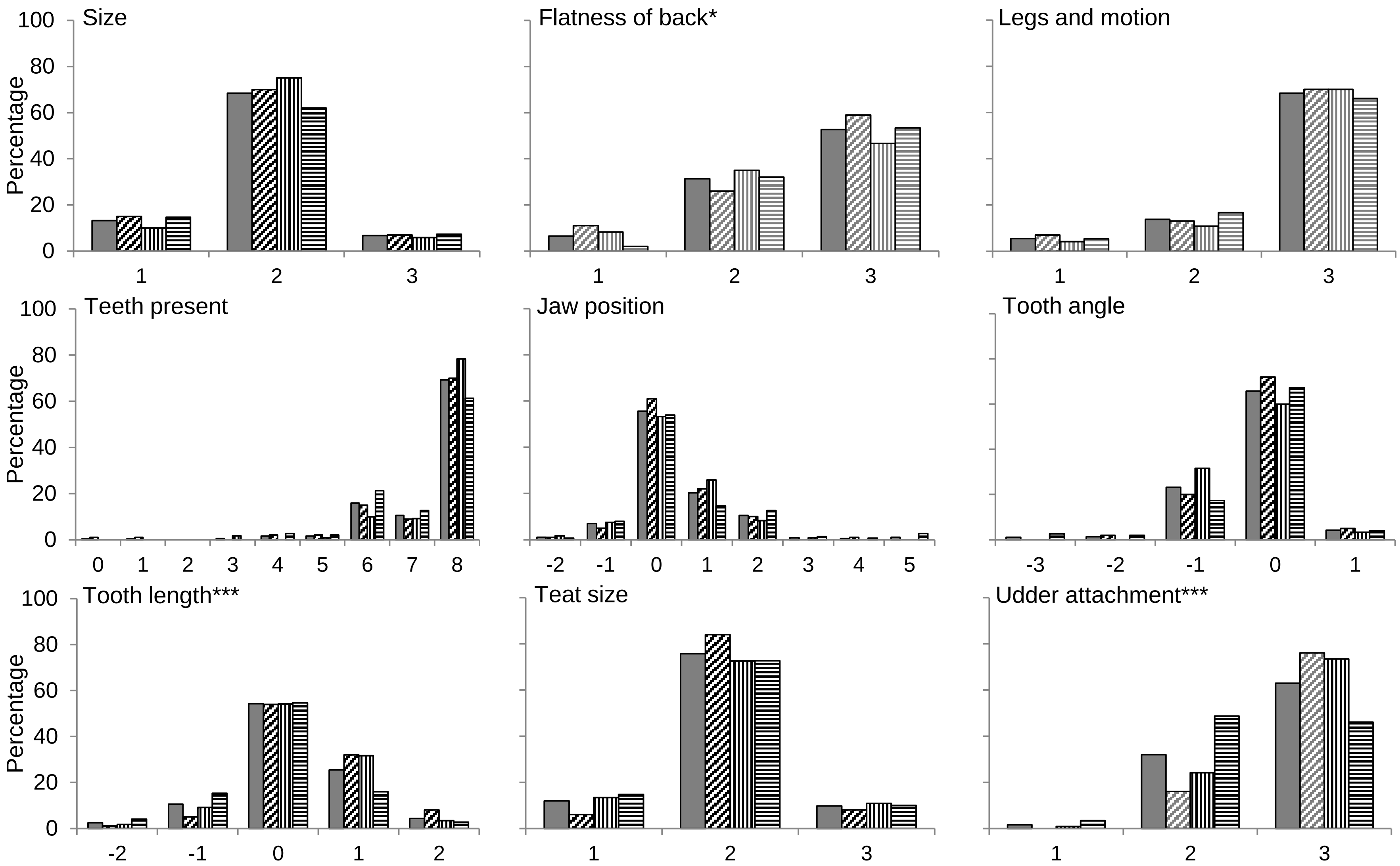
8.3.2 ANALYSIS 1: Results

Figure 8.2 shows the distribution and range of scores assigned for each attribute by the three different groups of test-raters (Selectors, Advisors and Lay People) carrying out the VAA on the 10 ewes. The total possible number of scores recorded against any single attribute was 370 (37 test-raters scoring 10 ewes). Eleven attributes had over 95 % of the total scores possible recorded, while “Face shape” had the lowest (only 31 % of scores).

The distribution of scores were different between the three groups of test-raters for the attributes: “Flatness of back” (P<0.05), “Tooth length” (P<0.001), “Udder attachment” (P<0.001), “Udder damage” (P<0.001), “Face colour” (P<0.001), “Face shape” (P<0.05), “Fleece length” (P<0.001) and “Retention decision” (P<0.01).

Agreement (as determined by Gwet’s AC2) between all test-raters, ranged from 0.33 (for “Face shape”) to 0.93 (for “Teeth present”, Table 8.4). Twelve out of the 15 attributes had good to very good strength of agreement (Table 8.2).

Table 8.4 also shows that the three different groups of test-raters had different strength of agreement (Gwet’s AC2) across the different VAA attributes. Selectors had a good to very good levels of agreement for 12 out of 18 attributes, followed by 11 for Advisors and 10 for Lay People.


Size
Flatness of back*
Legs and motion
Teeth present
Jaw position
Tooth angle
Tooth length***
Teat size
Udder attachment***
Percentage
Percentage
Percentage

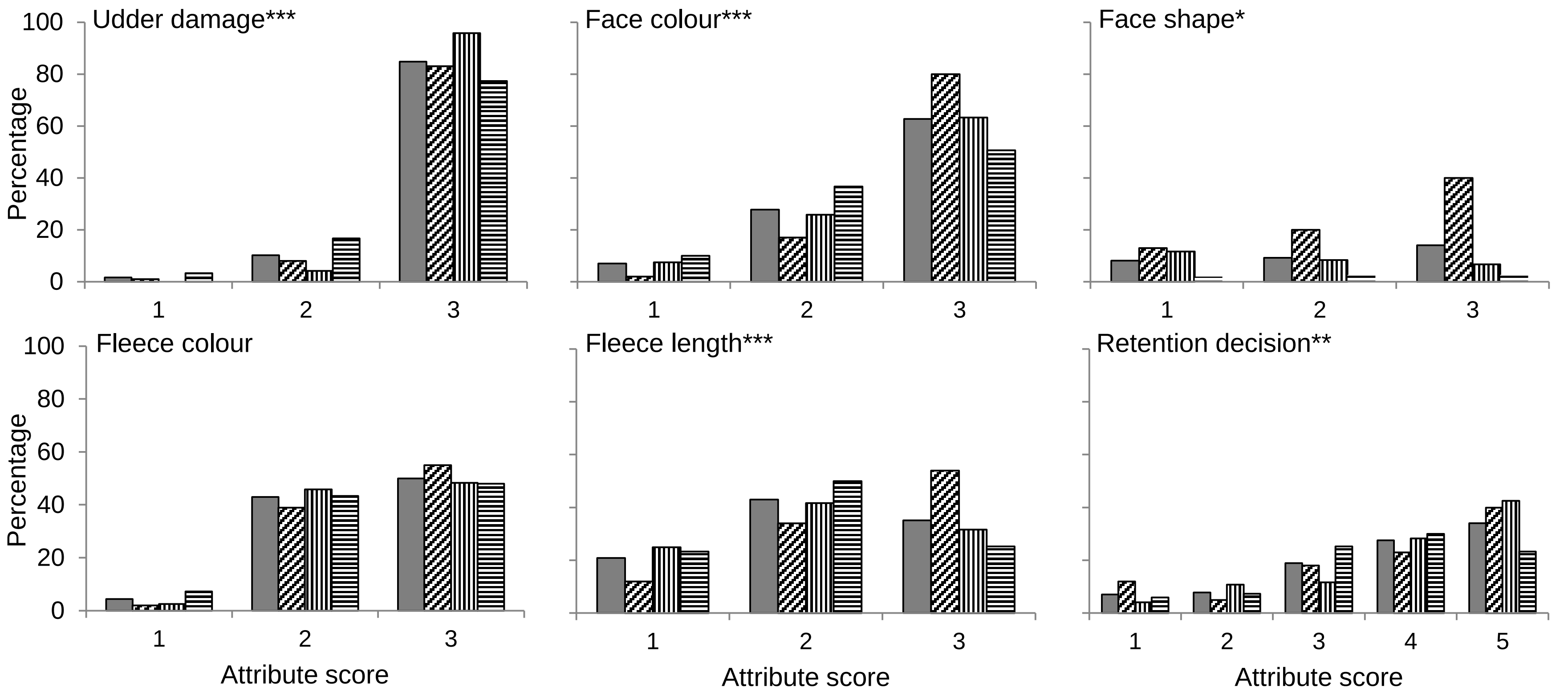


Figure 8.2 Distribution of scores for each Visual Appearance Assessment attribute as a percentage of the total scores available for each group of raters (all raters, Selectors, Advisors and Lay People). Difference in score counts between the three groups of raters shown for each attribute when: *P<0.05, **P<0.01 and ***P<0.001, according to a Chi-squared test.

Table 8.4 Between test-rater percentage agreement and Gwet's Agreement Coefficient (with ordinal weighting, AC2) for each attribute of the Visual Appearance Assessment (SE in brackets). All Gwet's AC2 values shown were significant (P<0.05).

	All		Selectors		Advisors		Lay People	
	Percent agreement	Gwet's AC2	Percent agreement	Gwet's AC2	Percent agreement	Gwet's AC2	Percent agreement	Gwet's AC2
Structural soundness								
Size	89	0.83 (0.03)	88	0.82 (0.04)	91	0.88 (0.04)	87	0.78 (0.04)
Flatness of back	82	0.63 (0.07)	79	0.59 (0.11)	80	0.57 (0.11)	86	0.73 (0.05)
Legs and motion	85	0.78 (0.08)	82	0.72 (0.11)	87	0.81 (0.09)	88	0.80 (0.09)
Mouth condition								
Teeth present	96	0.93 (0.03)	94	0.89 (0.05)	94	0.91 (0.04)	89	0.77 (0.07)
Jaw position	94	0.86 (0.02)	94	0.88 (0.03)	91	0.79 (0.04)	91	0.80 (0.04)
Tooth angle	94	0.90 (0.02)	92	0.87 (0.04)	84	0.69 (0.07)	92	0.87 (0.03)
Tooth length	89	0.77 (0.04)	93	0.86 (0.03)	90	0.78 (0.04)	87	0.72 (0.06)
Udder condition								
Teat size	88	0.81 (0.04)	92	0.90 (0.03)	86	0.78 (0.06)	87	0.79 (0.06)
Udder attachment	84	0.71 (0.04)	74	0.63 (0.12)	87	0.79 (0.05)	80	0.61 (0.03)
Udder damage	91	0.88 (0.02)	93	0.92 (0.04)	93	0.92 (0.05)	85	0.78 (0.04)
Breed characteristics								
Face colour	82	0.66 (0.11)	91	0.87 (0.07)	83	0.68 (0.12)	78	0.52 (0.10)
Face shape	74	0.33 (0.10)	85	0.65 (0.14)	58		50	
Fleece colour	83	0.65 (0.04)	89	0.78 (0.05)	84	0.68 (0.04)	79	0.56 (0.05)
Fleece length	77	0.41 (0.07)	79	0.55 (0.10)	79	0.45 (0.09)	77	0.43 (0.07)
Retention decision	81	0.44 (0.08)	79	0.40 (0.16)	82	0.52 (0.1)	82	0.45 (0.06)

8.4 ANALYSIS 2: Intra-rater reliability of test-raters

8.4.1 ANALYSIS 2: Materials and Methods

In the process of scoring on reliability testing days, the 37 test-raters carried out the VAA twice on two ewes from the original 10. Test-raters were not given warning this was to occur and so believed they had scored 12 different ewes. The same two ewes were used as the repeats across all three reliability testing days. The two ewes were selected as the first two to be scored on the first testing day. Stockpeople assisting in handling the ewes for the testing days could visually identify the two ewes to be scored twice. After the first scoring, the stockpeople brought the "repeat" ewes around the back of the shed and added them unseen back into the holding pen with the remainder of the group yet to be scored. Few raters identified they had scored the same ewe twice.

Where a test-rater failed to record a score for a particular "repeat" ewe on either the first, second or both repetitions, the attribute affected was removed for that ewe and that test-rater from the dataset for agreement analysis.

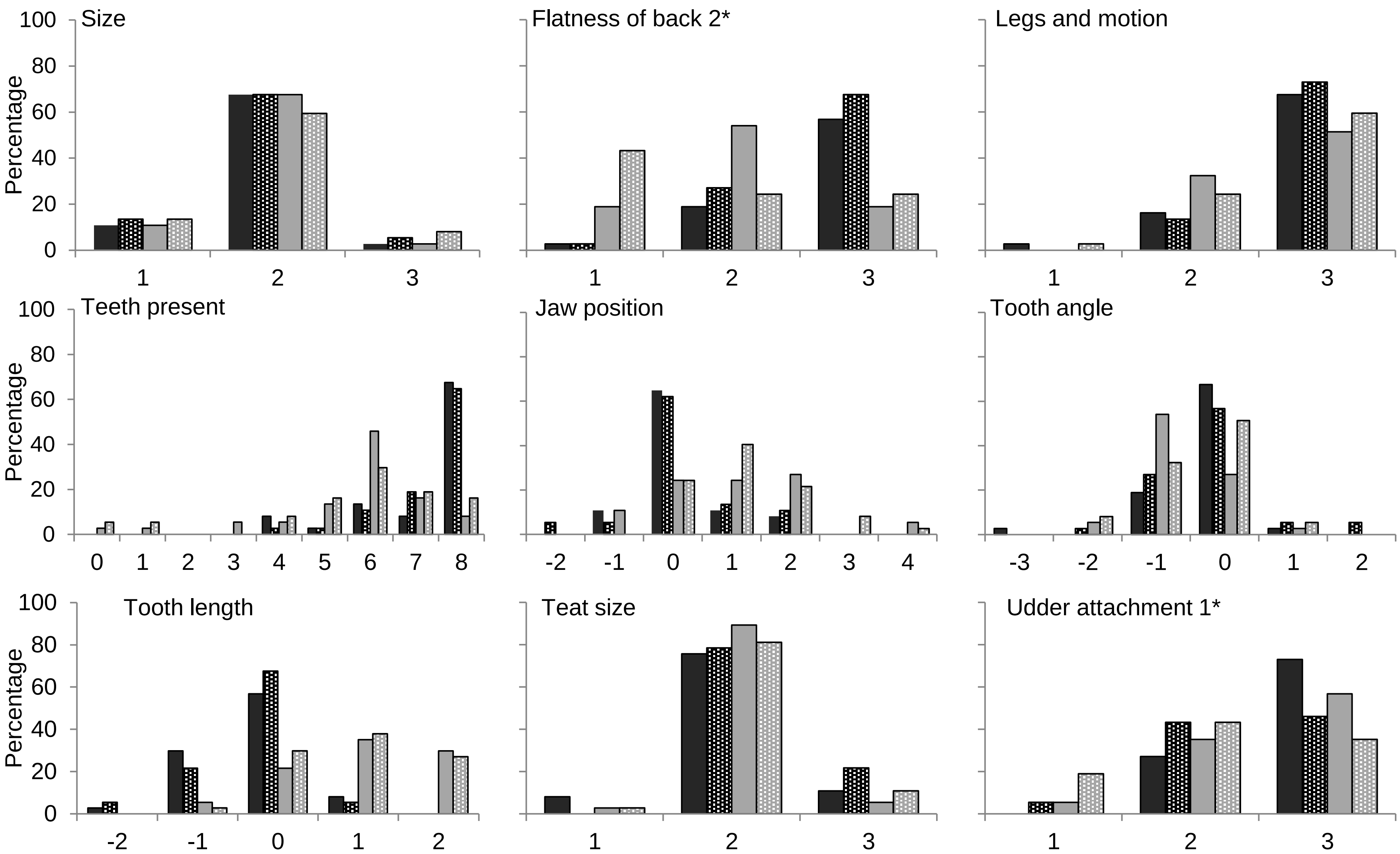
Agreement of scoring between first and second scores within test-raters was analysed (via Gwet's AC2) to evaluate the intra-rater reliability. Chi-squared tests were carried out on counts of scores to determine where differences in distributions existed.

8.4.2 ANALYSIS 2: Results

The distribution of scores recorded for each of the two repeated ewes was similar for the majority of attributes (12 out of the 15 attributes $P>0.05$, Figure 8.3). However, there was a difference in distributions between first and second scores for "Udder attachment" for ewe 1 ($P<0.05$) and "Flatness of back" and "Udder damage" for ewe 2 ($P<0.05$). Gwet's AC between the first and second scores showed that 9 out of 15 attributes had very good strength of agreement (Table 8.5).

Table 8.5 Within test-rater percentage agreement and Gwet's Agreement Coefficient (with ordinal weighting, AC2), for each attributes of the Visual Appearance Assessment (SE in brackets). All Gwet's AC2 were significant (P<0.05).

	Percent agreement	Gwet's AC2
Structural soundness		
Size	94	0.91 (0.03)
Flatness of back	87	0.69 (0.08)
Legs and motion	89	0.83 (0.05)
Mouth condition		
Teeth present	97	0.92 (0.02)
Jaw position	92	0.81 (0.05)
Tooth angle	94	0.87 (0.04)
Tooth length	89	0.70 (0.05)
Udder condition		
Teat size	91	0.88 (0.04)
Udder attachment	78	0.54 (0.08)
Udder damage	86	0.82 (0.06)
Breed characteristics		
Face colour	88	0.75 (0.06)
Face shape	93	0.81 (0.09)
Fleece colour	89	0.82 (0.04)
Fleece length	88	0.73 (0.06)
Retention decision	89	0.65 (0.08)


Size
Flatness of back 2*
Legs and motion
Teeth present
Jaw position
Tooth angle
Tooth length
Teat size
Udder attachment 1*
Percentage
0
20
40
60
80
100
1
2
3
0
1
2
3
4
5
6
7
8
-3
-2
-1
0
1
2
3
4

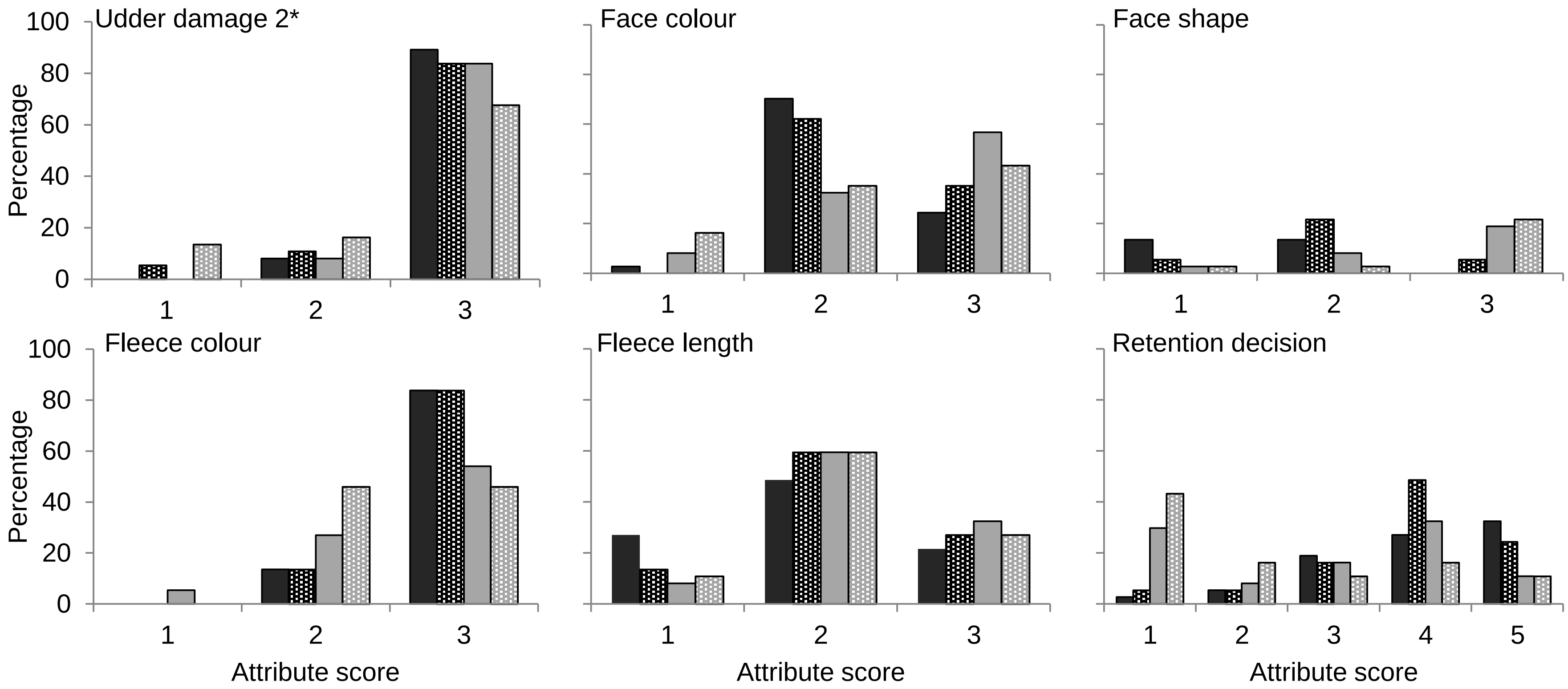


Figure 8.3 Distribution of first (■ ewe 1 and ■ ewe 2) and second (■ ewe 1 and ■ ewe 2) scores for the same two ewes, for each Visual Appearance Assessment attribute, as a percentage of the total scores available for each sheep per time scored. Difference in score counts between the first and second shown for each attribute and each ewe: 1*= P<0.05 for ewe 1; 2*P<0.05 for ewe 2, according to Chi-squared tests.

8.5 ANALYSIS 3: Intra-rater reliability of the Flock Manager

8.5.1 ANALYSIS 3: Materials and Methods

When carrying out the VAA on the whole flock during stockdraw in 2013 and 2014 (data used in Chapter 9) the Flock Manager had the VAA printed and visible when scoring each ewe (Appendix 8). The Flock Manager called out each score (or score description) which was recorded against the individual ewe.

The Flock Manager scored each half of the udder and each tooth, which were later translated into "Udder attachment" and "Teeth present". However, a slight variation of the "Teeth present" score, compared to during reliability testing days, was that the Flock Manager considered a tooth to be sound for gaps where a juvenile tooth had fallen out and the adult tooth was yet to erupt. The Flock Manager also commented if any teeth were broken, twisted or worn-down, these were not considered "sound" and so were not included in the "Teeth present" score.

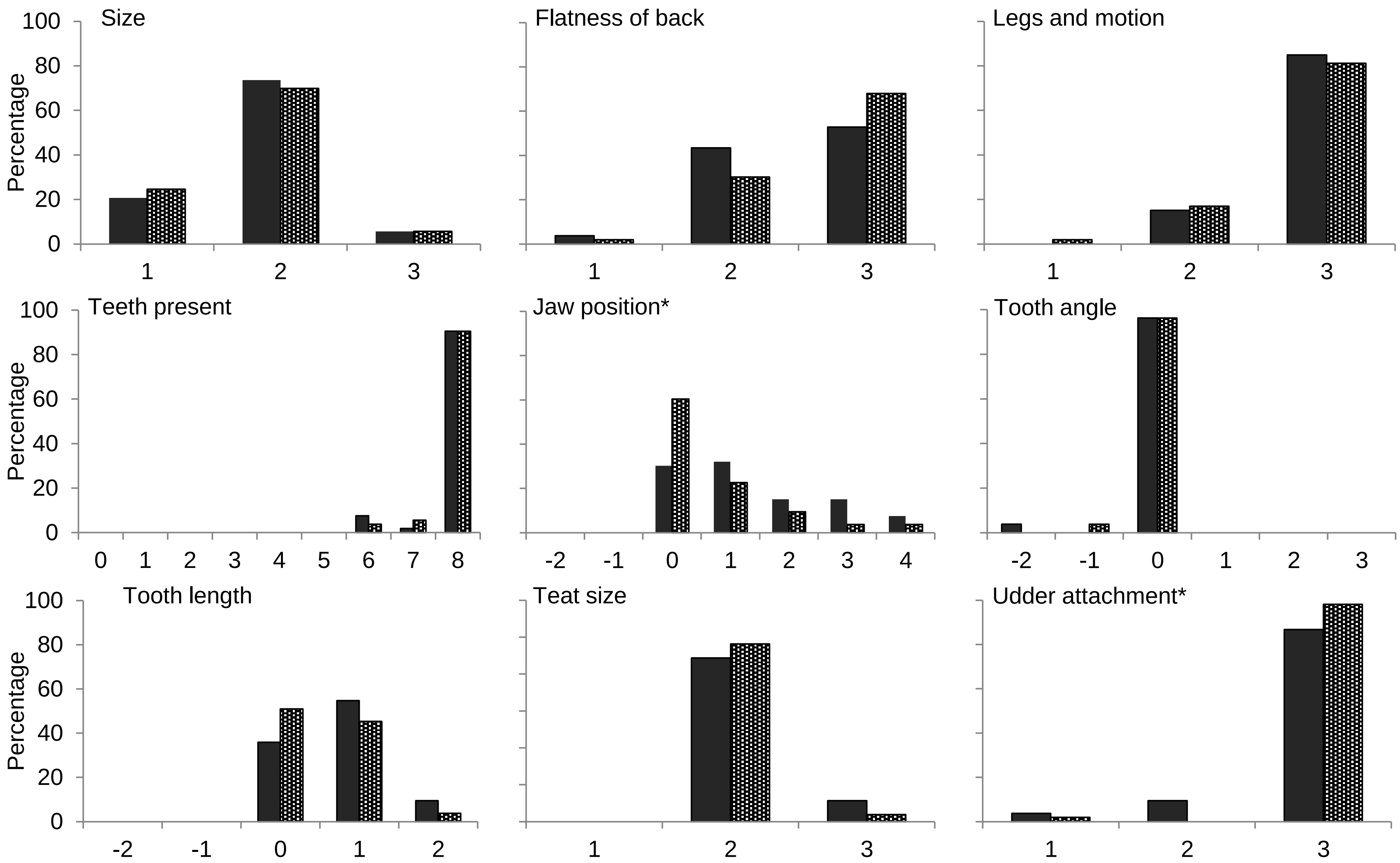
The Flock Manager carried out the VAA on 53 ewes twice on the 23rd September 2014, during the whole flock stockdraw for that year. In total 444 ewes underwent VAA during the day with the 53 repeat ewes being a sub-group of the bigger group that was scored in the morning and then mixed in with the ewes scored in the afternoon. The Flock Manager had been informed (prior to stockdraw beginning) that a selection of ewes would be scored twice, but identities of repeat ewes were unknown to the Flock Manager. Afterwards the Flock Manager confirmed the repeat ewes were not recognised and was not aware any were being assessing any for a second time. Agreement of scoring between first and second scores was analysed, via Gwet's AC2, to evaluate the intra-rater reliability. Chi-squared tests were carried out on counts of scores to determine where differences in distributions existed.

8.5.2 ANALYSIS 3: Results

The distribution of the first and second scores for the 53 ewes (scored twice by the Flock Manager) were similar across most attributes ($P>0.05$, Figure 8.4). The attributes "Jaw position" and "Udder attachment" had a different score distribution between the first and second scores ($P<0.05$). Gwet's AC showed that, apart from "Face shape", all VAA attributes had good to very good strength of agreement (Table 8.6). "Face colour" had 100 % agreement between the first and second score recorded for each of the 53 ewes.

Table 8.6 Within Flock Manager percentage agreement and Gwet's Agreement Coefficient (with ordinal weighting, AC2) for attributes of the Visual Appearance Assessment (SE in brackets). All Gwet’s AC2 were significant ($P<0.05$).

	Percent agreement	Gwet's AC2
Structural soundness		
Size	92	0.87 (0.04)
Flatness of back	89	0.80 (0.04)
Soundness of feet	96	0.96 (0.03)
Legs and motion	97	0.96 (0.02)
Mouth condition		
Teeth present	96	0.95 (0.03)
Jaw position	91	0.76 (0.05)
Tooth angle	97	0.97 (0.02)
Tooth length	87	0.73 (0.06)
Udder condition		
Teat size	92	0.91 (0.05)
Udder attachment	95	0.94 (0.03)
Udder damage	96	0.96 (0.03)
Breed characteristics		
Face colour	100	1.00 (0.00)
Face shape	82	0.58 (0.10)
Fleece colour	89	0.80 (0.08)
Fleece length	91	0.83 (0.05)
Retention decision	91	0.81 (0.04)


Size
Flatness of back
Legs and motion
Teeth present
Jaw position*
Tooth angle
Tooth length
Teat size
Udder attachment*
Percentage
0
20
40
60
80
100
1
2
3
4
5
6
7
8
-2
-1

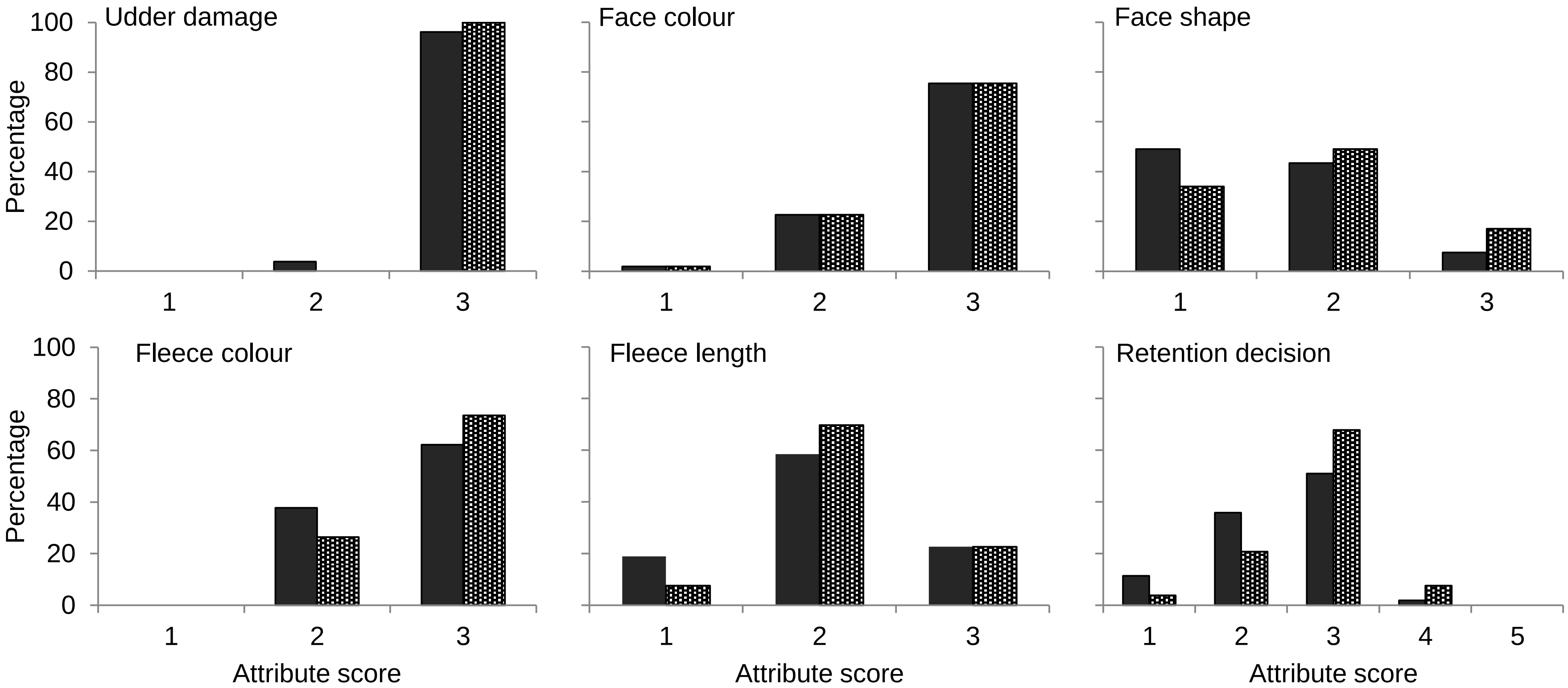


Figure 8.4 Distribution of Flock Manager's first (■) and second (▩) scores for each Visual Appearance Assessment attribute, as a percentage of the total number of ewes per round of scoring. Difference in score counts between the first and second scores shown per attribute when *P<0.05, according to a Chi-squared test.

8.6 ANALYSIS 4: Flock Manager comparison with test-raters

8.6.1 ANALYSIS 4: Materials and Methods

The Flock Manager also carried out the VAA on the 10 test-ewes, at the same time and in the same way as the group of test-raters on the 18th September 2015. The Flock Manager did not provide any indication of the ewe scores assigned, to the other raters.

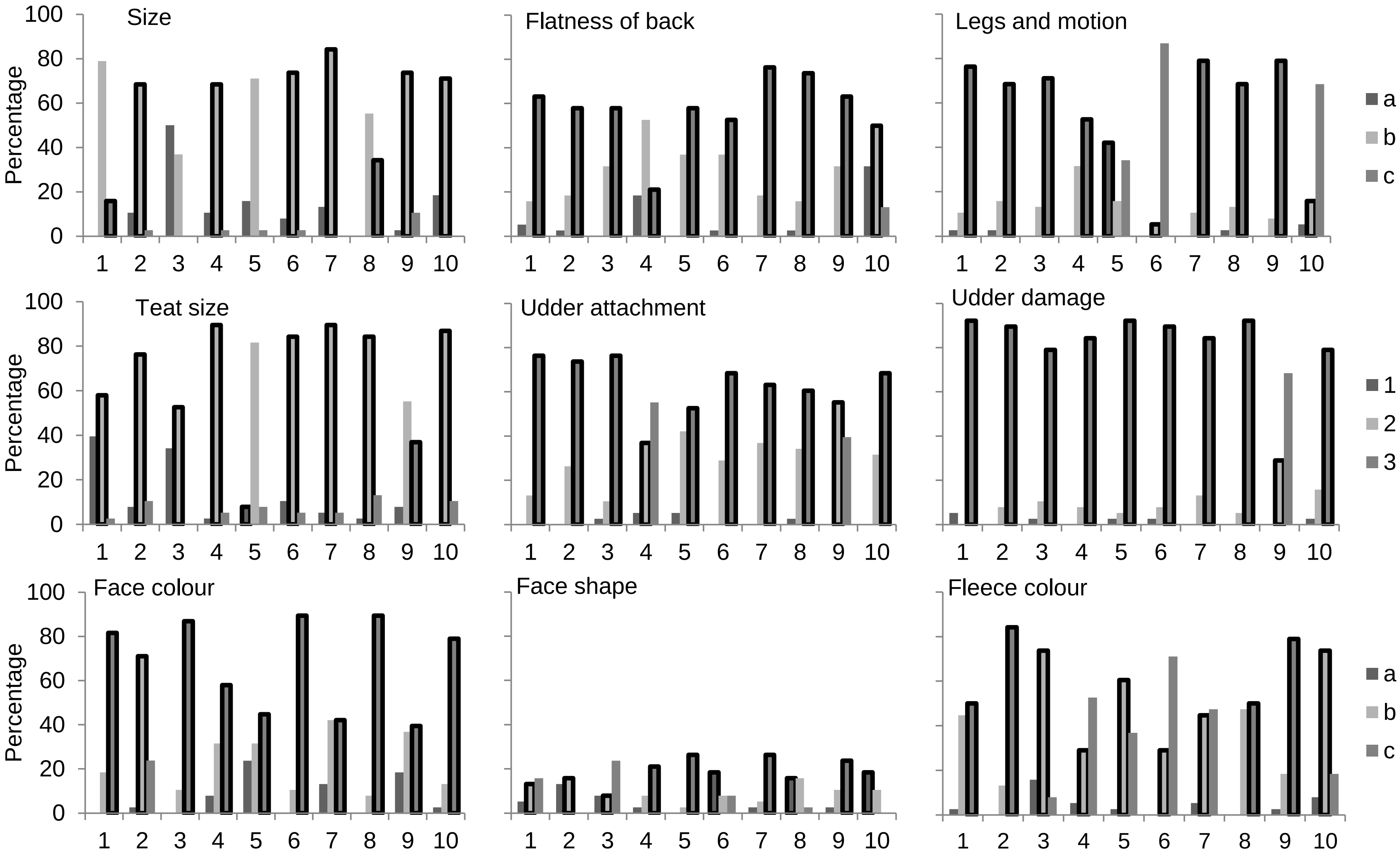
Agreement of scoring between the test-raters and the Flock Manager's scores was analysed (via Gwet's AC2), to evaluate reliability.

8.6.2 ANALYSIS 4: Results

The Flock Manager gave a score that was the mode for all test-raters for a ewe 110 times out of 150 (10 ewes scored on 15 attributes), or 73 % of the time (Figure 8.5). However, for the attribute "Retention decision" the Flock Manager only recorded the same score as the test-raters mode for two out of the 10 ewes. This is reflected when Gwet's AC were calculated between the Flock Manager's scores and all other test-raters. Indeed, "Retention decision" only received a fair strength of agreement (0.25 AC; Table 8.7). All other attributes had moderate to very good strengths of agreement.

Table 8.7 Between Flock Manager and test-raters percentage agreement and Gwet's Agreement Coefficient (with ordinal weighting, AC2) for attributes of the Visual Appearance Assessment (SE in brackets). All Gwet’s AC2 were significant ($P<0.05$).

	Percent agreement	Gwet's AC2
Structural soundness		
Size	90	0.84 (0.02)
Flatness of back	85	0.77 (0.02)
Legs and motion	85	0.74 (0.03)
Mouth condition		
Teeth present	97	0.96 (0.01)
Jaw position	96	0.92 (0.01)
Tooth angle	94	0.89 (0.01)
Tooth length	95	0.90 (0.01)
Udder condition		
Teat size	88	0.82 (0.02)
Udder attachment	88	0.80 (0.02)
Udder damage	93	0.92 (0.01)
Breed characteristics		
Face colour	85	0.78 (0.03)
Face shape	82	0.52 (0.06)
Fleece colour	86	0.72 (0.02)
Fleece length	78	0.51 (0.04)
Retention decision	79	0.28 (0.04)


Size
Flatness of back
Legs and motion
Teat size
Udder attachment
Udder damage
Face colour
Face shape
Fleece colour
Percentage
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10
a
b
c
1
2
3

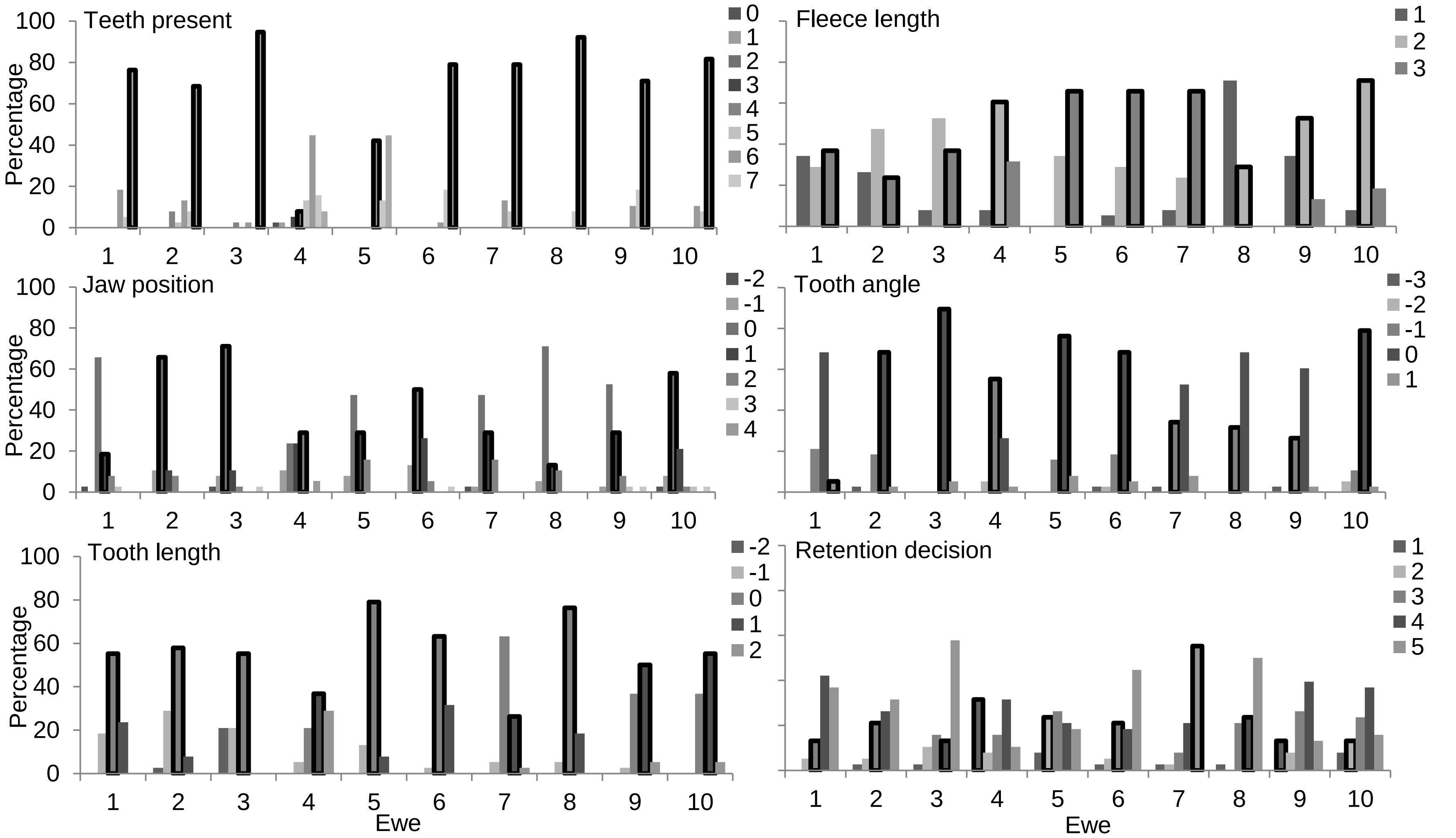


Figure 8.5 Distribution of score per sheep for all test-raters (percentage of the number of raters) for each Visual Appearance Assessment attribute, with the Flock Manager's single score identified by thick black border outlining the relevant bars.

8.7 ANALYSIS 5: Test-raters review of attributes

8.7.1 ANALYSIS 5: Materials and Methods

After scoring was completed on reliability testing days, all 37 test-raters completed a questionnaire (Appendix 9) that collected their opinions on the attributes included in the VAA. Responses were collected to the question: “How good an indicator do you believe each trait is on how the ewe performs the following year”. There were five possible options for each attribute, which were: “Very good indicator”, “Good indicator”, “Neutral”, “Poor indicator” and “Very poor indicator”. A “Very good indicator” was selected for attributes where the rater believed a good score would indicate good performance by the ewe the following year and a poor score would indicate poor performance. Likewise, for attributes that the rater believed would not indicate performance the following year (irrespective of score), a “Very poor indicator” response was given. It was the test-raters’ own interpretation as to what a “good” or “bad” score for each attribute meant. Responses were assigned a value of 1 (for “Very poor indicator”) to 5 (for “Very good indicator”). These values were then added together just for Advisors and Selectors.

8.7.2 ANALYSIS 5: Results

Eleven out of 15 attributes received 15 or more responses of “Good indicator” or “Very good indicator”, from the 22 Advisors and Selectors. This high level of positive responses is reflected in the high accumulated scores seen in Figure 8.6. The three attributes believed by test-raters to be the best indicators of future ewe performance were “Udder damage”, “Teeth present” and “Legs and motion”. Conversely, the three attributes that were believed to be the poorest indicators were all from “Breed characteristics” (“Face colour”, “Face shape”, “Fleece colour” and “Fleece length”). All other attributes received between 64 and 91 (out of a possible maximum of 110) accumulated scores for responses. “Retention decision” had the fifth lowest accumulated score (at 75), although 15 (out of 22) test-raters still gave a response of “Good” or “Very good”.

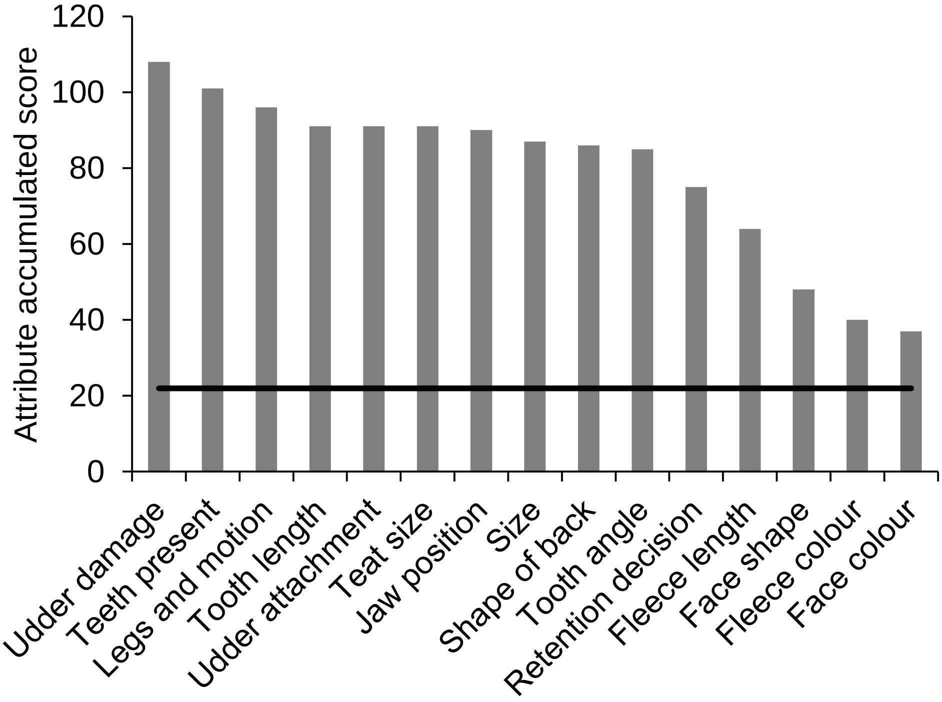


Figure 8.6 Selector and Advisor test-raters response for each attribute to the question “How good an indicator do you believe each trait is on how the ewe performs the following year?” Values for responses were added together to give the accumulated score (“Very poor” = 1, “Poor” = 2, “Neutral” = 3, “Good” = 4 and “Very good” = 5), where the maximum accumulated score possible was 110. The line shows the total if all respondents gave the minimum score of “Very poor” for the attribute.

8.8 Discussion

The VAA presented in this chapter, to my knowledge, is the first scoring system of its kind. It is unique because it aims to quantify appearance of breeding ewes by taking into account the attributes a stockperson might usually be considering when making retention and culling decisions. Through findings in Chapter 6, the VAA is believed to successfully capture all the main elements considered by the stockperson at stockdraw.

With retention and culling decisions often being based just on the visual appearance of the ewe (Chapter 6), the VAA was primarily developed to investigate whether any of these attributes were associated with the future performance of the ewe (as will be explored in Chapter 9). However, when producing any scoring system, reliability testing is important to understand the variability between raters, and therefore highlighting the quality of data produced by the system (as discussed in Gwet, 2014). Hence it was appropriate to test the VAA across a range of raters, including those with little or no experience of making retention and culling decisions (Lay People). Moreover, as the VAA data used in Chapter 9 were all assigned by one rater (the Flock Manager), it was important not only to test the quality of data the Flock Manager produced (intra-rater reliability) but also how representative of other raters the Flock Manager was.

8.8.1 Agreement of scoring

In general, across all inter- and intra-rater reliability comparisons, the strength of agreement was good or very good for most VAA attributes. The data produced by the VAA can therefore be considered reproducible. However, while agreement seemed good, the distribution in scores was sometimes significantly different. Therefore the VAA, while containing good accuracy, may suggest a lack of precision in scoring.

Across all rater comparisons, the “Mouth condition” attributes had higher agreement than other attributes. This may be because “Mouth condition” attributes had more objective scoring systems compared to other more subjective attributes. An improvement of the VAA, to increase reproducibility, would be to alter score description so they are more objective (for example, for attribute “Size” a height measurement of the “ideal” score could be provided).

The subjective attribute of “Retention decision” ranged between fair strength of agreement (for Flock Manager compared to all test-raters, Table 8.7) to very good (for within Flock Manager, Table 8.6). The Flock Manager tended to assign lower scores for “Retention decision” for individual ewes compared to all other test-raters. It is unclear why this would be, particularly when the Flock Manager’s score was most frequently the test-raters mode score for all other attributes (Figure 8.5). Furthermore, even within the Flock Manager’s scores (when 53 ewes were scored twice) the distribution between first and second scores for “Retention decision” was almost significant (P=0.07, Figure 8.4). This is interesting because the “Retention decision” attribute is the closest representation as to what would occur on farm (with a stock person making a culling decision based on a subjective opinion) but is the most variable of attributes, largely because it is so unspecified.

The lower strength of agreement of the “Retention decision” could be the result of some raters considering other attributes about the ewe that were not captured by the VAA. It is unknown what such attributes may be, however a possible option could be that raters were considering the general demeanour of the animals such as “alertness” or “brightness” (such as recorded by van Heelsum et al 2006).

8.8.2 Rater group comparison

Raters with greater retention and culling decisions making experience had higher levels of agreement compared to those with less experience (Selectors had a good to very good strength of agreement for 12 out of 15 attributes, followed by 11 for Advisors and 10 for Lay People). However Lay People still performed well compared with the other groups of raters. This suggests that the VAA was detailed enough to be used by naïve raters, which increases the application potential when an experienced stockperson is not available to collect VAA data. Other literature, exploring the reliability of visual assessments, have also shown the importance of trialling across raters with different levels of experience (Kaler et al., 2009; Phythian et al., 2013).

The attributes where Lay People had the poorest agreement level were “Breed characteristics”. These attributes often had the lowest level of agreement for all agreement comparisons, particularly for “Face type”. In fact “Face type” had high instances of being left blank, particularly from Advisors and Lay People groups. This lack of scoring was likely because raters did not know the difference between the scores. This is unsurprising as raters had to know “Face type” characteristics in order to provide a score. Out of all the raters only 43 % stated they had experience with Scottish Blackfaces and the majority of these were also within the Selectors raters group. Therefore, if breed characteristics are desired, more description for attributes is required, photographs could also be used instead of written descriptions. While all other groups of attributes could be applicable to any breed of sheep, the “Breed characteristics” would need to be altered to reflect the breed being assessed.

Conversely to the “Face shape” attribute, “Teeth present” often had the highest level of agreement for different rater comparisons. Disagreement would occur over what constituted a “sound” or “unsound” tooth, hence complete agreement was not necessarily expected. This attribute also received 100 % recorded scores from raters but this was an artefact of the scoring method, which required raters to leave tooth number blank if it was “sound”. Therefore, it was impossible for a rater not to record a score for this attribute. A future improvement to this attribute scoring system could be for raters to specify sound tooth number.

The Flock Manager mostly agreed with the mode score from test-raters for each ewe, which provides evidence that results from the Flock Manager was comparable to others. Indeed the reliability of Flock Manager scores was further strengthened by the good to very good strength of agreement within themselves. This means that the scores used for exploring future ewe performance in the next chapter can be considered reliable.

8.8.3 Evaluation of agreement analysis used

Previous research has frequently used Cohen’s Kappa (Cohen, 1960), or the weighted version (Cohen, 1986), to test agreement of visual assessment scores and scales (for example, Foddai et al., 2012; Kaler et al., 2009; Main et al., 2000). However the limitations of these, known as the kappa paradoxes, have been well documented (Feinstein and Cicchetti, 1990; Gwet, 2014; Marasini et al., 2016; Wongpakaran et al., 2013). Briefly, the paradoxical behaviour is associated with how the kappa statistic is calculated and can result in the coefficient being unexpectedly low (Feinstein and Cicchetti, 1990). The kappa struggles to identify agreement if scoring is unbalanced or where scoring is on an ordinal scale, and agreement should be higher for scores that are next to each other than if they were further apart (Feinstein and Cicchetti, 1990; Gwet, 2014; Marasini et al., 2016).

Gwet's AC was used to test agreement within this chapter as it had been presented as a paradox-resistant alternative to the kappa statistic (Gwet, 2014). Only a few examples could be found where Gwet's AC2 had previously been used within animal based research: two for diagnostic techniques in sheep (Ait Lbacha et al., 2017; Czopowicz et al., 2017) and one used for horse studies (Axling et al., 2016). Current use seems to be most prevalent within medical professions focusing on human subjects (for example, Crowle et al., 2017; Riley et al., 2017; Salyers et al., 2012; Tesselaar et al., 2016). However, with the evidence that it is a more appropriate method of calculating chance-corrected agreement than Cohen's Kappa (as presented by Czopowicz et al., 2017; Gwet, 2008, 2014; Wongpakaran et al., 2013), it is suitable for the setting applied within this chapter. Therefore, it is proposed for the first time in this thesis that Gwet's AC is an appropriate and useful method of agreement analysis, which may be superior to other methods and should be considered for use within other livestock research testing reliability of visual assessments.

There are a number of factors that question the high level of agreement found in this chapter. When considering the distribution of scores within attribute (Figure 8.2, Figure 8.3 and Figure 8.4), it is clear that some scores are recorded more often than others. Phythian et al. (2012b) found similar results when comparing different raters' scoring of BCS in sheep, where some scores were recorded more often than others. These authors stated that the agreement statistic presumed a normal distribution (Kappa with ordinal weighting was used) and where a narrower range of scores were produced, agreement increased. This could be the case with results from this current chapter. However, Gwet's AC tended to be higher (across all rater comparisons) for "Mouth condition" attributes, which had a wider range of scores than the other more subjective attributes with only three scores. This demonstrates the advantages of Gwet's AC over Cohen's Kappa, in that it is more resistant to unbalanced data (as explained in Czopowicz et al., 2017; Gwet, 2014; Wongpakaran et al., 2013).

8.8.4 Wider application

The limited number of scores available for many attributes was chosen to limit the time required for data collection for the VAA. However, scoring each ewe on the 16 VAA attributes would still be very time consuming. Therefore, if the VAA were to be used for other studies, it would be advisable to only select particular VAA attributes specific to those studies' aims.

8.8.5 Test-raters' opinion of attributes

The majority of test-raters (15 or more out of 22) thought that most of the attributes (11 out of 15) were either good or very good indicators of ewes performance the following year. This consensus of opinion is surprising but promising given that the aim of Chapter 9 is to look for predictors of future performance. Furthermore, this also highlights the potential wider application of the VAA attributes to predict future performance. The "Retention decision" also received a large number of positive responses (15 "Good indicator" or "Very good indicator"), suggesting that test-raters believe those carrying out retention and culling decisions were able to make good decisions regarding whether a ewe will perform well or not the following year. The relevance of that attribute will be considered in Chapter 9.

8.9 Conclusion

This is the first time a complete visual attribute scoring system for breeding ewes at stockdraw has been presented. The scoring of individual visual attributes produced reproducible results, suggesting they could be useful for considering retention and culling decision making both on farm and within research settings. While agreement was good (accurate), there was some variation in some score distributions. This raises the question of the precision for quantifying some of these attributes. Having some retention and culling experience prior to using visual attribute scoring could provide data of higher reliability but is not essential. Further improvements to the visual attribute scoring system include reducing the number of attributes scored, depending on the intended use, and improving objectivity of scoring description for subjective attributes.

Gwet's AC was shown to be an appropriate and useful method of agreement analysis, which may be superior to other methods, and could be considered for use within other livestock research testing reliability of visual assessments.

The Flock Manager had strong intra-rater reliability as well as good strength of agreement to other raters. Therefore scoring data recorded by the Flock Manager and used in the following chapter can be considered comparable between individual ewes within the dataset.

CHAPTER 9: PREDICTING FUTURE EWE PERFORMANCE FROM APPEARANCE, PERFORMANCE AND GENETIC ATTRIBUTES

Chapter 6 demonstrated that stockpeople are using visual traits to make retention and culling decisions on ewes at stockdraw. Chapter 8 showed it was possible to reliably capture these traits on an individual animal basis by using the Visual Appearance Assessment (VAA) developed. This chapter explores whether future ewe performance can be predicted from VAA variables, as well as from more quantitative (and less subjective) variables of recorded performance and EBVs.

Initial stages of this work were presented as a conference proceeding:

Wishart, H., Lambe, N., Morgan-Davies, C., Waterhouse, A., 2016. Brief Communication: Which traits best predict ewe performance and survival the following year on a UK hill farm?, in: Proceedings of the New Zealand Society of Animal Production. Adelaide, Australia, pp. 159–162.

9.1 Introduction

As seen in previous chapters, the appearance of the ewe at stockdraw is of particular consideration when stockpeople are making retention and culling decisions. Some visual attributes have also been shown to be associated with longevity of animals within a breeding flock or herd (Annett et al., 2011; Berry et al., 2005; Mekkawy et al., 2009). However, no literature was found that investigated how future productivity of ewes might be predicted from visual appearance at stockdraw and how this could inform retention and culling decisions.

9.1.1 Prediction tools for sheep systems

In Chapter 2, it was proposed that a PLF approach may be used to inform retention and culling decision making, as also suggested in previous literature (Richards et al. 2013, 2012). A key idea is that, as well as appearance data (such as that collected through VAA in Chapter 8), other information on each ewe could be used to identify high performers that could be kept longer, while less productive ewes could be identified and sold earlier (Richards et al., 2012). With this approach, predictions of how well a ewe would perform the following year could be made at stockdraw, from a selection of predictor variables.

In Australia, there are a number of commercially available prediction tools for sheep systems, which use farm and flock information to inform decision making. For example, there are three online websites to inform whether stockpeople should provide parasite treatment to their flock, for: flystrike (FlyBoss: Horton and Hogan, 2010; Sheep CRC, 2019a); gastrointestinal worms (WormBoss: Sheep CRC, 2019b; van Wyk et al., 2006); and lice (LiceBoss: Horton et al., 2007; Sheep CRC, 2019c). These are just for providing advice on one specific decision; whether to treat animals or not. Another online Australian decision making tool, aims to predict pasture growth, animal performance and health and climate risks, “ASKBILL” uses data collected on farm, climate data and information on animal genetics (Kahn et al., 2017; Sheep CRC, 2019d). Other models, such as wool growth and quality prediction from one year old merino lambs (Shahinfar and Kahn, 2018), are added to this online tool. No similar prediction tools were found for sheep systems anywhere else in the world and those mentioned still appear to be at a group level. None could be found to directly inform retention and culling decision making of individuals.

Within the dairy industry, there are many different computerised models that have been created and researched to assist with the replacement decision problem (Ben-Ari et al., 1983; Cabrera, 2012; Ducrocq et al., 1988; Kelleher et al., 2015; Kristensen, 2003; Stewart et al., 1977; Stott, 1994). However, all of these models and decision support systems are only designed for dairy cattle and cannot be adapted to sheep. Furthermore, their primary uses are for research purposes and modelling different scenarios, without considering suitable predictors of future performance for on-farm application.

9.1.2 Variables to inform retention and culling decision making

Research has been carried out to identify associations and heritabilities between different production variables with longevity and retention and culling (Annett et al., 2011; Kern et al., 2010; Mekkawy et al., 2009). These studies were carried out to inform genetic opportunities within the flock but also to provide information on variables associated with future production. Such variables could be useful in selecting potential predictor variables for developing a PLF approach for sheep.

For instance, Annett et al. (2011) found a range of factors for Scottish Blackface and Scottish Blackface cross breed ewes that were associated with the ewe’s chance of survival to mating. They included: breed, age at mating, BCS, number of missing teeth and average daily liveweight gain per litter. Breed was also found to have a significant effect on length of productive life for four different breeds in Northern Germany, as well as other variables including: number of lambings and age at first lambing and farm effect (Kern et al., 2010). The “Farm” also had a significant impact but this could be the result of different culling protocols, and stockperson judgement, on the individual farms. Mekkawy et al. (2009) found low genetic correlations between longevity and the range of traits investigated, which included: teeth/mouth condition and udder condition. A limitation of all these three studies was that longevity (or the equivalent measure used) was dependent upon the choices made by stockpeople when culling ewes. However, all associated variables suggested in these studies could be considered for inclusion in a PLF approach.

The most promising variables included visual attributes (teeth, mouth and udder condition), as well as attributes that require historical recording of data (age, BCS, liveweight of litter and number of lambings, Annett et al., 2011; Kern et al., 2010; Mekkawy et al., 2009). These can all be considered as potential predictors for consideration within this chapter. Other variables that could also be considered are those detailed as potential measures for PLF in Chapter 2 (Table 2.5), namely: ewe liveweight and liveweight change and production outputs (including: number of lambs scanned and born).

Another set of measures specific to individual ewes are Estimated Breeding Values (EBVs, as introduced in Chapter 2). While their use has been demonstrated to be effective in breeding programmes when applied to hill sheep systems (Conington et al., 2006; Lambe et al., 2014; McLaren et al., 2012), they are mainly used for the purpose of selecting ewe lambs to enter the flock and rams to be bred from. Whether they could be useful for making retention and culling decisions in older females and predicting future performance has not previously been explored.

9.1.3 Measure of ewe performance

How "future performance" is measured first needs to be determined in order to explore prediction potential between variables and ewe future performance. This chapter considers, measures of performance used in previous research: ewe survival (Hickey, 1960; Kenyon et al., 2014; Morgan-Davies et al., 2008; Young et al., 2011), number of lambs weaned (EBLEX, 2008; Kenyon et al., 2014; Young et al., 2011) and liveweight of lambs weaned (Annett et al., 2011, 2010; Young et al., 2011). As a result of the large economic impact of the retention and culling decision making process (as discussed by Cabrera, 2012; Kelleher et al., 2015; Stott, 1994), this chapter will also develop a single monetary value performance measure (in £/ewe). This measure will take into account the incomings and outgoings generated by a ewe over the production year. Generating such a value is a similar idea to the "Cow Own Worth" value developed for dairy cattle by Kelleher et al. (2015).

9.1.4 Aims of chapter

This chapter will provide the first step in developing a PLF approach to inform retention and culling decisions at stockdraw. Its aims are:

1) To create an individual ewe financial value that considers all incomings and outgoings associated with the ewe as a measure of performance over a year of production.
2) To compare a wide range of variables to establish which have stable relationships with future ewe performance and have the potential for being used in a PLF approach for making retention and culling decisions.
3) To present a statistical analysis method that could be used to i) screen and compare a wide range of explanatory and response variables, ii) create models to predict future ewe performance, and iii) evaluate the success of these models.
4) To consider the possibility of a PLF approach for making retention and culling decisions and provide suggestions on how current industry culling protocol practices could be improved.

9.2 Materials and Methods

9.2.1 Data collection

The dataset was composed of four measures of production and net output (response variables) and 55 traits of interest (explanatory variables) as shown in Figure 9.1.

Explanatory variables were collected or collated from individual animals at: stockdraw, the year prior to stockdraw or in previous years, while response variables were collected during the year after stockdraw. Two separate years' worth of data were collected for analysis (as a repeated method and not a longitudinal design, Figure 9.2), and are referred to as the year in which stockdraw was carried out (2013 and 2014). For those ewes remaining in the flock over both years, some 2013 response variable data appeared in 2014 data as explanatory variables.

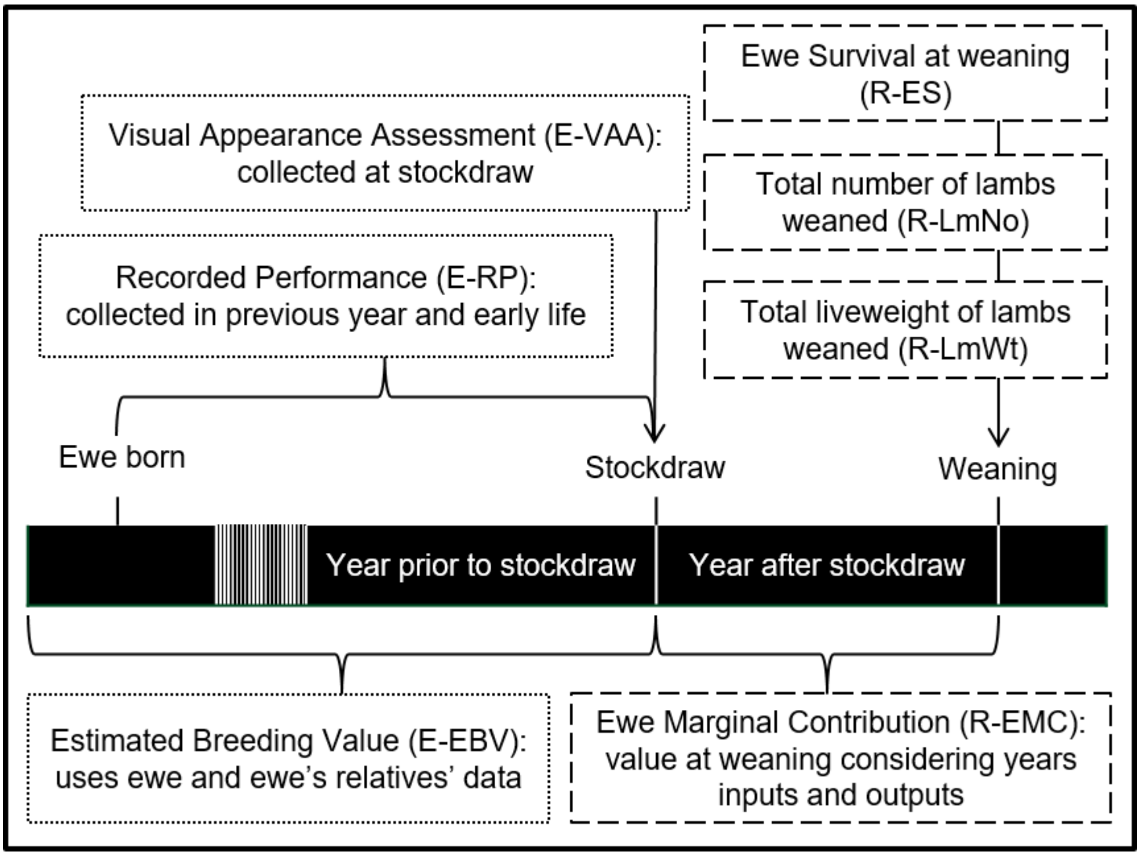


Figure 9.1 Timeline of Explanatory (E, dotted outlined boxes) and Response (R, dashed outlined boxes) variables.

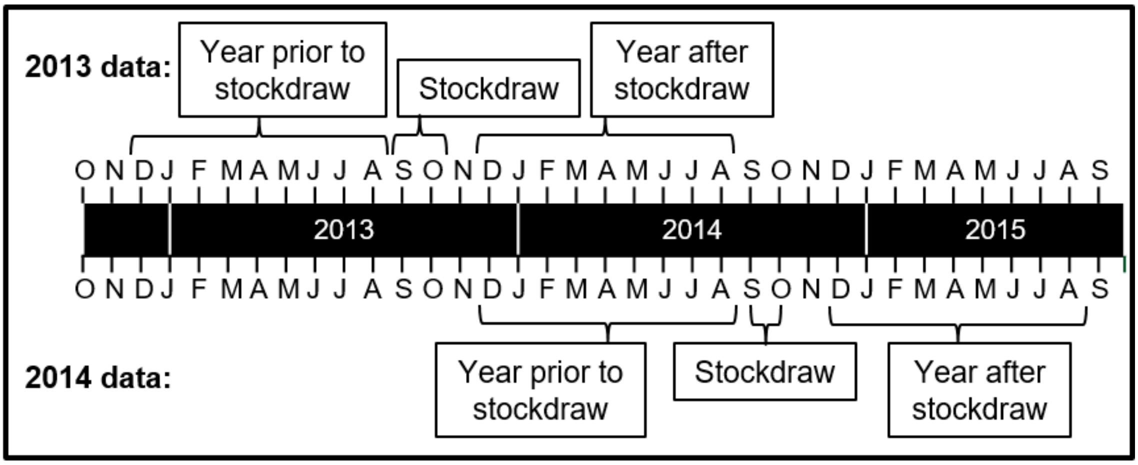


Figure 9.2 Timeline showing when data was collected for two separate years (2013 and 2014).

In total 766 ewe recordings (394 ewes in 2013; and 372 ewes in 2014) were available from 540 ewes. As some animals appeared in both years (226 ewes), years were analysed separately.

Data from Scottish Blackface ewes (in either PLF or CON management approaches, as explained in Chapter 3) were included in the dataset only if ewes met all the following requirements:

- Present and retained in the flock at stockdraw (in 2013 and/or 2014)
- Received VAA scoring at stockdraw
- At least 2.5 years old at stockdraw (and so had the potential to have at least one previous crop of lambs)

Ewes left the flock at stockdraw (2013 or 2014) if they met the predefined rules of the culling protocol (Table 7.1). Final retention and culling decisions were made by the same stockperson throughout this work; the Flock Manager. Data from ewes that were involved in fostering were removed from that year's dataset (22 records).

9.2.2 Response variables

The four response variables (R) per ewe were: Ewe Marginal Contribution (R-EMC, discussed below); Total liveweight of lambs weaned (R-LmWt); Total number of lambs weaned (R-LmNo); and ewe survival to weaning (R-ES). These response variables show ewe performance for the year after stockdraw (Figure 9.1).

One response variable that was initially considered and analysed but rejected was "survival to next pre-mating after weaning", around 14 months after stockdraw. This was considered as it took into account how well the ewe survived culling. However, as the aim was to look at the possibility of being productive over the year following stockdraw, this variable was discarded. Culling decisions are dependent on the opinion of the stockperson (in this case the Flock Manager); therefore focusing on survival until weaning avoided this potential bias.

9.2.2.1 Ewe Marginal Contribution (EMC)

To examine the financial performance of ewes, a final measure of production called Ewe Marginal Contribution (EMC) was developed. The EMC was calculated using each ewe's estimated financial inputs and outputs (excluding labour and fixed costs) and change in value over the year (Table 9.1, with distribution of incoming and outgoing amounts shown in Table 9.2):

EMC = (closing valuation - opening valuation) - (medicinal costs and feed costs) + (income from lambs)

Table 9.1 Values used for calculating the individual ewe financial performance measurement: Ewe Marginal Contribution (EMC).

	Options	Value	Details
Opening valuation	Sound	£ 68.00	per ewe[a]
Outgoing: feed cost		-£ 0.22	per kg[a]
Outgoing: medicinal cost			Different values for individual products administered[bc]
Income: lamb weaned value		£ 1.58	per kg weaned[a]
Closing valuation	Sound	£ 68.00	per ewe[a]
	Unsound	£ 32.78	per ewe[b]
	Dead	-£ 22.20	per ewe[bd]
	Missing	£ 0.00	per ewe[e]

[a]values taken from SAC Farm Management Handbook 2016/17;
[b]values are actual amounts paid/received closest to 2nd December 2016 by SRUC Kirkton Farm;
[c]medicinal costs were calculated on an individual animal basis using SRUC Kirkton farm accounts for unit values, this included all standard flock preventative health treatments (see Appendix 10 for more details) as well as individual antibiotic treatments;
[d]cost of ewe deaths derives from the carcass requiring collection by the knackery;
[e]ewes missing are presumed dead but no cost since no carcass required collection.

Table 9.2 Average individual ewe amounts for two years of data for outgoings and incomings within Ewe Marginal Contribution (EMC) value (with the range from 10th to 90th percentile shown in brackets).

	2013	**2014**	**Overall**
Outgoing: feed cost	£ 5.34 (2.40-7.73)	£ 4.35 (2.03-6.29)	£ 4.86 (2.40-6.98)
Outgoing: medicinal cost	£ 7.75 (4.42-11.32)	£ 8.19 (4.77-11.41)	£ 7.96 (4.63-11.39)
Income: lamb weaned value	£ 40.39 (0-93.50)	£ 47.67 (0-96.85)	£ 43.92 (0-94.89)

"Opening valuations" were determined at 2013 and 2014 stockdraw and "closing valuations" at 2014 and 2015 stockdraw (respective for data year). All ewes received the same opening valuation as all were assessed as suitable for breeding the next year (referred to as "sound"). While different valuation amounts could have been applied to ewes in their different years of production, a single value of £68 was chosen for sound ewes to allow for easier comparison (the same value was used for sound ewes at opening and closing valuation). This value was the cost to buy a Scottish Blackface ewe as published in SAC 2016 Farm Management Handbook 2016/17. If ewes were judged "unsound" (meaning unsuitable or incapable of breeding from within the hill system for another year), their "closing valuation" value was not £ 68 but instead was calculated as the average amount that unsound Blackface ewes from SRUC Kirkton Farm were sold for (at Stirling United Auctions, September and October sales in 2014, 2015 and 2016).

The individual ewe "feed cost" was calculated as the cost of concentrate supplementary feeding over pregnancy (January to April). Feed records maintained at a group level were used to calculate individual feed amount consumed, assuming each ewe within the feeding group consumed equal amounts. Where a record on ewe group allocation was incomplete or incorrect, an average amount of concentrate feed across the whole flock was used for that period, for each individual ewe.

"Medicinal" costs were also calculated at an individual ewe level. At each handling event the ewe (if present) was allocated a medicine cost based on a standard flock treatment regime (see Appendix 10) and at the recommended product dosage (often based on ewe weight). Products and quantities (per sheep or per kg depending on the product) were standardised to ensure results between ewes were comparable. Each medicinal product chosen was the one most often used on the research farm and was priced according to the amount charged closest to 2nd December 2016 (from the farm accounts). Medicinal treatments for each lamb were also calculated in a similar manner and added to their dam's "Medicinal cost". As well as these medicinal preventative health treatments, the number of individual antibiotic treatments was also recorded per ewe across the year and a fixed cost per treatment was added to that ewe's "Medicinal cost".

The majority of treatments of the standard flock treatment regime (as shown in Appendix 10) were for the prevention and treatment of endoparasite (specifically nematodes and fluke) and ectoparasite infestations (specifically ticks and lice). Individual antibiotic treatments were usually given in response to bacterial infections such as foot rot and mastitis.

9.2.3 Explanatory variables

The 55 explanatory variables (E) considered for each of the four response variables (R-EMC, R-LmWt, R-LmNo, R-ES) were grouped into four categories for analysis: Visual Appearance Assessment, collected at stockdraw (E-VAA, 16 variables); Recorded Performance, collected during early life and the year prior to stockdraw (E-RP, 29 variables); Estimated Breeding Values, available at stockdraw (E-EBVs, 10 variables, Figure 9.1); and all three of these sets of explanatory variables were also combined and considered as one group (E-all).

Year and farm specific data (such as sire of lamb, line and management approach, Chapter 3) were excluded from the range of potential explanatory variables so that predictive models produced could be applied to new data. However these variables were considered in preliminary analyses and are not presented here.

9.2.3.1 Visual Appearance Assessment (E-VAA)

The 16 variables of the E-VAA were detailed in Chapter 8 (Table 8.1) and were collected from ewes at stockdraw in 2013 and 2014 (Figure 9.1).

9.2.3.2 Recorded Performance (E-RP)

The 29 E-RP variables were collected during the year prior to stockdraw (PY: Previous Year) and during the ewes' early life (Figure 9.3). They included various indicators of production including: liveweights, liveweight change, BCS, number of lambs produced and liveweight of lambs produced as well as ewe age.

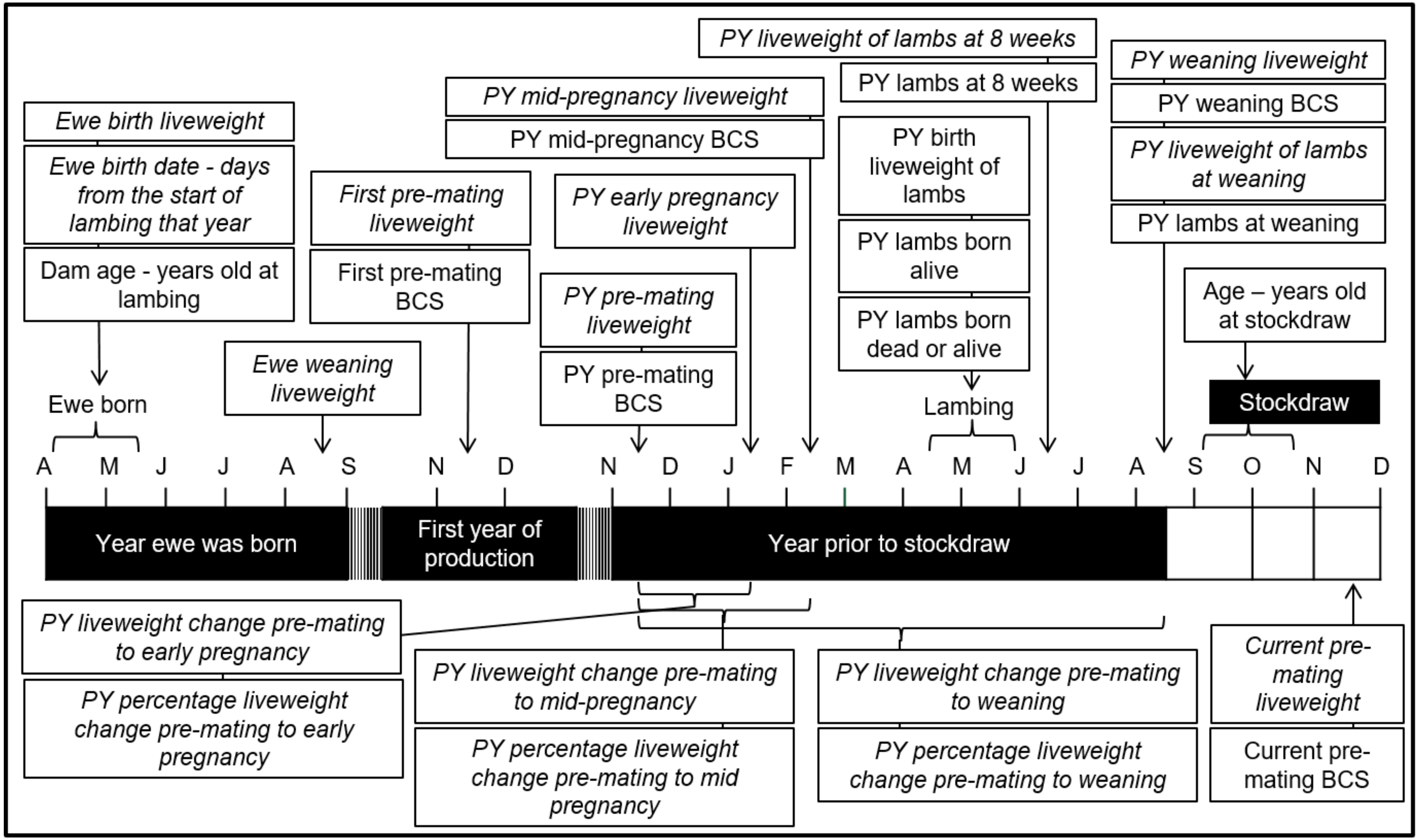


Figure 9.3 Timeline of when Recorded Performance explanatory variables (E-RP) were collected for each ewe in relation to stockdraw (continuous variables in italics). BCS: Body Condition Score; PY: Previous Year.

9.2.3.3 Estimated Breeding Values (E-EBV)

Commercially available EBVs were generated by Signet Breeding Services, as the flock was part of their “Sheepbreeder” breeding programme (Table 9.3). The ewes’ individual breeding Index (“Hill 2” index, for Scottish Blackfaces) was also included. E-EBVs were generated on 5th October 2013 and 8th October 2014 for 2013 and 2014 years, respectively. EBVs contained all data to the point of stockdraw. EBVs are calculated and published annually for individual sheep and change as additional data is added. Therefore the EBV for each ewe was the one that was published in the year of stockdraw. Ewes that appeared in the two years had different EBVs for each year.

Table 9.3 Estimated Breeding Values (EBV), descriptions by Signet (2015).

EBV	Trait	Signet definition and raw data used
Litter size	Prolificacy	This trait is defined as the total number of lambs born alive and dead when pregnancy reaches full term.
Maternal ability (kg)	Maternal ability of ewe, relates to milk production	The component of a lamb’s growth to eight weeks of age that is influenced by the ewes breeding potential for milk production.
Eight week weight (kg)	Growth rate to eight weeks of age, maternal ability of ewe Liveweight at eight weeks of age.	To achieve an adjusted eight week weight lambs must be weighed between 42 and 84 days of age.
Scan weight (kg)	Growth rate to 21 weeks of age	Liveweight at scanning time, when lambs are 21 weeks of age.
Ultrasound muscle depth (mm)	Carcass muscling	Measured at 21 weeks of age by a Signet-approved technician. Ultrasound measurements at the third lumbar vertebra.
Ultrasound fat depth (mm)	Leanness	Measured at 21 weeks of age by a Signet-approved technician. Three ultrasound measurements taken at the third lumbar vertebra.
Mature size (kg)	Ewe efficiency	Ewe liveweight at first mating (kg).
Carcass lean weight (kg)[a]	Muscle yield	Quantity of muscle tissue in the carcass assessed using Computed Tomography (CT) image analysis of breeding stock at 21 weeks of age.
Carcass fat weight (kg)[a]	Leanness	Quantity of fat in the carcass assessed using Computed Tomography (CT) image analysis of breeding stock at 21 weeks of age.

[a]Ewes and relatives did not undergo computed tomography (CT) so these are estimated from other information such as results from ultrasound back-fat scanning.

9.2.4 Data analysis and model construction

The ultimate aim was to generate a prediction model for each response variable (R-EMC, R-LmWt, R-LmNo, R-ES), by each set of explanatory variables (E-VAA, E-RP, E-EBV and E-all), giving 16 different models (four response variables by four sets of explanatory variables). Preliminary analysis of the response variables included using automated stepwise regression in the statistical software package GenStat (Payne et al., 2013) to generate these 16 models. However, more thorough model construction (as described below) demonstrated that many of the explanatory variables were highly confounded with each other, and in these circumstances, application of automated model selection processes was problematic. Use of automated methods can lead to arbitrary models and misleading results when optimal models are not unique due to lack of independence between candidate explanatory variables (Whittingham et al., 2006). Problems with automated variable selection methods such as stepwise selection are well documented within the literature (Breiman, 2001; Shmueli, 2010; Whittingham et al., 2006).

Therefore, findings of the preliminary automated model selection process are not presented. Instead the following sections describe the thorough model construction, which was carried out with the assistance of a statistical consultant from BioSS. GenStat programs (created by Sarah Brocklehurst from BioSS) were developed and used by the author of this thesis to carry out all analyses. Four steps were taken in this data analysis and model construction:

9.2.4.1 STEP 1: Exploratory analysis of individual variables

Exploratory analysis was carried for individual explanatory and response variables to establish each variable's distribution and summary statistics for each year.

9.2.4.2 STEP 2: Bivariate screening

To determine which explanatory variables had statistically significant relationships with the response variables or with other explanatory variables, all 55 explanatory variables (E-VAA, E-RP and E-EBV) and all four response variables (R-LmWt, R-LmNo, R-ES and R-EMC) were compared with each other (bivariate screening). Bivariate screening involved generating tables and graphs for all the different pairs of variables. ANOVA, Pearson's correlation coefficient and Chi-squared permutation tests, were used to determine statistically significant pairwise associations. Data from the two years was considered separately. This generated over 11,000 tables and graphs per year, which were then available for consideration.

Given the large number of models to be generated (four groups of explanatory variables by four response variables), and the number of variables to consider, a standardised method to decide which explanatory variables to include was implemented. This involved compiling two collections of candidate explanatory variables for each response variable: 1) Initial collection, and 2) Reduced collection. The Initial collection included all explanatory variables that had a probability value of $P<0.1$, for the response variable according to bivariate screening. The seemingly high *P*-value was not used to denote a statistical significance but was a means to identify explanatory variables of potential worth and to ensure these were available for further model construction. The Initial collections were then reduced further to form the Reduced collection. Explanatory variables were considered for removal if they were significantly related ($P<0.05$) to each other, together with considerations such as biological meaningful relationships and which variables would be most sensible, and/or practical, to collect in a real-life situation.

9.2.4.3 STEP 3: Preliminary model fitting based on single explanatory variables

Each response variable was modelled against each explanatory variable, with Linear Models (LM) fitted to linear response variables: R-EMC and R-LmWt, and Generalised Linear Models (GLM) with binomially distributed errors and a logit link function, fitted to discrete response variables: R-ES and R-LmNo. In 2013 no ewes weaned three lambs (R-LmNo = 3) and only 2 in 2014. To ensure this sparseness of data did not impact on results, these two ewe records were removed from all modelling when considering response variable R-LmNo and the binomial total in the GLM was set to 2. The binomial total in the GLM for R-ES was 1.

Categorical explanatory variables in Initial collections (STEP 2) for either R-ES or R-LmNo were examined in more detail. Where the GLM produced high standard errors (>2 indicating that the GLM model was inaccurate because the data was sparse), for a selected categorical variable, the counts of data at each level, for both years, were considered. Where data was missing or sparse, levels in categorical variables were appropriately combined. This occurred when no observations were available at either 0 or at the binomial total (1 for R-ES and 2 for R-LmNo). These alterations were made for an individual explanatory variable when included in all further modelling for the specific response variable, irrespective of year. It should be noted that LMs used for linear response variables (R-EMC and R-LmWt) gave *P*-values for individual explanatory variables that were the same as those from bivariate screening (test of Pearson's correlation coefficient = 0 for continuous explanatory variables or from ANOVA for categorical explanatory variables). GLMs for binomial response variables (R-ES and R-LmNo) resulted in *P*-values that differed slightly from those from the bivariate screening (ANOVA for continuous explanatory variables and Chi-squared permutation tests for categorical explanatory variables). However, the bivariate screening tests were used to select explanatory variable collections as it allowed a large scale analysis that identified important variables while avoiding the computational errors associated with missing and sparse data when included in binomial models.

9.2.4.4 STEP 4: Models based on multiple explanatory variables

Multi-variable models were fitted to the four response variables by including all explanatory variables in the Initial and Reduced collections, identified from bivariate screening in STEP 2, referred to as the Initial and Reduced models, respectively. Initial models allowed the maximum variation accounted for in the response variable to be determined and were fitted merely to obtain an upper bound for goodness-of-fit of alternative models. However, these were likely over-fitted and therefore could not be used for predictions. This resulted in a total of 16 Initial and 16 Reduced models (four response variables by four sets of explanatory variables: E-VAA, E-RP, E-EBV and E-all). Each model was applied to the data from the two years' separately. A range of goodness-of-fit statistics were examined in all 32 models.

The 16 Reduced models were then examined in more detail. Parameter estimates and their standard errors (SE) were generated for effects of individual explanatory variables when the response variables were fitted against each explanatory variable and against all explanatory variables in each Reduced model. For models with individual explanatory variables included, the mean values at the individual levels of categorical variables were calculated from estimated effects, along with estimated effects for standardised continuous variables (meaning the difference from the mean divided by the standard deviation of the variable where the summary statistics are calculated over both 2013 and 2014 together). Estimated effects on the standardised scale are invariant to the range of the explanatory variables and so are directly comparable between different explanatory variables for the same response measure. Also, for each model, residual plots, fitted value plots and Receiver Operating Characteristic (ROC) curves (for R-LmNo and R-ES), were produced for the different response variables.

9.3 Results

9.3.1 STEP 1: Exploratory analysis of individual variables

Response variable averages were lower in 2013 compared to 2014 (Table 9.4), although variability between ewes was quite high. Even though more ewes were included in 2013, compared to 2014 (394 observations compared to 372, respectively), more lambs were born to those ewes in 2014 (363 in 2013 compared to 386 in 2014). The proportion of ewes that did not survive in 2013 was slightly higher than to that in 2014 (7.9 % and 5.1 %, respectively).

For the explanatory variables (Table 9.5), E-VAA variables that had markedly different distributions of scores between 2013 and 2014, included: “Flatness of back”, “Jaw position”, “Tooth length” and “Face shape”. Out of the five BCSs present in the E-RP variables, three (“PY mid-pregnancy BCS”, “PY weaning BCS” and “Current pre-mating BCS”) had a different mode level between the two years. For “Current pre-mating BCS” in 2013, 74 % of ewes were at 2.75 BCS or above and in 2014 there was only 45 % within this range. For PY liveweight values, 2013 often had higher values (all variables of PY liveweight of lambs, and PY ewe liveweights) apart from “PY weaning liveweight” and “Current pre-mating liveweight” for which 2014 values were higher. Also for all previous year liveweight changes (actual and percentages), ewes in 2014, on average, gained more liveweight than in 2013. The averages for E-EBV variables were similar or slightly higher for 2014 data (apart from “Eight week weight” where 2013 was higher), but variability between ewes was quite high.

9.3.2 STEP 2 & 3: Bivariate screening and preliminary model fitting

Table 9.6 shows the results of the bivariate screening, the preliminary model fitting based on single explanatory variables, as well as which explanatory variables were included in Initial and Reduced models (Appendices 11 to 16 show actual *P*-values for Table 9.6).

Comparing so many variables through bivariate screening could lead to some significant comparisons occurring by chance. To address this issue, and to provide some internal validation, two years of data were used, as well as considering the estimated effects.

Table 9.4 Descriptions and summary statistics of response variables.

		2013	2014	Overall
Ewe Marginal Contribution (R-EMC)				
	Number of observations	394	372	766
	Mean (£)	14.20	23.28	18.61
	Standard deviation	43.65	41.83	42.99
	Standard error of the mean	2.20	2.17	1.55
Total liveweight of lambs weaned (R-LmWt)				
	Number of observations	388[a]	372	760
	Mean (kg)	25.90	30.03	27.92
	Standard deviation	23.00	22.22	22.70
	Standard error of the mean	1.17	1.15	0.82
Total number of lambs weaned (R-LmNo)				
	Number of observations	394	372	766
	Mean	0.92	1.04	0.98
Count at each level (percentage in brackets)	0	141 (35.8)	91 (24.5)	232 (30.3)
	1	143 (36.3)	178 (47.8)	321 (41.9)
	2	110 (27.9)	101 (27.2)	211 (27.5)
	3	0 (0)	2 (0.5)	2 (0.3)
Ewe survival to weaning (R-ES)				
	Number of observations	394	372	766
Count at each level (percentage in brackets)	Survived	363 (92.1)	353 (94.9)	716 (93.5)
	Did not survive	31 (7.9)	19 (5.1)	50 (6.5)

[a]In 2013 Six lambs were present at weaning but did not have wean liveweights measured and therefore were not included in the dataset for R-LmWt.

Table 9.5 All explanatory variables: means (with standard deviations) for continuous variables (names in italics) and counts (with percentages in brackets and mode level in bold and underlined) for categorical variables.

	Variables/description	Level	2013	2014	Overall
Visual Appearance Assessment (E-VAA)	Size[a]	1	25 (6.4)	64 (17.2)	89 (11.6)
	1: Smaller than ideal, 2: Ideal, 3: Bigger than ideal	2	**309 (78.4)**	**256 (68.8)**	**565 (73.8)**
		3	60 (15.2)	52 (14)	112 (14.6)
	Flatness of back[a]	1	14 (3.6)	7 (1.9)	21 (2.7)
	1: Very saddled back, 2: Slightly saddled back, 3:	2	**208 (52.8)**	129 (34.7)	337 (44)
	Flat level back	3	172 (43.7)	**236 (63.4)**	**408 (53.3)**
	Soundness of feet[a]	1	34 (8.6)	7 (1.9)	41 (5.4)
	1: Any foot not sound, 2: All feet sound	2	**360 (91.4)**	**365 (98.1)**	**725 (94.6)**
	Legs and motion[a]	1	19 (4.9)	3 (0.8)	22 (2.9)
	1: Any problem, 2: Less than ideal, 3: Ideal, straight	2	75 (19)	70 (18.8)	145 (18.9)
	legs	3	**300 (76.1)**	**299 (80.4)**	**599 (78.2)**
	Teeth present	3	0 (0)	1 (0.3)	1 (0.1)
	Number of sound incisor teeth present (0 to 8)	4	2 (0.5)	1 (0.3)	3 (0.4)
		5	4 (1)	0 (0)	4 (0.5)
		6	14 (3.6)	18 (4.8)	32 (4.2)
		7	21 (3.3)	21 (5.6)	42 (5.5)
		8	**353 (89.6)**	**331 (89)**	**684 (89.3)**
	Jaw position[b]	-1	1 (0.3)	1 (0.3)	2 (0.3)
	-5: Lower jaw 5mm back from upper jaw to 5: lower	0	20 (5.1)	**160 (43)**	180 (23.5)
	jaw 5mm in front of upper jaw	1	69 (17.5)	116 (31.2)	185 (24.2)
		2	**190 (48.2)**	38 (10.2)	**228 (29.8)**
		3	89 (22.6)	34 (9.1)	123 (16.1)
		4	23 (5.8)	23 (6.2)	46 (6)
		5	2 (0.5)	0 (0)	2 (0.3)
	Tooth angle[b]	-2	3 (0.8)	3 (0.8)	6 (0.8)
	-3: incisor teeth 45° forward from lower jaw to 3:	-1	15 (3.8)	9 (2.4)	24 (3.1)
	45° back; ideal position is at right angle with lower	0	**374 (94.9)**	**355 (95.4)**	**729 (95.2)**
	jaw	1	2 (0.5)	5 (1.3)	7 (0.9)
	Tooth length[ab]	0	**200 (50.8)**	167 (44.9)	**367 (47.9)**
	-2: very short to 2: very long	1	140 (35.5)	**180 (48.4)**	320 (41.8)
		2	54 (13.7)	25 (6.7)	79 (10.3)
	Teat size	1	1 (0.3)	0 (0)	1 (0.1)
	1: Smaller than ideal, 2: Ideal, 3: Larger than ideal	2	**364 (92.4)**	**327 (87.9)**	**691 (90.2)**
		3	29 (7.4)	45 (12.1)	74 (9.7)
	Udder attachment[a]	1	8 (2)	9 (2.4)	17 (2.2)
	1: Poorly attached, hanging, 2: Reasonable	2	30 (7.6)	19 (5.1)	49 (6.4)
	attached, 3: Well attached, close to body	3	**356 (90.4)**	**344 (92.5)**	**700 (91.4)**
	Udder damage[a]	1	0 (0)	0 (0)	0 (0)
	1: Abnormalities or blind both sides or any damage,	2	15 (3.8)	6 (1.6)	21 (2.7)
	2: Abnormalities or blind one side, 3: Sound	3	**379 (96.2)**	**366 (98.4)**	**745 (97.3)**
	Face colour[a]	1	9 (2.3)	8 (2.2)	17 (2.2)
	1: Lots of white coverage, 2: A little bit of white	2	54 (13.7)	79 (21.2)	133 (17.4)
	coverage, 3: Mostly black with grey nose	3	**331 (84)**	**285 (76.6)**	**616 (80.4)**
	Face shape[a]	1	24 (6.1)	**182 (48.9)**	206 (26.9)
	1: North type, 2: Between the two types, 3: South	2	**344 (87.3)**	151 (40.6)	**495 (64.6)**
	type	3	26 (6.6)	39 (10.5)	65 (8.5)

Continued

Table 9.5 Continued

	Variables/description	Level	2013	2014	Overall
E-VAA	Fleece colour[a]	1	26 (6.6)	2 (0.5)	28 (3.7)
	1: Lots of brown patches, 2: A few brown patches,	2	172 (43.7)	105 (28.2)	277 (36.2)
	3: All white	3	**196 (49.8)**	**265 (71.2)**	**461 (60.2)**
	Fleece length[a]	1	10 (2.5)	68 (18.3)	78 (10.2)
	1: Very woolly, 2: A bit woolly, 3: Short tight wool	2	**276 (70.1)**	**226 (60.8)**	**502 (65.5)**
		3	108 (27.4)	78 (21)	186 (24.3)
	Retention decision[a]	1	31 (7.9)	32 (8.6)	63 (8.2)
	1: would definitely sell to 5: would definitely keep	2	67 (17)	82 (22)	149 (19.5)
		3	**238 (60.4)**	**235 (63.2)**	**473 (61.7)**
		4	50 (12.7)	21 (5.6)	71 (9.3)
		5	8 (2)	2 (0.5)	10 (1.3)
Recorded Performance (E-RP)	Age	2.5	128 (32.5)	**140 (37.6)**	**268 (35)**
	Years old at stockdraw (2.5 to 7.5)	3.5	**136 (34.5)**	107 (28.8)	243 (31.7)
		4.5	108 (27.4)	89 (23.9)	197 (25.7)
		5.5	18 (4.6)	27 (7.3)	45 (5.9)
		6.5	4 (1)	8 (2.2)	12 (1.6)
		7.5	0 (0)	1 (0.3)	1 (0.1)
	Dam age	2	97 (25)	**112 (30.4)**	**209 (27.6)**
	Years old at lambing (2 to 5)	3	92 (23.7)	86 (23.3)	178 (23.5)
		4	95 (24.5)	92 (24.9)	187 (24.7)
		5	**104 (26.8)**	79 (21.4)	183 (24.2)
	First pre-mating BCS[ac]	2.25	2 (0.5)	3 (0.8)	5 (0.7)
		2.5	9 (2.4)	7 (1.9)	16 (2.1)
	1 to 5 (with quarter integers)	2.75	151 (39.4)	124 (34)	275 (36.8)
		3	**165 (43.1)**	**143 (39.2)**	**308 (41.2)**
		3.25	52 (13.6)	62 (17)	114 (15.2)
		3.5	4 (1)	24 (6.6)	28 (3.7)
		3.75	0 (0)	2 (0.5)	2 (0.3)
	PY pre-mating BCS[ac]	2	3 (0.8)	1 (0.3)	4 (0.5)
		2.25	11 (2.8)	10 (2.7)	21 (2.8)
	1 to 5 (with quarter integers)	2.5	55 (14.1)	46 (12.4)	101 (13.3)
		2.75	**214 (55)**	**149 (40.3)**	**363 (47.8)**
		3	61 (15.7)	83 (22.4)	144 (19)
		3.25	37 (9.5)	45 (12.2)	82 (10.8)
		3.5	8 (2.1)	33 (8.9)	41 (5.4)
		3.75	0 (0)	3 (0.8)	3 (0.4)
	PY mid-pregnancy BCS[ac]	1.25	1 (0.3)	0 (0)	1 (0.1)
		1.5	2 (0.5)	0 (0)	2 (0.3)
	1 to 5 (with quarter integers)	1.75	2 (0.5)	0 (0)	2 (0.3)
		2	15 (3.9)	0 (0)	15 (2)
		2.25	34 (8.8)	2 (0.5)	36 (4.8)
		2.5	131 (33.9)	83 (22.6)	214 (28.3)
		2.75	**164 (42.4)**	100 (27.2)	**264 (35)**
		3	33 (8.5)	**131 (35.6)**	164 (21.7)
		3.25	5 (1.3)	47 (12.8)	52 (6.9)
		3.5	0 (0)	5 (1.4)	5 (0.7)

Continued

Table 9.5 Continued

	Variables/description	Level	2013	2014	Overall
Recorded Performance (E-RP)	PY weaning BCS[ac]	1.75	0 (0)	1 (0.3)	1 (0.1)
		2	0 (0)	3 (0.8)	3 (0.4)
	1 to 5 (with quarter integers)	2.25	18 (4.6)	40 (10.9)	58 (7.6)
		2.5	108 (27.6)	**121 (33)**	229 (30.2)
		2.75	**164 (41.8)**	92 (25.1)	**256 (33.7)**
		3	58 (14.8)	55 (15)	113 (14.9)
		3.25	34 (8.7)	37 (10.1)	71 (9.4)
		3.5	9 (2.3)	16 (4.4)	25 (3.3)
		3.75	1 (0.3)	2 (0.5)	3 (0.4)
	Current pre-mating BCS[ac]	1.75	0 (0)	3 (0.8)	3 (0.4)
		2	7 (1.8)	24 (6.6)	31 (4.1)
	1 to 5 (with quarter integers)	2.25	14 (3.6)	56 (15.4)	70 (9.3)
		2.5	83 (21.2)	**118 (32.4)**	201 (26.6)
		2.75	**179 (45.7)**	110 (30.2)	**289 (38.2)**
		3	62 (15.8)	48 (13.2)	110 (14.6)
		3.25	23 (5.9)	5 (1.4)	28 (3.7)
		3.5	22 (5.6)	0 (0)	22 (2.9)
		3.75	2 (0.5)	0 (0)	2 (0.3)
	PY lambs born dead or alive	0	80 (20.3)	101 (27.2)	181 (23.6)
	0 to 3	1	**189 (48)**	**174 (46.8)**	**363 (47.4)**
		2	123 (31.2)	96 (25.8)	219 (28.6)
		3	2 (0.5)	1 (0.3)	3 (0.4)
	PY lambs born alive	0	85 (21.6)	109 (29.3)	194 (25.3)
	0 to 3	1	**195 (49.5)**	**172 (46.2)**	**367 (47.9)**
		2	113 (28.7)	90 (24.2)	203 (26.5)
		3	1 (0.3)	1 (0.3)	2 (0.3)
	PY lambs at 8 weeks	0	117 (29.7)	134 (36)	251 (32.8)
	0 to 3	1	**187 (47.5)**	**154 (41.4)**	**341 (44.5)**
		2	90 (22.8)	83 (22.3)	173 (22.6)
		3	0 (0)	1 (0.3)	1 (0.1)
	PY lambs at weaning	0	120 (30.5)	138 (37.1)	258 (33.7)
	0 to 3	1	**190 (48.2)**	**152 (40.9)**	**342 (44.6)**
		2	84 (21.3)	81 (21.8)	165 (21.5)
		3	0 (0)	1 (0.3)	1 (0.1)
	Ewe birth date		13.01 (6.53)	13.2 (6.97)	13.1 (6.74)
	Ewe birth liveweight (kg)		3.64 (0.64)	3.65 (0.65)	3.65 (0.64)
	Ewe wean liveweight (kg)		27.94 (3.37)	27.61 (3.06)	27.78 (3.22)
	First pre-mating liveweight (kg)		49.45 (4.85)	46.98 (5.95)	48.24 (5.55)
	PY pre-mating liveweight (kg)		52.67 (5.79)	45.84 (5.81)	49.34 (6.72)
	PY early pregnancy liveweight (kg)		48.96 (5.54)	47.03 (4.97)	48.02 (5.35)
	PY mid-pregnancy liveweight (kg)		47.43 (5.72)	46.87 (5.88)	47.16 (5.8)
	PY weaning liveweight (kg)		52.8 (5.78)	54.39 (6.94)	53.57 (6.42)
	Current pre-mating liveweight (kg)		48.81 (5.69)	53.73 (6.3)	51.19 (6.48)
	PY wt change pre-mating to early pregnancy (kg)		-3.71 (3.05)	1.17 (3.46)	-1.33 (4.07)
	PY wt change pre-mating to mid-pregnancy (kg)		-5.17 (3.53)	1.01 (3.26)	-2.15 (4.6)
	PY wt change pre-mating to weaning (kg)		0.24 (4.71)	8.57 (5.39)	4.31 (6.55)

Continued

Table 9.5 Continued

	Variables/description	Level	2013	2014	Overall
R-RP	*PY % wt change pre-mating to early pregnancy*		-6.9 (5.71)	3.09 (7.92)	-2.03 (8.5)
	PY % wt change pre-mating to mid-pregnancy		-9.68 (6.58)	2.46 (7.24)	-3.75 (9.2)
	PY % wt change pre-mating to weaning		0.85 (9.17)	19.33 (12.73)	9.87 (14.4)
	PY birth liveweight of lambs (kg)		3.8 (2.36)	3.5 (2.57)	3.65 (2.47)
	PY liveweight of lambs at 8 weeks (kg)		16.44 (13.37)	15.51 (14.22)	15.99 (13.78)
	PY liveweight of lambs at weaning (kg)		24.84 (20.27)	23.71 (21.8)	24.29 (21.02)
E-EBV	*Litter size*		0.1 (0.08)	0.1 (0.08)	0.1 (0.08)
	Maternal ability (kg)		0.67 (1.01)	0.7 (1.08)	0.69 (1.04)
	Eight week weight (kg)		0.69 (0.64)	0.67 (0.67)	0.68 (0.66)
	Scan weight (kg)		2.03 (1.38)	2.13 (1.36)	2.08 (1.37)
	Ultrasound muscle depth (mm)		0.8 (0.9)	0.89 (0.91)	0.84 (0.91)
	Ultrasound fat depth (mm)		0.11 (0.2)	0.13 (0.19)	0.12 (0.19)
	Mature size (kg)		2.58 (2.35)	2.64 (2.15)	2.61 (2.25)
	Carcass lean weight (kg)		0.76 (0.59)	0.82 (0.63)	0.79 (0.61)
	Carcass fat weight (kg)		0.59 (0.62)	0.67 (0.63)	0.63 (0.62)
	Index		179.47 (61.35)	183.4 (62.56)	181.38 (61.93)

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded Performance; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); wt: liveweight.
[a]subjective score;
[b]scored according to van Heelsum et al. (2006);
[c]scored on a 5 point scale with quarter integers according to Russel et al. (1969).

Table 9.6 Significant relationships between each explanatory variable (*continuous variables in italics*) with each response variable (*P*-value: °P<0.1, *P<0.5, **P<0.01, ***P<0.001). Also shown are explanatory variables included in Initial (P<0.1 in either year) and Reduced models (✓). Significant relationships between an explanatory variables and a response variable in both years (P<0.05) is highlighted.

		R-EMC				R-LmWt				R-LmNo						R-ES					
Group	Variable	2013 *P*-value[c]	2014 *P*-value[c]	In Initial models,	In Reduced models[a]	2013 *P*-value[c]	2014 *P*-value[c]	In Initial models,	In Reduced models[a]	2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models,	In Reduced models[a]	2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models,	In Reduced models[a]
Visual Appearance Assessment (E-VAA)	Size	**	-	√	√	**	**	√	√	**	*	***	**	√	√	*	-	*	-	√	√
	Flatness of back	-	***	√	√	*	-	√	√	°	-	**	-	√	√	-	**	-	**	√	√
	Soundness of feet	-	-			-	-			-	-	-	-			-	-	-	-		
	Legs and motion	-	*	√	√	-	-			-	-	-	-			°	*	-	-	√	√
	Teeth present	-	**	√	√	-	-			-	-	-	-			-	**	-[b]	*[b]	√	√
	Jaw position	-	***	√	√	-	*	√	√	-	*	-[b]	**[b]	√	√	-	-	-	-		
	Tooth angle	-	°	√	√	-	*	√	√	-	°	-	**			-	-	-	-		
	Tooth length	**	**	√	√	**	-	√	√	**	-	**	-	√	√	-	°	-	°	√	√
	Teat size	-	-			-	°	√	√	°	*	*[b]	**[b]	√	√	-	**	-[b]	**[b]	√	√
	Udder attachment	*	-	√	√	**	-	√	√	**	-	***	-	√	√	-	-	-	-		
	Udder damage	-	-			-	-			-	-	-	-			-	-	-	-		
	Face colour	-	-			-	-			-	-	-	-			-	-	*[b]	-[b]		
	Face shape	-	-			-	°	√	√	-	-	-	°			-	-	-	-		
	Fleece colour	-	-			-	-			-	°	-[b]	-[b]	√	√	-	-	-	-		
	Fleece length	-	-			-	-			-	-	-	-			-	-	-	-		
	Retention decision	*	**	√		-	°	√		-	-	*[b]	°[b]			-	-	-	-		
Recorded performance (E-RP)	Age	-	*	√	√	-	°	√	√	-	°	-[b]	-[b]	√	√	-	*	-[b]	°[b]	√	√
	Dam age	°	-	√	√	°	-	√	√	-	-	*	-			-	-	-	-		
	First pre-mating BCS	°	°	√		-	°	√	√	-	-	-[b]	**[b]			-	-	-	-		
	PY pre-mating BCS	°	-	√	√	-	-			-	°	-[b]	°[b]	√	√	-	-	-	-		
	PY mid-pregnancy BCS	*	-	√		-	-			-	-	-	-			**	-	*[b]	-[b]	√	√
	PY weaning BCS	**	-	√	√	***	-	√	√	***	-	**[b]	*[b]	√	√	-	-	-	-		
	Current pre-mating BCS	***	-	√		**	-	√		**	-	***[b]	-[b]	√		**	-	**[b]	°[b]	√	√
	PY lambs born dead or	*	-	√		**	*	√		**	*	***[b]	**[b]	√		-	-	-	-		
	PY lambs born alive	**	-	√		**	**	√		**	*	***[b]	**[b]	√		-	-	-	-		
	PY lambs at 8 weeks	*	-	√		*	**	√		**	*	**[b]	**[b]	√		-	-	-	-		
	PY lambs at weaning	*	-	√		*	*	√		°	*	*[b]	**[b]	√		-	-	-	-		
	Ewe birth date	-	-			-	-			-	-	-	-			-	-	-	-		
	Ewe birth wt	**	-	√	√	*	-	√	√	°	-	**	-	√	√	*	-	°	-	√	√
	Ewe wean wt	*	-	√	√	**	-	√	√	*	-	**	-	√	√	-	-	-	-		
	First pre-mating wt	*	-	√		-	*	√		-	**	-	*	√		-	-	-	-		
	PY pre-mating wt	°	-	√	√	*	*	√	√	**	**	**	°	√	√	-	-	-	-		

Continued

Table 9.6 Continued

		R-EMC				R-LmWt				R-LmNo						R-ES					
		2013 *P*-value[c]	2014 *P*-value[c]	In Initial models,	In Reduced models[a]	2013 *P*-value[c]	2014 *P*-value[c]	In Initial models,	In Reduced models[a]	2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models,	In Reduced models[a]	2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models,	In Reduced models[a]
Recorded performance (E-RP)	*PY early pregnancy wt*	°	-	√		**	-	√		**	*	**	-	√		-	-	-	-		
	PY mid-pregnancy wt	°	-	√		**	**	√		**	**	**	*	√		-	-	-	-		
	PY weaning wt	**	-	√	√	***	***	√	√	***	***	***	***	√	√	-	-	-	-		
	Current pre-mating wt	***	*	√		***	***	√		***	***	***	***	√		*	-	*	-	√	√
	PY wt change pre-mating to early pregnancy	-	-			-	°	√	√	-	*	-	°	√		-	***	-	-	√	
	PY wt change pre-mating to mid-pregnancy	-	-			-	-			-	-	-	-			-	-	-	-		
	PY wt change pre-mating to weaning	°	*	√		**	**	√		**	**	**	**	√		-	-	-	-		
	PY % wt change pre-mating to early pregnancy	-	-			-	-			-	*	-	°	√	√	-	***	-	-	√	√
	PY % wt change pre-mating to mid-pregnancy	-	-			-	-			-	-	-	-			-	-	-	-		
	PY % wt change pre-mating to weaning	-	*	√	√	**	**	√	√	*	**	**	**	√	√	-	-	-	-		
	PY wt of lambs at birth	**	-	√	√	**	-	√	√	**	-	**	-	√	√	*	-	*	-	√	√
	PY wt of lambs at 8 weeks	**	-	√		*	-	√		°	-	*	-	√		°	-	°	-	√	
	PY wt of lambs at	*	-	√		*	-	√		-	-	°	-			°	-	°	-	√	
E-EBV	*Litter size*	***	-	√		***	*	√		***	-	***	°	√		-	-	-	-		
	Maternal ability	***	-	√	√	***	*	√	√	**	-	***	-	√	√	-	-	-	-		
	Eight week weight	*	-	√		*	*	√		*	-	*	-	√		-	-	-	-		
	Scan weight	**	-	√		*	°	√		*	-	*	-	√		-	-	-	-		
	Ultrasound muscle depth	**	-	√	√	*	-	√	√	°	-	*	-	√	√	**	-	**	-	√	√
	Ultrasound fat depth	-	-			-	-			-	-	-	-			*	°	*	°	√	√
	Mature size	*	-	√		*	-	√		**	-	*	-	√		-	-	-	-		
	Carcass lean weight	**	-	√		**	-	√		*	-	**	-	√		°	-	°	-	√	
	Carcass fat weight	*	-	√	√	-	-			-	-	°	-			-	-	-	-		
	Index	***	-	√		***	*	√		**	-	***	-	√		-	-	-	-		

E: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); wt: liveweight; GLM: Generalized Linear Models; R: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.
See Appendices 11 to 16 for actual *P*-values.
[a]further selection for Reduced models by considering and removing associated variables;
[b]categorical variables where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.

9.3.2.1 Explanatory variable selection

Many of the E-RP liveweight variables were mildly to strongly correlated to one another (r = 0.3 to 0.9 in 2013 and r = 0.2 to 0.8 in 2014, all P<0.05, from bivariate screening). So, when selecting these variables, only one or sometimes two (if not correlated) were included in the Reduced collections (Table 9.6).

A strong association was found between all BCSs and, when multiple BCSs were available, "PY weaning BCS" was the BCS that was selected. Weaning was the last handling and data collection point prior to stockdraw; it is also a handling point which is fairly standard across other farms and is a practical time to collect data on ewes. Therefore, where a choice between strongly correlated explanatory data occurred, weaning data was chosen over the others (provided that weaning data was P<0.1, to the response variable). This related to variables: "PY weaning liveweight", "PY weaning BCS", "PY liveweight change pre-mating to weaning" and "PY percentage liveweight change pre-mating to weaning".

The explanatory variables relating to the number of lambs during the year prior to stockdraw ("PY lambs born dead or alive", "PY lambs born alive", "PY lambs at 8 weeks" and "PY lambs at weaning") were all strongly correlated to one another and with the corresponding liveweight of the lambs collected at the same time points (r>0.7, P<0.001, "PY birth liveweight of lambs", "PY liveweight of lambs at 8 weeks" and "PY liveweight of lambs at weaning"). Liveweight of lambs was chosen for inclusion over number of lambs because of its nature (continuous data is preferable for analyses). "PY birth liveweight of lambs" was chosen as the lamb liveweight variable to include as it best reflected what the ewe could produce without being affected by later management of the lambs.

The explanatory variables "Current pre-mating liveweight" and "Current pre-mating BCS" were actually collected after stockdraw, they would not be suitable for inclusion in a predictive model to be used at stockdraw. Therefore, while they were both highly significant for the response variables: R-EMC, R-LmWt and R-LmNo, they were not included in Reduced models. However, they were included for R-ES models due to the shortage of E-RP variables that were significantly associated with this response variable (Table 9.6).

Although many of the E-VAA variables were significantly related to one another they were all still included in the Reduced collections (Table 9.6). This was because there was no obvious reason for them to be associated. Furthermore, there was a high chance that ewes receive the mode level for most variables (as the majority of scores had a level which was assigned to ewes far more often than the other levels within the score), hence the association. “Retention decision” was included in the Initial collections for R-EMC and R-LmWt but was highly associated with other E-VAA variables (“Tooth length”, “Jaw position”, “Teeth present”, “Flatness of back”, “Legs and motion” and “Fleece length” $P<0.05$ in each year) as the Flock Manager most likely based his overall decision on these variables. The individual variables were more interesting for predicting performance so “Retention decision” was not included in the Reduced collections.

The majority of E-EBVs were significantly related to all response variables (when considering 2013 data) apart from R-ES, where only two E-EBV variables were significant (“Ultrasound muscle depth” and “Ultrasound fat depth”, $P<0.05$ for 2014 data, Table 9.6). The E-EBVs that were based on number of lambs or liveweight data (“Litter size”, “Maternal ability”, “Eight week weight”, “Scan weight” and “Mature size”) were positively associated with one another within both years (bivariate screening $r>0.7$, $P<0.001$). Therefore, only one of these was included in a Reduced collection of variables where appropriate. The variable “Maternal ability” was chosen in preference to all others as it had the lowest *P*-value in tests relating it to the response variables (Table 9.6). The E-EBV “Index” was included in Initial collections for R-EMC, R-LmWt and R-LmNo but was highly associated ($P<0.001$ in both years) with all other E-EBV variables. This is probably because it is a composite variable of the other E-EBV variables. As such, it was not included in Reduced collections.

The explanatory variables included in the Initial and Reduced collections (and models) are indicated on Table 9.6. There were only seven explanatory variables that were chosen to be included in Reduced models for all four response variables. From E-VAA these were: “Size”, “Flatness of back” and “Tooth length”; from E-RP: “Age”, “Ewe birth liveweight” and “PY liveweight of lambs at birth”; and from E-EBV: “Ultrasound muscle depth”.

9.3.2.2 Combined categorical explanatory variables

Both R-LmNo and R-ES had categorical explanatory variables where levels had to be combined due to incidence of sparse data. A total of six categorical variables had to be altered for R-LmNo Reduced models (“Jaw position”, “Teat size”, “Fleece colour”, “Age”, “PY pre-mating BCS” and “PY weaning BCS”) and five for R-ES

("Teeth present", "Teat size", "Age", "PY mid-pregnancy BCS" and "Current pre-mating BCS"). Groupings of levels are shown in the following tables of estimated effects (Table 9.10 to Table 9.12).

9.3.3 STEP 4: Models based on multiple explanatory variables

The success of models is shown as a range of goodness-of-fit statistics in Table 9.7. Different measures were generated because of the number of different response variables and datasets used (one for each year). The percentage sum of squares (%SofS, for LMs) and percentage deviation (%Dev, for GLMs) both show the variability explained by the model as a percentage of the variability in the data. Adjusted R^2 is similar as it shows the amount of variation explained by the model but is also adjusted for the number of variables in the model. These three variables are all relative to the amount of variation in the original data, so if they account for more variation when the model is fitted to one year compared to the other year, this could be a result of having more variation in the first year that can be accounted for. Therefore, %SofS, %Dev and Adjusted R^2 should only be compared within the same year and for the same response variable. However, the Mean Squared Error (MSE) shows the variability not accounted for by the different models (therefore lower values were preferable). The MSE provides an absolute measure of the model fit explained by the model relative to the scale of measurement, so can be compared across year data but for the same response variable.

The majority of Initial and Reduced models resulted in statistically significant fits for the four different response variables (Table 9.7). However, even with the Initial models, which included the maximum number of variables, the highest Adjusted R^2 possible was only 24.69 % (for R-ES when fitted with E-all explanatory variables to 2014 data). Furthermore, when this same model was fitted to 2013 data the Adjusted R^2 was 15.72 %. The amount of variation not accounted for by the model was higher in 2013 compared to 2014 (MSE of 0.461 in 2013 and 0.310 in 2014). This shows the limited amount of variation that was accounted for by the models and also the disparity in model fits between years. The %SofS (or %Dev, for GLMs) and Adjusted R^2 decreased within each year further for Reduced models, as they were less subjected to over-fitting than Initial models. The only goodness-of-fit statistics that remained consistent were those for R-LmWt and R-ES when fitted against E-VAA models because no variables were removed from Initial to Reduced models.

Table 9.7 Goodness-of-fit for all Initial models (explanatory variables related, at P<0.1, to response variable) and Reduced models (Initial model variables with further levels of processing to reduce variable lists) run on ewe data in two years.

	Model[a]	Year	R-EMC No.[b]	R-EMC MSE[c]	R-EMC %SofS[d]	R-EMC Adj R[2e]	R-LmWt No.[b]	R-LmWt MSE[c]	R-LmWt %SofS[d]	R-LmWt Adj R[2e]	R-LmNo No.[b]	R-LmNo MSE[c]	R-LmNo %Dev[d]	R-LmNo Adj R[2e]	R-LmNo Sens[f]	R-LmNo Spec[f]	R-ES No.[b]	R-ES MSE[c]	R-ES %Dev[d]	R-ES Adj R[2e]	R-ES Sens[f]	R-ES Spec[f]
Initial models	E-all	13	42***	1580	39.69	16.98	40***	439.8	36.23	17.36	36***	1.633	22.72	7.84	62.5 (64.5)	62.4 (65.1)	19*	0.461	22.51	15.72	68	68
	E-VAA	13	9*	1809	11.61	5.09	9**	489.3	13.44	7.46	7***	1.675	8.13	4.74	60.5 (68.2)	61.7 (67.3)	6	0.534	6.03	3.32	60	58
	E-RP	13	24**	1682	26.74	11.63	23***	470.3	23.37	11.62	22***	1.690	14.31	4.58	59.7 (60.9)	59.6 (60.9)	10***	0.475	16.78	13.17	61	61
	E-EBV	13	9**	1814	6.97	4.79	8**	508.4	5.83	3.85	7***	1.726	3.58	1.83	54.9 (58.2)	55.3 (57.7)	3*	0.533	4.19	3.45	59.0	58
	E-all	14	42**	1519	37.55	13.19	40**	426.7	33.85	13.10	36***	1.318	23.36	7.76	63.4 (69.3)	63.7 (69.1)	19*	0.310	31.04	24.69	79.0	79
	E-VAA	14	9***	1536	18.38	12.23	9**	460.8	12.48	6.69	7***	1.388	7.32	3.67	58.4 (64.4)	58.2 (65.8)	6***	0.335	19.72	17.26	75	79
	E-RP	14	24*	1630	23.57	6.89	23**	434.7	24.42	11.47	22***	1.340	16.27	6.26	62.7 (64.4)	62.6 (64.3)	10	0.394	8.42	4.24	58	58
	E-EBV	14	9	1771	1.26		8	493.6	2.20	0.05	7	1.448	1.47		53.8 (53.5)	53.8 (53.5)	3	0.398	2.39	1.59	61	63
Reduced models	E-all	13	21***	1657	25.53	13.59	21***	456.0	26.35	14.84	19***	1.654	15.71	6.55	60.9 (63.6)	61.0 (63.4)	15*	0.471	19.68	13.71	64.5	64.5
	E-VAA	13	8*	1821	10.04	4.45	8**	493.1	11.81	6.75	7***	1.675	8.13	4.74	60.5 (68.2)	61.7 (67.3)	6	0.540	6.03	3.32	59.5	58.1
	E-RP	13	10***	1737	15.56	9.42	11***	473.5	17.80	11.57	10***	1.687	9.84	4.64	57.3 (60.9)	57.4 (60.9)	7***	0.481	14.85	11.93	58.1	58.1
	E-EBV	13	3**	1836	4.37	3.64	2***	509.8	4.09	3.59	2***	1.727	2.31	1.81	54.5 (56.4)	54.6 (56.3)	2*	0.532	4.19	3.70	60.1	61.3
	E-all	14	21***	1471	26.40	13.85	21**	431.3	23.74	10.99	19***	1.357	14.15	4.41	63.1 (65.3)	62.6 (65.4)	15*	0.315	28.09	22.54	73.7	73.7
	E-VAA	14	8***	1530	17.71	12.53	8**	460.6	11.51	6.74	7***	1.388	7.32	3.67	58.4 (64.4)	58.2 (65.8)	6***	0.340	17.92	15.88	75.4	78.9
	E-RP	14	10	1663	10.20	2.56	11*	457.4	13.44	5.60	10*	1.392	7.48	1.98	62.7 (61.4)	62.6 (61.3)	7	0.393	6.61	3.28	61.8	63.2
	E-EBV	14	3	1754	0.58		2***	489.6	1.40	0.87	2	1.440	0.63	0.09	49.5 (56.4)	49.5 (56.9)	2	0.398	2.11	1.58	57.8	57.9

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded performance; EBV: Estimated Breeding Values; R: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival.

[a]contains different groups of explanatory variables based on previous selection criteria;

[b]number of explanatory variables in model and whether model fitted is significant compared to nothing in the model *P<0.05, **P<0.001, ***P<0.001;

[c] MSE: Mean Squared Error, showing the variability not explained by the model relative to the scale of measurement;

[d]%SofS: Percentage sum of squares for Linear Models (R-EMC, R-LmWt), and %Dev: Percentage deviation for Generalized Linear Models (R-LmNo, R-ES), both show the variability explained by the model as a percentage of the variability in the data;

[e]Adj R^3: Adjusted R^2, showing the variability explained by the model adjusted for the number of variables in the model;

[f]Sensitivity (Sens) and Specificity (Spec) percentage generated for R-ES and R-LmNo ≥1 (≥2 in brackets).

As expected, the models fitted to the response variables with E-all explanatory variables accounted for a higher level of variation than when restricted datasets for each of the three sets of explanatory variables (E-VAA, E-RP and E-EBV) only were included. There was no consistent pattern between years for which of these three sets of variables accounted for more variation. E-RP accounted for more variation in 2013 than R-VAA and R-EBV for all response variables apart from R-LmNo where E-VAA accounted for the most. With 2014 data E-VAA accounted for more variation to the other two sets of explanatory variables for all response variables. E-EBV accounted for the least variation within year in all cases apart from R-ES in 2013 when E-VAA accounted for the least. The MSE was lower for all models of 2014 data compared to 2013 data but the variation in the original data was also slightly less in 2014 than in 2013 (Table 9.4).

For Reduced models, fitted values were plotted against observed data. Examples of these are shown for E-all models for R-EMC (Figure 9.4) and R-LmWt (Figure 9.5). Both figures show the general lack of fit from the models. Had the fit been better, the points would have followed a positive diagonal line instead of the “clouds” of points seen. The clustering of data seen for R-EMC (Figure 9.4) are a result of the stepped nature of the R-EMC values depending on the closing valuation classification (Sound, Unsound, Dead Missing) and on the number of lambs weaned. The clustering of data points for R-LmWt (Figure 9.5) is also a result of the number of lambs weaned.

Table 9.7 shows the goodness-of-fit statistics of sensitivity and specificity for binomial response measures (R-LmNo and R-ES). The sensitivity measures how well the model identifies ewes that did survive or did have a certain number of lambs. It is the proportion of the positive responses correctly identified (Petrie and Watson, 2013). The specificity measures how well the model identified ewes of the alternate response; in this case those that did not survive or did not have a specific number of lambs. It is the proportion of the negative responses correctly identified (Petrie and Watson, 2013), such as the proportion of ewes predicted to not survive amongst those that did not survive. The optimum sensitivity and specificity (defined as when the absolute difference between them is minimised) achievable for Initial and Reduced models are presented in Table 9.7. All demonstrate a lack of agreement between fitted and observed values, as most sensitivity and specificity are between 49.5 % and 79 %. Perfect predictions would be 100 % (Petrie and

Watson, 2013), whilst 50 % means there is a 50 % chance that the model predicted the response correctly (no better than random).

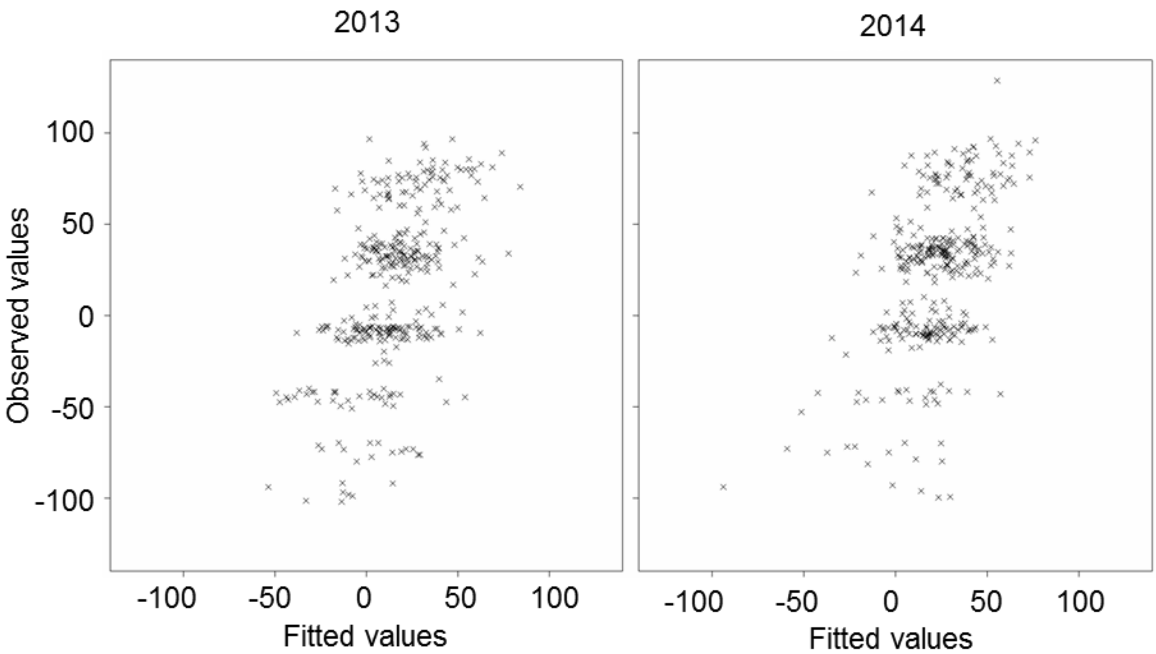


Figure 9.4 Observed values versus fitted values when E-all Reduced model variables were fitted for Ewe Marginal Contribution (R-EMC), in 2013 and 2014.

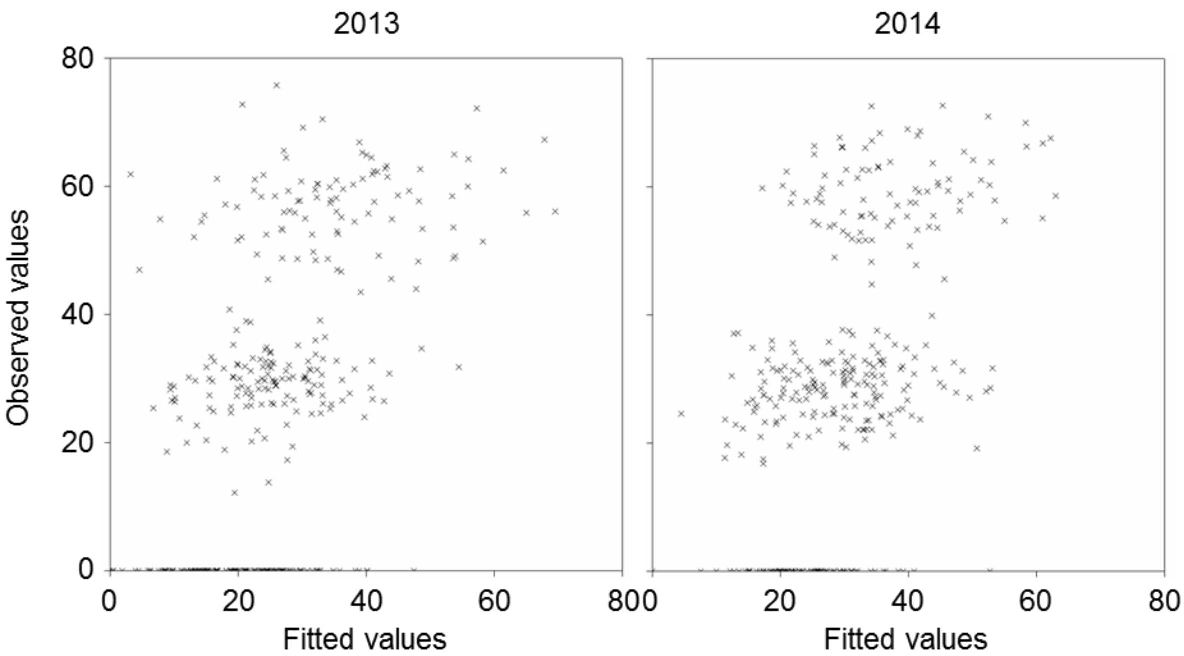


Figure 9.5 Observed values versus fitted values when E-all Reduced model variables were fitted for Total liveweight of lambs weaned (R-LmWt) in 2013 and 2014.

Additionally, ROC curves were produced for each model for the binomial response measures (R-LmNo and R-ES). These curves showed, for all possible cut-off points, the true positive rate (sensitivity) when plotted against the false positive rate (1-specificity), and connecting the points with a line (Steensels et al., 2016; Watson and Petrie, 2010). However, even though the E-all models accounted for the greatest variation accounted for, the ROC curves produced (Appendix 17) only further demonstrated the lack of model fit.

For Reduced models, sensitivity and specificity was highest for R-ES with E-VAA, using 2014 data (75.4 % and 78.9 %, respectively, Table 9.7). However, the percent deviation accounted for was still low (17.92 %) and the mean square error was lower than for 2013 data for which sensitivity and specificity was low (59.5 % and 58.1 %). Also with only 5.1 % (19 observations) of ewes that did not survive in 2014 and 7.9 % (31 observations) in 2013, the high levels are likely a result of over-fitting with such low levels of observations.

A model that had higher sensitivity and specificity (73.7 %) was for R-ES when fitted against E-all variables in 2014. Prediction was also better for 2014 (28.09 %Dev) compared to 2013 (19.68 %Dev). Figure 9.6 shows the fitted values for R-ES when fitted against E-all compared to observed survival. However, even with sensitivity and specificity at 73.7 % (for R-ES when fitted against E-all variables for 2014 Table 9.7) there was still a large overlap between observations “Did not survive” and “survive”. For example, if it was presumed that any animal with a fitted value of 0.8 or above (as identified on Figure 9.6) was presumed to survive, from the observed data a large proportion of those ewes that did not survive (R-ES = 0) also received a fitted value of over 0.8. For good predictive ability there should be two clear peaks on Figure 9.6 that have different fitted values for ewes that were observed to survive (R-ES = 1) and those that did not (R-ES = 0). This example demonstrated the inability to predict survival.

The Reduced models were used to generate the estimated effects of explanatory variables on the response variable, when each individual explanatory variable were included, and when Reduced collections of explanatory variables were included in models, for R-EMC (Table 9.8), R-LmWt (Table 9.9), R-LmNo (Table 9.10) and R-ES (Table 9.11). For individual explanatory variables models, the mean values at the individual levels of categorical variables were calculated from estimated effects, along with estimated effects for standardised continuous variables (Table 9.12).

Means for categorical explanatory variables for discrete response variables are shown in Table 9.12 on the logit scale so it is possible to compare them to the gradients of the continuous explanatory variables. The categorical explanatory variables were back transformed when fitted values for the response variables were fitted.

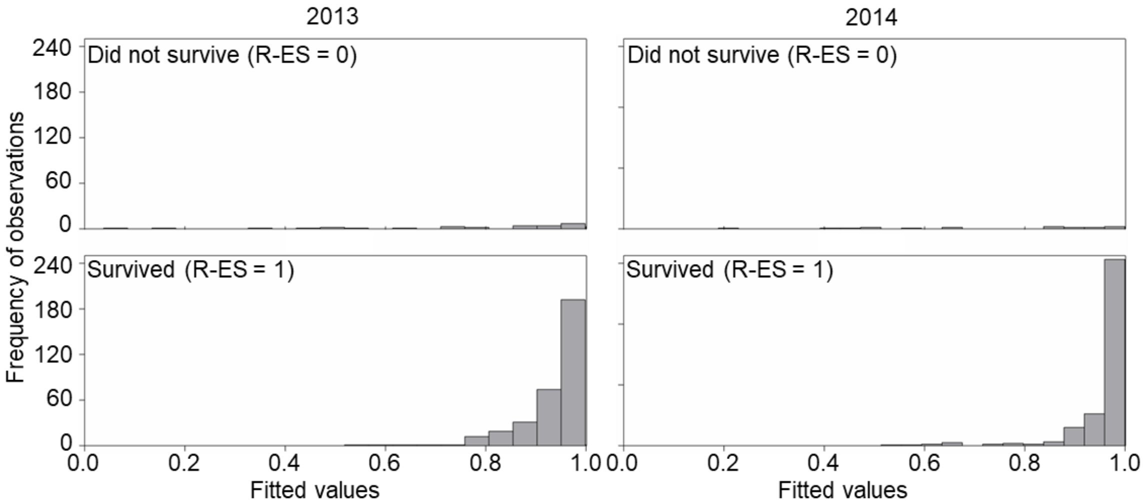


Figure 9.6 Frequency of fitted values for survival compared to the observed ewe survival (R-ES) with E-all models fitted to each of two years of data.

Table 9.8 Estimates of the effect (with SE) of explanatory variables used in Reduced models of **Ewe Marginal Contribution (R-EMC)**. Estimates are given when R-EMC is fitted against each single explanatory variable and for multiple explanatory variable models (E-all, E-VAA, E-RP and E-EBV, continuous variables in italics).

	Variable name	Level	Type[b]	Single variable[a]		E-all		E-VAA		E-RP		E-EBV	
				2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
	Models with multiple variables		I			-85.87 (86.89)	-329.71 (100.36)	-67.90 (59.59)	-185.64 (66.99)	-60.88 (40.94)	-68.67 (63.15)	5.54 (3.28)	21.47 (3.53)
Visual Appearance Assessment (E-VAA)	Size	1		**-13.45 (8.63)**	**18.18 (5.23)**								
		2		29.39 (8.98)	5.07 (5.84)	26.13 (9.95)	4.66 (6.64)	28.27 (9.01)	6.16 (5.64)				
		3		30.23 (10.27)	11.50 (7.81)	21.85 (12.89)	15.18 (10.33)	25.47 (10.42)	13.27 (7.55)				
	Flatness of back	1		**17.92 (11.66)**	**-32.01 (15.51)**								
		2		-7.19 (12.04)	50.87 (15.92)	-7.61 (12.09)	51.97 (16.72)	-10.39 (12.21)	49.82 (16.57)				
		3		0.16 (12.12)	59.34 (15.74)	-7.71 (12.23)	56.46 (16.68)	-4.13 (12.24)	55.20 (16.43)				
	Legs and motion	1		**17.92 (10.04)**	**-10.25 (23.97)**								
		2		-5.97 (11.24)	23.31 (24.48)	-23.27 (12.56)	-19.43 (30.83)	-4.18 (11.42)	-22.02 (29.06)				
		3		-3.40 (10.35)	36.26 (24.09)	-13.80 (11.63)	-7.39 (30.62)	-2.15 (10.53)	-11.38 (28.79)				
	Teeth present	3			**-93.90 (41.18)**								
		4		**6.81 (30.86)**	87.20 (58.24)		137.67 (74.19)		122.40 (66.96)				
		5		12.58 (37.80)	-	0.78 (53.02)	-	16.43 (40.18)	-				
		6		-14.43 (33.00)	98.30 (42.31)	-46.68 (46.18)	96.30 (59.78)	-18.46 (35.72)	83.55 (50.57)				
		7		2.73 (32.30)	103.75 (42.15)	-37.02 (44.94)	95.85 (59.94)	-8.34 (34.75)	85.78 (50.59)				
		8		8.51 (30.95)	119.50 (41.25)	-39.28 (44.58)	116.03 (58.86)	-4.81 (33.60)	96.87 (49.76)				
	Jaw position	-1		**-47.39 (43.43)**	**21.30 (40.22)**								
		0		70.54 (44.50)	13.73 (40.35)	72.49 (43.41)	46.82 (42.91)	71.61 (43.93)	54.98 (41.73)				
		1		61.98 (43.74)	-5.00 (40.39)	69.57 (42.22)	26.92 (43.03)	64.61 (43.11)	38.90 (41.87)				
		2		65.28 (43.54)	1.09 (40.75)	74.24 (42.13)	33.50 (43.70)	66.95 (42.96)	44.55 (42.34)				
		3		57.49 (43.67)	-5.07 (40.81)	74.54 (42.66)	28.42 (43.74)	63.78 (43.32)	40.29 (42.44)				
		4		41.25 (44.36)	-32.65 (41.09)	69.26 (44.00)	6.10 (44.52)	56.11 (44.50)	20.39 (43.07)				
		5		54.50 (53.19)	-	82.60 (53.13)	-	60.92 (54.12)	-				
	Tooth angle	-2		**-0.28 (25.27)**	**-7.30 (24.03)**								
		-1		17.47 (27.68)	60.30 (27.75)	20.53 (32.80)	48.34 (28.88)	7.89 (30.29)	52.66 (27.08)				
		0		14.59 (25.37)	29.90 (24.13)	15.82 (30.72)	14.95 (24.11)	5.55 (27.88)	16.84 (23.31)				
		1		-7.27 (39.96)	43.34 (30.39)	10.39 (42.98)	37.00 (29.80)	-0.29 (41.12)	37.23 (28.95)				
	Tooth length	0		**14.80 (3.05)**	**29.87 (3.20)**								
		1		5.18 (4.76)	-10.07 (4.44)	4.30 (5.70)	-1.53 (5.41)	6.93 (5.29)	-2.74 (4.72)				
		2		-17.83 (6.62)	-25.68 (8.87)	-15.66 (10.62)	1.71 (11.52)	-13.54 (9.38)	-2.79 (10.90)				
	Udder attachment	1		**16.93 (15.30)**	**14.35 (13.97)**								
		2		19.88 (17.22)	3.65 (16.95)	20.55 (20.67)	-4.46 (16.56)	21.21 (17.47)	-1.18 (16.39)				
		3		-4.70 (15.47)	9.45 (14.15)	-1.06 (19.07)	8.66 (14.56)	-2.23 (15.74)	7.43 (13.96)				
E-RP	Age	2.5		**16.27 (3.87)**	**27.85 (3.50)**								
		3.5		-2.02 (5.39)	-3.81 (5.32)	1.26 (6.22)	10.77 (7.14)			-2.46 (5.97)	-0.57 (6.84)		
		4.5		-2.54 (5.72)	-10.25 (5.62)	-1.05 (8.23)	10.78 (8.22)			-5.85 (6.54)	-6.84 (7.67)		
		5.5		-10.51 (11.02)	-4.65 (8.71)	-11.37 (13.88)	20.61 (12.41)			-14.55 (12.22)	-0.95 (11.33)		
		6.5		-19.73 (22.23)	-16.63 (15.06)	-35.49 (27.09)	23.62 (18.48)			-34.60 (25.20)	1.76 (17.49)		
		7.5		-	-121.75 (41.58)	-	-			-	-137.66 (51.33)		

Continued

Table 9.8 Continued

Recorded Performance (E-RP)	Dam age	1		**6.39 (4.42)**	**24.76 (3.96)**								
		2		5.41 (6.34)	0.94 (6.00)	2.99 (6.52)	-2.61 (6.05)			3.15 (6.43)	-1.15 (6.18)		
		3		16.16 (6.29)	-3.85 (5.89)	13.10 (6.64)	-7.63 (5.99)			12.13 (6.54)	-5.37 (6.18)		
		4		9.74 (6.15)	-5.18 (6.15)	5.51 (6.37)	-5.08 (6.32)			6.57 (6.19)	-6.14 (6.46)		
	PY pre-mating BCS	2		**-7.93 (24.95)**	46.32 (43.67)		-				-		
		2.25		-10.15 (28.15)	**32.09 (13.17)**	22.03 (33.86)				12.89 (32.65)			
		2.5		13.83 (25.63)	-8.81 (14.53)	32.62 (31.74)	-3.75 (15.10)			27.51 (30.57)	-17.91 (15.47)		
		2.75		23.77 (25.13)	-15.27 (13.60)	39.52 (31.62)	-12.33 (14.26)			34.07 (30.46)	-24.47 (14.66)		
		3		30.79 (25.56)	-7.82 (13.94)	51.40 (32.09)	-4.99 (14.61)			44.18 (31.14)	-17.13 (15.09)		
		3.25		22.77 (25.95)	1.39 (14.56)	44.05 (32.93)	3.88 (15.51)			35.06 (31.78)	-11.25 (15.94)		
		3.5		22.51 (29.26)	-4.76 (15.03)	41.40 (35.58)	-4.95 (15.79)			31.11 (34.35)	-14.95 (16.30)		
		3.75		-	3.11 (27.41)	-	20.73 (31.34)			-	11.16 (33.10)		
	PY weaning BCS	1.75		-	**-42.35 (41.75)**	-				-			
		2		-	48.56 (48.21)	-	139.60 (52.20)			-	96.00 (53.58)		
		2.25		**16.77 (10.06)**	60.77 (42.27)		119.11 (43.68)				72.59 (44.86)		
		2.5		-13.69 (10.87)	63.94 (41.92)	-22.44 (11.60)	113.89 (43.43)			-20.37 (11.53)	69.62 (44.49)		
		2.75		-2.39 (10.60)	62.63 (41.98)	-21.57 (11.63)	108.48 (43.50)			-13.95 (11.41)	66.06 (44.58)		
		3		8.52 (11.52)	66.25 (42.13)	-7.74 (13.06)	113.18 (43.31)			1.27 (12.59)	71.32 (44.46)		
		3.25		-1.07 (12.44)	72.49 (42.31)	-19.87 (14.23)	112.11 (43.79)			-9.29 (13.94)	73.81 (45.00)		
		3.5		42.98 (17.43)	88.82 (43.04)	22.02 (18.83)	134.12 (44.59)			30.64 (18.41)	91.97 (45.83)		
		3.75		16.05 (43.86)	104.41 (51.13)	-10.93 (44.75)	151.16 (52.06)			14.97 (44.80)	117.05 (53.24)		
	Ewe birth liveweight		I	-21.31 (12.71)	16.71 (12.51)								
			G	9.74 (3.44)	1.74 (3.37)	3.55 (4.10)	-1.36 (3.90)			1.58 (4.00)	0.75 (3.90)		
	Ewe wean liveweight		I	-23.06 (18.37)	-1.24 (19.70)								
			G	1.33 (0.65)	0.88 (0.71)	-0.57 (0.90)	1.24 (0.89)			0.36 (0.79)	1.03 (0.83)		
	PY pre-mating liveweight		I	-19.59 (20.18)	33.37 (17.31)								
			G	0.64 (0.38)	-0.22 (0.37)	-5.10 (4.09)	2.11 (3.97)			-2.20 (4.01)	0.54 (4.08)		
	PY weaning liveweight		I	-50.95 (19.98)	5.36 (17.16)								
			G	1.23 (0.38)	0.33 (0.31)	5.21 (4.10)	-2.35 (3.41)			2.60 (4.02)	-0.45 (3.49)		
	PY % wt change pre-mating to weaning		I	13.97 (2.21)	16.05 (3.93)								
			G	0.37 (0.24)	0.37 (0.17)	-2.15 (2.07)	0.99 (1.53)			-0.83 (2.04)	0.51 (1.57)		
	PY birth liveweight of lambs		I	2.73 (4.20)	25.64 (3.65)								
			G	3.13 (0.94)	-0.54 (0.84)	3.16 (1.11)	1.03 (1.11)			3.71 (1.04)	0.93 (1.09)		
E-EBV	*Maternal ability*		I	8.97 (2.60)	21.22 (2.58)								
			G	7.79 (2.15)	2.94 (2.01)	1.07 (3.00)	3.15 (2.97)					7.23 (2.43)	2.95 (2.51)
	Ultrasound muscle depth		I	9.03 (2.92)	23.25 (3.03)								
			G	6.45 (2.42)	0.02 (2.38)	4.29 (2.90)	-2.10 (2.68)					5.30 (2.57)	-0.31 (2.50)
	Carcass fat weight		I	9.58 (3.04)	21.32 (3.18)								
			G	7.81 (3.56)	2.90 (3.46)	6.04 (4.91)	-1.45 (4.91)					-0.74 (4.24)	0.03 (4.49)

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded Performance; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); SE: standard error; wt: liveweight.

[a]for categorical variables the constant is shown in bold and the values for other levels are the difference to the constant level;

[b]type, where: I: Intercept; G: Gradient.

Table 9.9 Estimates of the effect (with SE) of explanatory variables used in Reduced models of **Total liveweight of lambs weaned (R-LmWt).** Estimates are given when R-LmWt is fitted against each single explanatory variable and for multiple explanatory variable models (E-all, E-VAA, E-RP and E-EBV, *continuous variables in italics*).

	Variable name	Level	Type[b]	Single variable[a]		E-all		E-VAA		E-RP		E-EBV	
				2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
	Models with multiple variables		I			1.12 (47.45)	-96.90 (46.02)	27.43 (37.43)	-9.50 (28.80)	-27.80 (21.20)	-49.11 (34.54)	21.61 (1.64)	29.04 (1.72)
Visual Appearance Assessment (E-VAA)	Size	1		**13.18 (4.54)**	**23.46 (2.74)**								
		2		12.65 (4.73)	6.70 (3.07)	8.55 (5.22)	3.47 (3.66)	11.92 (4.68)	5.43 (3.14)				
		3		18.46 (5.42)	13.99 (4.10)	9.49 (6.83)	8.13 (5.59)	16.25 (5.47)	10.60 (4.31)				
	Flatness of back	1		**30.99 (6.09)**	**16.89 (8.38)**								
		2		-8.33 (6.30)	11.47 (8.60)	-8.29 (6.35)	14.21 (8.46)	-9.29 (6.37)	12.20 (8.48)				
		3		-1.62 (6.34)	14.44 (8.50)	-6.87 (6.38)	14.93 (8.43)	-3.66 (6.38)	13.69 (8.40)				
	Jaw position	-1		**0.00 (23.07)**	**45.60 (21.96)**								
		0		30.32 (23.64)	-11.42 (22.03)	32.82 (23.33)	10.12 (23.45)	28.50 (22.89)	12.33 (22.96)				
		1		25.15 (23.23)	-19.21 (22.06)	33.36 (22.63)	-3.02 (23.54)	25.44 (22.43)	3.48 (23.03)				
		2		25.36 (23.13)	-17.07 (22.25)	31.49 (22.56)	0.28 (23.94)	24.63 (22.35)	4.75 (23.30)				
		3		27.79 (23.20)	-15.08 (22.28)	38.91 (22.80)	-2.26 (23.93)	27.93 (22.53)	4.74 (23.30)				
		4		21.81 (23.58)	-25.01 (22.44)	33.98 (23.63)	-9.08 (24.27)	24.75 (23.17)	-4.17 (23.62)				
		5		32.65 (28.25)		44.49 (27.98)		29.30 (27.98)					
	Tooth angle	-2		**30.23 (13.32)**	**16.37 (12.72)**								
		-1		-5.88 (14.59)	34.41 (14.69)	3.50 (17.59)	23.69 (15.81)	-7.82 (14.79)	28.46 (14.89)				
		0		-4.24 (13.37)	13.17 (12.77)	6.43 (16.39)	6.19 (13.16)	-4.64 (13.47)	5.78 (12.77)				
		1		-16.08 (21.05)	19.05 (16.09)	-2.15 (22.34)	14.34 (16.06)	-15.56 (20.45)	14.61 (15.85)				
	Tooth length	0		**23.68 (1.62)**	**30.47 (1.72)**								
		1		7.09 (2.53)	-0.58 (2.39)	4.17 (3.08)	1.98 (2.93)	6.89 (2.80)	1.97 (2.59)				
		2		-2.08 (3.52)	-2.51 (4.78)	-9.57 (5.57)	4.28 (6.10)	-3.80 (4.73)	6.58 (5.84)				
	Teat size	1		**53.60 (22.92)**									
		2		-28.35 (22.95)	**29.19 (1.22)**	-35.06 (22.95)		-14.33 (22.79)					
		3		-20.56 (23.31)	6.89 (3.52)	-36.44 (23.41)	1.63 (4.96)	-16.59 (23.11)	8.43 (4.13)				
	Udder attachment	1		**36.14 (8.56)**	**31.41 (7.43)**								
		2		3.82 (9.50)	0.34 (9.02)	5.09 (11.09)	-1.14 (9.06)	3.24 (10.10)	3.04 (9.00)				
		3		-11.65 (8.64)	-1.52 (7.52)	-4.20 (10.56)	6.78 (8.62)	-10.58 (9.63)	7.52 (8.26)				
	Face shape	1		**32.68 (4.69)**	**32.51 (1.64)**								
		2		-7.23 (4.86)	-5.43 (2.44)	-3.22 (5.16)	1.82 (2.81)	-6.12 (4.90)	-3.16 (2.53)				
		3		-7.16 (6.57)	-2.62 (3.91)	-3.75 (6.84)	-2.14 (4.14)	-8.15 (6.46)	-2.80 (3.86)				
E-RP	Age	2.5		**22.53 (2.04)**	**26.63 (1.87)**								
		3.5		3.64 (2.84)	5.12 (2.84)	2.78 (3.21)	5.30 (3.96)			2.16 (3.12)	1.40 (3.71)		
		4.5		7.48 (3.02)	4.39 (2.99)	6.67 (4.19)	4.76 (4.46)			5.25 (3.47)	-0.95 (4.11)		
		5.5		1.72 (5.78)	11.34 (4.64)	0.36 (6.84)	13.70 (6.65)			-0.70 (6.36)	6.41 (5.86)		
		6.5		-0.48 (11.64)	5.59 (8.03)	-3.90 (13.67)	10.77 (9.99)			-11.15 (13.18)	9.86 (9.03)		
		7.5			-26.63 (22.17)		-36.15 (27.47)				-39.10 (26.70)		

Continued

Table 9.9 Continued

Recorded Performance (E-RP)	Dam age	1	**21.31 (2.34)**	**31.12 (2.10)**								
		2	4.03 (3.37)	-2.32 (3.19)	3.34 (3.47)	-2.72 (3.28)			3.49 (3.43)	-2.80 (3.27)		
		3	8.01 (3.33)	-2.07 (3.13)	6.18 (3.53)	-4.29 (3.23)			6.43 (3.50)	-3.84 (3.25)		
		4	6.46 (3.27)	-1.02 (3.27)	4.16 (3.34)	-1.56 (3.39)			4.98 (3.30)	-2.81 (3.39)		
	First pre-mating BCS	2.25	**14.50 (16.26)**	**28.70 (12.68)**								
		2.5	3.84 (17.98)	16.27 (15.15)	-7.39 (17.34)	23.16 (14.99)			-0.24 (17.48)	17.21 (15.04)		
		2.75	9.32 (16.37)	-2.39 (12.83)	-0.63 (15.62)	8.33 (12.60)			4.51 (15.79)	-1.39 (12.72)		
		3	11.84 (16.36)	3.43 (12.81)	1.98 (15.70)	11.19 (12.69)			6.26 (15.87)	2.87 (12.80)		
		3.25	17.25 (16.58)	3.88 (12.98)	8.66 (15.98)	13.94 (12.85)			12.75 (16.09)	4.44 (12.90)		
		3.5	12.50 (19.92)	-5.34 (13.45)	10.54 (18.91)	5.64 (13.29)			13.22 (19.12)	-2.59 (13.39)		
		3.75		-10.35 (20.05)		14.78 (25.10)				10.40 (25.49)		
	PY weaning BCS	1.75		**0.00 (22.11)**								
		2		30.73 (25.53)		75.48 (28.15)				56.38 (27.82)		
		2.25	**26.10 (5.28)**	28.55 (22.38)		54.27 (23.59)				39.47 (23.43)		
		2.5	-5.17 (5.71)	26.91 (22.20)	-7.53 (6.07)	49.34 (23.49)			-6.80 (6.00)	34.59 (23.27)		
		2.75	-1.50 (5.56)	29.35 (22.23)	-7.39 (6.01)	49.42 (23.51)			-5.36 (5.92)	35.20 (23.30)		
		3	6.60 (6.04)	33.04 (22.31)	2.84 (6.76)	51.60 (23.47)			4.42 (6.53)	37.40 (23.25)		
		3.25	1.92 (6.56)	34.38 (22.41)	-7.23 (7.55)	50.99 (23.76)			-4.43 (7.36)	38.43 (23.57)		
		3.5	27.94 (9.14)	38.79 (22.79)	19.29 (9.94)	58.36 (24.21)			21.87 (9.69)	44.82 (24.00)		
		3.75	5.20 (23.00)	60.95 (27.08)	2.44 (23.21)	70.46 (28.15)			5.90 (23.13)	63.79 (27.85)		
	Ewe birth liveweight	I	8.73 (6.85)	29.87 (6.65)								
		G	4.71 (1.85)	0.01 (1.79)	1.11 (2.17)	-1.77 (2.14)			-0.06 (2.13)	-0.96 (2.08)		
	Ewe wean liveweight	I	-1.02 (9.67)	14.07 (10.45)								
		G	0.96 (0.34)	0.57 (0.38)	0.17 (0.45)	0.52 (0.47)			0.49 (0.43)	0.64 (0.45)		
	PY pre-mating liveweight	I	-1.63 (10.64)	10.00 (9.15)								
		G	0.52 (0.20)	0.44 (0.20)	-2.81 (2.11)	1.43 (2.15)			-2.22 (2.03)	0.63 (2.12)		
	PY weaning liveweight	I	-28.12 (10.38)	-7.63 (8.91)								
		G	1.02 (0.20)	0.69 (0.16)	2.94 (2.14)	-1.12 (1.85)			2.71 (2.05)	-0.22 (1.81)		
	PY wt change pre-mating to early pregnancy	I	26.08 (1.86)	30.63 (1.22)								
		G	0.08 (0.39)	-0.57 (0.33)	-0.14 (0.47)	-0.42 (0.47)			-0.34 (0.45)	-0.51 (0.47)		
	PY % wt change pre-mating to weaning	I	25.57 (1.17)	25.28 (2.08)								
		G	0.33 (0.13)	0.24 (0.09)	-1.27 (1.08)	0.72 (0.82)			-0.99 (1.05)	0.47 (0.81)		
	PY birth liveweight of lambs	I	21.07 (2.22)	29.38 (1.95)								
		G	1.33 (0.50)	0.25 (0.45)	1.04 (0.60)	0.65 (0.63)			1.20 (0.55)	0.64 (0.59)		
E-EBV	*Maternal ability*	I	23.08 (1.38)	28.38 (1.37)								
		G	4.19 (1.13)	2.35 (1.06)	2.03 (1.39)	1.61 (1.32)					3.86 (1.15)	2.41 (1.07)
	Ultrasound muscle depth	I	23.63 (1.55)	30.48 (1.61)								
		G	2.86 (1.28)	-0.52 (1.26)	1.01 (1.55)	-1.19 (1.47)					2.12 (1.28)	-0.79 (1.26)

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded Performance; EBV: Estimated Breeding Value; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); SE: standard error; wt: liveweight.

[a]for categorical variables the constant is shown in bold and the values for other levels are the difference to the constant level;

[b]type, where: I: Intercept; G: Gradient.

Table 9.10 Estimates of the effect (with SE) of explanatory variables used in Reduced models of **Total number of lambs weaned (R-LmNo).** Estimates are given when R-LmNo is fitted against each single explanatory variable and for multiple explanatory variable models (E-all, E-VAA, E-RP and E-EBV, *continuous variables in italics*).

	Variable name	Level	Type[c]	Single variable[a]		E-all		E-VAA		E-RP		E-EBV	
				2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
	Models with multiple variables		I			-0.73 (1.62)	-1.94 (1.98)	0.32 (0.84)	-1.24 (0.88)	-3.61 (1.11)	-1.60 (1.46)	-0.43 (0.11)	0.06 (0.11)
Visual Appearance Assessment (E-VAA)	Size	1		**-1.15 (0.33)**	**-0.35 (0.18)**								
		2		0.98 (0.34)	0.40 (0.20)	0.91 (0.40)	0.21 (0.25)	1.00 (0.35)	0.37 (0.21)				
		3		1.45 (0.38)	0.90 (0.27)	1.22 (0.50)	0.63 (0.40)	1.41 (0.39)	0.78 (0.28)				
	Flatness of back	1		**0.29 (0.38)**	**-0.59 (0.56)**								
		2		-0.67 (0.39)	0.53 (0.57)	-0.80 (0.45)	0.74 (0.62)	-0.79 (0.41)	0.66 (0.60)				
		3		-0.22 (0.40)	0.72 (0.57)	-0.63 (0.45)	0.85 (0.62)	-0.41 (0.41)	0.79 (0.60)				
	Jaw position	≤0[b]		**0.19 (0.31)**	**0.32 (0.11)**								
		1		-0.39 (0.35)	-0.49 (0.17)	0.08 (0.43)	-0.77 (0.21)	-0.24 (0.37)	-0.56 (0.19)				
		2		-0.40 (0.33)	-0.32 (0.26)	0.08 (0.41)	-0.49 (0.30)	-0.32 (0.35)	-0.48 (0.27)				
		3		-0.24 (0.34)	-0.14 (0.27)	0.49 (0.45)	-0.60 (0.34)	-0.12 (0.38)	-0.38 (0.31)				
		≥4[b]		-0.51 (0.42)	-1.08 (0.34)	0.26 (0.58)	-1.54 (0.46)	-0.24 (0.50)	-1.37 (0.43)				
	Tooth length	0		**-0.30 (0.10)**	**0.10 (0.11)**								
		1		0.46 (0.16)	-0.06 (0.15)	0.38 (0.21)	-0.03 (0.21)	0.49 (0.18)	0.09 (0.18)				
		2		-0.15 (0.22)	-0.18 (0.30)	-0.48 (0.39)	0.49 (0.45)	-0.25 (0.31)	0.56 (0.41)				
	Teat size	≤2[b]		**-0.20 (0.07)**	**-0.02 (0.08)**								
		3		0.62 (0.28)	0.61 (0.23)	-0.40 (0.39)	0.53 (0.36)	-0.04 (0.33)	0.73 (0.29)				
	Udder attachment	1		**0.79 (0.54)**	**0.22 (0.47)**								
		2		0.06 (0.61)	-0.01 (0.58)	-0.45 (0.86)	0.15 (0.65)	0.19 (0.66)	0.26 (0.61)				
		3		-1.05 (0.54)	-0.18 (0.48)	-1.25 (0.81)	0.54 (0.62)	-0.81 (0.62)	0.58 (0.57)				
	Fleece colour	≤2[b]		**-0.13 (0.10)**	**0.23 (0.14)**								
		3		-0.05 (0.14)	-0.24 (0.16)	-0.30 (0.17)	-0.20 (0.19)	-0.14 (0.15)	-0.25 (0.17)				
Recorded Performance (E-RP)	Age	2.5		**-0.36 (0.13)**	**-0.17 (0.12)**								
		3.5		0.20 (0.18)	0.38 (0.18)	0.17 (0.22)	0.61 (0.29)			0.19 (0.21)	0.27 (0.26)		
		4.5		0.47 (0.19)	0.29 (0.19)	0.53 (0.30)	0.60 (0.32)			0.42 (0.23)	0.21 (0.27)		
		5.5		0.14 (0.36)	0.64 (0.31)	-0.17 (0.50)	1.02 (0.49)			-0.04 (0.44)	0.63 (0.41)		
		≥6.5[b]		-0.15 (0.74)	0.17 (0.49)	-0.91 (1.16)	0.35 (0.66)			-1.37 (1.12)	0.34 (0.57)		
	PY pre-mating BCS	≤2.25[b]		**-0.92 (0.42)**	**0.41 (0.46)**								
		2.5		0.59 (0.46)	0.04 (0.50)	0.62 (0.61)	0.02 (0.59)			0.47 (0.55)	-0.31 (0.56)		
		2.75		0.81 (0.43)	-0.60 (0.47)	0.87 (0.59)	-0.47 (0.55)			0.75 (0.53)	-0.74 (0.53)		
		3		0.88 (0.46)	-0.19 (0.48)	1.24 (0.63)	0.04 (0.57)			1.12 (0.57)	-0.28 (0.55)		
		3.25		0.81 (0.48)	-0.23 (0.50)	1.36 (0.68)	0.19 (0.61)			1.09 (0.61)	-0.23 (0.58)		
		≥3.5[b]		0.41 (0.66)	-0.57 (0.51)	0.77 (0.82)	-0.38 (0.61)			0.46 (0.77)	-0.58 (0.59)		
	PY weaning BCS	≤2.25[b]		**-0.11 (0.33)**	**-0.23 (0.22)**								
		2.5		-0.38 (0.36)	0.07 (0.25)	-0.59 (0.42)	0.01 (0.28)			-0.53 (0.40)	-0.05 (0.27)		
		2.75		-0.12 (0.35)	0.30 (0.26)	-0.66 (0.41)	0.05 (0.32)			-0.50 (0.40)	0.03 (0.29)		
		3		0.39 (0.38)	0.53 (0.29)	-0.14 (0.47)	0.37 (0.36)			0.01 (0.44)	0.27 (0.33)		
		≥3.25[b]		0.43 (0.40)	0.75 (0.29)	-0.34 (0.50)	0.41 (0.41)			-0.15 (0.48)	0.47 (0.38)		

Continued

Table 9.10 Continued

Recorded Performance (E-RP)	*Ewe birth liveweight*	I	-1.26 (0.42)	0.08 (0.42)								
		G	0.30 (0.11)	-0.01 (0.11)	0.07 (0.15)	-0.10 (0.14)			-0.02 (0.14)	-0.02 (0.14)		
	Ewe wean liveweight	I	-1.75 (0.61)	-0.87 (0.67)								
		G	0.06 (0.02)	0.03 (0.02)	0.00 (0.03)	0.07 (0.03)			0.02 (0.03)	0.05 (0.03)		
	PY pre-mating liveweight	I	-1.93 (0.67)	-1.07 (0.59)								
		G	0.03 (0.01)	0.02 (0.01)	-0.36 (0.16)	0.07 (0.15)			-0.30 (0.15)	0.01 (0.14)		
	PY weaning liveweight	I	-3.90 (0.70)	-2.42 (0.60)								
		G	0.07 (0.01)	0.05 (0.01)	0.36 (0.16)	-0.09 (0.13)			0.34 (0.15)	0.00 (0.12)		
	PY % wt change pre-mating to early pregnancy	I	-0.13 (0.11)	0.10 (0.08)								
		G	0.01 (0.01)	-0.02 (0.01)	-0.02 (0.02)	-0.02 (0.01)			-0.01 (0.02)	-0.02 (0.01)		
	PY % wt change pre-mating to weaning	I	-0.18 (0.07)	-0.29 (0.14)								
		G	0.02 (0.01)	0.02 (0.01)	-0.16 (0.08)	0.04 (0.06)			-0.13 (0.08)	0.02 (0.06)		
	PY liveweight of lambs at birth	I	-0.49 (0.14)	0.05 (0.12)								
		G	0.09 (0.03)	0.01 (0.03)	0.10 (0.04)	0.04 (0.04)			0.10 (0.04)	0.04 (0.04)		
E-EBV	*Maternal ability*	I	-0.34 (0.09)	-0.02 (0.09)								
		G	0.26 (0.07)	0.10 (0.07)	0.12 (0.10)	0.06 (0.09)					0.24 (0.07)	0.11 (0.07)
	Ultrasound muscle depth	I	-0.30 (0.10)	0.12 (0.10)								
		G	0.18 (0.08)	-0.08 (0.08)	0.06 (0.10)	-0.14 (0.10)					0.13 (0.08)	-0.09 (0.08)

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded Performance; EBV: Estimated Breeding Value; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); SE: standard error; wt: liveweight.

[a]for categorical variables the constant is shown in bold and the values for other levels are the difference to the constant level;

[b]combined level which were grouped as a result of sparse data;

[c]type, where: I: Intercept; G: Gradient.

Table 9.11 Estimates of the effect (with SE) of explanatory variables used in Reduced models of **Ewe survival to weaning (R-ES)**. Estimates are given when R-EMC is fitted against each single explanatory variable and for multiple explanatory variable models (E-all, E-VAA, E-RP and E-EBV, continuous variables in italics).

	Variable name	Level	Type[c]	Single variable[a]		E-all		E-VAA		E-RP		E-EBV	
				2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
	Models with multiple variables		I			-5.63 (2.72)	-3.50 (3.70)	-0.85 (1.39)	-0.40 (1.87)	-2.84 (2.03)	1.97 (2.55)	2.12 (0.21)	2.70 (0.30)
E-VAA	Size	1		**1.39 (0.50)**	**3.43 (0.71)**								
		2		1.34 (0.55)	-0.58 (0.77)	0.46 (0.88)	-0.68 (1.07)	1.25 (0.58)	-0.53 (0.89)				
		3		0.64 (0.64)	-0.64 (0.93)	-0.27 (1.11)	-0.21 (1.52)	0.42 (0.67)	0.10 (1.13)				
	Flatness of back	1		**1.79 (0.76)**	**0.29 (0.76)**								
		2		0.69 (0.81)	2.43 (0.85)	0.20 (1.07)	3.54 (1.19)	0.78 (0.83)	2.81 (1.00)				
		3		0.71 (0.82)	3.06 (0.84)	-0.19 (1.12)	4.34 (1.23)	0.83 (0.84)	3.58 (1.01)				
	Legs and motion	1		**1.32 (0.56)**	**0.69 (1.22)**								
		2		1.32 (0.73)	1.67 (1.30)	1.01 (1.01)	0.94 (1.83)	1.24 (0.77)	0.24 (1.59)				
		3		1.21 (0.60)	2.48 (1.26)	1.18 (0.92)	2.17 (1.85)	1.30 (0.65)	1.19 (1.56)				
	Teeth present	≤6[b]		**2.20 (0.74)**	**1.73 (0.63)**								
		7		-0.41 (0.97)	0.06 (0.88)	-0.41 (1.13)	-1.15 (1.17)	-0.55 (1.05)	-0.41 (1.03)				
		8		0.33 (0.77)	1.46 (0.69)	0.75 (1.01)	1.27 (0.99)	0.36 (0.88)	0.78 (0.77)				
	Tooth length	0		**2.44 (0.26)**	**3.71 (0.50)**								
		1		0.02 (0.41)	-1.23 (0.57)	0.23 (0.52)	-1.39 (0.75)	0.06 (0.43)	-1.09 (0.62)				
		2		0.08 (0.58)	-0.53 (1.13)	0.11 (0.77)	0.13 (1.47)	0.14 (0.68)	0.64 (1.33)				
	Teat size	≤2[b]		**2.41 (0.19)**	**3.27 (0.29)**								
		3		0.91 (0.98)	-1.58 (0.51)	1.13 (1.12)	-1.28 (0.80)	1.16 (1.08)	-1.14 (0.67)				
Recorded Performance (E-RP)	Age	2.5		**2.85 (0.38)**	**3.82 (0.57)**								
		3.5		-0.76 (0.47)	-1.16 (0.69)	-0.94 (0.60)	1.18 (1.10)			-0.92 (0.57)	-0.51 (0.85)		
		≥4.5[b]		-0.25 (0.51)	-1.26 (0.67)	-0.45 (0.80)	2.01 (1.33)			-0.66 (0.63)	-0.81 (0.85)		
	PY mid-pregnancy BCS	≤2.5[b]		**2.00 (0.23)**	**2.41 (0.39)**								
		2.75		1.27 (0.47)	0.34 (0.58)	0.92 (0.57)	1.14 (0.76)			1.02 (0.53)	0.46 (0.62)		
		≥3[b]		0.89 (0.76)	0.97 (0.57)	0.26 (0.87)	1.79 (0.81)			0.37 (0.82)	0.68 (0.62)		
	Current pre-mating BCS	≤2[b]		**-0.29 (0.76)**	**2.53 (0.73)**								
		2.25		2.08 (1.08)	0.04 (0.90)	1.21 (1.44)	0.18 (1.23)			1.21 (1.24)	-0.04 (0.92)		
		2.5		2.39 (0.84)	1.12 (0.94)	1.93 (1.23)	1.32 (1.25)			1.73 (1.03)	0.98 (0.95)		
		2.75		2.92 (0.82)	0.02 (0.82)	2.34 (1.22)	-0.38 (1.18)			2.18 (1.02)	0.00 (0.86)		
		≥3[b]		3.56 (0.92)	0.71 (1.03)	3.39 (1.38)	0.29 (1.37)			3.15 (1.21)	0.64 (1.09)		
	Ewe birth liveweight		I	0.09 (1.09)	2.17 (1.35)								
			G	0.67 (0.31)	0.21 (0.37)	0.57 (0.41)	0.19 (0.50)			0.63 (0.39)	0.27 (0.42)		
	Current pre-mating liveweight		I	-0.83 (1.62)	4.85 (2.05)								
			G	0.07 (0.03)	-0.04 (0.04)	0.03 (0.05)	-0.03 (0.08)			0.01 (0.04)	-0.01 (0.05)		
	PY % wt change pre-mating to early pregnancy		I	2.44 (0.30)	2.82 (0.24)								
			G	0.00 (0.03)	0.04 (0.03)	-0.01 (0.04)	0.03 (0.04)			-0.02 (0.04)	0.03 (0.04)		
	PY birth liveweight of lambs		I	1.86 (0.30)	3.13 (0.43)								
			G	0.18 (0.08)	-0.04 (0.09)	0.11 (0.11)	0.01 (0.13)			0.13 (0.10)	0.00 (0.11)		

Continued

Table 9.11 Continued

E	Variable	Type										
E-EBV	*Ultrasound muscle depth*	I	2.10 (0.21)	2.71 (0.30)								
		G	0.59 (0.21)	0.27 (0.26)	0.18 (0.31)	-0.18 (0.46)					0.43 (0.27)	0.00 (0.32)
	Ultrasound fat depth	I	2.30 (0.19)	2.70 (0.25)								
		G	2.51 (1.01)	2.29 (1.29)	1.26 (1.52)	1.40 (2.09)					1.22 (1.27)	2.29 (1.60)

E: explanatory variables; VAA: Visual Appearance Assessment; RP: Recorded Performance; EBV: Estimated Breeding Value; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); SE: standard error; wt: liveweight.

[a]for categorical variables the constant is shown in bold and the values for other levels are the difference to the constant level;

[b]combined level which were grouped as a result of sparse data;

[c]type, where: I: Intercept; G: Gradient.

Table 9.12 Means for categorical explanatory variables estimated from effects, and estimates for standardised continuous explanatory variables (in italics), when individually fitted against response variables.

	Variable name	Level	Type[c]	R-EMC 2013	R-EMC 2014	R-LmWt 2013	R-LmWt 2014	R-LmNo[d] 2013	R-LmNo[d] 2014	R-ES[d] 2013	R-ES[d] 2014
Visual Appearance Assessment (E-VAA)	Size	1		-13.45	18.18	13.18	23.46	-1.15	-0.35	1.39	3.43
		2		15.93	23.25	25.83	30.16	-0.18	0.06	2.73	2.85
		3		30.23	29.68	31.64	37.46	0.30	0.55	2.02	2.79
	Flatness of back	1		17.92	-32.01	30.99	16.89	0.29	-0.59	1.79	0.29
		2		10.73	18.85	22.66	28.36	-0.38	-0.06	2.48	2.72
		3		18.08	27.33	29.37	31.33	0.07	0.14	2.50	3.35
	Legs and motion	1		17.92	-10.25					1.32	0.69
		2		11.95	13.06					2.64	2.37
		3		14.52	26.00					2.54	3.17
	Teeth present	≤6[b]								2.20	1.73
		3			-93.90						
		4		6.81	-6.70						
		5		19.40							
		6		-7.61	4.39						
		7		9.54	9.85					1.79	1.79
		8		15.32	25.60					2.53	3.20
	Jaw position	≤0[a]						0.19	0.32		
		-1		-47.39	21.30	0.00	45.60				
		0		23.15	35.03	30.32	34.18				
		1		14.59	16.30	25.15	26.39	-0.20	-0.17		
		2		17.89	22.39	25.36	28.53	-0.21	0.00		
		3		10.10	16.23	27.79	30.52	-0.04	0.18		
		4		-6.14	-11.36	21.81	20.59				
		5		7.11		32.65					
		≥4[a]						-0.32	-0.76		
	Tooth angle	-2		-0.28	-7.30	30.23	16.37				
		-1		17.18	53.00	24.35	50.78				
		0		14.31	22.60	25.99	29.54				
		1		-7.56	36.04	14.15	35.42				
	Tooth length	0		14.80	29.87	23.68	30.47	-0.30	0.10	2.44	3.71
		1		19.98	19.80	30.77	29.90	0.16	0.03	2.46	2.47
		2		-3.03	4.19	21.61	27.96	-0.45	-0.08	2.53	3.18
	Teat size	≤2[ab]						-0.20	-0.02	2.41	3.27
		1				53.60					
		2				25.25	29.19				
		3				33.04	36.08	0.42	0.59	3.32	1.69
	Udder attachment	1		16.93	14.35	36.14	31.41	0.79	0.22		
		2		36.81	18.00	39.97	31.75	0.85	0.21		
		3		12.23	23.80	24.49	29.89	-0.26	0.04		
	Fleece colour	≤2[a]						-0.13	0.23		
		3						-0.18	-0.02		
	Face shape	1				32.68	32.51				
		2				25.45	27.07				
		3				25.52	29.88				

Continued

Table 9.12 Continued

	Variable name	Level	Type[c]	R-EMC 2013	R-EMC 2014	R-LmWt 2013	R-LmWt 2014	R-LmNo[d] 2013	R-LmNo[d] 2014	R-ES[d] 2013	R-ES[d] 2014
Recorded Performance (E-RP)	Age	2.5		16.27	27.85	22.53	26.63	-0.36	-0.17	2.85	3.82
		3.5		14.25	24.03	26.16	31.75	-0.16	0.21	2.09	2.66
		4.5		13.73	17.60	30.01	31.02	0.11	0.11		
		5.5		5.76	23.20	24.25	37.97	-0.22	0.47		
		6.5		-3.46	11.21	22.05	32.23				
		7.5			-93.90		0.00				
		≥4.5[b]								2.60	2.56
		≥6.5a						-0.51	0.00		
	Dam age	1		6.39	24.76	21.31	31.12				
		2		11.80	25.70	25.34	28.79				
		3		22.55	20.91	29.32	29.05				
		4		16.13	19.58	27.78	30.10				
	First pre-mating BCS	2.25				14.50	28.70				
		2.5				18.34	44.97				
		2.75				23.82	26.31				
		3				26.34	32.13				
		3.25				31.75	32.58				
		3.5				27.00	23.36				
		3.75					18.35				
	PY pre-mating BCS	≤2.25[a]						-0.92	0.41		
		2.00		-7.93	78.41						
		2.25		-18.08	32.09						
		2.50		5.90	23.28			-0.33	0.44		
		2.75		15.84	16.82			-0.10	-0.19		
		3.00		22.86	24.26			-0.03	0.22		
		3.25		14.84	33.48			-0.11	0.18		
		3.50		14.59	27.33						
		3.75			35.20						
		≥3.5[a]						-0.51	-0.17		
	PY mid-pregnancy BCS	≤2.5[b]								2.00	2.41
		2.75								3.27	2.75
		≥3[b]								2.89	3.38
	PY weaning BCS	≤2.25[a]						-0.11	-0.23		
		1.75			-42.35		0.00				
		2			6.21		30.73				
		2.25		16.77	18.41	26.10	28.55				
		2.5		3.08	21.59	20.93	26.91	-0.49	-0.17		
		2.75		14.38	20.28	24.60	29.35	-0.23	0.07		
		3		25.29	23.89	32.70	33.04	0.28	0.29		
		3.25		15.70	30.14	28.02	34.38				
		3.5		59.76	46.46	54.04	38.79				
		3.75		32.82	62.06	31.30	60.95				
		≥3.25[a]						0.32	0.52		
	Current pre-mating BCS	≤2[b]								-0.29	2.53
		2.25								1.79	2.56
		2.5								2.11	3.65
		2.75								2.63	2.55
		≥3[b]								3.27	3.24

Continued

Table 9.12 Continued

	Variable name	Level	Type[c]	R-EMC		R-LmWt		R-LmNo[d]		R-ES[d]	
				2013	2014	2013	2014	2013	2014	2013	2014
Recorded Performance (E-RP)	*Ewe birth liveweight*		I	14.24	23.05	25.90	29.92	-0.16	0.05	2.52	2.92
			G	6.26	1.12	3.03	0.01	0.19	-0.01	0.43	0.13
	Ewe wean liveweight		I	13.92	23.23	25.64	30.01	-0.17	0.05		
			G	4.29	2.84	3.09	1.85	0.18	0.11		
	PY pre-mating liveweight		I	12.14	22.38	24.13	31.48	-0.27	0.14		
			G	4.32	-1.50	3.51	2.93	0.23	0.16		
	PY weaning liveweight		I	15.00	22.87	26.56	29.39	-0.12	0.01		
			G	7.90	2.10	6.55	4.44	0.45	0.29		
	Current pre-mating liveweight		I							2.68	3.02
			G							0.44	-0.23
	PY liveweight change pre-mating to early pregnancy		I			25.96	31.38	-0.14	0.13	2.45	2.73
			G			0.34	-2.31	0.05	-0.14	-0.04	0.37
	PY percentage wt change pre-mating to weaning		I	17.63	19.68	28.87	27.67	0.05	-0.12		
			G	5.33	5.30	4.81	3.48	0.34	0.25		
	PY birth liveweight of lambs		I	14.16	23.67	25.92	30.31	-0.16	0.07	2.51	2.97
			G	7.73	-1.33	3.28	0.63	0.22	0.01	0.44	-0.11
EBV (E-EBV)	*Maternal ability*		I	14.31	23.23	25.95	29.99	-0.16	0.05		
			G	8.14	3.06	4.37	2.45	0.27	0.10		
	Ultrasound muscle depth		I	14.47	23.27	26.04	30.05	-0.15	0.06	2.61	2.94
			G	5.87	0.02	2.60	-0.47	0.16	-0.07	0.54	0.25
	Ultrasound fat depth		I							2.59	2.97
			G							0.49	0.44
	Carcass fat weight		I	14.51	23.15						
			G	4.86	1.81						

E: explanatory variables; EBV: Estimated Breeding Values; R: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: ewe survived to weaning; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); wt: liveweight.

[a]combined level which were grouped as a result of sparse data for response variable R-LmNo;

[b]combined level which were grouped as a result of sparse data for response variable R-ES;

[c]type, where: I: Intercept; G: Gradient;

[d]all means for categorical explanatory variables are presented on the logit scale so are comparable to gradients of continuous explanatory variables.

9.3.4 Interesting explanatory variables

Given the large number of explanatory variables included in the models and the number of different models, only the results for a selection of explanatory variables of interest and apparent importance to response variables are presented. They include variables that had statistically significant (at $P<0.05$) relationships in both years to one or more response variable (highlighted in Table 9.6). Explanatory variables for lamb liveweight over the previous year (for example, “PY birth liveweight of lambs) are also considered, as well as “Age”, for reasons to be explained.

9.3.4.1 E-VAA variables of interest

Four E-VAA variables were significant (*P*<0.05) in both years for at least one response variable: “Size”, “Tooth length”, “Teat size” and “Retention decision”.

9.3.4.1.1 *E-VAA “Size”*

Out of all E-VAA variables “Size” was the variable that had significant relationships with each of the four response variables the most times across both years (6 out of 8 possible comparisons to response variables) and was included in the Reduced models for all response variables (Table 9.6).

E-VAA “Size” was recorded on a three level scale where ewe size increased with level (1: Smaller than ideal, 2: Ideal, 3: Bigger than ideal). There was a similar spread of scoring across both years with the majority of ewes being classified as being the “Ideal” size (level 2) in both years (78.4 % in 2013 and 68.8 % in 2014, Table 9.5). Although, according to this classification, there was a greater proportion of larger ewes in 2013 and greater proportion of smaller ewes in 2014, when comparing years. In total 15.2 % of ewes were scored as “Larger than ideal” in 2013 compared to 14 % in 2014, while there were 6.4 % and 17.2 % of ewes scored as “Smaller than ideal” in each year, respectively.

Results showed that ewes scored “larger than ideal” weaned a greater number (R-LmNo) and greater weight (R-LmWt) of lambs than smaller ewes (bivariate screening results not presented here). This is demonstrated by as ewe “Size” increased, the number (R-LmNo) and liveweight (R-LmWt) of lambs weaned the year after stockdraw also increased in both years (*P*<0.01, through bivariate screening, and when the individual variable was fitted to R-LmWt, as shown in Figure 9.7). This relationship appears to be relatively stable when fitted into models with other variables (E-all and E-VAA, Table 9.9) as demonstrated when the estimates and SEs are considered. Within a year the estimates and SEs for individual levels are similar when the single variable effects are compared with when they are fitted within the other models. For example, in 2013, when the single variable of “Size” was fitted, the R-LmWt estimate for levels 2 and 3 were 12.65 kg (SE 4.73) and 18.46 kg (SE 5.42) respectively, which is similar to estimates obtained when fitted with E-VAA (level 2: 11.92 kg, SE 4.68 and level 3: 16.25 kg, SE 5.47). However, when fitted with E-all there was a greater drop seen in estimated effects and larger increase in standard errors (for both R-LmWt and R-LmNo, in each year at all levels) than when fitted with just E-VAA (Table 9.9). This suggests “Size” was possibly associated with (and so confounded by)variable(s) within E-all that were not present in the E-VAA models. On average ewes considered “Larger than ideal” produced the greatest liveweight of lambs weaned at 31.64 kg in 2013, and at 37.46 kg in 2014. In 2014 greater averages were observed compared to 2013 (Table 9.12).

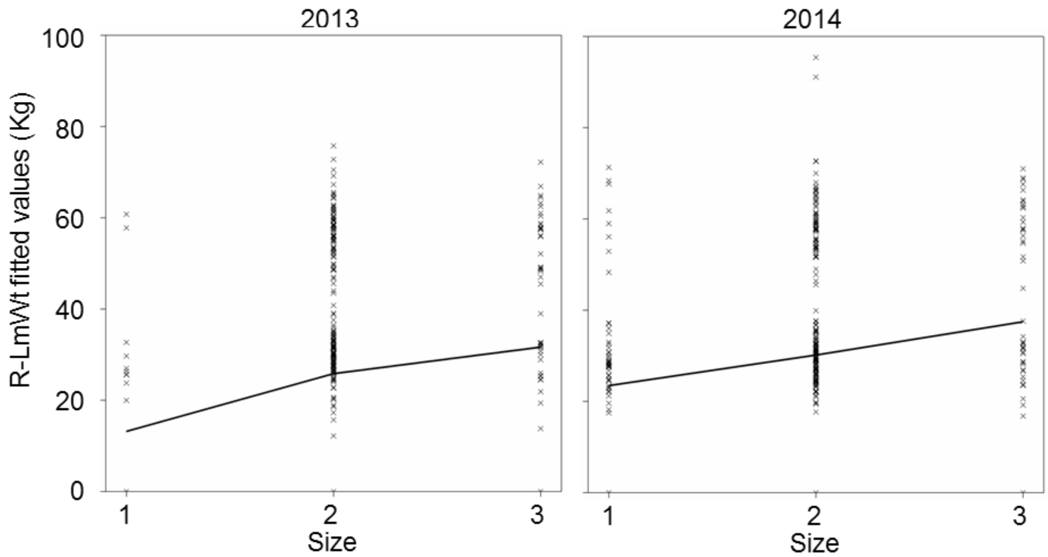


Figure 9.7 Total liveweight of lambs weaned (R-LmWt) fitted values when explanatory variable “Size” modelled for two years.

As size of ewe increased the R-EMC also increased but only in 2013 ($P<0.01$, Table 9.6). In 2013, ewes considered “Smaller than ideal” had a negative R-EMC (-£ 13.45), whereas in 2014 it was positive (£ 18.18). However in both years, R-EMC increased as size increased with a maximum at “Larger than ideal” (£ 30.23 in 2013, £ 29.68 in 2014; Table 9.12).

When bivariate screening results were considered (not presented here), conflicting relationships were seen between “Size” and future ewe survival (R-ES) between the two years, although comparison of the two suggest an “Ideal” size is likely to be preferable for ewe survival. In 2013 more ewes died if they were considered “Smaller than ideal” (20 % died) than either other level. Although more ewes died if they were considered “Larger than ideal” (11.67 %) compared to “Ideal” size (6.15 %). However in 2014, as size decreased, the proportion of ewes to die also decreased (“Larger than ideal” 5.77 %; “Ideal” 5.47 % and “Smaller than ideal” 3.13

%). While the relationships was significant in 2013 (P<0.05) the 2014 relationship was not.

9.3.4.1.2 *E-VAA "Tooth length"*

The E-VAA explanatory variable "Tooth length" was measured on a range of levels where -2 was very short to 2, very long. However, across the two years, no ewes were scored as having short teeth (levels -1 or -2). In 2013 the majority of ewes (50.8 %) scored a level of 0 whereas in 2014 the majority of ewes were scored as having longer teeth (48.4 % received level 1 score, Table 9.13).

In 2014 as "Tooth length" increased, R-EMC decreased (P<0.01, Table 9.13). However in 2013, while the relationship with R-EMC was still significant (P<0.01, Table 9.6), the pattern was different; ewes with slightly longer teeth (level 1) had the highest R-EMC, followed by those at level 0 then 2 (Table 9.13) and when single variable fitted to R-EMC, Table 9.8).

Table 9.13 Bivariate screening results of explanatory variable "Tooth length" (where level was -2 very short to 2 very long) to response variable Ewe Marginal Contribution (R-EMC).

"Tooth length" Level	Percentage of scores in 2013	Percentage of scores in 2014	R-EMC mean (SE) 2013 (£)	R-EMC mean (SE) 2014 (£)
0	50.8	44.9	14.80 (2.97)	29.87 (2.94)
1	35.5	48.4	19.98 (3.85)	19.80 (3.36)
2	13.7	6.7	-3.03 (5.60)	4.19 (6.82)

The pattern seen in 2013 data of ewes with slightly longer teeth (level 1) being associated with higher performance was also seen in relation to R-LmWt (P<0.01, Table 9.6, Table 9.12) and R-LmNo (P<0.01, Table 9.6, Table 9.12) and the lowest performance was seen for ewes with very long teeth (level 2). Tooth length of 1 had a weaning percentage (calculated from R-LmNo) the year after stockdraw of 108 % followed by 85 % at level 0 and 78 % at level 2. Within 2014 data R-LmWt and R-LmNo was not associated with "Tooth length" (P>0.05, Table 9.6).

When added into models with other variables (E-all and E-VAA), this relationship pattern within 2013 data appeared relatively stable for response variables R-EMC (Table 9.8), R-LmWt (Table 9.9) and R-LmNo (Table 9.10). While the standard error associated with each level did increase (compared to the single variable fitted to the response variable) this was often only slightly. The recurrent pattern of level 1 being the best followed by 0 and then 2, remained constant, suggesting it was not confounded by other variables within the model.

While included in Initial and Reduced models for R-ES, "Tooth length" did not have a significant relationship in either year (Table 9.6).

9.3.4.1.3 *E-VAA "Teat size"*

The third E-VAA that was significant in both years for any one response variable and included in Reduced models was "Teat size" (*P*<0.05 in both years for R-LmNo, Table 9.6). The majority of ewes were assigned an "Ideal" (level 2) "Teat size" in both years (92.4 % of ewes in 2013 and 87.9 % in 2014,Table 9.5). Only one ewe was scored as having "Smaller than ideal" (level 1) "Teat size" in 2013.

The relationship to R-LmNo appeared similar between years (Table 9.14) and suggested that ewes with "Larger than ideal" (level 3) "Teat size" were more often associated with those that had weaned twins (R-LmNo = 2) compared to ewes weaning no (R-LmNo = 0) or a single lamb (R-LmNo = 1, Table 9.14, *P*<0.05 through GLM for both years Table 9.6). When fitted into the R-LmNo model (Table 9.10), estimates for "Teat size" appeared similar between years (estimate at level 3 was 0.62 for 2013 and 0.61 for 2014). However, they did alter, with large SEs, when other variables were added.

Table 9.14 Distribution of "Teat size" scores (shown as percentage of scores) in 2013 and 2014 (level number shown in brackets) for Total number of lambs weaned (R-LmNo).

		Teat size					
		2013			**2014**		
		Smaller than ideal (1)	**Ideal (2)**	**Larger than ideal (3)**	**Smaller than ideal (1)**	**Ideal (2)**	**Larger than ideal (3)**
R-LmNo	**0**	0	34.01	1.78	0	22.31	2.15
	1	0	34.01	2.28	0	43.55	4.30
	2	0.25	24.37	3.30	0	21.51	5.65
	3	0	0	0	0	0.54	0

In 2014 a larger "Teat size" was associated with a lower rate of ewe survival (R-ES, *P*<0.05 through GLM, Table 9.6); where 96 % of ewes scored as having "Ideal" (level 2) "Teat size" survived compared to 84 % of those with "Larger than ideal" (level 3) size (bivariate screening results not shown). However, no association was found between “Teat size” and R-ES in 2013 (Table 9.6).

In both years “Teat size” was not found to have any significant association with R-EMC or R-LmWt (Table 9.6).

9.3.4.1.4 *E-VAA “Retention decision”*

As previously noted, “Retention decision” was not included in Reduced models, this was because it was highly correlated with other E-VAA variables, it was a subjective overall score provided by the Flock Manager, and other variables were more important to include in the models. However, given it could be considered as the Flock Manager’s overall opinion of the sheep, it was deemed interesting to consider how this variable performed in bivariate screening.

The E-VAA variable “Retention decision” (which was measured on a scale of 1 “would definitely sell” to 5 “would definitely keep”) had a similar distribution of scores at each level in both years (Table 9.5), with level 3 having 60.4 % of observations in 2013 and 63.2 % in 2014. “Retention decision” had a positive relationship with R-EMC in both years (*P*<0.05 Table 9.6, Figure 9.8).

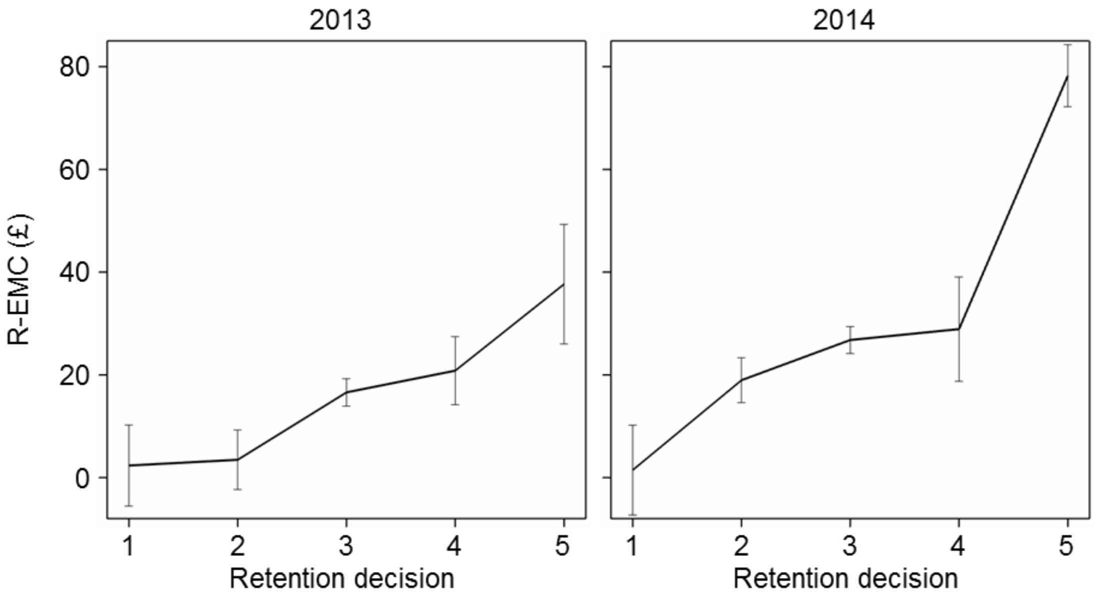


Figure 9.8 The relationship between explanatory variable “Retention decision” (level from 1: would definitely sell to 5: would definitely keep) and the response variable Ewe Marginal Contribution (R-EMC) for two years, with SE shown.

"Retention decision" was associated with R-LmNo in 2013 only (*P*<0.05, Table 9.6). Ewes that had weaned twins (R-LmNo = 2) had previously received a higher "Retention decision" score (21.8 % received "Retention decision" scores of level 4 or 5) compared to ewes that weaned no lambs (R-LmNo = 0, 12.1 %) or just a single lamb (R-LmNo = 1, 11.9 %, results from bivariate screening).

9.3.4.2 E-RP variables of interest

9.3.4.2.1 *E-RP "Age"*

Distribution of ewe "Age" across the two years appeared different but was not significantly so (*P*=0.08 from Chi-squared test through bivariate screening). In 2013 the age group that had the most ewes was 3.5 years old at stockdraw (34.5 % of ewes) and in 2014 it was 2.5 years old (37.6 %, Table 9.5) but average age was similar (3.57 years old in 2013 and 3.58 in 2014).

"Age" only had a significant association with one response variable; R-EMC and only within 2014 data (*P*<0.05, Table 9.6). Although a trend of increased "Age" to decreasing R-EMC could be observed (Figure 9.9).

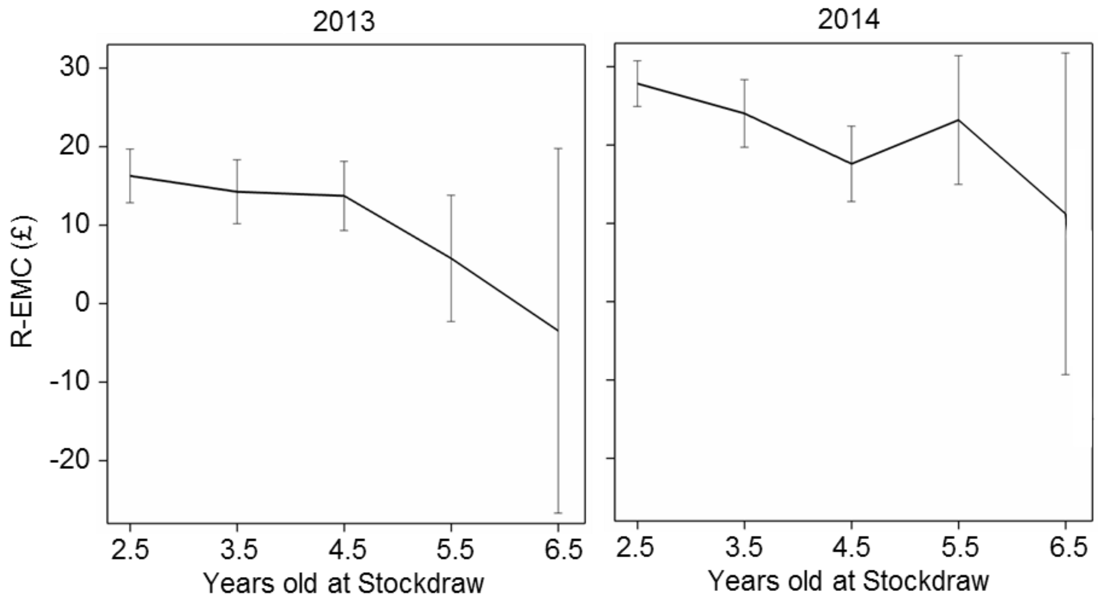


Figure 9.9 The relationship between explanatory variable "Age" and response variable Ewe Marginal Contribution (R-EMC) for two years, with SE shown. Data point for ewes 7.5 years old at stockdraw in 2014 removed as only one ewe value.

Bivariate screening showed that R-LmWt increased as “Age” increased, at the lower ages (Figure 9.10). While this relationship was not significant (*P*=0.18 for 2013 and *P*=0.09 for 2014) the low number of ewes at the older age groups may be impacting on the results (ages 6.5 and 7.5 had 4 animals in 2013 and 9 in 2014).

While “Age” was only statistically significant for R-EMC, it had relationships with probability of *P*<0.1 in 2014 for all other response variables. Given the importance age of ewe had on culling and retention decisions (and the interests of this thesis) it was decided “Age” should be included in Reduced models for all response variables.

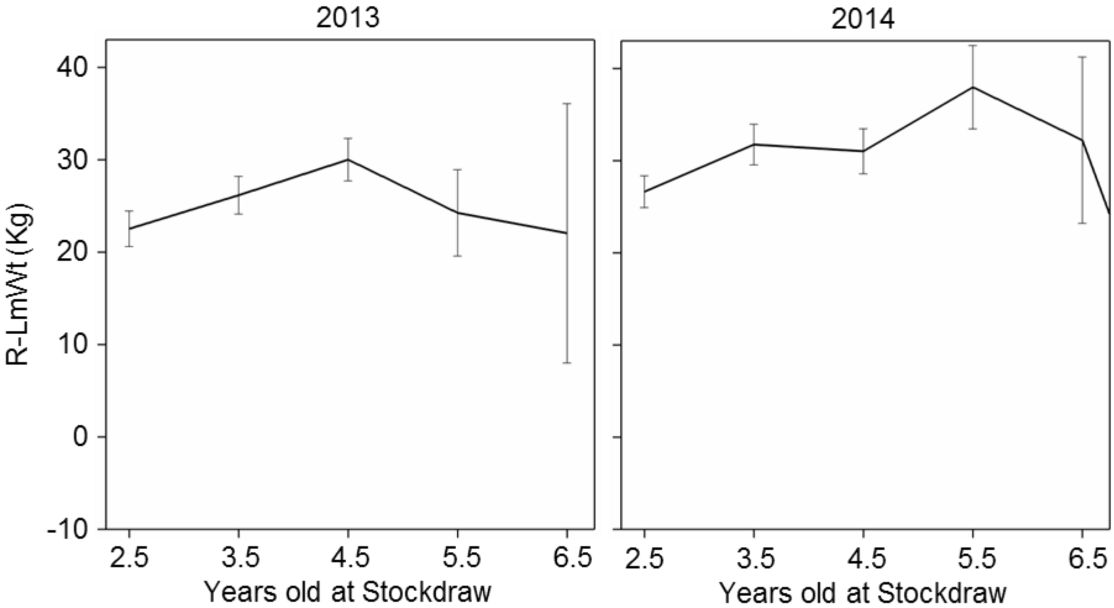


Figure 9.10 The relationship between explanatory variable “Age” (in years old at stockdraw) and response variable Total liveweight of lambs weaned (R-LmWt) for two years, with SE shown. Data point for ewes 7.5 years old at stockdraw in 2014 removed as only one ewe value.

Within 2014 data, “Age” was significantly associated with R-ES (*P*<0.05, Table 9.6). When “Age” was the only variable fitted against R-ES for 2014 data (Table 9.11), estimates were negative, suggesting survival decreased as age increased. These estimates remained negative when fitted in E-RP models but when fitted with E-all they became positive (although they then had large SEs, suggesting other variables were confounding the effect. Estimated proportions (calculated from estimated means in Table 9.12) for 2014 data, showed a 98 % chance of survival for Age 2.5 compared to Age 3.5 or older at 93 % chance of survival.

9.3.4.2.2 *E-RP "PY weaning BCS"*

Variation in ewe BCS and liveweights was seen between weighing events within the same year and at individual weighing events between the two years of data (Figure 9.11).

Out of the five different BCS E-RP variables, only "PY weaning BCS" had a significant relationship (at $P<0.05$) with a response variable in both years (R-LmNo, from GLM, Table 9.6). The distribution of "PY weaning BCS" scores appeared different between 2013 and 2014, with the mode score being 2.75 in 2013 and 2.5 in 2014 (Figure 9.12), but this distribution was not significantly different between years ($P=0.21$).

The general trend for both years appeared to be that as "PY weaning BCS" increased, so did R-LmNo (Figure 9.13). Although when fitted into models (Table 9.10), estimates had very large standard errors and the majority of estimates for 2013 were negative (suggesting as BCS increased R-LmNo decreased).

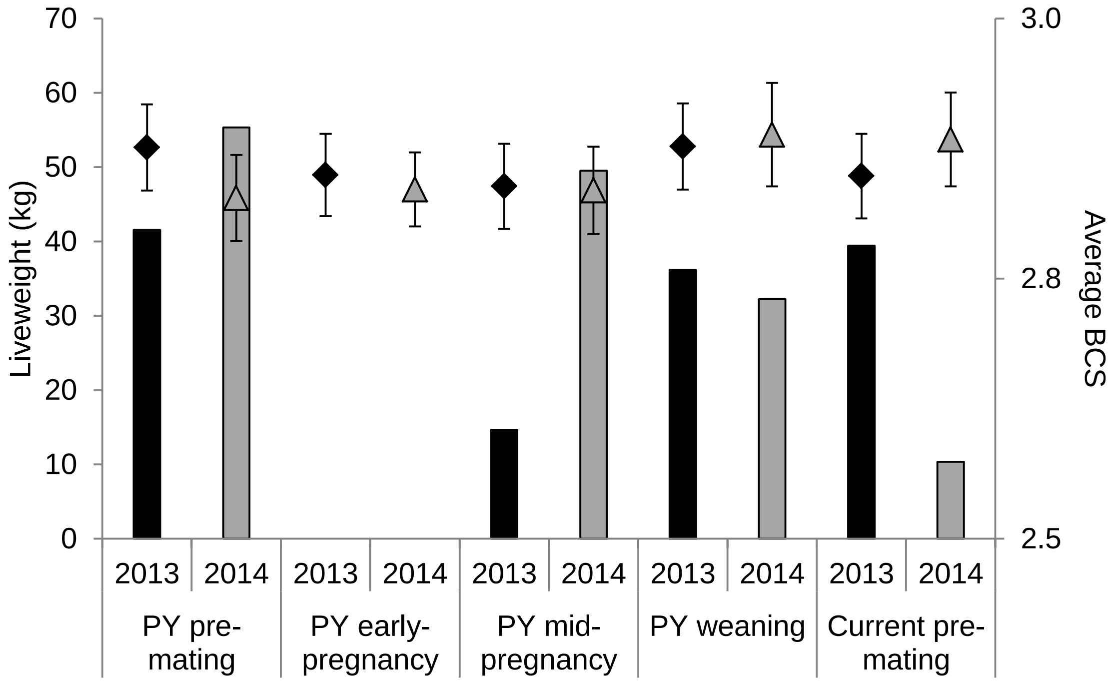


Figure 9.11 Average liveweights of ewes (points, with SD) and Body Condition Score (BCS, bars show arithmetic mean) shown at different time points through the previous year (PY) for datasets 2013 (black diamond points and bars) and 2014 (grey triangle points and bars).

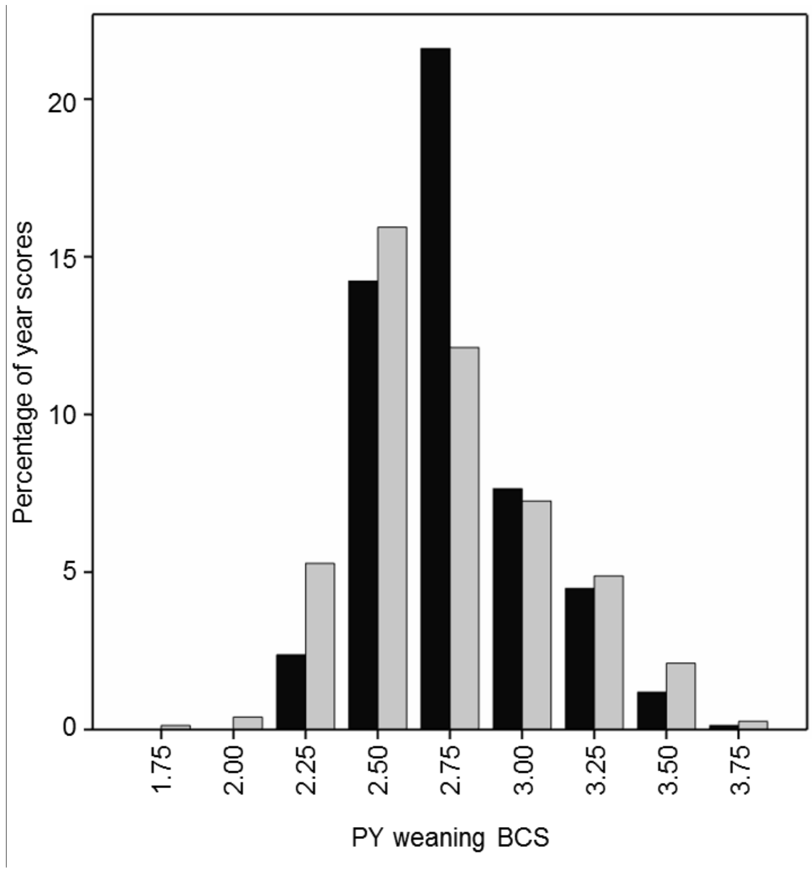


Figure 9.12 Distribution of previous year (PY) weaning body condition score (BCS) for 2013 (black bars) and 2014 (grey bars).

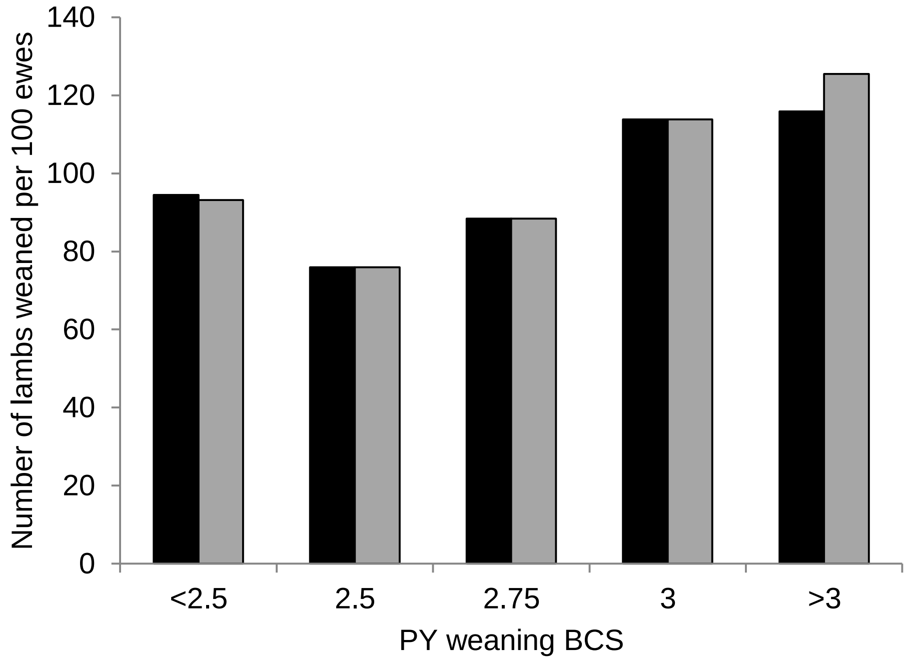


Figure 9.13 Number of lambs weaned (R-LmNo) for ewes Body Condition Score (BCS) at the previous years (PY) weaning for 2013 (black) and 2014 (grey).

9.3.4.2.3 *E-RP PY ewe liveweights*

As seen in Figure 9.11, liveweights varied across the year prior to stockdraw. The average liveweight was higher in 2013 compared to 2014 at time points “PY pre-mating weight” and “PY early-pregnancy” (*P*<0.001); while for “PY weaning” and “Current pre-mating weight” the average liveweight in 2014 was higher compared to 2013 (*P*<0.001). “PY mid-pregnancy weight” was the only E-RP ewe liveweight over the previous years that was similar between the two years (*P*=0.19).

Ewe liveweight variables were often found to be significantly associated with a response variable for one year’s data, however, few were found to be significant in both years (Table 9.6). “PY weaning liveweight” had significant relationships in both years to R-LmWt and R-LmNo (*P*<0.001 for both, Table 9.6). Ewes average “PY weaning liveweight” in 2014 was 54.39 kg which was significantly higher compared to 2013 (52.8 kg, *P*<0.001, Table 9.5, from bivariate screening).

When comparing the relationship between the ewes weaning liveweight prior to stockdraw (“PY weaning liveweight”) and R-LmWt, correlations were weak but positive (*r* = 0.26 in 2013 and *r* = 0.22 in 2014, both *P*<0.001, from bivariate screening). When fitted values were generated for ewes “PY weaning liveweight” for both years, a positive relationship was also seen (Figure 9.14). Clustering of data points seen was caused by litter size.

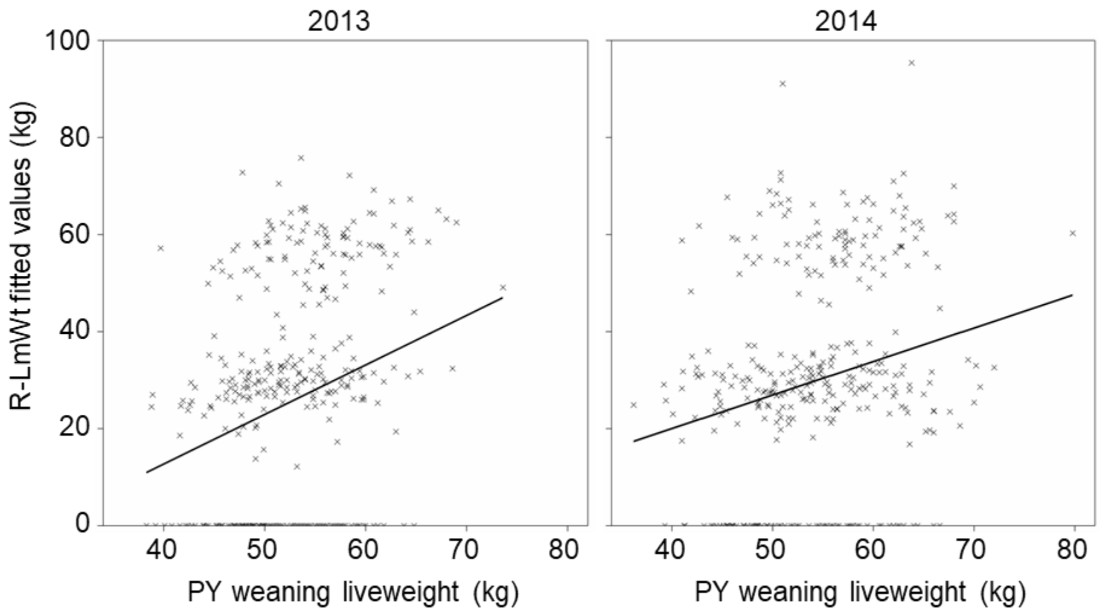


Figure 9.14 Estimates from model for Total liveweight of lambs weaned (R-LmWt) as a function of “PY weaning liveweight” for each year.

The gradient (Table 9.9) was positive in both years (2013, 1.02, SE 0.20 and in 2014 0.69, SE 0.16), however it became negative (with larger SEs in 2014) for Reduced model E-all (2013, 2.94, SE 2.14; 2014, -1.12, SE 1.85, Table 9.9). The change in estimates (shift in gradient) and high standard errors when the full model was fitted (E-all) suggested that the explanatory variable was highly confounded with other variables in the model. Estimated effects on the standardised scale for "PY weaning liveweight" (Table 9.12) had the steepest gradient in 2013 (6.55) and in 2014 (4.44), compared to all other continuous variables in each year suggesting a larger impact on the R-LmWt with increased ewe "PY weaning liveweight".

The positive impact that increased ewe weaning liveweight ("PY weaning liveweight") had on performance the year after stockdraw was also demonstrated when compared to number of lambs weaned (R-LmNo, *P*<0.001 in both years, Table 9.6). As the number of lambs weaned during the year after stockdraw (R-LmNo) increased, so did average ewe liveweight at the previous weaning (Figure 9.15). However, when fitted into models with other response variables (E-RP and E-all), estimates of gradients and standard errors for R-LmNo altered greatly compared to when only the single explanatory variable "PY weaning liveweight" was fitted (Table 9.9). This suggested other variables within these models were confounded with the explanatory variable "PY weaning liveweight".

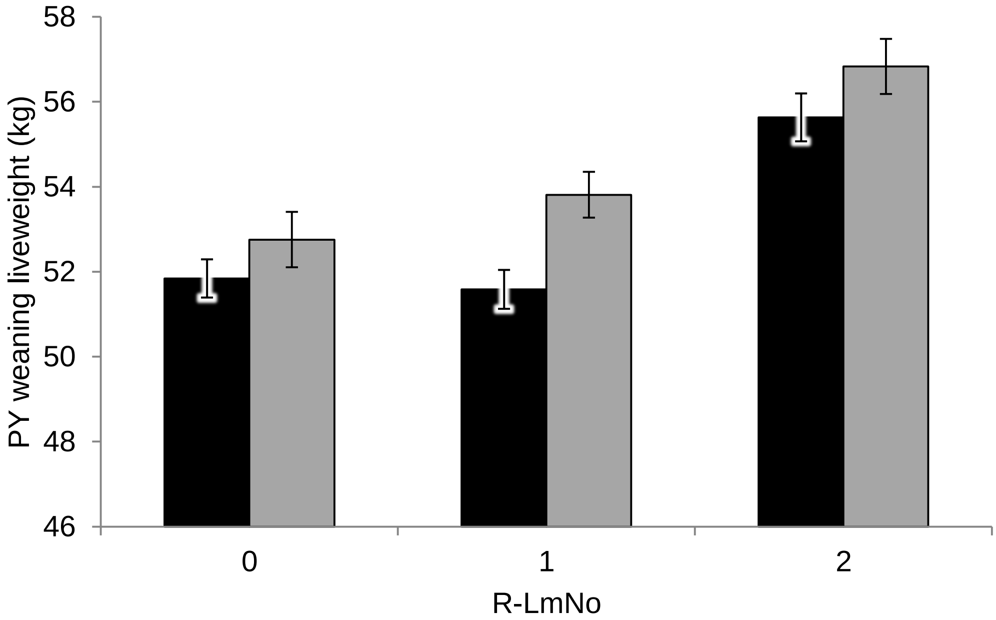


Figure 9.15 Liveweight of ewes at weaning the year prior to stockdraw ("PY weaning liveweight") compared to the number of lambs weaned the year after stockdraw (R-LmNo) within 2013 (black bars) and 2014 data (grey bars), with standard errors.

9.3.4.2.4 *E-RP "PY liveweight changes pre-mating to weaning"*

For the three E-RP variables for liveweight change and the three for percentage of liveweight change, ewes gained more in 2014 compared to 2013 (*P*<0.001, Table 9.5, Figure 9.11). The greatest difference within and between years was seen for "PY liveweight change pre-mating to weaning" (8.57 kg gain in 2014 compared to 0.24 kg in 2013) and for "PY percentage liveweight change pre-mating to weaning" (19.33 % gain in 2014 compared to 0.85 % in 2013).

These two variables were also significantly associated with R-LmWt and R-LmNo in both years (*P*<0.01, Table 9.6). With R-LmWt the relationship was weak but positive (*r* = 0.13 to 0.16, for any combination of each year to each explanatory variable, from bivariate screening). The relationship with R-LmNo was also positive. As ewe liveweight and percentage liveweight change increased between pre-mating and weaning, so did R-LmNo (from bivariate screening).

The two variables were calculated from the same liveweights and so were highly correlated (2013 *r* = 0.99, 2014 *r* = 0.98, both years *P*<0.001, from bivariate screening). As such, only "PY percentage liveweight change pre-mating to weaning" was included in Reduced models. Parameter estimates for R-LmNo showed that the gradient was exactly the same for "PY percentage liveweight change pre-mating to weaning" for both years (0.02, SE 0.01, Table 9.10). However, when further variables were included in the model, the 2013 gradient became negative (-0.16). Although for 2014 it seemed this variable was less affected by other variables in the E-RP model as the gradient did not alter but the SE did increase to 0.06. The estimated proportions for R-LmNo appeared similar across years also (Figure 9.16).

9.3.4.2.1 *E-RP PY lamb counts*

All counts of lambs over the year prior to stockdraw ("PY lambs born dead or alive", "PY lambs born alive", "PY lambs at 8 weeks", "PY lambs at weaning") had a strong positive correlation with each other (*r*>0.8 *P*<0.001, through bivariate screening). Also these four explanatory variables had significant relationships across both years with R-LmWt (*P*<0.05) and R-LmNo (*P*<0.05, Table 9.6). Therefore, only one of these explanatory variables was considered to understand the relationship with future performance.

The majority of ewes (63.3 % in 2013, and 77.5 % in 2014) that did not wean any lambs the year prior to stockdraw ("PY lambs at weaning" = 0) did have lambs the year after stockdraw (R-LmNo = 1, 2 or 3, from bivariate screening). Likewise, the majority of ewes (64.6 % in 2013, 74.4 % in 2014) that did wean lambs the year prior to stockdraw (“PY lambs at weaning” = 1, 2 or 3), weaned lambs the year after stockdraw (R-LmNo = 1, 2 or 3).

Due to their close associations with PY lamb liveweight variables, these lamb count explanatory variables were not included in Reduced models for the response variables R-LmNo and R-LmWt. The lamb liveweight explanatory variables were used instead.

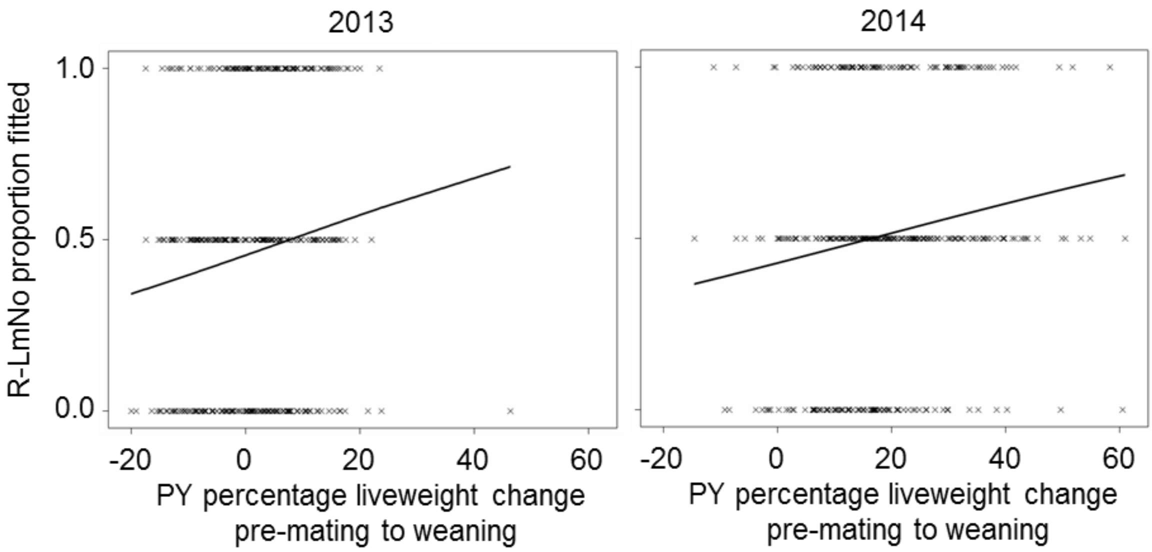


Figure 9.16 Proportion estimated from the model for Total number of lambs weaned (R-LmNo) modelled as a function of year prior to stockdraw (PY) “percentage liveweight change pre-mating to weaning” for two years.

9.3.4.2.2 *E-RP PY lamb liveweights*

The E-RP variables for liveweights of lambs during the year prior to stockdraw (“PY birth liveweight of lambs”, “PY liveweight of lambs at 8 weeks” and “PY liveweight of lambs at weaning”) were highly associated to one another. Therefore, only “PY birth liveweight of lambs” was included in Reduced models.

Average “PY birth liveweight of lambs” was similar across the two years (Table 9.5, 3.8 kg in 2013 and 3.5 kg in 2014, P=0.09). However, whilst significant relationships were found for all response variables to “PY birth liveweight of lambs” in 2013 (P<0.05), none were found for the 2014 dataset (Table 9.6). As such, only the 2013 relationships are discussed. The relationship between R-EMC and R-LmWt with “PY birth liveweight of lambs” was found to be significant (P<0.01 from Pearson’s correlation) but it was very weak (*r* = 0.17 for R-EMC and *r* = 0.13 for R-LmWt, from bivariate screening).

Ewes that weaned no lambs the year after stockdraw (R-LmNo = 0) had a lighter average total lamb birth liveweight ("PY birth liveweight of lambs") in the year prior to stockdraw at 3.31 kg (SD 2.36), compared to ewes that had weaned lamb(s) the year after stockdraw (R-LmNo = 1, 4.09 kg SD 2.06 and R-LmNo = 2, 4.05 kg SD 2.63, from bivariate screening). While the difference in "PY birth liveweight of lambs" was small between number of lambs weaned the year after stockdraw (R-LmNo) it was significant (P<0.01, Table 9.6).

Ewes that survived the year after stockdraw (R-ES) had on average a greater "PY birth liveweight of lambs" the year prior to stockdraw at 3.88 kg (SD 2.35) compared to those ewes that did not survive (R-ES = 0, 2.87 kg SD 2.35, P<0.05, from bivariate screening).

When fitted into Reduced models (R-RP and R-all) for each response variable, estimates of the response variables, and standard errors did not change much compared to those estimates when the single variable of "PY birth liveweight of lambs" was fitted alone (Table 9.8 to Table 9.11). For example, when "PY birth liveweight of lambs" was fitted alone, R-EMC estimated gradient was 3.13 (SE 0.94) which only altered slightly when fitted in E-all (gradient of 3.16 SE 1.11) and E-RP models (gradient of 3.17 SE 1.04, Table 9.8). This suggests that no other explanatory variables fitted into the E-all and E-RP models had a confounding effect. However, this is only the case for 2013 data. For 2014 data the relationship with R-EMC went from negative (gradient of -0.54 SE 0.84) when only "PY birth liveweight of lambs" was fitted, to positive when fitted with E-RP (gradient of 0.93 SE 1.09) and E-all (gradient of 1.03 SE 1.11, Table 9.8).

9.3.4.3 E-EBV variables of interest

Four E-EBV variables ("Litter size", "Maternal ability", "Eight week weight" and "Index") had very small positive relationships with R-LmWt in both years (P<0.05, Table 9.6 and Table 9.15) with R-LmWt.

9.3.4.3.1 *E-EBV "Maternal ability"*

"Maternal ability" was included in the Reduced model for R-LmWt. It had a similar average for both years (0.67 kg in 2013 and 0.7 kg in 2014, Table 9.5). When fitted alone, R-LmWt estimates for the intercept and gradients were similar between years; however the gradient altered when other variables were added into the Reduced models (E-EBV and E-all, Table 9.9).

Table 9.15 Pearson's correlation coefficients (*r*) for response variable of Total liveweight of lambs weaned (R-LmWt) when compared to Estimated Breeding Values explanatory variables (E-EBV) available at the previous stockdraw for two years of data (significance of comparison shown: *P*< *0.05, **0.01 and ***0.001).

E-EBV	2013	2014
Litter size	0.18***	0.12*
Maternal ability	0.18***	0.11*
Eight week weight	0.12*	0.10*
Index	0.19***	0.11*

9.3.4.3.2 *E-EBV "Index"*

E-EBV "Index" is a composite score of all the other EBVs. While not included in any Reduced models, as it was too highly correlated to many other E-EBV variables, it was interesting to consider bivariate screening results to determine potential relationships. E-EBV "Index" had a slightly higher average in 2014 (183.4) compared to, 2013 (179.47 Table 9.5) and had a significant relationship to all response variables in at least one year apart from R-ES where no relationship existed in either year (Table 9.6).

For 2013 data, "Index" had a positive relationship with R-LmNo (*P*<0.001, from bivariate screening). The respective histograms (Figure 9.17) should show that as "Index" mean increased, so did R-LmNo. However this graph also provides a good example of how significance does not alone lead to good predictive ability. For a good predictive ability, the histogram at each R-LmNo should have clearly different peaks so that a threshold line could be drawn at specific "Index" values to split into different R-LmNo. However, in this example, no line could be drawn on the histograms because the distributions overlap each other too much.

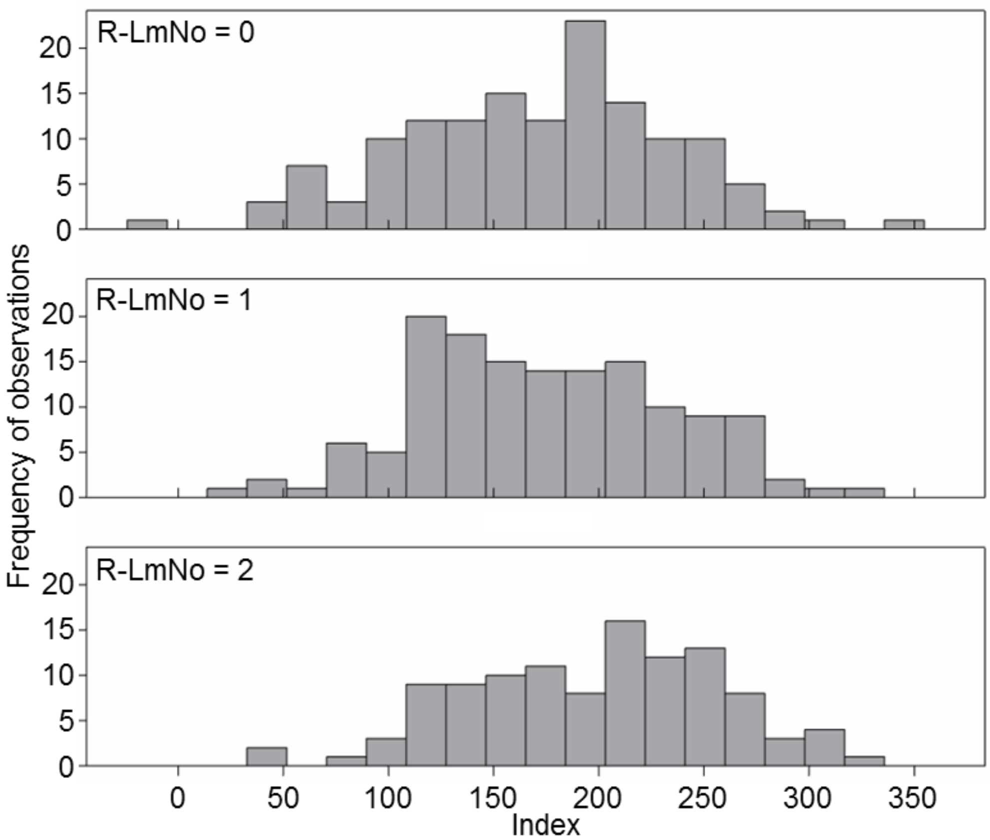


Figure 9.17 The relationship between explanatory variable “Index” and the response variable Total number of lambs weaned (R-LmNo).

9.4 Discussion

This discussion considers the results of this chapter in relation to findings from the previous three chapters (6, 7 and 8) and the wider literature. It also presents variables (or attributes) that show prediction potential for future performance. These identified attributes could then be considered when researching and developing PLF approaches for making retention and culling decisions. This section also discusses the statistical method employed to carry out this work, including the unaccounted for variation. Finally, the implications of the findings, for research and for stockpeople when making retention and culling decisions, will be considered.

This is the first time that such a range of variables at stockdraw have been considered to predict the performance of a ewe within the breeding flock over the following year. There were many statistically significant relationships between response variables to candidate explanatory variables and many fitted models were found to be significant, all of which could be used to inform development of PLF approaches for making culling and retention decisions. There was however, much variation unaccounted for by the models, and relationships between explanatory and response variables varied between models and data sets, therefore it was inappropriate to continue developing and finalising prediction models. There are many other studies that have found low heritability between ranges of traits to longevity and stayability (Borg et al., 2009a; Getachew et al., 2015; McIntyre et al., 2012; Mekkawy et al., 2009). While these had a different focus and statistics to that of this chapter, it does demonstrate a similar lack of association between measurable traits or variables to future performance.

9.4.1 Interesting explanatory variables

The vast range of variables, compared to future performance allowed for the opportunity to consider which attributes have the potential to be included in a PLF approach for informing retention and culling decisions. It was an essential and useful first-step in developing such an approach. The variables with the greatest potential were identified as those that had the strongest relationships with future performance and were unaffected by year effects and other variables. These were considered as any explanatory variables that had a significant association (at $P<0.05$) with one or more of the four response variables in both years of data.

9.4.1.1 E-VAA variables

There were four appearance variables (E-VAA) that had significant relationships in both years to one or more of the response variables. It was surprising that, for a number of variables, a poor score was not associated with poor future performance. This was the case for "Soundness of feet", "Legs and motion" and some of the mouth and udder variables. This is likely to be a result of the current culling protocol implemented on the research farm, which targeted ewes with issues in those particular variables (for examples, ewes were culled if they had mastitis or had an over-shot jaw). Therefore poorer scores for these variables could have been associated with decreased performance, but it was not possible to show this as the ewes that would have received these poorer scores had already been culled.

Unsurprisingly, variables related to the animal's looks (for example, "Face shape", "Face colour", "Fleece colour" and "Fleece length"), had few instances of being associated with future performance. However, these attributes could still have economic importance for a farm. This is a result of Scottish Blackface ewes typically being brought and sold on appearance. The EMC did not take into account appearance of the ewe or the ewe's lambs to consider how much they were worth.

9.4.1.1.1 *E-VAA "Size"*

Findings showed that as "Size" increased so did the number and liveweight of lambs weaned (R-LmNo and R-LmWt); however this was confounded by other variables in E-all models. It appeared that as liveweight of ewes increased so did "Size"; this is logical and could be a confounding source. Therefore such a subjective measure could be replaced by a more quantitative measure of body mass, such as liveweight (see section below).

9.4.1.1.2 *E-VAA Mouth attributes*

Mouth and udder condition scores were often associated with response variables. This is in agreement with other research, such as Mekkawy et al. (2009) who found a genetic correlation between similar traits and longevity.

Chapter 6 showed that questionnaire respondents believed mouth (followed by udder) condition was the most important reasons to cull. Raters in Chapter 8 believed that udder damage followed by the number of teeth present were the best indicators of ewe performance the year after stockdraw. Other literature also supports such findings; Lima et al. (2018) found the most common cull reason reported by sheep farmers was tooth loss followed by mastitis. However, results of this chapter did not show strong relationships between either mouth or udder condition and performance the year after stockdraw, even though significant relationships were found.

The E-VAA attribute “Tooth length” appeared to be a potentially important trait for future performance. The results showed that, while teeth considered slightly long could have a positive impact on future performance ($P<0.05$ in both years for R-EMC and in 2013 only for R-LmWt and R-LmNo), very long teeth were likely to be associated with poorer performance. However, no relationship was found between tooth length and ewe survival the year after stockdraw (in 2013 relationship was $P=0.99$ and 2014 $P=0.06$).

Finding relationships between the condition of the ewe’s mouth and future performance is in agreement with previous literature (Mekkawy et al., 2009). It therefore may seem surprising that out of the four E-VAA variables associated with a ewe’s mouth, only one attribute (“Tooth length”) had a relationship with future performance in both years of data. However, the four mouth E-VAA variables did have instances of significant relationships to response variables, and at least two mouth variables were included in Reduced models for each of the four response variables. This indicates the level of importance mouth variables have in future performance.

However, given that the culling protocol of the research flock was to cull ewes based on poor mouth conditions (see culling protocol Table 7.1), this could have restricted the range of mouth conditions within the flock in the year following stockdraw. For example, ewes were culled from the flock if they were missing any one of their four middle incisor teeth. Therefore, the only conclusions that could be drawn from the “Teeth present” variable within this chapter is that there is no consistent difference in performance between ewes with four to eight incisor teeth (when the middle four incisors were present) but association with having none to four incisor teeth could not be ascertained. Previous research has suggested stockpeople may cull too much based on broken mouths when the scientific evidence for the decision is less certain (McGregor, 2011). Indeed Gunn, (1970) found that having a broken mouth only had a negative relationship with number and liveweights of lambs for ewes in their fourth crop of lambs and not their third.

For making retention and culling decisions, in terms of mouth condition, tooth length is an attribute that should be considered. Other mouth traits should also be considered as wider literature indicates their likely importance for performance (Gunn, 1970; McGregor, 2011; Mekkawy et al., 2009), even though this chapter was not able to prove or disprove their importance.

9.4.1.1.3 *E-VAA Udder attributes*

Results suggested that ewes with larger teats were associated with subsequently having more lambs (R-LmNo). However this attribute could be detrimental for R-ES, as larger teats were found to be associated with a lower rate of survival (P<0.05 in 2014 only). When added into the E-all model, R-LmNo estimates for “Teat size” altered with greater standard errors compared to when the single variable was fitted. This suggests that “Teat size” could be confounded with other variables in the model. One explanatory variable that could be having an effect was “Age”. Indeed, when “Teat size” was considered against “Age”, older ewes were more likely to have larger teat scores. This is in agreement with previous studies scoring udder confirmation that reported teat size increased with number of parities in dairy ewes (de La Fuente et al., 1996). Anecdotally, the stockpeople on the research farm reported that lambs had difficulties to suck from ewes with larger teats. This meant that extra labour was required to get lambs sucking and ensuring they had enough milk. Therefore, size of teat may have other implications that have not been recorded here but should be considered in future research.

Culling ewes based on mastitis is encouraged within the industry to manage the disease (Conington et al., 2008; EBLEX, 2014; Fthenakis et al., 2012). This practice is also carried out on the research farm. As a result, “Udder damage” was not found to be associated with future performance as, potentially, ewes with poor udders would already have been culled.

It is likely that udder traits would be useful to consider when making retention and culling decisions or developing a PLF approach further. Teat size should be considered and other attributes to do with any presence of mastitis should also be considered given their reported importance for performance (Conington et al., 2008; Fthenakis et al., 2012).

9.4.1.1.4 *E-VAA “Retention decision”*

R-EMC was the only response variable that “Retention decision” was significantly associated with in both years, with R-EMC increasing as “Retention decision” increased (meaning the Flock Manager was more likely to retain the ewe). This was likely an artefact of the method used. The Flock Manager provided the “Retention decision” score at stockdraw (on a 5 point scoring scale) and then decided whether a ewe was “Sound” or “Unsound” at the end of the year after stockdraw. Therefore a low scoring ewe at stockdraw may have been more likely categorised as being Unsound at the following stockdraw (12 months later), based on the Flock Manager’s decision. Given the difference in closing valuation amounts used within R-EMC between “Sound” (£ 68.00) and “Unsound” (£ 32.78), the large effect the Flock Manager’s decision had on R-EMC is clear. Furthermore Chapter 8 demonstrated that this attribute often lacked agreement between and within raters suggesting a greater impact of subjectivity of the rater.

The impact a stockperson’s opinion can have on retention and culling decisions has been shown in other studies. For example, Berry et al. (2005) found that when considering what caused cows to be culled from a dairy herd, farmer’s opinion had the greatest impact. Furthermore, Conington et al. (2006) showed that lambs from rams that had been selected based on EBVs had improved genetic potential (as indicated by increasing EBVs) compared to those that had been selected based on the stockperson’s own judgement. This suggests that a stockperson’s judgement is subjective and not reliable at identifying superior animals compared to using data to inform decisions.

Making retention and culling decisions based on the stockperson’s opinion alone does not seem to result in greater performance, therefore other specific variables should be given precedence when considering which ewes to cull.

9.4.1.2 E-RP variables

9.4.1.2.1 *E-RP “Age”*

Age of ewe has been an important consideration throughout this thesis. Chapter 6 confirmed ewes are often culled from hill flocks based on their age. Chapter 7 showed that, if ewes beyond a standard cull age were retained within the flock, they were still productive and could potentially result in a more profitable flock than when culled on age. Within this chapter, age was only significantly associated with performance in one instance (R-EMC within 2014), reinforcing that age did not have a negative impact on ewe performance within this flock. Although, as discussed for Chapter 7 data, there are limitations with these findings as there was a limited number of ewes in the data sets over the standard cull age (only 7.6 % of data was from ewes 5.5 years or older). A greater number of years of study and more ewes at older ages would be beneficial.

Although research has shown that performance does deteriorate with age, it was for wild populations where no management was carried out to artificially set a maximum age (Clutton-Brock and Sheldon, 2010; Festa-Bianchet and King, 2007). Furthermore the ages of animals within these wild populations were greater than those within the research flock. This suggests that while performance may deteriorate with age, it is at a level that is unlikely to be relevant to farmed sheep. Research within farmed sheep has actually shown that performance is unaffected (Getachew et al., 2015) or has increased with ewe age (Dickerson and Glimp, 1975).

Given the stratified nature of the UK sheep industry there is still a market for sound older ewes, but if they are retained until they are unsound they would be worth less when sold at market. However, Chapter 7 suggested that in hill sheep systems, greater financial benefit could be gained by retaining these older ewes and allowing younger animals to be sold. It could therefore be concluded that ewe age should not be considered as a potential variable for inclusion within a PLF approach or by stockpersons for making retention and culling decisions. More precise culling attributes should be considered instead.

9.4.1.2.2 *E-RP Ewe liveweights, liveweight changes and BCS*

All E-RP (and E-all) Reduced models included at least one variable of: ewe early life liveweight (for example, “Ewe birth liveweight”); previous year liveweight; previous year liveweight change or percentage liveweight change; previous year lamb total liveweight; and BCS. While the majority of the E-RP variables were liveweights (or derived from liveweights) or BCSs (22 in total out of 29 variables), it does demonstrate the importance of these body measurements within these models and their potential importance for developing predictive models. This is especially relevant as the equivalent variables in E-VAA (“Size”) and E-EBV (“Mature size”, “Eight week weight”, “Scan weight”, “Maternal ability”) were also associated with the response variables and included in Reduced models. This association of body measures to future performance is also found in research and models looking at longevity and survival (Annett et al., 2011; Cote and Festa-Bianchet, 2001; Jones et al., 2005; Mekkawy et al., 2009).

It is worth noting that while the actual liveweight change and percentage of liveweight change pre-mating to weaning was important for future performance, those for pre-mating to early pregnancy and pre-mating to mid-pregnancy were not. During early to late pregnancy, supplementary feeding methods were being implemented (as presented in Chapter 5). This suggests that the supplementary feeding methods were effective in ensuring ewes were provided with sufficient nutrition to avoid long term negative effects on performance. Results showed that gaining a greater proportion of liveweight between pre-mating and weaning resulted in greater liveweight of lambs being weaned the year after stockdraw. This shows that the change in liveweight over a year is important for future performance, as has been previously reported (Young et al., 2011). Furthermore, not only is liveweight simple to measure, it can also be monitored through the year and be positively affected by management (such as providing supplementary feeding to pregnant ewes).

While liveweight, liveweight changes and BCS of the ewe should be considered for future development of PLF approaches for making retention and culling decisions, Chapters 4 and 5 showed how changeable and manageable these can be. Therefore identifying ewes at the incorrect body measurement may result in nutrient prioritisation to these ewes to allow them to be corrected before decisions to cull are made. This also highlights the importance and potential of a PLF approach, to measure, monitor and manage elements of the system (in this case liveweights) throughout the year.

9.4.1.2.3 *E-RP PY lamb counts and liveweights*

It was unsurprising that the explanatory variables of number of lamb counts over the year prior to stockdraw (“PY lambs born dead or alive”, “PY lambs born alive”, “PY lambs at 8 weeks” and “PY lambs at weaning”) were strongly correlated to one another ($r>0.7$, $P<0.001$), given that the majority of ewes would wean the number of lambs born. It is interesting however that these variables were associated with the number (R-LmNo) and liveweight (R-LmWt) of lambs weaned in the year after stockdraw (identified in both years of data at $P<0.05$).

The most common cull reason stockpeople reported culling ewes from the main breeding flock was “failure to get pregnant” (Chapter 6). However, when actual numbers were considered, barren ewes did not appear to be more likely to be unproductive the year after stockdraw. Ewes that had a lamb the year prior to stockdraw were more likely to wean a lamb the year after stockdraw than not. However, of the ewes that had no lambs born alive in the year prior to stockdraw, only 25.9 % of these were barren the year after stockdraw (R-LmNo = 0) compared to 54.7 % of single-bearing ewes the year prior to stockdraw that were barren the year following stockdraw. Equally, Nugent and Jenkins (1992) not only found that repeatability of fertility was low but went on to suggest that culling should not focus on infertility. Therefore, while the number of lambs could be associated with future performance, culling a ewe that was barren for one year may not remove ewes that are barren the year after stockdraw.

These results suggest that lamb counts and liveweights should not be taken into account when developing a PLF approach for making retention and culling decisions. However, there were other ewes in the flock the year prior to stockdraw that would not have weaned a lamb and were culled at stockdraw so did not appear in the dataset. They may have been culled from the flock for any one of the culling protocol reasons, which included not rearing a lamb two years in a row (culling protocol, Table 7.1). Had these other barren ewes been retained within the flock, a difference in performance the year after stockdraw may have been identifiable.

9.4.1.3 E-EBV variables

Relationships between response variables and E-EBVs seemed surprisingly weak. While positive relationships were found in both years between some E-EBV variables and the Total liveweight of lambs weaned (R-LmWt), these were very weak ($r<0.2$). Stronger relationships were expected between EBVs and performance, since the purpose of these EBVs is to select superior animals whose progeny should perform better (Conington et al., 2006). Moreover, key traits of the Hill Index include lamb growth and reduced lamb losses, so evidence of these in performance would have been expected.

The main purpose of EBVs are to select which ewe lambs to incorporate into the flock and which sires to use, for which they have been shown to be successful (Conington et al., 2001; Lambe et al., 2014, 2008). Furthermore, it has been demonstrated that animals with higher EBVs have improved performance

(Conington et al., 2006). Therefore, while EBVs are not designed to make retention and culling decisions later in a ewe's life, it would have been expected to see some positive relationships between EBVs and performance.

Some breeds of sheep have a longevity EBV in Signet's breeding programs (for example the Lleyn breed, Signet, 2015), which may well be a better indicator of future performance. Additionally, research is underway to better identify longevity traits in breeding indexes (ERA NET research program, SusSheP). Therefore, including EBVs in a PLF approach to make retention and culling decisions is only tentatively advised based on previous research and not on this chapter's findings.

9.4.1.4 Variables with potential

In summary, variables that could be considered in a PLF approach for making retention and culling decisions are shown in Table 9.16.

9.4.2 Comparison of sets of explanatory variables

As expected, for all four response variables, the models that accounted for the most variation (as measured by Adjusted R^2) were when more variables were available in the models (namely E-all, the highest being 22.54 % for R-ES in 2014, Table 9.7), compared to individual categories of explanatory variables. Besides E-all, the models in 2013 that accounted for the most variation were, in order of importance: E-RP, E-VAA and E-EBV (in all bar a few cases). However in 2014 the order was: E-VAA, E-RP and E-EBV, for all response variables. It seems logical that future performance should be more strongly associated with objectively collected previous performance (E-RP) than variables based on a ewe's appearance (E-VAA). It is unclear why the 2014 pattern differed to that for the 2013 dataset but could be a result of the precision with which E-VAA variables can be collected (to be discussed). Furthermore, as previously discussed, it is surprising stronger relationships were not found between individual and groups of E-EBVs.

9.4.2.1 Investment for each set of explanatory variables

The different sets of explanatory variables all required different levels of investment of money and labour to collect. This may have an impact on whether or not a stockperson would use them for making retention and culling decisions. The E-VAA variables would usually take the least effort; they would not be formally recorded (as with the VAA) and would involve the stockperson's own (subjective) assessment. Although it still takes time to handle and check each animal.

Table 9.16 List of attributes available at stockdraw and their potential for being used to predict future ewe performance.

	Attribute	Potential predictor	Justification[a]
Visual Appearance Assessment (E-VAA)	Size	Depends	Preferable to use ewe liveweights.
	Flatness of back	No	Poor associations with future performance.
	Soundness of feet	Unknown	Not enough evidence found to consider.
	Legs and motion	Unknown	Not enough evidence found to consider.
	Teeth present	Possibly	Some evidence of association with future performance and evidence in literature.
	Jaw position	Possibly	Some evidence of association with future performance and evidence in literature.
	Tooth angle	Possibly	Some evidence of association with future performance and evidence in literature.
	Tooth length	Yes	Association with future performance found.
	Teat size	Yes	Association with future performance found.
	Udder attachment	Possibly	Some evidence of association with future performance and evidence in literature.
	Udder damage	Yes	Evidence from literature that culling on this is important.
	Face colour	No	No association found with performance (only reason to consider is for breeders)
	Face shape	No	No association found with performance (only reason to consider is for breeders)
	Fleece colour	No	No association found with performance (only reason to consider is for breeders)
	Fleece length	No	No association found with performance (only reason to consider is for breeders)
	Retention decision	Depends	Decisions made by stockpersons need to be justifiable from other attributes (also results from Chapter 8).
Recorded performance (E-RP)	Age	No	Little association found with performance (also results from Chapter 7).
	Dam age	No	Poor associations with future performance.
	First pre-mating BCS	No	Poor associations with future performance.
	PY pre-mating BCS	No	Poor associations with future performance.
	PY mid-pregnancy BCS	No	While some association found, better to use weaning BCS.
	PY weaning BCS	Yes	Association with future performance found.
	Current pre-mating BCS	Depends	If making culling decisions after stockdraw at pre-mating this could be a useful attribute.
	PY lambs born dead or alive	Depends	Preferable to use lamb liveweights.
	PY lambs born alive	Depends	Preferable to use lamb liveweights,
	PY lambs at 8 weeks	Depends	Preferable to use lamb liveweights,
	PY lambs at weaning	Depends	Preferable to use lamb liveweights,
	Ewe birth date	No	Poor associations with future performance.

Continued

Table 9.16 Continued

	Attribute	Potential predictor	Justification[a]
Recorded performance (E-RP)	Ewe birth wt	Possibly	Some evidence of association with future performance.
	Ewe wean wt	Depends	Preferable to use other ewe liveweights.
	First pre-mating wt	Depends	Preferable to use other ewe liveweights.
	PY pre-mating wt	Yes	Association with future performance found.
	PY early pregnancy wt	Depends	Preferable to use other ewe liveweights.
	PY mid-pregnancy wt	Depends	Preferable to use other ewe liveweights.
	PY weaning wt	Yes	Association with future performance found.
	Current pre-mating wt	Depends	If making culling decisions after stockdraw at pre-mating this could be a useful attribute.
	PY wt change pre-mating to early pregnancy	No	Poor associations with future performance.
	PY wt change pre-mating to mid-pregnancy	No	Poor associations with future performance.
	PY wt change pre-mating to weaning	Depends	Preferable to use percentage change instead.
	PY percentage wt change pre-mating to early pregnancy	No	Poor associations with future performance.
	PY percentage wt change pre-mating to mid-pregnancy	No	Poor associations with future performance.
	PY percentage wt change pre-mating to weaning	Yes	Association with future performance found.
	PY birth wt of lambs	Yes	Association with future performance found.
	PY wt of lambs at 8 weeks	Depends	Preferable to use other lamb liveweight.
	PY wt of lambs at weaning	Depends	Preferable to use other lamb liveweight.
E-EBV	Litter size	Depends	Preferable to use Maternal ability.
	Maternal ability	Yes	Association with future performance found.
	Eight week weight	Depends	Preferable to use Maternal ability.
	Scan weight	No	Poor associations with future performance.
	Ultrasound muscle depth	Yes	Association with future performance found.
	Ultrasound fat depth	No	Poor associations with future performance.
	Mature size	No	Poor associations with future performance.
	Carcass lean weight	No	Poor associations with future performance.
	Carcass fat weight	No	Poor associations with future performance.
	Index	Depends	If no other EBVs included this may be useful as associations found with future performance.

E: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); wt: liveweight.
[a]justification provided through results of this chapter unless stated otherwise.

For E-RP variables to be available, a stockperson would have to collect information about a ewe and her lambs over the year prior to stockdraw and early life. Whilst possible to do on paper, such information would be easier to collect using technology such as data loggers or EID weigh-crates (Morgan-Davies and Wishart, 2015). However, purchasing such equipment would add extra financial cost.

Finally, E-EBVs potentially require the greatest investment, not only in terms of time to collect the information and parentage over several generations but also the financial cost to Signet (or equivalent service) in order to produce the EBVs. Nonetheless, the cost could be offset by the financial gains from selecting and breeding from individuals based on EBVs (as demonstrated by, Conington et al., 2006; Lambe et al., 2014, 2008). Given these different levels of investment it is interesting that the E-RP variables appear to have greater associations with response variables compared to E-EBVs.

It should also be noted that while E-RP can require greater investment than E-VAA, if EID technology is used to assist in data collection (such as with an automated EID weigh-crates), this could still be an efficient method and limit the labour time required when collecting any performance information (Morgan-Davies et al., 2018b). Apart from BCS, E-RP variables had less subjective limitations than VAA variables. Therefore, while prediction ability appeared low, recorded performance variables may have more potential (over the other sets of variables) for generating predictive models in the future.

9.4.3 Model success and methodology

The Initial models included a large number of the explanatory variables, many of which were confounded with each other and these models were likely over-fitting. However, even under these circumstances, the variation accounted for was low. For example, the most variation accounted for by a single model was when E-all model was fitted to R-LmWt when using 2013 data (Adjusted R^2 = 17.36 %). Similarly, when Reduced models were produced, the variation left over was still very large (as shown by the MSE). These, coupled with the lack of consistency of relationships to response variables, shown through the estimated parameters generated in different years or models, demonstrate that generating prediction models was inappropriate.

Previous research that explored culling and longevity in sheep all appear to discuss relationships between variables (often via explanatory models) to show what variables and situations may produce better outcomes (Annett et al., 2011; Jones et al., 2005). When used to inform retention and culling decisions, as were the aims of this chapter, predictive and not explanatory modelling was more appropriate, hence the use and discussion here. The difference between explanatory and predictive models, while well known within statistical research, is often confused in subject-based research (as explained by Shmueli, 2010). Prediction models are used for the purpose of predicting new or future observations (Shmueli, 2010; Vergara et al., 2014). Therefore stronger relationships need to be sought (with models that must initially be a good fit to the data), than when explanatory models are used to explore how variables are associated. However, a good fit is not sufficient for predictive models and consistent relationships must also be seen. This is why a predictive model approach was used in this chapter.

Retrospective fit is when fitted values are generated from data that itself has been used to generate the model being fitted to it. This is often used as a way to produce predictive values and is what was carried out in this chapter. For true prediction, cross-validation should be used (Shmueli, 2010). This is when the parameter estimates generated through modelling are applied to new data. A comparison between the new observed data values to the predicted value can then be made. For exploring both retrospective fit and cross-validation, goodness-of-fit statistics are appropriate.

Within this chapter, to move to the stage of cross-validation would have required low MSE values and clear relationships between explanatory and response variables in models that were unaffected by the inclusion of other variables or when applied to different subsets of the data (so across different years or explanatory variable sets). Various examples were used within the results (for example, “Index” in 2013 for R-LmNo) to demonstrate that, in order to generate predictions, more than just statistical significance indicating a relationship on average is required.

9.4.4 Sources of variation

9.4.4.1 Year differences

Two years of data had originally been collected in order to provide a ready mechanism for cross-validation, with models generated in one year and validated with the other year’s data. However, as was evident throughout the results, this was not considered statistically appropriate due to differences in models between years. Instead both years were considered individually.

Variation between years is a known issue within livestock systems research and is often a factor fitted into models (Annett et al., 2011; Getachew et al., 2015; Jones et al., 2005; Mekkawy et al., 2009). The difference between years suggests that other factors, which were not captured by the explanatory variables, were impacting on the response variables. These would need to be identified in order for future prediction models to be attempted.

The response and explanatory variable summary tables (Table 9.4 and Table 9.5) showed that while variation was similar between years, ewe performance differed. For instance, R-EMC, R-LmWt, R-LmNo and R-ES were higher in 2014 compared to 2013. Also the current BCS (collected at pre-mating after stockdraw) was higher in 2013 (73.5 % were 2.75 or above) compared to 2014 (44.8 % were 2.75 or above), which suggests the ewes started the year after stockdraw with different body conditions. This could result in them performing differently, as it is known BCS can impact performance and survival (Brown et al., 2015; Kenyon et al., 2014; Morgan-Davies et al., 2008).

9.4.4.2 The year after stockdraw

The lack of predictive ability may demonstrate that events during the year after stockdraw had a greater impact on performance that year (from conception to weaning) than information or condition of the ewe at stockdraw. While management practices were standardised across years and efforts were made to reduce changes in husbandry of the ewes, some differences were uncontrollable.

For example, the weather has a major impact not only on the grass quality and quantity (and consequently nutrition of the ewe and lambs) but also on the animals themselves and how they perform (Fogarty et al., 1992; Henderson, 2002; Jones et al., 2005; Starr, 1981). Weather data collected at the research farm (from the Met Office Automatic Weather Station, near Tyndrum) showed that 2013 was a comparatively drier warmer year compared to 2014 (MetOffice data with analysis carried out by Dr John Holland, personal communications). A paper by Catchpole et al. (2000) found that March rainfall was associated with survival of the St Kilda's Soay sheep.

Although ewes in 2013 dataset started the year after stockdraw in better condition with more favourable weather conditions than those in the 2014 dataset, surprisingly, ewes in 2014 dataset appeared to perform better in terms of response variables. It could be that more preferential treatment (in terms of supplementary feed and grazing resource) occurred in 2014 due to farm staff concerns over the animals' condition and the weather (anecdotal observations). Data throughout the year after stockdraw would need to be scrutinised to be able to identify where differences had occurred. However, this demonstrates that even when procedures are meant to be standardised, other unknown factors can cause variation within such real-life systems.

9.4.4.3 Farm specific sources

Three variables that could have impacted on response variables were line, management approach and sire of lamb (Chapter 3). These are very specific to the research farm and year so would not be appropriate to include for predictive models. To include them in models would require estimating effects of each new sire, line or approach used in the future. Therefore, a generic model was required with estimated parameters that could be used across a range of farms and years without refitting the model. However, all three of these variables were tested against the response variables in bivariate screening and single variable fitted models.

Management approach (PLF and CON) had no significant relationship with any of the response variables, neither did the genetic line in all except a few cases (R-LmWt was significantly associated with line in both years, as was R-LmNo in 2013 only, both $P<0.05$). Sire of lamb was found to have a significant impact on all response variables in all years ($P<0.05$), apart from R-ES in 2014. For predictive models, where the aim is to generate models that could be applied to new data, sire cannot be included. However, this shows the large impact that sire has on lamb performance, seen through differences in ewe performance. Including sire variables (such as sire's EBV index) could be a worthwhile development.

9.4.4.4 Reliability of E-VAA scoring

A further source of variation unaccounted for by the models could originate from the precision with which E-VAA variables were collected. In Chapter 8, it was shown that visual attributes could be collected in a reliable manner (accurate) but variation between scores showed a lack of precision. The difference in distribution of scores between the two years in this chapter could be a result of lack of precision in scoring instead of year differences.

Many E-VAA variables had similar distribution of scores across levels between the two years (Table 9.5). These were “Tooth angle”, “Udder attachment”, “Teeth present”, “Udder damage”, “Teat size” and “Face colour” (all $P>0.05$ between years). However, the ten other E-VAA variables were significantly different between years ($P<0.05$). All those not significantly affected by year had a level within the score which received the vast majority of scores (for example, level 3, “Sound”, of “Udder damage” received 90.4 % and 98.4 % of scores in 2013 and 2014 respectively).

It is unclear which of the variables with different distribution of scores between years are valid and a result of year difference, and which ones are a result of a change in allocation by the Flock Manager. Given the lack of precision found in Chapter 8, human inconsistency could be a major source of variation. An example is “Face shape”. In 2013 the majority of ewes were classified as “Between the two types” (at 87.3 %) whereas in 2014, the distribution of scores varied with two levels receiving a majority and similar allocation (“North type” at 48.9 % and “Between the two types” at 40.6 %). This divergence in scoring is unlikely to be a result of ewes changing type between the two years, since a large proportion would have been the same animals and all had similar heritage. Instead this is likely to be a subjective change in how the Flock Manager assigned the different types.

9.4.5 Response variables

9.4.5.1 R-EMC

Of the four response variables three had been used to measure performance in previous research: ewe survival (Hickey, 1960; Kenyon et al., 2014; Morgan-Davies et al., 2008; Young et al., 2011), number of lambs weaned (EBLEX, 2008; Kenyon et al., 2014; Young et al., 2011) and liveweight of lambs weaned (Annett et al., 2011, 2010; Young et al., 2011). However, one of the aims of this chapter was also to produce a single measure of performance that had a ewe monetary value for a year’s production. This was done through the calculation of the R-EMC. The distribution of the R-EMC values was stepped in nature, as R-EMC markedly increased for every extra lamb that the ewe reared and for different discrete closing valuation classifications of the ewe (“Sound”, “Unsound”, “Dead” or “Missing”).

No similar monetary value has been calculated on an individual ewe level before. Kelleher et al. (2015) calculated a cow own worth (COW) for dairy cows to determine lifetime profitability, however this was more sophisticated than the EMC developed here. The EMC could be a simple and useful measure for other research looking at the monetary value of a ewe over a year and could also be adapted for any situation and farm.

9.4.5.2 R-LmNo and R-LmWt

A challenge of the response variables R-LmNo and R-LmWt was the impact each number of lambs had on the distribution of the data. Large steps in the data were seen for every extra lamb weaned by the ewe. Also there was a large number of "0" values in the dataset from ewes who weaned no lambs. These were important to retain within the dataset as at the beginning of the year it is not possible to determine how many lambs each ewe will have. Had it been possible to split the data, and therefore split model formulation into barren, single- and twin-bearing ewes, the relationships seen with explanatory variables may have been stronger. However, given that one response variable was to predict the number of lambs weaned (R-LmNo), modelling each separately was not appropriate.

9.4.5.3 R-ES

A reason why R-ES had low association with explanatory variables could be a result of the limited number of observations per year where ewes did not survive (31 in 2013 and 19 in 2014). Across combined years, an average of 6.5 % of ewes died (including those that were missing presumed dead), this is somewhat lower than recorded deaths in the literature (Morgan-Davies et al., 2008).

There is also an issue of survival bias for the ewes within this dataset (similar to that discussed in Chapter 7). One reason is because of the research farm's culling protocol. Ewes were not included within the dataset if they had already been culled as per the protocol, which removed the majority of each cohort. For example, for the 2009 born cohort of ewes (who were 4.5 and 5.5 age groups in 2013 and 2014 data respectively), of 174 ewes that joined the flock for their first year of production in November 2010, only 29 (16.7 %) remained in the flock in 2014. Of the rest of the cohort, 111 (63.8 %) were culled for culling protocol reasons and only 34 (19.5 %) died or were missing presumed dead (results presented in Chapter 7, SECTION 2).

If all culled ewes had remained within the flock, relationships between explanatory and response variables may have been stronger, as previously mentioned. However, it was believed that retaining these ewes was not appropriate because of their current poor welfare state, risk of their welfare deteriorating or they were considered unproductive. However, the results of this chapter questions the importance of some of the culling reasons practiced. An alternative approach could have been to retain all ewes and monitor their condition regularly and identify when their welfare was compromised and not likely to improve, and only culling these when needed. This would be challenging to regularly monitor all ewes on a hill environment.

A number of more marginal ewes did remain within the flock though. These were ewes with a low “Retention decision” score of 2 or 1 (*n* = 212 or 30 % of all observations, where 1 = “would definitely sell”). This also made it a unique dataset, compared to other research where a stockperson could have greater authority over culling decisions. Consequently, had all ewes remained in the flock, more and stronger associations may have been found. Interestingly, ewes that scored 1 or 2 for “Retention decision” appeared to perform as well as the flock average for the response variable Total lamb liveweight weaned (average was 26.8 kg, compared to the flock average of 28.3 kg) but worse for the others (average of R-EMC £ 8.99 compared to the remainder at £ 22.29, R-LmNo 95.3 % compared to the remainder at 99.1 % and for R-ES 9.5 % died compared to the remainder at 5.1 %).

9.4.6 Implications of findings

9.4.6.1 Future development and research

The results presented here provide a first step in developing a PLF approach for making retention and culling decisions by predicting ewe performance the year after stockdraw.

9.4.6.1.1 *Greater amounts of data and new variables*

To move to a single complete PLF approach based on prediction modelling, further research is required. Given the variation seen between the years, a larger number of years would be preferable. Also future work may involve including other explanatory variables. How variables are collected could also be considered; new or different technology may provide different ways to collect data. Other variables associated with ewe performance could be considered. They include: behaviour, for example measures of circadian rhythm collected via activity monitors (Sarout et al., 2018), proximity between ewes and lambs (Sohi et al., 2017), grazing patterns (Werner et al., 2018); biological, for example time to conceive (Nugent and Jenkins, 1993) and feed conversion efficiency (Johnson et al., 2015); biochemical markers, for example cortisol to show stress levels (Kearton et al., 2019); or environmental, for example weather (Kahn et al., 2017) or grass availability measures (Coates and Penning, 2000).

9.4.6.1.2 *Retention and culling decisions at other times of the year*

A different approach could aim to make retention and culling decisions throughout the year after stockdraw, as data are collected. This might help address the issue of the variation unaccounted for in the models. Indeed, as shown in Chapter 6, some stockpeople often culled ewes at different time points during the production year, such as pregnancy scanning. Making culling decision around mid-pregnancy would also be appropriate as BCS at this time has been shown to be an important indicator of ewe survival (Morgan-Davies et al., 2008) and those ewes not in lamb can be identified through scanning results. Considering individual data about these barren ewes could inform decision on whether they should be retained in the flock for the remainder of the production year (even though they will not produce a lamb) or whether they should be culled immediately.

9.4.6.1.3 *Data handling*

If new or different data were available then the method presented in this chapter, to explore all variables and then create and evaluate models, would be appropriate to use. Given the difficulties of finding predictor variables for informing retention and culling decision making, PLF approaches that are able to overcome this would be of great value. A growing area of research is the use of artificial intelligence to process large quantities of farm data in order to produce usable output for stockpeople (Smith, 2018). Such an approach could be utilised to process ewe data collected over the year of production and inform retention and culling decisions.

9.4.6.2 Application on farm

Chapter 7 showed that more ewes left the flock as a result of culling decisions rather than death. Furthermore, many of the culling attributes that stockpeople believed to be important (Chapter 6), were not found to have significant associations with future performance. Therefore if culling and retention decisions were carried out differently (potentially reducing the number of animals culled) this could have a large impact on the animals within the flock and so could impact on productivity and economic viability of the flock. However, for stockpeople to alter which attributes are considered for making culling decisions would require a large and potentially challenging behavioural change.

Another challenge of applying such a PLF approach onto hill sheep systems is the wide range of data that may be needed. This is likely to involve access to and skills to operate EID and computer based technology, as well as potentially extra labour to collect the data. Therefore, systems that do not regularly handle ewes, or have EID technology to collect data, potential application would be more challenging.

PLF approaches are, in part, based on data driven decision making (as discussed in Chapter 2). This chapter has highlighted that stockpersons opinion alone does not result in greater ewe performance when selecting which animals to retain within the system. This strengthens the argument that retention and culling decisions should be more data driven, and it could be possible for stockpeople to adapt their current retention and culling decision making protocol to be more in line with a PLF approach immediately. The results discussed within this chapter (and shown in Table 9.16) highlight which attributes could be considered, measured and monitored by stockpeople.

9.5 Conclusions

This is the first time such a wide range of variables have been considered to predict performance of a ewe the year after stockdraw within the hill sheep breeding flock.

The culmination of findings from the last four chapters suggests that stockpeople are making retention and culling decisions largely based on personal opinion. However, for some culling reasons no association with future performance was found within this chapter. Therefore, if a stockperson's aim was to improve future performance of the flock, a PLF data driven approach would be advised, rather than a subjective approach. Attributes to consider for each ewe could include: mouth, udder, feet, BCS at weaning, and liveweight change over the last production year. Attributes that appear less important are: age, breed appearance traits and number of lambs previously weaned. EBVs could also be important for improving overall genetic potential but evidence for association with future performance of the individual was not found within this research.

Identifying variables with prediction potential provides a basis for future research. The more that is learnt about the interactions and relationships between different performance, appearance and genetic attributes, the more likely a single PLF prediction model can be developed. With developing PLF approaches it is first important to understand the science and what measures are linked to future performance. Therefore this chapter is an essential first step in developing a PLF approach for assisting with making retention and culling decisions for ewes in hill sheep systems.

In this chapter, too much variation was unaccounted for by the models and so it was inappropriate to finalise development of reliable prediction models. There were other factors that were impacting year-to-year which were not being captured by the variables, resulting in differences seen between years and for relationships between variables. However, the statistical analysis method presented within this chapter is an effective robust method that can be used to: screen and compare a wide range of explanatory and response variables; create models to predict future performance; and evaluate the success of these models. Therefore it is a viable method that can be used for future handling of large numbers and types of variables to develop prediction models.

Another aim of this chapter was to create an individual ewe financial value that considered all incomings and outgoings associated with the ewe as a measure of performance over a year of production. This was done through the development of the Ewe Marginal Contribution (EMC). It was a useful response measure and could be adapted and used in other research as a single monetary value of ewe performance over a year.

This work has shown the complexity of cause-and-effect within hill sheep systems. This could hamper attempts of precision techniques because of the wide and potentially unknown sources of variation within the system. Future research looking to produce predictive models of performance the year after stockdraw may benefit from: having a large number of years of data; use different ways to measure variables (potentially through use of new technology); include a wider range and different variables; and use the statistical approach to develop prediction models as presented in this chapter.

CHAPTER 10: DISCUSSION AND CONCLUSIONS

The aim of this thesis was to investigate and understand the capacity for application and potential impacts of Precision Livestock Farming for hill sheep systems, when considered for two challenge areas: ewe pregnancy supplementation and ewe retention and culling decision making. For the first challenge, a PLF approach was successfully applied to allocate supplementation to ewes during pregnancy (Chapter 5). For the second challenge, many important attributes were identified, which could be used within a PLF approach to make informed retention and culling decisions (Chapter 9). Throughout this thesis, other tools, methods and statistical analyses were developed or tested which could be useful in future PLF development and sheep research in general.

It was also found that the PLF approaches explored had the potential to address some of the difficulties faced by hill sheep systems, as discussed in Chapter 2, in particular: poor economic viability (Morris, 2009; Renwick et al., 2008; Riddell and Walker, 2011); low productivity (Fraser et al., 2013; QMS, 2016; Waterhouse, 1996); ensuring good welfare (Goddard et al., 2006; Morris et al., 2012; Munoz et al., 2018; Stott et al., 2012); and labour availability and capability (Morgan-Davies et al., 2006; Royal Society of Edinburgh, 2008; The Scottish Government, 2016b).

Specific findings for the two PLF approaches have been discussed in detail within their respective chapters. What follows here is a broader discussion, including: the application and uptake potential of PLF for hill sheep systems; the evaluation of the research methodology used throughout this thesis; suggested future developments of PLF; and the wider implications of findings. This chapter concludes by summarising all findings of the thesis and provides some concluding remarks.

10.1 Application and uptake potential

The application and potential uptake by commercial farms will be considered in the light of this thesis's findings and what the broader literature suggests. The three main factors to consider for adoption of the PLF approaches are the potential extent of positive impacts, the practicality of adoption, and finally the willingness of stockpeople to adopt. It should be noted that although the discussion points to follow originate from the work focusing on Scottish hill sheep systems, they are also highly relevant to other sheep systems (in and out of Scotland), and to many PLF applications for other livestock systems.

10.1.1 PLF potential impacts

As presented in Chapter 2, adopting PLF approaches should aim to result in improved efficiency of the livestock system by some, or all of the following: improving productivity, economic viability, sustainability, welfare, and labour requirements (Banhazi et al., 2012b; Berckmans, 2004; Morris et al., 2012; Wathes et al., 2008). The potential extent to which PLF has been found to achieve these, as demonstrated within this thesis, is considered below.

10.1.1.1 PLF to improve productivity and economic viability

Both PLF approaches showed potential for improving productivity and economic viability. However, actual measurable improvements were either absent or limited. For the pregnancy supplementation PLF approach, no differences were seen, compared to an alternative approach of allocating feeding based on body condition, in terms of productivity (number and liveweight of lambs produced) and economic viability (amount of feed required). As already explained, both allocation approaches were sophisticated in their sorting methods. Had the PLF approach been compared to a system where ewes remained in a single supplementation group, differences may have been observed. Nevertheless, this pregnancy supplementation PLF approach is still believed to have great potential for improving productivity and economic viability by allocating resources (feed) to where it is needed. Furthermore these findings are not restricted to Scottish hill sheep systems and can be relevant to any sheep systems that provide supplementary feed.

Chapter 9 showed that some of the ewe culling reasons often used by stockpeople were not associated with future productivity, such as: ewe appearance, ewe age and stockperson's subjective opinion. However, other more quantitative culling reasons were important, including: liveweight, BCS and liveweight change. Therefore retention and culling decision making based on attributes associated with future performance could improve productivity. Additionally, this thesis's findings suggested that different ewes would be retained within the flock if culling decisions were based more on data and information (the PLF approach) than on subjective opinion. Retaining different ewes within the flock was demonstrated to increase productivity and economic viability by a small margin, by not culling ewes on age (Chapter 7). Even though results were modest they still support the idea that using a PLF approach, to decide which ewes remain within the flock, has the potential to improve productivity and economic viability of the whole system. As with the pregnancy supplementation approach, these findings are likely applicable to all sheep systems, although establishing which attributes are important for retention and culling decisions may vary between systems.

Although improvement to productivity and economic viability are well promoted as positive impacts to be gained from PLF approaches in the literature (Banhazi and Black, 2009; Berckmans and Guarino, 2017; Morris et al., 2012; Wathes et al., 2008), little or nothing is reported about the quantity of improvement to be seen or expected. Terminology seems to focus on the "potential" impacts. This suggests that the limited improvements identified in this thesis may well reflect the wider literature. Moreover, while PLF is a growing area of research, it is still in its infancy. Development of many technologies and tools are emerging but further development and applications within commercial farms are likely needed before the real extent of any positive impacts can be quantified.

Impacts on productivity and economic viability were specifically considered for both PLF approaches. However, potential impacts can still be considered more broadly for improvements to sustainability, labour and welfare.

10.1.1.2 PLF to improve sustainability

Although sustainability was not a specific focus of this thesis, it has been identified as an important impact of PLF approaches (Banhazi et al., 2012a; di Virgilio et al., 2018; van Hertem et al., 2016). A useful definition of sustainability is "*The ability of an ecosystem to maintain ecological processes, functions, biodiversity and productivity into the future"* (Thompson, 2009, p.72). How resources are used within the system can be considered part of the sustainability issue. For example, if the pregnancy supplementation PLF approach had required less feed than the conventional approach, this could have been considered as an improvement of the sustainability of the system. Any future PLF developments that reduce feed requirements would have the potential to improve sustainability.

Improving longevity of ewes within the breeding flock is believed to have environmental and thereby sustainability impacts (Beauchemin et al., 2011; EBLEX, 2009; Jones et al., 2013; Nguyen et al., 2013). Flock longevity could increase if ewes were not culled on age and instead a PLF approach to making retention and culling decisions were used.

Therefore, although this thesis provided no quantification of the impact of PLF approaches to sheep system sustainability, it highlights the potential to do so.

10.1.1.3 PLF to reduce labour

With labour availability and capability being a difficulty for hill sheep systems (Morgan-Davies et al., 2006; Royal Society of Edinburgh, 2008; The Scottish Government, 2016b), it was hoped PLF approaches would provide some assistance in reducing requirements.

Labour was not directly measured or specifically considered as part of this thesis. However, parallel research at SRUC's Hill & Mountain Research Centre found that the pregnancy supplementation PLF approach required significantly less labour than the conventional allocation approach (Morgan-Davies et al., 2018b, Appendix 2). Although, both approaches were relatively complex, and likely required more labour than would conventionally occur on hill sheep systems. The retention and culling PLF approach suggested utilising data collected prior to stockdraw. On commercial systems, this data would unlikely be collected routinely and therefore would add to the labour requirements. In contrast, in other more labour intensive sheep systems, PLF could have more potential to reduce labour requirements.

Therefore, it could be argued that application of PLF approaches may in fact add to labour requirements and the capabilities needed (in terms of skills required to operate the technology) in hill sheep systems. However, a PLF approach could improve decision making, thereby potential problems could be identified earlier allowing for earlier interventions. This in turn could prevent or limit future problems that would result in increased labour requirements. There is limited research considering how labour is associated with PLF in sheep systems. However, this is currently the focus of a European Research Area Network Sustainable Animal Production Framework (ERA NET SusAn) funded project: Sustainable Sheep

Production (SusSheP, Morgan-Davies et al., 2018a), which may provide greater insight into the issue in the future.

Over the course of this PhD, labour savings to collect ewe liveweight and BCS data on the research farm have been evident. Prior to use of the automated EID enabled weigh-crate, the setup was labour intensive. Two people were required to fill pens feeding into the weigh-crate and to individually read each ewe’s ear tag number prior to entry into the crate. A third person then operated the doors of the weigh-crate and recorded liveweights on paper. If body condition scoring was being carried out as well, a fourth person was often required. If ewes needed to be split into multiple groups this was carried out after weighing. The whole process often took a week (five days) to handle the whole flock (of 900 ewes), and longer if more complicated sorting was required (for example, sorting ewes into pre-determined mating groups). Also a further half day was required to enter all liveweight and BCS data onto a computer spreadsheet.

With the automated EID weigh-crate, which also drafted ewes into up-to five different pens, labour was reduced. With this setup a single person was required to move ewes into pens feeding into the weigh-crate. Another person operated the entry gate into the weigh-crate (via a remote controller) and, if body condition scoring was being carried out, this same person assessed ewes and entered the data directly into the weigh-head. Weighing and sorting were carried out at an estimated 500 ewes per hour, or 200 ewes per hour when condition scoring as well. The whole process to weigh and sort ewes was completed with half as many people and in under half the time (normal handling of the flock was usually completed within two days), compared to the old system. Furthermore, data was uploaded from the weigh-head directly into a computer spreadsheet, reducing labour and improving integrity of the data.

Therefore, where PLF methods replace processes already being carried out on farm, there is huge potential to reduce labour. Furthermore, this is a finding that it is believed would be realised by any livestock system anywhere in the world. Indeed if PLF is successful at reducing labour it would therefore reduce the associated costs and thereby improve the profitability of the system.

10.1.1.4 PLF to improve welfare

Another element of applying PLF approaches to livestock systems is the potential to improve or ensure good animal welfare (Morris et al., 2012; Rutter, 2014; Wathes et al., 2008). While this was not a specific focus of this thesis, and not directly measured, potential impacts on sheep welfare can still be considered.

The setup of weighing, sorting and body condition scoring using the automated weigh-crate not only reduced labour time but also handling time. Handling can cause stress in livestock so improving methods and reducing duration should be better for welfare (Goddard et al., 2006; Grandin, 2014; Hutson, 2014). Furthermore the author observed that the ewes appeared calmer when weighed in the new EID enabled weighing setup, compared to the former setup. Previously each ewe had to be physically handled and restrained prior to entering the weigh-crate, in order for their ear tag number to be read. In the new setup, ewes required little encouragement to walk through the weigh-crate. A single person standing at the back of the group was the only pressure needed for them to continue to walk through. While no research has been found that quantifies how EID enabled weighing and handling setups may reduce stress, these observations appear to suggest a link. Furthermore this is supported by Grandin (2014) who suggested improved handling, with smoother flowing systems, can reduce stress and improve welfare.

PLF approaches also have the potential to improve welfare by improving and increasing monitoring of individuals (Morris et al., 2012; Rutter, 2014). Both PLF approaches strived to monitor individuals to ensure resources were effectively and appropriately applied. For pregnancy supplementation, ewes should be provided with the correct level of nutrition and large liveweight and body condition losses should be limited (Fthenakis et al., 2012; Henderson, 2002). Therefore, closer monitoring to maintain body condition and liveweight can ensure good welfare. Furthermore, improved data collection methods (such as the EID enabled weighing setup), could increase the likelihood that data is collected more frequently. Indeed on the research farm, ewe liveweights are now routinely collected at every handling, due to the ease of weighing and sorting. Previously, ewe liveweight data would only have been collected at a limited number of key handling times throughout the production year. This increase in data collection means that, liveweights could be monitored more closely and could provide early warning if health problems exist, therefore potentially resulting in improved welfare.

10.1.2 Practicality of PLF adoption

The potential for positive impacts from PLF adoption has been explained but the practicalities of adoption now need to be considered. Certain practicalities to be addressed include: technology, skills and farm setup.

10.1.2.1 Technology available

For both PLF approaches presented, a certain amount of EID technology was required. For example, both approaches would benefit from an EID enabled weigh-crate, especially for the pregnancy supplementation approach. Furthermore, while data for a retention and culling PLF approach could be collected and collated by hand, the process would be improved by use of EID readers, data loggers, handheld computers, farm management software and mobile applications. However, uptake of such technology and methods has been challenging within farm environments (Lima et al., 2018; Lissaman et al., 2013; Pierpaoli et al., 2013).

In the UK, it has been compulsory to tag sheep with EID ear tags since 2010. Associated EID technologies (such as EID readers) have also been available during this time. However a recent survey of UK sheep farmers revealed that only 53 % had an EID reader and only 21 % used them for management purposes (Lima et al., 2018). Poor use of EID readers was also reported through Europe-wide questionnaires across eight countries (including the UK), that found that only 38 % of sheep farmers owned any kind of EID reader (Rivallant et al., 2019). The low proportion of respondents in Chapter 6 who said they made culling decisions with EID assistance (17 %), appears to be in line with the wider low levels of uptake of such technology. Therefore, it would appear the majority of sheep systems (including hill systems) do not have EID technology on farms to allow immediate application of PLF approaches. One barrier to technology uptake is the cost of equipment (Morgan-Davies and Lambe, 2015; Rivallant et al., 2019). Government financial support could help with this if it were provided.

10.1.2.2 Skills available

Without frequent access to and use of EID technology, stockpeople will likely lack the knowledge needed to use them. Research has shown that age of stockperson alone did not have an impact on the uptake of technologies (Lima et al., 2018;

Lissaman et al., 2013). However, younger generations have more general experience of digital technologies, and may be more capable and able to learn the skills required to operate EID technologies and PLF approaches. Indeed, survey results from 900 Irish farmers (including sheep farmers) found that older farmers and those living alone were less likely to own and use a computer for business needs, compared to younger farmers or those living with children (Hennessy et al., 2016). Indeed, with the general age of those working in farming increasing (The Scottish Government, 2016a), relying on younger people to take on such responsibilities may not be possible. Alternatively the increase in technology within agriculture in general (King, 2017) may provide an extra pull to a younger generation to be involved in farming.

Interestingly, another source of assistance to the farm for technical expertise may come from women. This idea is one that was presented by Hay and Pearce (2014), who considered technology adoption of beef cattle producers in Australia. They found that women were three times more likely to use online technology than men in the household and that taking on digital tasks gave them a sense of empowerment and of being valued. Therefore, in future discussions and research about technology adoption on farms it could be beneficial to consider the role of young or female members of the farming family.

10.1.2.3 Farm setup and situation

As previously discussed, extra labour may be required for carrying out both PLF approaches. For hill sheep systems that may only gather and handle ewes a few times during the year, the extra labour required for PLF approaches may be a significant factor. If labour is limited on the farm it could be challenging to adopt these approaches, although the trade-offs with adoption might outweigh these concerns (as previously discussed).

Furthermore, the farm setup might make the approaches unpractical to carry out. For example, the pregnancy supplementation PLF approach required ewes to be split into numerous feeding groups, which required the farm to have suitably sized and sufficient numbers of fields. Given the nature of hill sheep systems, the majority of land is likely to be large areas of hill land and fields, which would render group segregation difficult. Practicality of adoption of PLF approaches will ultimately depend on individual farm’s resources and situation. Application of the PLF approaches presented may be easier to implement onto upland or lowland systems that may have more fields available and may handle ewes more frequently.

10.1.3 Willingness to adopt PLF

While hill sheep systems may lack the technology, skills and farm setup required to adopt PLF approaches, this situation could be changed. Equipment could be bought (if funds allow), skills could be learnt (if options to learn are accessible) and farm setups could be changed (where possible). However, these changes all depend on the willingness of stockpeople to make them.

There is evidence that improved profitability can be attributed to increased technology use if stockpeople have a drive to increase production. Lima et al. (2018) found that adoption of EID technology was improved when they had been bought with the intention to increase production. Furthermore Nuthall (2004) identified associations between purchasing computers on-farm (in New Zealand) with increased profits.

Both PLF approaches presented require a change in behaviour for stockpeople and trust to be placed in data, as opposed to their own opinion, to make decisions. Decisions regarding which ewes require more supplementation and which should be culled, would likely previously have been made based on the stockperson's subjective opinion (Chapter 5). If the stockperson views their enterprise as already financially viable, they may not wish to increase risk by altering how their decisions are made.

It has been demonstrated that uptake is increased if the benefits for adoption are worthwhile and stockpeople perceived them as useful (Lima et al., 2018; Pierpaoli et al., 2013; Rivallant et al., 2019). Part of this is ensuring that benefits are well promoted (Banhazi et al., 2012b). However, while PLF has many potential impacts for hill sheep systems, the results of this thesis did not find substantial quantifiable impacts. Furthermore most literature also only focuses on the "potential" impacts (Banhazi and Black, 2009; Berckmans and Guarino, 2017; Morris et al., 2012; Wathes et al., 2008). Therefore promotion of PLF approaches for hill sheep systems is still challenging. Further research and development are required to quantify positive impacts, before there can be any realistic expectations that stockpeople would be willing to adopt such approaches.

In the future, when the benefits of PLF approaches can be demonstrated and well defined, agricultural consultants and advisors may be able to help in implementing new technology and methods (as suggested by Lissaman et al., 2013).

10.1.4 Application and uptake conclusions

To conclude this section, limited quantifiable results were found for improved productivity and economic viability when applying PLF to hill sheep systems. However, findings suggested that there was potential to improve productivity and economic viability if approaches were further developed, as well as potential for improving sustainability, labour requirements and animal welfare.

This thesis demonstrated that EID technology can be utilised for PLF approaches in hill sheep systems. However, the current limited positive impacts of PLF approaches mean that promotion of findings are unlikely to motivate stockpeople to adopt such approaches. Moreover, there are many issues with uptake, in terms of the practicality and willingness to adopt, that remain largely unresolved. Therefore, while thesis findings provide useful information for stockpeople on improving efficiency, further research and development are required for these PLF approaches to reach realistic application potential for hill sheep systems.

Many of the potential positive impacts discussed are relevant for other extensive sheep systems in harsh environments, as well as other sheep systems and, indeed, other livestock systems in general. These different systems may have less barriers to uptake, compared to those discussed here and may gain benefits of PLF adoption more readily than hill sheep systems. Therefore, while application and uptake potential of PLF for hill sheep systems may appear challenging, the findings can have wide ranging interesting implications for many other livestock systems.

10.2 Evaluation of research methodology

The following sections evaluate the research methodology of this thesis, providing some possible explanations for why more conclusive results were not found, and also what developments could be made to improve the impact of PLF approaches.

10.2.1 Research farm environment

10.2.1.1 System complexity

Within this thesis, the majority of data collected and results presented were from a research hill sheep farm. Carrying out research in this setting has a number of challenges, including the number of different management practices carried out. Therefore other farm decision making could have impacted on results. For example, the effect of retention and culling decisions (Chapter 9) were being considered the same year as the pregnancy supplementation approach was carried out (Chapter 5). The supplementation approach aimed to identify and support ewes in need of extra feeding. Therefore, any ewes with poor attributes at stockdraw that year may have performed differently during the following year because they had been targeted through the supplementation approach and received extra assistance. Moreover, the pregnancy supplementation protocol, as well as other husbandry practices (such as the culling protocol), aimed to identify and correct extreme animals. However, without these extreme examples present, the true extent of findings is unknown.

While there are challenges and potential limitations of carrying out research on a flock managed under commercial practices, these are well known issues of livestock systems research (Gibon et al., 1999). Furthermore, it was important that this realistic environment was used as findings hold greater validity to other commercial farms.

10.2.1.2 Farm decision making

Another concern of carrying out the research in this farm environment was the effect individuals making decisions could have on data and findings. For example, it was the Farm Manager who decided which ewes did not meet the culling protocol criteria and were culled from the flock. The Flock Manager and other farm staff also decided: which ewes entered the high levels of supplementation for the conventional approach, when to feed supplementary hay, and when to move groups of sheep to different pastures. While research protocols were in place for all these examples, final decisions were still subjective and had the potential to affect data. This is a concern for any large systems research being carried out across a farm, where different staff are involved in decision making. However, under these situations, procedures were as appropriate and thorough as they could be.

10.2.1.3 Genetic lines

Another consideration was the genetic lines within the research flock, as explained in Chapter 3. Ewes had been selected as lambs to be retained within the flock based on their genetic potential. For the “selection” line, individuals with the highest EBV index were retained, while the “control” line individuals were selected for having an average index. These two genetic lines of ewes have been shown to perform differently (Conington et al., 2006; Lambe et al., 2008; McLaren et al., 2012). However genetic line was not considered in the results of this thesis, given other elements of the methodology in place. The two lines were evenly distributed between the two management approaches of pregnancy supplementation. Moreover, for the second half of this thesis, having a wider range of EBVs available was an advantage for investigating associations with future performance.

10.2.2 Greater understanding and control of variation

A recurring theme throughout this thesis was the difficulty associated with unaccounted variation within datasets. Sources of variation were important for research and PLF methodology. Unaccounted variation in data is a problem for research as it becomes challenging to determine what is having an impact or not (Coates and Penning, 2000; Scott, 2011). Indeed, Watson et al. (2013) specified that variation in livestock data could occur from differences between animals, changes in environmental conditions and residual or technique error; all of these are potential sources within this thesis. Meanwhile, PLF approaches should aim to monitor the variation within systems and between individuals, in order to identify where and when interventions are required (French et al., 2015; Richards et al., 2012; Wathes et al., 2008).

Within Chapter 4 there were a number of factors that impacted on the ability to correct liveweights (including: age, sex, breed, time of day, and grass availability). This demonstrated that even for a single data point, there was a huge potential for factors to cause variation. Likewise, the amount of unknown sources of variation in Chapter 9 could have had an effect and resulted in poor model predictions. While, livestock systems are known to be very complex with a lot of variation (Jones et al., 2017), findings from both approaches may have been stronger and clearer if the associated variation had been better understood and controlled.

10.2.2.1 Variation from the weather

One factor likely to be adding to the variation in data is the weather. In extensive systems weather and climate cannot be controlled but are known to have large impacts on performance (Catchpole et al., 2000; Fournel et al., 2017; Henderson, 2002; Jones et al., 2005). Furthermore, weather has been shown to impact liveweight change by affecting circadian rhythms of sheep (Sarout et al., 2018). This highlights a complexity of trying to apply PLF to extensive systems compared to indoor systems. Within indoor PLF approaches, the environment can be carefully monitored and controlled (for example, Berckmans, 2017; Fournel et al., 2017; Xin and Liu, 2017). While it is not possible to control the weather in extensive systems, altering management decisions in response to it and possibly utilising weather forecasts to plan might be possible.

Incorporating weather forecasting into decision making would be an interesting area for future research of PLF for hill sheep systems, and is indeed a topic that has begun to be included in current research and applications (Kahn et al., 2017). Therefore, gaining knowledge on how changes in the environment affect ewe performance would be worthy of further research. Greater levels of recording could be implemented to monitor and measure the whole system and environment in order to explore this. One example, of how real-time data on the current environmental conditions from an extensive system could be monitored, comes from the research farm. Remote weather sensors providing real-time data have currently been implemented onto the farm. The sensors record temperature, wind speed and direction, and river heights across the farm, including on elevated slopes of the hill land. These devices communicate in real-time via a low-power wide-area network.

10.2.3 Precision and accuracy of PLF

The importance of precision and accuracy of decision making and of the data used was evident throughout this thesis. PLF should be carried out in a precise manner but the accuracy which is used to inform decision making is equally important.

Chapter 4 demonstrated that liveweights could be collected at a precise level but accuracy of liveweights was poor if collected after a delay period prior to weighing. Conversely, Chapter 8 showed that appearance of ewes at stockdraw could be collected via the VAA in an accurate manner but this was often with poor precision. This highlights that both the precision and accuracy of the data, used by PLF approaches to make management decisions, is important and needs to be understood. Standardising methods of data collection is one way to improve accuracy and reliability (Bahlo et al., 2019; Petrie and Watson, 2013), such as collecting liveweights from animals as soon as possible when they leave grass (as suggested in Chapter 4). Where such standardised operating procedures cannot be adopted, use of corrections could also be useful. Without such mitigation to alleviate these issues, PLF can become less beneficial. Improving precision is also important, and Chapter 9 suggested that objectively collected continuous data was more useful for PLF approaches than subjectively collected quantitative data.

However, implementing PLF onto commercial farms may be challenging given these issues of precision and accuracy. Understanding the importance of standardising liveweight collection, for example, would need to be emphasised but the practicality and willingness for this to occur may still not be present. One option to try and reduce the perceived extra burden associated with adopting PLF approaches may be to develop approaches that are more flexible. For instance, allocating supplementation groups based on a range of liveweight change instead of a single liveweight change value, would allow for extra variation in liveweight data. Alternatively, altering how liveweights are collected is another option. For example, walk-over-weighing technology could be used to collect liveweights directly from animals at grass (Brown et al., 2015, 2014b, 2014a; González-García et al., 2018; Richards et al., 2012).

10.3 PLF further developments

For both challenge areas in this thesis, a valuable framework has been presented, which could be developed in the future. Specific developments have been detailed in Chapter 5 and Chapter 9. The key principles or advice proposed for both PLF approaches could be adopted onto commercial hill sheep systems immediately, as well as onto other types of sheep systems. However, further research developments would be beneficial.

Development of the pregnancy supplementation PLF approach is likely to focus on: altering liveweight change cut-off; altering levels of supplementation; and some way to consider BCS of ewes. Whereas the development of a retention and culling PLF approach not only needs to determine the combination of variables that could predict performance, and the complex associations between these, but also how the importance of individual variables may vary between farms.

10.3.1 Other hill sheep system challenges

Only two challenge areas were considered for PLF approaches within this thesis. Other challenges exist within the system that could be targeted by PLF in the future. Banhazi and Black (2009, p.3) stated that when deciding where to apply PLF approaches to a system it was important to "*identify those processes, which if not carried out correctly, will have a major impact on either productivity or profitability of an enterprise*". Key processes of the hill sheep system were assessed for their potential impact on not just productivity and economic viability but also welfare and labour (Table 2.2). Other specific processes within hill sheep systems that appear most appropriate for PLF application could include: health and disease monitoring and treating both prophylactically and reactively (Fthenakis et al., 2012; Henderson, 2002; Rutter, 2014); husbandry of lambs early in life to ensure survival (Brown et al., 2015; Jones et al., 2005; Young et al., 2014); effective frequent checks of sheep in extensive hill landscape (Goddard et al., 2006; Kilgour et al., 2008; Umstätter et al., 2008); and finishing of lambs for slaughter (Conington et al., 2006; Galvani et al., 2014; Morris, 2017).

Therefore, there are many other challenges that exist that could benefit from a PLF approach. One of the ideals of PLF is that the whole system is monitored. Given the complexity of hill sheep systems, it is likely that development of PLF methods will focus on individual elements of the system, which could later be combined together.

Different approaches may use similar EID based technology, as presented in this thesis, or may require different or new equipment.

10.3.2 New or different technology and techniques

The two PLF approaches in this thesis could be improved by the incorporation of new, emerging or different technology or techniques. Those used throughout this thesis were believed at the time to be the most appropriate for fulfilling the aims. One of the criteria was that technology used would be commercially available and based on EID technology, to improve uptake potential. However, there is a wide range of technologies that could be useful for addressing other challenge areas within the system. Many options were listed in Chapter 2 (Appendix 1), and specific promising technology are discussed below.

10.3.2.1 Alternative weighing technology

Alternative weighing technology, could improve the reliability of liveweight data. The importance of liveweight data for PLF in hill sheep systems has been repeatedly demonstrated throughout this thesis. However all liveweight data were collected from groups gathered into a single handling point for weighing. Liveweight reliability could be improved if more frequent liveweights were collected and in closer proximity to the grazing sheep. Walk-over-weighing technology, as presented in Chapter 2, provides one solution for how liveweight data could be collected more frequently and whilst grazing in fields and without handling (Brown et al., 2015, 2014b, 2014a; González-García et al., 2018; Richards et al., 2012). Although within a hill situation, where sheep may not cover the same area of land or when animals are split into multiple grazing locations (as with the pregnancy supplementation approach), it is likely that multiple weighing units would be required, adding to cost and practicality issues.

10.3.2.2 Sensors

Sensors were only briefly mentioned in Chapter 2 but are an important part of many PLF approaches (Fogarty et al., 2018; Halachmi et al., 2019; Neethirajan, 2017). There are a wide range of on-animal sensors for sheep, as recently reviewed by Fogarty et al. (2018), which measure location, movement, heart rate, chewing, oestrus, urine, contact, respiration and temperature. One issue with incorporating sensors into PLF approaches is the need for data from sensors to be shared with other software in order to assess many elements of the same system (Bahlo et al., 2019; Halachmi et al., 2019).

10.3.2.3 Big data techniques

Another challenge with PLF is the handling and processing of large amounts of data (as seen in Chapter 9). Knowledge and approaches used to handle Big Data (Bronson and Knezevic, 2016; Kamilaris et al., 2017; Wolfert et al., 2017) and to derive meaning, such as through Artificial Intelligence (Smith, 2018) and Machine learning (Shahinfar and Kahn, 2018), could clearly have an application within this topic area. If more technology is adopted onto farms and data is collected more frequently, it is important that individual processes share the data and the technology works together (Bahlo et al., 2019).

Farming is said to be going through a digital or technological revolution (Bronson and Knezevic, 2016; Gallardo and Sauer, 2018; King, 2017). Within this wider setting and rate of research and technological development, PLF can only become more promising and hold greater potential for hill sheep systems.

10.4 Wider implications of results and findings

10.4.1 Growing PLF interest and research

From the time this PhD began (in 2013) until submission (in 2019), the quantity of PLF literature has greatly increased. This is demonstrated by the number of general review articles published (Berckmans, 2017; Berckmans and Guarino, 2017; Bucci et al., 2018; Fogarty et al., 2018; French et al., 2015; Halachmi et al., 2019; Halachmi and Guarino, 2016; King, 2017; Lindblom et al., 2017; Rutter, 2014; van Hertem et al., 2016) and published literature on specific approaches and methods for sheep systems, including: walk-over-weighing (Brown et al., 2014b; González-García et al., 2018); anthelminthic targeted-selective-treatment of lambs (Kenyon et al., 2017a, 2017b; McBean et al., 2016); matching lambs to their dams (Kemmis et al., 2016; Sohi et al., 2017); recording mating between individual rams and ewes (Alhamada et al., 2017, 2016); and monitoring behaviour (Giovanetti et al., 2017; Grisot et al., 2018). The findings of this PhD are therefore highly relevant and will add to current research interests, as they cover areas with currently limited exploration of PLF in sheep.

10.4.2 Other tools developed

As well as PLF approaches for the two challenge areas, this thesis has also presented a number of tools that could be useful for other sheep and livestock research. Firstly, Chapter 4 demonstrated the importance of having a standardised procedure when collecting liveweights from sheep as well as a method that could be used to correct delayed liveweights. Secondly, Chapter 8 presented a VAA that can be used to collect data on the appearance of a ewe and could be used by others trying to quantify ewe appearance. Thirdly, Chapter 8 also demonstrated Gwet’s ACs as a superior alternative to Cohen’s Kappa statistic. Finally, Chapter 9 presented an approach to create prediction models from a wide range of different types of explanatory and response variables. These findings could be relevant and useful for a wider range of research.

10.4.3 Current industry environment

Another consideration for the development and adoption of PLF approaches for hill sheep systems is the current and changing state of the wider setting in which the systems operate.

If and how Brexit finally occurs remains to be seen but all current reports suggest large negative impacts on sheep enterprises within the UK (Davis et al., 2017; Dwyer, 2018; Hubbard et al., 2018). This will largely be a result of disruption to current trade deals (Hubbard et al., 2018), with the UK being the third largest exporter of sheep meat globally, and a quarter of its production going to EU countries (Colby, 2015). Furthermore, hill sheep systems rely heavily on government financial support. There are concerns that if trade was significantly disrupted, farmers would resort to culling large proportions of their flock. There is indication that extra emergency subsidies would be provided to stop this occurring (Loeb, 2019), and reassurances have been made that the level of subsidy received by UK farmers will remain the same as under the CAP until 2022 (Hubbard et al., 2018). However, longer term support is unknown.

In this current political environment, future outlooks for the UK sheep industry are uncertain and do not appear optimistic. However, lessons can be learnt from New Zealand's sheep industry when subsidies were removed in the 1980s, partly as a result of over production without a market for product (Vitalis, 2007). The sheep industry saw the largest drop in livestock numbers, compared to dairy and deer industries (from 70 million sheep to 40 million over 20 years, Vitalis, 2007). However even with 31 % fewer sheep farmers, those that remained became more efficient and more profitable, with higher lamb weaning percentages, heavier carcass weights and improved sheep breeding (Smith and Montgomery, 2004; Vitalis, 2007). Irrespective of the outcome of Brexit or future changes to government support, it is essential to ensure that systems are as efficient and resilient as possible. For this, adoption of PLF holds great potential.

The UK government has also announced a new livestock traceability system affecting all livestock, coming into effect during 2019 (UK Government, 2018). Currently it is unknown what this new system will entail but if improving traceability is the aim, then greater use of EID would be expected. There are currently no requirements for cattle to be EID tagged however this may change within the new system. Therefore findings of this thesis could be useful to cattle systems (as previously discussed). Indeed such increased use of EID across different livestock systems would likely increase development and adoption of PLF approaches for hill sheep systems.

10.4.4 Broad outlook

While hill sheep systems were the principle focus of this thesis, the approaches and findings could be applied to other sheep systems in harsh environments, and to other livestock systems. Findings from the two challenge areas are widely applicable to other extensive sheep systems globally however; some adaptation to the methods presented here may be required. For example, when providing pregnancy supplementation, different liveweight change levels would likely be used and different levels (and types) of supplementation provided.

The problem of when to remove individual females from the breeding group is a challenge for all livestock systems. The proposed approach to consider retention and culling decisions using individual data and information is therefore widely applicable. However, different variables are likely to have different levels of influence and importance under different conditions.

10.5 Thesis conclusions

Across all chapters of this thesis, a wide range of conclusions have been made.

PLF approaches and hill sheep systems:

- Potential ewe measurements under a PLF approach within hill sheep systems include: liveweight, liveweight change, production outputs, and (to a lesser extent) body condition.
- Commercially available EID and associated technology are useful tools for PLF approaches for hill sheep systems.
- Both pregnancy supplementation and retention and culling decision making are suitable targets for improvement within hill sheep systems.

Liveweight collection for sheep systems:

- The importance of Individual liveweight data for PLF approaches has been strengthened.
- EID weighing technology allows liveweights to be collected quickly and reliably.
- Sheep lose a significant amount of liveweight over a short-term delay prior to weighing, as a result of practical handling operations.
- Ewes can lose 1.8 kg (3.5 %) and 2.9 kg (5.6 %) liveweight after three and six hours (respectively) delay from being removed off grass prior to weighing.
- Sheep liveweights should be collected as soon as possible after being removed from grass or correction equations, to account for the delay, should be used.
- When management decisions of sheep are based on liveweight and liveweight change, unaccounted delays prior to weighing can result in unreliable liveweight data which may alter final decisions.
- Much research literature insufficiently reports sheep weighing procedures and the measures taken to control for variation in liveweights.

PLF approach for allocating supplementation to pregnant ewes:

- A PLF approach to allocate supplementation to pregnant ewes based on liveweight change can be applied to hill sheep systems and has the potential to improve productivity and economic viability.
- A PLF approach can be more successful at moving ewes out of high mid-pregnancy supplementation levels into lower supplementation levels

compared to a conventional approach of allocation, based on subjective assessment of body condition (52 % compared to 25 %, respectively).

- Two approaches to allocate ewes to pregnancy supplementation using liveweight change (PLF) and current body condition (conventional) have similar outputs of: supplementation required; number of lambs scanned, born and weaned; and liveweight of lambs at birth and eight weeks old.
- Future work is required to develop the PLF approach for pregnancy supplementation in order to realise its potential.

Current culling practices of sheep systems:

- Stockpeople within the UK cull ewes from the main breeding flock for a wide range of reasons, with the most common reported being: failure to get pregnant (selected by 96 % of those surveyed), mastitis (91 %), and not thriving (87 %).
- A larger proportion of hill sheep systems (68 % of those surveyed) sell sound ewes and/or cull ewes based on age compared to upland (41 %) and lowland systems (48 %).
- Of those surveyed only 47 % of stockpeople use any sort of records to inform ewe culling decisions, and only 39 % of hill sheep systems.

Hill sheep longevity:

- Culling on age is likely to disadvantage hill sheep systems by limiting longevity; and retaining older ewes could also improve flock productivity, sustainability and economic viability.
- Scottish Blackface ewes retained, within the breeding flock of a hill sheep system, beyond a standard cull age (of 5.5 years old) can perform as well or better than younger ewes in the flock (for survival, number of lambs produced, liveweight of lambs produced, ewe liveweight and ewe body condition).
- With a large proportion of ewes leaving the flock as a result of culling decisions rather than death, there is an opportunity to alter current practices and impact flock performance.
- When the cull age of 5.5 years old is removed from a hill flock, the number of replacements required reduces, ewes over the cull age increase (to 13.3 % of the flock after four years), and sound ewes are not available for sale.

Visual appearance assessment of ewes at stockdraw:

- Collecting information on a ewe's appearance at stockdraw can be carried out in a reliable and consistent manner using the complete visual attribute scoring system developed.
- Scoring of individual visual attributes of ewes can produce reproducible results, which is useful for considering retention and culling decision making both on farm and within research.
- Gwet's AC is an appropriate and useful method of agreement analysis, which may be superior to other methods.

PLF approach for informing retention and culling decisions:

- PLF approaches that utilise previous performance data are likely to be more important for making retention and culling decisions rather than a subjective approach (although the process could not be simplified).
- Using a PLF data informed approach to make retention and culling decisions has the potential to improve flock productivity and economic viability (by increasing longevity).
- Ewe attributes to consider when making retention and culling decisions include: mouth, BCS at weaning, and liveweight change over the last production year.
- Attributes that have little association with future performance but are often used by stockpeople to make ewe culling decisions, include: ewe age, breed appearance traits, and number of lambs previously weaned.
- Further development of a PLF approach for making retention and culling decisions is required and may benefit from utilising skills and tools from other research that handles Big Data.

Adoption and uptake of PLF:

- Use of new and emerging technology will likely increase development of PLF for hill sheep systems.
- Adoption of PLF into hill sheep systems is a worthy area of research due to the advantages it could bring individual farms and the industry as a whole.

10.5.1 Final words

This thesis has demonstrated the challenges and possibilities of applying PLF approaches to hill sheep systems. When applied to pregnancy supplementation and to retention and culling decision making, there is potential for improvements to productivity and profitability. Results currently show potential benefits and present frameworks that could be easily further developed. While only two challenge areas were considered in this thesis, many other points and processes within the hill sheep systems could be targeted by PLF approaches.

This thesis has also contributed to the knowledge of how to collect liveweight data reliably and the current factors stockpeople use to make retention and culling decisions. Furthermore, EID weighing technology has been demonstrated to be a useful tool for PLF in sheep systems that can be used to collect accurate and precise liveweight data. Adoption of PLF technology and approaches remain, however, a challenge and will require further support and promotion of the benefits of adoption.

Hill sheep systems face a number of difficulties but have important roles for the rural community, environmental management, the UK sheep industry and producing protein for human consumption. These systems must evolve and adapt in order to remain viable. PLF provides an approach to managing hill sheep systems that can improve efficiency and offers a framework allowing new technologies and methods to be considered.

With the expanding field of PLF research and development, the digital livestock revolution is well underway. With the adoption of PLF approaches, hill sheep systems hold great potential to evolve into sustainable, profitable and robust enterprises, ensuring their place in the Scottish culture, economy and landscape for many generations to come.

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APPENDICES

Appendix 1 Examples of some Precision Livestock Farming approaches

Example and description[a]	Species	Efficiency improvement[b]	Measures to monitor and manage	Technology[c]	References and example products
Ultrasound pregnancy scanning Carried out part-way through pregnancy allows number of offspring being carried to be identified so can manage those carrying different numbers of offspring differently (e.g. provide feed to those that carry more and sell animals not pregnant).	Cattle, sheep, pig	W, £, P	Number of foetus	Ultrasound scanner	Sheep: Logue et al. (1987) Ovi-Scan sheep, BCF technology
Video image analysis in hen houses[a] Used to carry out tasks of counting hens in cages and identifying foreign objects (not eggs) in collection belts, which are both normally carried out by a stockperson. Alerts stockperson when and where attention is required.	Chicken (egg)	L, W, £	Counting hen legs, foreign object detection.	Camera	(Cronin et al., 2008)
Record feed intake in broiler houses[a] Microphones used to record and monitor pecking and therefore feed intake of a small group of chickens in real-time, continuously and without disturbing the birds. Stockperson could then accurately manage quantity of feed given.	Chicken (meat)	W, £, E	Feed intake	Microphone	(Aydin and Berckmans, 2016)
Automatic milking Dairy cattle are trained and able to use milking robots at any time during the day. Resulting in more regular milking and more milk produced.	Dairy	L, W, £, P	Milk quantity and quality	Milking robot	(de Koning and Rodenburg, 2004; John et al., 2016) M[2]erlin, Fullwood Ltd. DaLaval VMS,

Continued

Appendix 1 Continued

Behaviour monitoring and oestrus detection in cattle Accelerometer worn on a collar around a cows neck monitors activity. This allows detection of abnormal behaviour which could indicate illness or oestrus. Stockperson is then alerted.	Dairy	L, W, £, P	Movement (oestrus)	Collar with tri-axial accelerometer	Silent Herdsmen (Afimilk Ltd., Kibbutz Afikim, Israel)
Body condition scoring Cattle walk underneath a camera which takes a 3D picture of cows' lower back estimating current condition. Can then manage appropriately (e.g. increase or restrict feeding, check for health issues).	Dairy	L, W, £, P, S	Body Condition	Camera	(Halachmi et al., 2013) DeLaval BCS,
Oestrus detection in pigs[a] When sows are in oestrus they would 'visit' a boar through a gateway which contained an RFID reader. So, alerting stockperson when sows became in oestrus.	Pigs	L, P	Sow 'visits' to a boar	RFID tags and reader	(Ostersen et al., 2010)
Identify general problems within housing Cameras positioned within broiler and pig houses monitor the location and behaviour of animals. This then indicates whether there is a problem such as a blocked feeder line. The system sends an alert of the problem.	Chickens, pigs	L, W, £, P	Animal distribution within a shed	Camera	(Berckmans, 2017; van Hertem et al., 2016) eYeNamic™ system (Fancom BV®, Panningen, The Netherlands)
Audio disease and welfare assessment Audio equipment used to record and track sounds emitted from livestock to pick up coughing as an indicator of disease.	Dairy, pigs	W, £, P	Coughing	Microphone	(Guarino et al., 2008; Meen et al., 2015) Pig Cough Monitor™ (Panningen, The Netherlands)

Continued

Appendix 1 Continued

Example and description[a]	Species	Efficiency improvement[b]	Measures to monitor and manage	Technology[c]	References and example products
Targeted selected treatment of anthelmintic treatment in lambs[a] Lambs liveweight compared to a target liveweight. If liveweight not reached presumed to be suffering from a high worm burden and requires treatment with anthelmintics.	Sheep	L, W, £, P	Liveweight	RFID tags, reader and weigh-crate	(Greer et al., 2009; Kenyon et al., 2009; Morgan-Davies et al., 2018b)
Automated liveweight monitoring Animals walk over "Walk-over-weighing" scales which automatically records liveweight against individual ID number. Allowing liveweight to be monitored and changes identified which could indicate health issues.	Dairy, sheep	W, P	Liveweight	RFID tags, reader and weigh-crate	(Dickinson et al., 2013; González-García et al., 2018; Richards et al., 2012) Tru-test WOW scales (Tru-Test Pty Ltd., Sunnybank, Australia)
Environment control Constant monitoring of internal environment of the shed, allows deviations from the ideal environment to be seen and interventions to be made.	Pig, chickens	L, W, £, P, E	Temperature		(Xin and Liu, 2017)
Pedigree Match Marker Maternal parentage of lambs determined by identifying associations between RFID ear tag reads of lambs to ewes when animals pass through reader gates.	Sheep	£, P	Individual identification number and proximity to others	RFID tags and readers	(Kemmis et al., 2016; Richards and Atkins, 2007)

[a]For methods which are still in development and not yet commercially available;
[b]Improvements to system identified in the referenced articles are: L= reduced labour, W= improved health and welfare of animals, £= reduced cost and/or increased profits, P= improved productivity of animals, E= reduced environmental impact e.g. reduced GHG emissions;
[c]All methods require extra computer hardware and software not specified in table.

Appendix 2 Morgan-Davies, C., Lambe, N., Wishart, H., Waterhouse, A., Kenyon, F., McBean, D., McCracken, D., 2018. Impacts of using a precision livestock system targeted approach in mountain sheep flocks. Livestock Science 208, 67–76.

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Impacts of using a precision livestock system targeted approach in mountain sheep flocks

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ABSTRACT

Although mountain sheep systems suffer from climatic and environmental handicaps that constrain productivity and economic viability, they have an important economic role, maintain habitats and species of high nature conservation value and support the provision of a range of ecosystem services of benefit to society. Using Precision Livestock Farming (PLF) in extensive mountain sheep systems could bring benefits for animal performance, economical performance and labour. This paper presents results from a 3 year experiment where PLF principles were implemented on an extensive mountain sheep farm and an assessment made of whether or not such an approach could benefit more marginal sheep systems. A 900 ewe flock (600 Scottish Blackface ewes, 300 Lleyn ewes) was divided equally into two separate systems, one where the flock was managed conventionally (CON) at group level, and the other where the individuals in the flock were subjected to a PLF management protocol where electronic weighing, recording and drafting equipment were used, linked to the electronic identification (EID) tags of the animals. Two main management strategies were compared and contrasted; one relating to winter feeding of the pregnant ewes, the other relating to anthelmintic treatment of lambs during the summer. Yearly labour profiles were created by measuring the time spent doing individual tasks associated with the two management systems. Net margins (£/ewe) were calculated for the two systems. Additionally, the yearly labour profiles were scaled-up using commercial data to quantify potential labour savings on more traditionally managed mountain farms if PLF principles were adopted. Analyses indicated that the two different management systems did not result in any significant difference in terms of ewe weights, mid-pregnancy scanning figures, ewe and lamb mortality rates, or lamb weight post-weaning. However, the proportion of lambs needing anthelmintic treatment was significantly reduced by 40% between the CON and the PLF, resulting in a reduction of 46% in the amount of anthelmintic used. Over a whole year, the total amount of labour required in the PLF management system was reduced by 36%. Across the 3 years, the net margin for the two systems showed an average difference of £3/ewe higher in the PLF. For a more traditional farm embracing a PLF approach, analyses suggested labour reduction of 19%, equating to £1.60/ewe savings. This study shows that it is beneficial for farmers to consider managing a mountain ewe flock at an individual rather than at flock or batch level using PLF technology.

1. Introduction

Extensively managed mountain livestock systems in North West Europe suffer from climatic and production handicaps (Morgan-Davies et al., 2012), that constrain productivity and economic viability in these areas. As a result, farming in these marginal areas of Europe has often been challenging (MacDonald et al., 2000). Such extensive mountain systems are also characterised by larger sheep flocks or cattle herds, grazing very large areas of poor quality grasslands (Bocquier et al., 2014), with low production levels, efficiency and labour supply (Cabaret et al., 2009), compared to their more intensive counterparts in the European lowlands. The farming population in these areas is also an ageing one, with succession problems and not enough attraction to retain the next generation of farm labour (Madelrieux and Dedieu, 2008).

However, these extensive mountain systems have an important economic and societal role in these areas (Ripoll-Bosch et al., 2012; O'Rourke et al., 2012; Ross et al., 2016), contributing to the rural economy and providing a source of local skilled labour, even if it is very seasonal (Waterhouse, 1996). Mountain systems are also increasingly

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recognised for their important role in maintaining habitats and species considered to be of high nature conservation value and for the provision of ecosystem services for wider society (Bernùes et al., 2014).

These systems are however often poor in terms of animal performance and welfare. They suffer from poor ewe survival over winter and high lamb mortality (Waterhouse, 1996; Dwyer, 2009), including what is commonly referred as 'black loss' – the unaccountable disappearance of lambs from farms (Morgan-Davies et al., 2008a). Management techniques that would help farmers to assess health and welfare of their animals more regularly, in a time-efficient manner, would be beneficial and would potentially help improve survival and sustainability of these types of flocks.

In Europe, mountain systems have not seen the same uptake of mechanisation and innovation as the more intensive areas of agriculture. Livestock farming in more intensive areas has indeed seen a rise in the use of innovations (Riddell and Walker, 2011) in such fields as genetics, breeding, feeding systems, milking devices and, more recently, what is called Precision Livestock Farming.

Precision Livestock Farming (PLF) can be defined as the management of livestock production using the principles and technology of process engineering (Wathes et al., 2008). It can also be described as farming using equipment, data or software which allows the use of information at an individual level for targeting decisions, inputs and treatments more precisely (Morgan-Davies et al., 2015a). It relies on being able to identify an animal individually, most often using a tag or a bolus. This principle has been enabled by Electronic Identification (EID), which was introduced in livestock farming in the early 1980s (Rossing, 1999). In 2004, the European Union rendered it mandatory to uniquely identify all sheep and goats via EID technology (Council Regulation (EC) No 21/2004), further increasing scope for use of these technologies and management systems.

Although PLF historically has been more associated with intensive systems (Wathes et al., 2008; Jago et al., 2013), some authors (e.g. Bocquier et al., 2014; Australian Sheep Industry CRC, 2007) argue that these technologies could equally be beneficial if introduced in more extensive systems, whereby livestock management decisions are traditionally considered at the level of a group of animals rather than individually.

Some of the constraining factors in extensive conditions that could be improved by the use of these technologies encompass labour demand at handling (Bocquier et al., 2014; Morgan-Davies et al., 2015b), the management of reproduction (Bocquier et al., 2014), winter nutrition of pregnant animals, and the management of parasite burden and resistance (Umstatter et al., 2013).

In particular, labour requirements on farm could be rationalised and farm performance improved by implementing such new technologies (Olaizola et al., 2008). The introduction of PLF on livestock farms could impact on labour organisation, as shown by Hostiou et al. (2014). Internationally, the quantification of workloads on livestock farms has been studied and various methods have already been proposed (Dedieu et al., 2000; Dedieu and Servière, 2012; Dieguez et al., 2010). Some studies also highlighted the variation of workload over the year (O'Donovan et al., 2008). However, labour data at farm-task level are often not measured (Sørensen et al., 2005)., or only quantified as a yearly figure (e.g. Nix, 2014), which does not reflect the seasonal variation in task workload.

The nutritional state of sheep can be assessed by body condition scoring (BCS) and live body weight (Behrendt et al., 2011). Body condition scoring provides a reliable measure of fat coverage and thus predicts overall body reserves and is not affected by sheep size or gut-fill at the time of assessment. However, it is subjective and time-consuming (Russel et al., 1969). Weight or weight change are more objective measures to identify if a ewe is maintaining, gaining or losing body mass (Brown et al., 2014), and can be easily collected using EID ear-tags and a compatible weigh-crate.

The growing concern about anthelmintic resistance on sheep farms, as previous worming strategies are increasingly failing and expensive (Garland and Leathwick, 2015), could also be relieved using technology. Targeted Selective Treatment (TST), or targeted worming, is a refugia-based approach to lamb worming, where only a proportion of the animals are treated with anthelmintics, based on their individual weight change (Kenyon et al., 2013). This approach relies on individual identification of animals, which is possible using electronic identification (EID) tags. It has been successfully implemented on lowland farms (Busin et al., 2014; McBean et al., 2016), and its introduction on a mountain farm could present some advantages.

In some areas of Europe, the introduction of mandatory EID in the sheep industry has been controversial (Moxey, 2011; Cappai et al., 2014) and farmers, especially in extensive systems, seem to perceive EID as an additional burden, without necessarily appreciating the benefits that this technology could bring to sheep management (Umstatter et al., 2013). One of the reasons is often a lack of quantification of all the potential benefits, including economic as well as the less quantifiable benefits, such as animal welfare (Morris et al., 2012) or farmer well-being (Hostiou and Fagon, 2012). Eory et al. (2015) also highlighted the lack of information regarding the financial benefits of PLF. The aim of this article is to investigate in more detail the potential, in economic, animal performance and farm labour terms, of introducing a more targeted or precision approach of sheep management into extensive mountain systems.

This paper presents results from a 3 year experiment where a targeted sheep management approach using EID based technology has been implemented and evaluated on an extensive mountain farm.

2. Methods

2.1. *The research farm*

Research was conducted on a mountain research farm in the western Highlands of Scotland, at SRUC's Hill and Mountain Research Centre, Kirkton and Auchtertyre. The farm carries a total of 1300 ewes (Scottish Blackface and Lleyn), and 22 cattle, on 2200 ha of ground. The 1300 ewe flock is composed of two sub-flocks, a commercial flock of 400 ewes and a research flock of 900 ewes, grazing in two separate areas of the farm. Most of the land is permanent grassland of poor quality (mountain grazing pasture), with only 230 ha of improved and semi-improved pastures. There are 2.5 full-time stockpersons employed on the farm.

The altitude ranges from 170 m to over 1000 m above sea-level, and the mean annual rainfall is 3000 mm, with the first three months of the year tending to be the wettest. Average temperatures peak in June and August at 15 °C, and are lowest in January at 1 °C.

2.2. *Animals and management systems*

In this long-term study, the 900 ewe research flock (approximately 600 Scottish Blackface and 300 Lleyn) was divided equally between two system groups, one managed conventionally (CON), and used as a comparison, and the other subjected to a new Precision Livestock Farming (PLF) management protocol, which encompassed a series of different targeted management approaches, making use of new technologies and handling systems.

The study ran over 3 full sheep production years (Nov. 2012- Nov. 2015) and involved an average of 902 individual ewes every year (435 and 467 in the CON and PLF systems respectively). The average numbers of ewes in each system were balanced for breed, age, live weight, litter size the previous year and sire and remained for their lifetime on the same treatment. Over the 3 years reported here, the average number of ewes per treatment per year was 574 Scottish Blackface ewes, 273 in the CON, 301 in the PLF; 328 Lleyn ewes, 162 in the CON, 167 in the PLF, for 2012-13, 2013-14, 2014-15 respectively. The animals were part of a performance recorded breeding scheme, which required single sire mating groups, tagging and recording at lambing, and weighing at set times across both systems.

The animals shared the same pastures. In the CON approach, the animals were identified, weighed and recorded manually, and managed at a group level. In the PLF targeted approach, the animals were managed using automatic identification, weighing and recording technology, with each animal identified individually using their electronic identification (EID) ear-tags. Although all of the animals on the farm were electronically identified using an EID RFID tag, in line with EU regulations (Council Regulation (EC) No 21/2004), only the PLF approach made specific use of the technology. In the CON approach, the EID tags were used as if they were standard non-EID management tags.

2.2.1. Handling systems

In the PLF system group, each animal was tagged with an EID ear tag (Richey's RD2000, Shearwell Data's SetTag or Allflex's button tags) containing a unique identification number, read by an Allflex® radio frequency identification portal reader (Allflex Australia, Queensland, Australia). This reader was contained within a weigh-crate incorporated into a Prattley 5-way Auto Draft (Prattley Industries, Temuka, NZ) with Tru-Test™ MP600 load bars.

When an animal entered the weigh crate, its weight was automatically recorded against its EID number on a TruTest™ XR3000 weigh head (Tru-Test Group, Auckland, NZ). This setup allowed PLF animals to be automatically sorted into their respective management groups, based on weight, weight change or any other information stored in relation to the animal's EID.

In the CON system group, each animal was also tagged with an EID ear tag, as required by the regulation. They were allocated manually to their different management groups, based on a shepherd's assessment of their condition. The equipment used for handling the CON ewes was a digital weigh crate (Pharmweigh©), with a race and a manual two-ways drafter.

All the animals were handled at various times during the production year (Fig. 1 and Table 1).

2.2.2. Targeted managements

2.2.2.1. Winter feeding. During the winter, ewes were grazed outside and received supplementary feeding in the form of mineral blocks, concentrate pellets and hay, as recommended by common husbandry practices (AFRC, 1993). The ewes were allocated to different feeding groups (standard or corrective). Two winter feeding periods were considered: early-pregnancy and mid-pregnancy (Fig. 1), each lasting approximately two months.

The feeding levels in the standard and corrective groups aimed to provide enough supplementary feed to respectively maintain or improve ewe current body reserves. The supplementary feed was provided at a level appropriate to meet the aim of the relevant feeding group.

Ewes in the CON management were allocated to their feeding groups based on ewe condition assessment, done manually by a shepherd by palpating the loin, whilst the ewes in the PLF management group were allocated to their feeding group based on their percentage weight change (and number of lambs expected) since last weighed, as measured by the automated EID reader and weigh crate, with the five-way automated drafter (Table 1).

2.2.2.2. Targeted worming. In this study, lambs in the PLF system were subjected to a targeted worming approach or Targeted Selective Treatment (TST) (Fig. 1). At 8 weeks of age, all lambs were wormed and weighed. Thereafter, lambs were weighed monthly– in July, August and September - and wormed only if they did not reach their individual target weight, which was calculated using the "Happy Factor" algorithm developed by Greer et al. (2009), based on pasture availability. Lambs were automatically sorted into those that did not require dosing, or did require dosing. In the latter case, lambs were further subdivided into groups with different weight ranges and wormer doses were based on animal weight (always to the level recommended for the heaviest animal, within a 10 kg weight range). The treatment stopped once the lambs were removed from pasture for finishing indoors (October).

Lambs in the CON system were wormed using a whole flock approach, based on the findings from pooled faecal samples. If the faecal egg count (FEC) was > 500 eggs/g, all lambs in that grazing group were wormed (dose based on the heaviest animals in that group); if the count was lower, all lambs were not wormed.

2.3. Measurements

2.3.1. Animal performance

Ewe and lamb performance data were recorded at each of the handling events in the production year (Fig. 1). Key flock (litter size at mid-pregnancy ultrasound scanning, barren rate, weaning rate, kg lamb weaned/ewe scanned) and welfare indicators (ewe and lamb mortality) were also collected and calculated for both the CON and PLF groups. Data were collected over three years of production (2012-13, 2013-14, 2014-15), and assessed year by year, as well as on average.

2.3.2. Labour

Yearly labour profiles were created by measuring the time spent doing each individual task under the two different management

Fig. 1. Sheep production year handling events for both CON and PLF management systems (hashed boxes show the targeted management events in the PLF).

Table 1
List of tasks carried out at each handling event, in the CON and PLF management systems, and grazing locations.

Handling events	CON	PLF
Mating (Nov) *On improved and semi-improved pastures*	Gather Manually read ID tag, weigh and condition score Manually sort into mating groups Worm ewes	Gather Automatically read EID tag, weigh and sort into mating groups Worm ewes
Early pregnancy/post-mating (Jan) *On mountain and semi-improved pastures*	Gather Manually sort into feeding groups	Gather Automatically read EID tag, weigh and sort into feeding groups
Mid-pregnancy (Feb-March) *On mountain, semi-improved and improved pastures*	Gather Ultrasound scanning Manually read ID tag, weigh and condition score Manually sort into feeding and pregnancy groups Worm/vaccinate ewes	Gather Ultrasound scanning Automatically read EID and sort into pregnancy groups Automatically read EID, weigh and sort into feeding groups Worm/vaccinate ewes
8 weeks after lambing (June) *On semi-improved and improved pastures*	Gather Worm, ear-notch, castrate, vaccinate lambs Manually read ID tag and weigh lambs Manually read ID tag and weigh ewes Mother -up	Gather Worm, ear-notch, castrate, vaccinate lambs Automatically read ID tag and weigh lambs Automatically read ID tag and weigh ewes Mother -up
Shearing (July) *On semi-improved, improved and mountain pastures*	Gather Faecal Egg Count (FEC) lambs Manually sort into lamb worming groups Worm lambs based on FEC Shear ewes	Gather Automatically read EID, weigh, sort lambs in to worming groups Worm lambs based on weight assessment Shear ewes
Weaning (August) *On improved, semi-improved and mountain pastures*	Gather Manually read ID and weigh lambs Manually sort into lamb worming groups Worm lambs + FEC lambs Manually read ID, weigh and condition score ewes Vaccinate ewes	Gather Automatically read EID, weigh and sort lambs into worming groups Worm lambs Automatically read EID and weigh ewes Vaccinate ewes
Post-weaning (Sept) *On improved pastures*	FEC lambs Manually sort lambs into worming groups Worm lambs	Automatically read EID, weigh and sort lambs into worming groups Worm lambs
Sales (lambs) (every 2 weeks from Oct to March) *In shed*	Manually read ID and weigh lambs Manually record lamb ID for sale	Automatically read and record EID and weigh lambs Automatically sort lambs into sale groups and record lamb ID for sale
Sales (ewes) (Sept/Oct) *On semi-improved and improved pastures*	Manually read and record ID and weigh ewes	Automatically read and record EID and weigh ewes

systems. At each major handling task (Fig. 1), two observers directly recorded each sub-task (Table 1) using a stop-watch and hand-held devices for continuous recording (The Observer XT, version 9.0, Noldus Information Technology)). Depending on the tasks, the number of workers involved varied, from 2 persons (e.g. weighing sheep in the EID crate) up to 4 persons (e.g. gathering the sheep on the mountain pastures). To allow a comparison, the number of seconds needed for the task was apportioned to the number of persons needed for that particular task (in seconds per sheep). The individual tasks being measured were seasonal and followed the sheep production year (Fig. 1) and encompassed (Table 1) mating (November), early-pregnancy (January), mid-pregnancy (February/March), 8 weeks after lambing (June), shearing (July), weaning (August), post-weaning (September), ewe stock draw and lamb selection for sales (October). The daily tasks (e.g. monitoring the animals or moving animals from one pasture to another) were not taken into account, as both CON and PLF animals were run together as one flock. For this particular study, labour recording during lambing was deliberately not included. Both systems were managed identically at lambing, due to the requirements of the performance recording protocol, so it was assumed that there would be no differences due to lambing labour. The labour requirements for both systems were calculated in minutes/animal over the whole year for each year of production (2012-13, 2013-14, 2014-15). The total labour requirements (in working days of 8 h) for the full flock were also calculated for each year of production, based on the flock number data on these particular years.

Additionally, a comparison of labour required to do the tasks involved in more typical extensive 'traditional' low-input sheep management systems, with (Trad-PLF) or without PLF technology (Trad-CON) was carried out. These two additional yearly labour profiles were created using questionnaire answers from 17 extensive sheep farmers who attended a farm open day in 2014. These farmers had farms and sheep farming systems typical of the area where the research farm is located, with similar number of animals to the research farm (between 500 and 1200 ewes). However, they tended to handle their sheep less often, and thus were more representative of the extensive sheep farmers in these areas. The farmers were asked to select which pre-defined tasks they carried out on their farms. The tasks concerned the same sheep production year tasks as described in Table 1, namely: mating, early-pregnancy, mid-pregnancy, 8 weeks after lambing, shearing, weaning, post-weaning, ewe stock draw and lamb sales. The resulting labour profiles (Trad-CON and Trad-PLF) were quantified by task by multiplying the proportion of farmers that selected those different tasks (Table 2), with the actual labour measurements (minute/animal) from both the PLF and CON systems (Table 1). That allowed a scaling of tasks, to create these two profiles (Trad-CON and Trad-PLF), as if a 'typical extensive' farm was implementing a PLF and a CON approach. This was to investigate whether applying a PLF approach to a farm that handles animals less often than a research farm could still be beneficial, specifically in terms of labour.

The assumptions for modelling labour demand on such a 'typical extensive farm' were a flock of 1200 ewes, with a mid-pregnancy

Table 2
Proportion of farmers (%) who carry out the farm tasks at each handling event in the sheep production year.

Handling events	Tasks	Percentage of farmers who carry out the task on their own farm
Pre-mating (Nov)	Gather ewes	94.1%
	Weigh the ewes	5.9%
	Condition score the ewes	52.9%
	Sort ewes in mating groups	78.6%
	Worm ewes	71.4%
Early pregnancy (Jan)	Gather ewes	76.5%
	Condition score the ewes	23.5%
	Weigh the ewes	0.0%
	Sort ewes in feeding groups	29.4%
Mid-pregnancy (Feb-March)	Gather ewes	100.0%
	Ultra-sound scanning the ewes	82.4%
	Weigh the ewes	0.0%
	Condition score the ewes	64.7%
	Sort ewes in feeding/pregnancy groups	76.5%
	Worm ewes	94.1%
	Vaccinate ewes	88.2%
Marking (June)	Gather the animals	88.2%
	Weigh the ewes	0.0%
	Condition score the ewes	17.6%
	Vaccinate ewes	5.9%
	Worm ewes	35.3%
	Treat ewes for ectoparasites	35.3%
	Weigh lamb	5.9%
	Tag lamb	23.5%
	Ear-notch lamb	58.8%
	Vaccinate lamb	29.4%
	Worm lamb	41.2%
	Treat lamb for ectoparasites	58.8%
	Castrate lamb	82.4%
	Tail lamb	58.8%
	Mother up	88.2%
Shearing (July)	Gather the animals	100.0%
	Weigh lamb	5.9%
	Worm lamb	76.5%
	FEC lamb	17.6%
	Treat lamb for ectoparasites	47.1%
	Worm ewes	35.3%
	Weigh ewes	5.9%
	Treat ewes for ectoparasites	35.3%
	Shear ewes	100.0%
Weaning (August)	Gather the animals	100.0%
	Weigh lamb	23.5%
	FEC lamb	17.6%
	Worm lamb	82.4%
	Vaccinate lamb	52.9%
	Weigh ewe	5.9%
	FEC ewe	5.9%
	Condition score ewes	23.5%
	Sort ewes/lambs	70.6%
Post-weaning (Sept)	Weigh lamb	29.4%
	FEC lamb	5.9%
	Worm lambs	41.2%
Sales (lambs)(every 2 weeksfrom Oct to March)	Weigh lambs	47.1%
	Read/record lamb ID	52.9%
	Send lambs to market	76.5%
	Send lambs to abattoir	11.8%
Sales (ewes)(2x main)	Weigh ewe	5.9%
	Condition score the ewe	52.9%
	Read/record ewe ID	29.4%
	Treat ewes for ectoparasites	58.8%

ultrasonographic scanning rate of 100%, weaning 1000 lambs, and a ewe replacement rate of 25%. Most of the lambs (86% - based on Table 2) were sold to the market in August/September, with the remaining being sent to the abattoir. The modelled results were then converted into working days (of 8 h) over a whole year of production.

2.3.3. Economic performance

Inputs (feed quantity, anthelmintic and medicine quantity, fertilisers, market costs, etc.) and outputs (number of animals sold, wool produced) were collected on the SRUC research farm for the financial years 2012–2013; 2013–2014; 2014–2015. Fixed costs (rent, building

Table 3
Ewe and lamb performance data (weights in kg with standard deviation (SD), barren, scanning and mortality rates in %, kg lamb/ewe in kg) for the 3 study years, for both PLF and CON management systems.

	2012–2013		2013–2014		2014–2015	
	CON	PLF	CON	PLF	CON	PLF
Mating weight (kg ± SD)	51.9 ± 9.9	53.3 ± 8.2	46.9 ± 6.0	46.9 ± 6.7	51.8 ± 6.1	52.4 ± 6.4
Early pregnancy weight (kg ± SD)	48.7 ± 5.8	50.1 ± 5.7	48.1 ± 5.8	48.3 ± 6.0	52.3 ± 6.3	52.7 ± 6.4
Mid-pregnancy weight (kg ± SD)	45.4 ± 11.0	46.3 ± 11.7	47.7 ± 5.9	48.1 ± 6.5	50.7 ± 5.9	51.2 ± 6.1
Number lamb/ewe scanned at mid-pregnancy	1.33	1.35	1.14	1.16	1.33	1.31
Barren rate at mid pregnancy	0.11	0.12	0.18	0.16	0.11	0.12
Pre-lambing weight (kg ± SD)	51.1 ± 6.5	51.6 ± 7.3	51.2 ± 7.1	51.1 ± 7.8	53.3 ± 8.2	54.2 ± 8.5
Ewe 8 weeks post lambing weight (kg ± SD)	46.4 ± 13.5	48.4 ± 11.0	52.2 ± 7.7	51.9 ± 8.0	51.8 ± 6.6	52.2 ± 6.7
Ewe Weaning weight (kg ± SD)	52.6 ± 6.1	52.7 ± 7.0	55.1 ± 7.1	55.2 ± 7.3	53.7 ± 6.8	53.8 ± 7.0
Ewe mortality (%)	6.0	5.2	9.6	6.6	5.2	5.9
Lamb birth weight (kg ± SD)	3.4 ± 0.9	3.4 ± 0.9	3.7 ± 0.9	3.6 ± 0.9	3.8 ± 0.8	3.8 ± 0.8
Lamb weaning weight (kg ± SD)	27.2 ± 4.6	27.3 ± 4.6	28.6 ± 4.3	27.3 ± 4.6	28.8 ± 4.6	28.3 ± 4.3
Lamb post-weaning weight (kg ± SD)	29.6 ± 5.0	30.0 ± 5.1	32.3 ± 4.9	31.6 ± 5.2	30.5 ± 5.2	29.9 ± 4.8
Lamb mortality (%) from birth to weaning[a]	19.7	22.9	14.1	15.8	19.1	16.2
Number of lamb weaned/ewe scanned at mid-pregnancy	0.98	0.86	0.93	0.93	0.98	1.1
kg lamb weaned/ewe mated	23.9	23.7	25.6	23.0	26.1	26.4
kg lamb weaned/ewe scanned pregnant	25.6	25.6	31.2	29.4	29.4	30.0

[a] Includes lamb born dead or aborted.

costs, insurance, etc.) were also collected for the same periods; however, they were divided equally across both systems as the animals were run together, except at handling times. The labour costs were calculated using the labour measurements collected for the two different management systems.

An annual gross margin (£/ewe) and a net margin (£/ewe) were subsequently calculated for the two systems. Subsidy and support payments were not included in the calculations of the net margin (SAC, 2010). In this study, we were interested in the economic comparison between two management systems on the same farm, so, although the fixed costs (including rate of labour costs) were farm-specific, the resulting comparison is still relevant to any mountain farm. A return on investment for the weighing/-EID equipment was also subsequently calculated based on flock size and costs of equipment.

2.4. Statistical analysis

The results were analysed using parametric and non-parametric tests in the Genstat statistical package (VSN International Ltd, 2013). The animal (ewe and lamb) performance differences between the two management systems were investigated by means of Linear Mixed Models (LMM), with 'year' as a random effect. For the ewe performance (ewe weights at mating, early pregnancy, mid-pregnancy, pre-lambing, 8 weeks post-lambing and weaning), the ewe breed, ewe age, number of lambs expected/born/reared and previous weights were considered in the models as fixed effects. For the lamb weight at lambing, weaning and post-weaning, the lamb breed, lamb sex, lamb parity (single or multiple), and system were fitted in the LMM. The ewe mid-pregnancy scanning and weaning results between the two management systems were analysed using a Generalised Linear Mixed Model (GLMM), with a binomial distribution and a logit link function. The fixed effects considered in the models included ewe breed, ewe age and previous weights (mating and early pregnancy), as well as management system; year was fitted as a random effect.

The ewe and lamb mortality rates and the percentage of lambs given anthelmintic in each system were compared using non-parametric tests (χ^2 test). The kg lamb/ewe mated and the kg lamb/ewe scanned pregnant were calculated for both management systems and analysed using an F test.

3. Results

3.1. Ewe performance

The unadjusted animal (ewe and lamb) performance data across both systems for the 3 study years are presented in Table 3.

When considering the management system alone as a fixed effect in the model, the LMM showed that, over the 3 years, the system did have a significant effect on mating weights ($P = 0.018$), early pregnancy weights ($P = 0.004$) and 8 weeks post lambing weights of the ewes ($P = 0.043$), with the PLF ewes being heavier than the CON ewes (Table 3). However, when breed, age, scanned lamb numbers and previous weights were also included in the models, the management system did not have a significant effect on any of the ewe weights (mating, early pregnancy, mid-pregnancy, pre-lambing, 8 weeks post-lambing and weaning). Breed, age, scanned lamb numbers and previous weights were significant ($P < 0.001$), except for breed on early pregnancy weights ($P = 0.140$), mid-pregnancy weights ($P = 0.083$) and pre-lambing weights ($P = 0.106$).

The GLMM analysis of the mid-pregnancy scanning results over the 3 years did not show a significant effect of the management systems ($P = 0.884$) even when breed ($P < 0.001$), age ($P = 0.413$) and previous (early pregnancy) weights ($P < 0.001$) were included in the model. The GLMM analysis of the barren rate (ewe pregnant or not) over the 3 years were not significantly affected by the management system ($P = 0.945$), ewe age ($P = 0.726$) and the mating weight ($P = 0.130$). However, the breed ($P < 0.001$; Lleyn ewes having a lower barren rate than the Blackface ewes) and the early pregnancy weights ($P < 0.001$) did have a significant effect when included in the GLMM.

The ewe and lamb mortality rates over the 3 years were not significantly affected by the management system (χ^2, $P = 0.306$ and $P = 0.88$ respectively). Likewise, the kg lamb/ewe mated and the kg lamb/ewe scanned pregnant were not different (F test, $P = 0.58$ and $P = 0.82$ respectively) across both systems.

Overall, the PLF management system did not have an impact on ewe performance or animal mortality (welfare indicator).

3.2. Lamb performance and targeted worming

For the lamb performance at lambing, weaning and post-weaning, the system alone did not have a significant effect over the 3 years. At lambing, when breed, sex, and parity were accounted for in the Linear

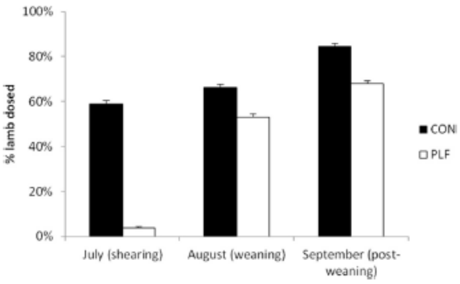

Fig. 2. Proportion of lamb dosed at shearing, weaning, post-weaning (3 year average across both systems).

Mixed Model, these variables had a significant effect (Lleyn being heavier than Scottish Blackface, $P < 0.001$; male being heavier than female lambs, $P < 0.001$; single being heavier than twin and triplet, $P < 0.001$, but the system did not ($P = 0.679$).

At weaning, when breed, sex, parity, were included in the Linear Mixed Model alongside the system, sex ($P < 0.001$) and parity ($P < 0.001$) were significant on weaning weights. The breed did not have an effect ($P = 0.939$), neither did the system ($P = 0.08$, with predicted means: PLF = 27.33 kg, CON= 27.65 kg). However, at post-weaning, the sex ($P < 0.001$), parity ($P < 0.001$) and the breed ($P = 0.039$; predicted means: Scottish Blackface = 30.07 kg, Lleyn = 30.48 kg) had significant effect on post-weaning weights, but not the system ($P = 0.114$; predicted means: PLF = 30.12 kg, CON= 30.43 kg).

Despite the PLF system lambs' final weight at post-weaning (Table 3) being slightly lower than their CON counterparts, the difference observed was not significantly affected by the management system.

However, on average over the three years, the proportion of lambs receiving worming treatment (Fig. 2) was significantly reduced by 40% (χ^2 test, $P < 0.001$) between the CON and the PLF approach. In terms of amount of anthelmintic used, this resulted in a three year average difference of 46% (15 l) between the two systems.

3.3. Labour profiles

Over the 3 years, the total amount of seasonal labour required for one ewe and one lamb in the CON system averaged 35 min, compared to 23 min in the PLF system (Fig. 3), which equated to a labour reduction of 36%. There were however differences between the months, with some periods showing a larger difference than others (e.g. June, July, August, September, average difference of 1.5 min, compared to November- March, average difference of 0.5 min).

Using the number of animals in each management system, their respective scanning percentage, and taking into account the lamb mortality (applied at weaning time), the calculated total number of 8 h working days of labour required in each management system year by year and on average over the 3 years are shown in Table 4.

Over the 3 years, the total amount of labour required per year varied from 40 to 43 working days for the CON system versus 23–26 working days for the PLF system, an averaged difference of 17 days per year.

Looking specifically at the targeted management for the winter feeding period (January-March, Fig. 1) and the lamb worming period (June – September, Fig. 1), the savings between the two systems were, respectively, 1 and 4 working days per year (Table 4). Combining both targeted management approaches, the total savings would equate to 5 working days per year.

For a more traditional farm, with different tasks being carried out routinely (as defined by the farmer questionnaire results, see Table 2), the impacts of implementing a PLF approach are also shown in Fig. 3. Over a whole year, the total amount of labour required for one ewe and one lamb in a traditional farm with a conventional approach (Trad-CON) averaged 21 min, compared to 16 min if a traditional farm took a PLF approach (Trad-PLF). This would equate to a labour reduction of 19%.

Assuming this modelled traditional farm was a typical mountain farm with 1200 ewes and 1000 lambs, the total number of 8 h working days of labour required without PLF (Trad-CON) equated to 48 days,

Table 4
Amount of labour (in 8 h days) required in each management system for every year and on average over the 3 years: in total, at winter feeding and for lamb worming, for all animals, and the amount of labour (in 8 h days) required in the modelled traditional farm with or without PLF over one year (shown as an average).

	2013	2014	2015	*average*
CON total	42	40	43	***42***
PLF total	26	23	26	***25***
CON winter feeding	4	4	4	***4***
PLF Targeted winter feeding	3	3	3	***3***
CON worming	13	12	14	***13***
PLF Targeted worming	10	8	10	***9***
Trad-CON total[a]				***48***
Trad-PLF total[a]				***39***

[a] Modelled for 1200 ewes and 1000 lambs over one year.

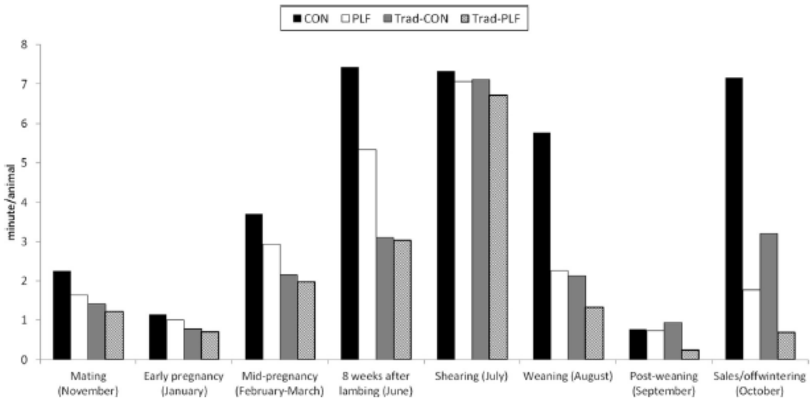

Fig. 3. Yearly labour profiles for both study systems (PLF and CON) and for a modelled traditional farm without (Trad-CON) or with PLF (Trad-PLF) – in minute/animal.

Table 5
Net margins (£/head) for the two management systems for the 3 study years.

	2012–2013		2013–2014		2014–2015		AVERAGE	
	CON (£/head)	PLF (£/head)	CON (£/head)	PLF (£/head)	CON (£/head)	PLF (£/head)	CON (£/head)	PLF (£/head)
lamb income	£68	£69	£63	£63	£56	£55	£62	£62
ewe income	£35	£31	£43	£42	£46	£44	£41	£39
wool income	£2	£2	£2	£2	£2	£2	£2	£2
total output	***£105***	***£102***	***£109***	***£107***	***£104***	***£102***	***£106***	***£104***
winter feed	£16	£15	£11	£11	£15	£16	£14	£14
finishing feed	£27	£27	£23	£26	£20	£20	£23	£24
off-wintering	£14	£14	£15	£15	£17	£17	£15	£15
health costs	£11	£11	£8	£7	£9	£8	£9	£9
total variable costs	***£68***	***£67***	***£56***	***£59***	***£61***	***£61***	***£62***	***£62***
gross margin *(output minus variable costs)*	**£37**	**£35**	**£52**	**£48**	**£43**	**£40**	**£44**	**£41**
labour[a]	£15	£10	£16	£10	£16	£11	£16	£10
other fixed costs[b]	£55	£55	£56	£56	£56	£56	£56	£56
total fixed costs	***£70***	***£65***	***£73***	***£66***	***£72***	***£67***	£72	£66
NET MARGIN *(gross margin minus fixed costs)*	**-£33**	**-£29**	**-£20**	**-£18**	**-£29**	**-£26**	**-£27**	**-£24**

[a] Based on contract shepherding, not permanent labour.
[b] Includes: fuel, rent, buildings costs (electricity, maintenance), fencing maintenance, vehicle repairs, machinery costs, haulage, dead stock.

versus 39 days with PLF (Trad-PLF). This meant a difference of 9 working days over a whole year (Table 4).

3.4. Economic data

Based on the number of animals in each system across the 3 years, the net margin (gross margin minus fixed costs) for the two systems over the 3 study years (Table 5) varied from -£33/ewe to -£20/ewe in the CON system, and from -£29 to -£18 in the PLF system, depending on the year. On average, there was a difference of £3/ewe, to the benefit of the PLF system.

The initial cost of an EID Prattley 5-way Auto Draft weigh crate was £10,000 (approximately), which, given the average number of PLF ewes (470), meant an additional cost of £21 per ewe. However, since the use of the technology brought an average annual saving of £3/ewe, this meant that the equipment would be paid off after 7 years. This estimation did not take into account depreciation costs. After that initial period of 7 years, this PLF approach could potentially provide an extra £1260 per year (470 x £3/ewe).

If the PLF management approach was deployed to the whole flock (average of 902 ewes over 3 years), then the cost of the EID weigh crate could be paid off after 4 years (£10,000/ (902 animals x £3/ewe)), and the financial benefits would be increased to £2700 per year (902 x £3/ ewe) after the fourth year.

From these results, an approximation of savings was estimated for a situation more typical of traditional farms. The savings of £3/ewe were largely due to the 36% reduction in labour (Fig. 2). Based on that figure, and using the modelled traditional farm results showing a 19% reduction in labour by using a PLF approach (Fig. 2), the savings per ewe could be approximated at £1.60 (£3 × 0.19/0.36) per year. For an assumed flock of 1200 ewes, this could mean that the equipment worth £10,000 would be paid off in 5 years, bringing a surplus of £1920 per year thereafter.

4. Discussion

This long-term study showed that the implementation a PLF management approach on a mountain sheep farm can be useful, despite the fact that these types of farms handle livestock less frequently than their more intensive lowland farms counterparts (Hargreaves and Hutson, 1997), and operate in harsh environment where the technology may have limitations (Ruiz-Garcia and Lunadei, 2011). Performance of the animals was not affected by the introduction of the technology to aid in decision-making. Although the benefits of implementing the PLF approach translated into an increase in ewe performance, with PLF ewes displaying slightly heavier weights than their CON counterparts, statistically, once the effects of breed, age and expected litter size were accounted for, this difference was not significant. However, in the context of ewe pregnancy, Wishart et al. (2015) argued that, a weight-based PLF approach could bring further benefits, such as managing body reserves more efficiently to reduce business risks, despite no difference in performance. Moreover, although the targeted winter feeding did not impact on the animal weights after the winter, that approach nevertheless provided an average labour difference of one working day (8 h) between the 2 systems. Alvarez and Nuthall (2006) also argued that although farmers use technology to ease their workload and improve their management, it often does not inherently have any impact upon biological efficiency.

Likewise, this study showed that introducing a targeted approach to lamb worming, with large reductions in drug usage and some reductions in labour, did not prevent the young animals achieving similar post-weaning weights as their CON counterparts. The reduction in drug usage in such a worming approach has been demonstrated in lowland conditions (Kenyon et al., 2013; Busin et al., 2014). This study, however, further demonstrates its potential in a mountain environment, with less handling events and different grazing conditions. Benefits to this targeted approach also go beyond the effects on performance alone. The additional benefits in terms of slowing down any wormer-resistance build-up (with the significant reduction in the proportion of lambs being wormed) in these livestock systems are important, especially since gastrointestinal nematode anthelmintic treatments can have a high failure rate (Keane et al., 2014). Further, if resistance is allowed to build up on any farm, this can lead to performance loss and ultimately have negative financial impacts (Sutherland et al., 2014). Reducing resistance to anthelmintic treatments also has beneficial impacts on animal welfare (McBean et al., 2016), and on the wider soil fauna (e.g. invertebrates).

A targeted management approach within a flock can also provide better control over the flock, since each animal is identified individually, and can, if necessary, be targeted with any treatment or feeding regime (Banhazi et al., 2012). This has the potential to increase efficiency (and ultimately reduce carbon footprint) of the whole flock, by targeting treatments and differential management towards animals that need it most. For instance, Bowen et al. (2009) in Australia demonstrated the benefits of using a remote drafting system for supplementing ewes. Wishart et al. (2016) has also shown the benefits of using ewe individual lifelong performance to predict their future outputs. Bocquier et al. (2014) highlighted the potential benefits of such a targeted approach to extensive livestock systems in France, and Morris et al. (2012) showcased the cost-effectiveness, welfare benefits and labour efficiency that these technological tools can bring to extensive systems in Australia.

This study has shown that the main benefit of such a PLF approach was the labour savings and cost-effectiveness of using the technology, which leads to financial gain for the whole system. Although the net margin is negative in all cases, mostly due to non-accounting of subsidies on the farm that contribute, in these types of mountain farms, to a substantial amount of the farm income (Morgan-Davies et al., 2008b), it is the difference between the two managements that is interesting. The £3/ewe annual difference is mainly due to labour costs. This reinforces the thoughts of Aubron et al. (2016) who stated the crucial role of labour to any trajectory changes of French sheep marginal production systems. Similarly, Conradie and Piesse (2015) in South Africa, argued that labour self-efficiency on extensive sheep farms is a key factor to optimal intensity. Likewise in Greece, where Theodoridis et al. (2012) suggested that, in their sample of sheep farms, efficient farms used less labour. Jouven et al. (2010) in Mediterranean rangeland systems also argued that a framework of precision livestock system could minimise human intervention and labour at farm scale.

The CON and PLF approach profiles in this study were designed to directly compare and benchmark the effect of using technology on an extensive research farm, with a relatively high input management input, in terms of labour as well as performance indicators. However, the modelled traditional profiles allowed further comparisons of labour input, as they represented more of the inherent variation in husbandry practices within the extensive farmers' population (Morgan-Davies et al., 2012). Although introducing technology on relatively lower input management sheep did not bring savings of the same magnitude, it demonstrated how the use of technology can still bring potential benefits in terms of labour efficiency.

Additionally, these labour savings can also be identified as a form of opportunity labour savings, where the farmer can devote the extra time gained through the use of PLF to any off-farm work (farming or non-farming). In these remote areas, such opportunity is valuable and can increase financial farm outputs (Lien et al., 2010). The financial benefit becomes also a social one; labour can be scarce in such marginal areas and this is becoming a wider social issue (Sutherland et al., 2014; Jouven et al., 2010). Having the opportunity to reduce labour on a mountain sheep farm while still maintaining livestock productivity means that other forms of occupation (sometimes more lucrative) could be found, such as tourism diversification or off-farm contractual work (Meert et al., 2005; Maye et al., 2009). A better labour efficiency can also ease pressure on farming life, potentially making it more attractive to the younger generations who have different life aspirations (Blanc et al., 2008).

However, the benefits highlighted in this study can only become widely applicable if the farmers themselves are keen to embrace these forms of technology. Bocquier et al. (2014) already mentioned constraints and barriers (such as diversity of the information required in extensive systems, as well as cost of the technology) that farmers face to implement such an approach. The cost of upwards of £10,000 for a state of the art handling system may appear excessive to mountain farmers, who do not always have large financial outlays for farm machinery, unlike lowland livestock or crop farmers. So, in parallel to this presented study, farmer surveys at sheep shows and events have been carried out in 2013 and 2015 to better understand barriers to uptake of the technology. Although the majority (97%) of respondents thought that the technology could help farm management, only a quarter of them had EID readers that they actively used on their farms. The main barriers for further implementation and use were the (perceived) cost of the technology, the lack of specific training on how to use the equipment, and the diversity of systems and type of readers available on the market (Morgan-Davies and Lambe, 2015; Morgan-Davies et al., 2015a). Although the lack of financial help for farmers to equip their farm with technology to exploit EID for management purposes were identified as barriers to enable increased uptake, active demonstration and face to face training were thought to be part of the solution. This knowledge transfer demand and the potential role that advisory services should play to enhance any uptake has already been identified by Cabaret et al. (2009). Likewise, Reichardt et al. (2009) in Germany stated that to promote awareness of precision farming, information and training materials must be adapted to the relevant educational levels of the farmers targeted. Bocquier et al. (2014) equally stressed the need for advisory services and professional knowledge transfer towards the farmers.

Introducing a precision livestock farming approach to sheep management in mountain areas can bring a range of potential benefits, as highlighted in this study. However, to ensure that this approach prevails and to promote it, an integrated process that couples farmer training, efficient knowledge transfer and financial incentive would also be valuable.

5. Conclusions

This study indicates that it is feasible and beneficial to consider and manage a mountain ewe flock at individual rather than flock or batch level using technology. Segregating large flocks for winter nutrition, reducing the amount of anthelmintic products used on lambs without compromising lamb final weights, reducing labour at handling and providing increasing economic returns were all advantages that such an approach can provide.

A precision livestock farming approach, which incorporates the use of technology such as in this study, can therefore bring benefits in terms of labour efficiency, anthelmintic control, animal welfare and economic resilience, even when the variation in farmers' practices (high input management or low input management) are taken into account. Provided the initial costs of the associated technology can be met and uptake by the farming community further fostered, precision livestock can make mountain farming systems more labour efficient and resilient. The benefits of using such technology do not simply relate to the UK and Europe; they can relate to other areas of the globe where either EID is now mandatory (such as Victoria Australia from 2016).

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Appendix 3 Feed analysis report from supplemenatary feed provided to ewes.

7624

Animal Feed Report

SAC
COMMERCIAL LTD

Client: Jenna Kyle
SRUC Hill & Mountain R Centre
Kirkton Farm

Your reference:	Ewe Volls

Lab sample no:	14300219
Batch no:	A58530
Date received:	23/01/2014
Date reported:	04/02/2014

Farm Sampled:	HARBRO

Determination	Result	Units
Dry matter	855.4	g/kg
CRUDE PROTEIN	191	g/kgDM
* AHEE	48.2	g/kgDM
NCGD	75.6	%DM
* ME (WET CHEM) Ruminant	11.8	MJ/kgDM

* Not UKAS Accredited

Contact: Oban Advisory Office
Oban FBS

Authorised by June Gay (Client Manager): June Gay

Page 1 of 1

Analytical Services Department, Central Analytical Laboratory, SAC Bush Estate, Penicuik, Midlothian, EH26 0QE
No other party may rely on the report and if they do so, then they rely upon it at their own risk.
All work undertaken is in accordance with our written Standard Terms and Conditions of Supply and Service.
SAC Commercial Ltd (registered in Scotland, No 148684)

Appendix 4 Condensed groups used to join different responses together from the "most important cull reasons" open-ended question.

Condensed group	Original descriptions given
poor feet/legs lame	"feet", "legs", "Persistent foot problems", "Recurrent feet problems"
barren	"fertility", "failure to get pregnant", "breeding ability", "not in lamb", "Infertility", "not pregnant", "Lack of pregnancy", "infertility/subfertility", "Reproduction - prolapse - consistently barren - single bearing", "Not going in lamb"
poor condition	"body condition", "thin at tupping", "low BMI", "condition", "BCS", "ewe constantly thin"
not thriving	"poor do-er", "Lack of thrift", "Poor thrive", "thrift"
lame	"lameness", "Bad feet & legs due to lameness/injury"
lambing difficulty	"assistance with lambing", "lambing"
poor mouth	"bad mouth", "broken mouth", "missing teeth", "teeth", "lost teeth", "Mouth - missing teeth, loose teeth, no teeth, long teeth", "Mouth and teeth problems"
poor udder	"bad udder", "lost a teat", "wrong udder", "udder", "vessel", "Only milk in one or no teats"
bad behaviour/attitude	"management (jumping fences, not there at gathering)", "Temperament"
poor mothering ability	"mothering", "bad mother", "bad mothering", "Lamb rearing/milkiness" , "maternal ability", "lack of milk", "milk"
incorrect appearance	"appearance", "look", "Visual", "Bad type of animal in each ewe group", "Not true to type", "size", "body weight"
poor productivity	"Poor lambs identified by management tag and related back to dam", "Unproductive", "No raising a lamb", "notice producing a lamb", "Poor lamb", "poor lamb performance", "Non productive"
Other	All just got mentioned 1 time: “Functionality”, “Pelvis problems”, “welfare”, “foot, mouth or other abnormalities/poor development”, “Unfit for breeding”, “don't think she will live another year”, “general health issues”, “History”, “market”, “Poor quality”, “Wore out”, “Triplets”

Appendix 5 Written instructions provided to test raters of VAA

Scorer instructions

The scoring system was designed to collect information about the current physical appearance and condition of the sheep at stock draw/selection time (September/October). The system has been devised to include issues the stockperson may be taking into consideration when deciding whether to keep a ewe in the flock for the following year. We are interested to then compare scores with actual performance.

The purpose of checking multiple scorers of this scoring system is to measure how much variation there is between scorers and to establish if people with different backgrounds and experience of working with sheep would score the same sheep in the same way. This type of checking is essential if results are to be published in a scientific journal or in a PhD thesis.

This involves three parts:

- A short questionnaire to gather information about you so that your experience and background can be considered when looking at the results.
- Scoring of a group of ewes using the scoring system.
- A final questionnaire where you can provide feedback on the scoring system.

Instructions for scoring:

- Complete one scoring sheet per sheep.
- On each sheet fill in your scorer number (which you will be given). This allows for your results to be combined together but ensures that your identity is unknown allowing your results to remain anonymous.
- On each sheet fill in the ewe's ID number (the shepherd assisting will tell you this).
- If there are any other comments you would like to add about an animal please put these on the back of the scoring sheet. This might be important criticism or anything else of interest about this ewe that this scoring sheet does not capture.
- Do not discuss the sheep or scores you are awarding with any other scorers until the final questionnaire has been completed.
- If you do not understand the scores ask the researcher present.
    - If you do not feel you have the expertise to assign a score (such as face shape), just leave blank.
    - For question on "Jaw position", 5mm is three 16ths of an inch.
    - For scoring teeth present, it is the sheep's left and right.
- Consider each ewe's appearance in relation to what you believe a Scottish Blackface ewe on a commercial hill sheep farm (such as this) should look like.

If you have any questions or concerns over this process please speak to the organising researcher or myself at the contact details below. Completing the questionnaires and scoring sheet will be taken as your consent for us to use your results.

Your involvement in this research is greatly appreciated.

Harriet Wishart

PhD student & technician
SRUC Kirkton and Auchtertyre Farms, Crianlarich, FK20 8RU
Harriet.Wishart@sruc.ac.uk
01838 400524

Appendix 6 Information about VAA test rater questionnaire.

Questions about you

Your scorer number: ☐ **Date:** ☐

What is your current position (tick)?

Farmer, owner, tenant, manager ☐
Shepherd/stockperson ☐
Contract shepherd/stockperson ☐
Agricultural consultant ☐
Agricultural researcher ☐
Agricultural student ☐
Do not work in agriculture ☐
Other (please state):________________

How often do you work directly with sheep (tick)?

Daily ☐ Weekly ☐ Monthly ☐ Less than monthly ☐ Never ☐

What breed(s) of sheep do you have a good level of experience working with?

If Scottish Blackface, then: North type ☐ South type ☐ Not one specific type ☐
Lleyn ☐ None ☐

Other hill breed(s) (please state): ____

Upland breed(s) (please state): ____

Lowland breed(s) (please state): ____

What sort of farm(s) do you have a good level of experience working with?

Hill ☐ Upland ☐ Lowland ☐ No farm experience ☐ Other __________

In your lifetime what is the highest level of responsibility you have had with selecting which ewes are kept in a flock for the following year (tick)?

Solely responsible ☐
Take advice from others but make the final decision ☐
Advice which sheep to keep but others make the final decision ☐
Not involved with deciding ewes to kept ☐

Which of the following are you most concerned about producing from your flock (rank in order of preference with 1 being the highest)?

Replacement ewe lambs ☐
Ewe lambs/gimmers to sell ☐
Cast ewes for sale ☐
Finishing lambs ☐
Store lambs ☐
Breeding tups ☐

Other, please state: ____

When do you select which ewes to keep for the following year (stock draw)?____________

Do you or would you cull ewes on (tick)?

	Yes	No	
A specific age			If yes, what lamb crop years at selection:
Any of the 8 incisor teeth were missing			
Any of the middle 4 incisor teeth were missing			
No lamb had been born over previous year			
Specific body condition not reached at selection			If yes, what condition score:

Any other reasons____

Appendix 7 VAA test-raters scoring sheet.

SCORER NUMBER: **SHEEP ID:**

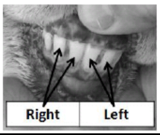
Breed Characteristics (circle one choice per row)

Fleece length:	Very woolly	A bit woolly	Short wool
Fleece colour:	Lots of black patches	A few black patches	Clear, all white
Face shape: *(leave blank if unsure of the difference)*	North type	Between the two types	South type
Face colour:	Lots of white coverage	A little white coverage	Black with grey nose
Size:	Smaller than ideal	Ideal	Bigger than ideal

Structural soundness (circle choice)

Legs/locomotion:	Specific problems	Less than ideal	Ideal, straight legs
Back:	Very saddled back	Slightly saddled back	Flat level back

Teeth (fill in each box per tooth)



R4	R3	R2	R1	L1	L2	L3	L4

Blank cell= sound adult tooth present S= tooth slack
L= sound lamb tooth present X= tooth missing

Mouth (circle one score per row)

Jaw position (position lower jaw in relation to upper jaw)

-5 lower jaw 5mm back from upper	-4	-3	-2	-1	0	1	2	3	4	5 lower jaw 5mm in front of upper jaw

undershot ←------ ------→ overshot

Tooth angle (angle of incisor teeth in relation to lower jaw)

-3 Teeth 45° back into mouth	-2	-1	0 Teeth at right angles with lower jaw (on pad)	1	2	3 Teeth 45° forward from mouth

Tooth length (in your opinion)

-2 Very short	-1	0	1	2 Very long

Udder (circle choice one for each row)

Right half:	Sound good udder	Some abnormalities	Severely damaged
Left half:	Some good udder	Some abnormalities	Severely damaged
Attachment:	Poorly attached, hanging	Reasonably attached	Well attached, close to body
Teat size:	Smaller than ideal	Ideal	Larger than ideal

Your overall opinion of sheep to keep for the following year on a commercial hill sheep farm,

1 Would definitely sell	2	3	4	5 Would definitely keep

It was only discovered after scoring that there was an error on this scoring form. For "Tooth angle" a negative score should have indicated how far forward teeth were and a positive score for how far back. However this was mistakenly reversed on the form (for example, it said "-3 teeth 45° back into mouth"). Therefore after scoring all results were corrected by making positive scores negative and negative scores positive. The final score, on overall opinion of which sheep to keep, is termed "Retention decision" within the main body of this thesis.

Appendix 8 The Flock Manger's visual aid for VAA when scoring research flock.

Breed characteristics		
Fleece length	1	Very wooly
Lleyn and Blackface	2	A bit wooly
	3	Short wool
Fleece colour	1	Lots of brown patches
Only Blackface	2	A few brown patches
	3	Clear, all white
Face shape	1	North type
Only Blackface	2	Between the two types
	3	Perth type
Face colour	1	Lots of white coverage
Only Blackface	2	A little bit of white coverage
	3	Mainly black with grey nose
Size	1	Smaller than ideal
Lleyn and Blackface	2	Ideal
	3	Bigger than ideal
Structural Soundness		
Legs/locomotion	1	Any problem e.g. hooked legs, post leg etc.
	2	Less than ideal
	3	Ideal, straight legs
		CULL if in very poor legs and feet
Back	1	Very saddaled back
	2	Slightly saddaled back
	3	Flat level back
Mouth		
Teeth		Adult tooth is present and sound
	L	Lamb tooth present
	S	Tooth slack
	X	Tooth missing
		CULL if any of middle four teeth slack or missing
Jaw position	-5 to 5	-5 lower jaw 5mm back from upper jaw to 5 lower jaw 5mm in front of upper jaw
Tooth angle	-3 to 3	−3 (45° forward) to 3 (45° back); ideal position is at right angle with lower jaw
Tooth length	-2 to 2	−2 (very short) to 2 (very long)
Feet		Note any problems
		Cull for bad feet if feet very poor
Udder		
Mastitas		Sound good udder
	A	Some abnormalities
	X	Serverly damaged
		Cull for bad udder if any sign of mastitas
Attachment	1	Poorly attached, hanging
	2	Reasonable attached
	3	Well attached, close to body
Teat size	1	Smaller than ideal
	2	Ideal
	3	Larger than ideal
Shepherds choice	1 to 5	1= would definitely get rid off, 5= would definitely keep
Other comments	Is ewe to be culled or anything else of interest.	

“Shepherds choice” is named “Retention decision” within the main body of this thesis

Appendix 9 Test-rater review questionnaire of VAA

Post scoring questions

Scorer number: [ ]

For a lot of the traits it is obvious which is the "best" and which is the "worst" score, however some are more subjective. **For the following few scores put a circle around your opinion of the "best" score and put a cross over the "worst" score:**

Breed Characteristics	Circle best score, Cross worst score per line		
Fleece length:	Very woolly	A bit woolly	Short wool
Fleece colour:	Lots of brown patches	A few brown patches	Clear, all white
Face shape:	North type	Between the two types	South type
Face colour:	Lots of white coverage	A little white coverage	Black with grey nose

Structural soundness	Circle best score, Cross worse score per line		
Back:	Very saddled back	Slightly saddled back	Flat level back

Udder	Circle best score, Cross worse score per line		
Attachment:	Poorly attached, hanging	Reasonably attached	Well attached, close to body

How good an indicator do you believe each trait is on how the ewe performs the following year? Where:

Very good indicator = a good score of this indicator will result in the ewe performing well AND a poor score will result in the ewe performing poorly over the following year.

Very poor indicator = a good or bad score in this indicator will have no bearing on the performance of the ewe over the following year.

(tick one choice per line)	Very good indicator	Good indicator	Neutral	Poor indicator	Very poor indicator
Fleece length					
Fleece colour					
Face shape					
Face colour					
Size					
Legs/locomotion					
Shape of back					
Number of teeth					
Teeth that have been lost (gaps)					
Tooth looseness					
Jaw position					
Tooth angle					
Tooth length					
Damage within udder					
Udder attachment					
Teat size					
Overall opinion					

Continued

Appendix 9 Continued

How would a poor score in each of the traits impact on your decision to sell the ewe?

(tick one choice per line)	Would definitely sell	Might sell	Would not impact on decision to sell
Fleece length			
Fleece colour			
Face shape			
Face colour			
Size			
Legs/locomotion			
Shape of back			
Number of teeth			
Teeth that have been lost (gaps)			
Tooth looseness			
Jaw position			
Tooth angle			
Tooth length			
Damage within udder			
Udder attachment			
Teat size			
Overall opinion			

Are there any traits of physical condition or appearance that have been missed off this scoring system that you believe would be associated with productivity of the ewe over the following year?

Any final comments or opinions on this scoring system, the indicators or what is hoped to be achieved with this research?

Finally, thank you for taking the time to be part of this research it is hugely appreciated.

Harriet Wishart

Appendix 10 Standard flock medicine treatments and costs

Handling event	Treatment	Product	Cost	for	Cost £…	…per…	given at a rate of	Source of price
Oct - Stockdraw	Flukicide oral drench	Fasinex	£ 102.60	5Lt	0.0205	1ml	1ml per 5kg	Fasinex Fluke Drench 5% 5L at £85.50 + VAT £17.10 = £102.60 (from Carrs Bilington invoice 29/9/16)
	Ectoparasiticides pour-on	Crovect	£ 78.00	5Lt	0.0156	1ml	10ml per 20kg up to 40ml	Crovect Pour-on for sheep 5L at £65 +VAT £13 = £78 (Carrs Billington invoice 19/10/16)
	Endoparasiticides injection	Dectomax	£ 174.00	500ml	0.3480	1ml	1ml per 33kg	Dectomax injection 500ml at £145 + VAT £29 = £174 (Harbro invoice 15/4/16)
Nov - Pre-mating	Mineral oral drench	Potassium iodide	£ 91.84	500g	0.0514	10ml dose	70g diluted with 2.5lt, then 10ml per dose, means a cost per does of: £0.0514304	Potassium Iodide 500g at £76.53 + VAT £15.31 = 91.84 (Oban vets invoice 3/2/16)
	Mineral bolus	Copinox	£ 76.20	4gx250	0.3048	4g capsule	1 capsule	Copinox Ewe/Calf capsules 4gx250 at £63.50 + VAT £12.70 = £76.20 (Carrs Billington invoice 19/10/16)
Jan - Post-mating	Flukicide and anthelmintic combined oral drench	Flukiver	£ 131.40	5Lt	0.0263	1ml	1ml per 5kg	Flukiver 5Lt at £109.50 +VAT £21.90 = £131.40 (Carrs Billington invoice 11/7/16)
Mar - Vacination	Immunological vacination	Heptavac P Plus	£ 186.00	500ml	0.7440	2ml dose	2ml	500ml at £155 + VAT £31 = £186 (Carrs Billington invoice 17/8/16)
	Flukicide and anthelmintic combined oral drench	Flukiver	£ 131.40	5Lt	0.0263	1ml	1ml per 5kg	Flukiver 5Lt at £109.50 +VAT £21.90 = £131.40 (Carrs Billington invoice 11/7/16)
	Ectoparasiticides pour-on	Crovect	£ 78.00	5Lt	0.0156	1ml	10ml per 20kg up to 40ml	Crovect Pour-on for sheep 5L at £65 +VAT £13 = £78 (Carrs Billington invoice 19/10/16)
	Anthelmintic oral drench	Depidex	£ 118.80	12.5Lt	0.0095	1ml	2.5ml per 10kg	Depidex Drench 12.5L at £99 + VAT £19.8 = £118.8 (Carrs Billington invoice 23/6/16)
Apr - Pre-lambing	Mineral oral drench	Ewes in lamb - Potassium iodide	£ 91.84	500g	0.0514	10ml dose	70g diluted with 2.5lt, then 10ml per dose, means a cost per does of: £0.0514304	Potassium Iodide 500g at £76.53 + VAT £15.31 = 91.84 (Oban vets invoice 3/2/16)
	Mineral bolus	Ewes in lamb - Copinox	£ 76.20	4gx250	0.3048	4g capsule	1 capsule	Copinox Ewe/Calf capsules 4gx250 at £63.50 + VAT £12.70 = £76.20 (Carrs Billington invoice 19/10/16)
Apr to June - Lambing	Antibiotic injection	Lambs - Ultrapen	£ 21.98	100ml	0.0659	0.3ml dose	1ml per 15kg, so 0.3ml per lamb	Ultrapen LA 100ml at £18.32 + VAT £3.66 = £21.98 (Oban vets invoice 1/6/16)
June - Marking	Flukicide and anthelmintic combined oral drench	Ewes - Flukiver	£ 131.40	5Lt	0.0263	1ml	1ml per 5kg	Flukiver 5Lt at £109.50 +VAT £21.90 = £131.40 (Carrs Billington invoice 11/7/16)
	Ectoparasiticides pour-on	Ewes - Crovect	£ 78.00	5Lt	0.0156	1ml	Up to 25kg-20ml, 25-40kg - 30ml, >40kg-40ml	Crovect Pour-on for sheep 5L at £65 +VAT £13 = £78 (Carrs Billington invoice 19/10/16)
	Anthelmintic oral drench	Ewes - Depidex	£ 118.80	12.5Lt	0.0095	1ml	2.5ml per 10kg	Depidex Drench 12.5L at £99 + VAT £19.8 = £118.8 (Carrs Billington invoice 23/6/16)
	Anthelmintic oral drench	Lambs - Depidex	£ 118.80	12.5Lt	0.0095	1ml	2.5ml per 10kg	Depidex Drench 12.5L at £99 + VAT £19.8 = £118.8 (Carrs Billington invoice 23/6/16)
	Immunological vacination	Lambs - Heptavac	£ 186.00	500ml	0.7440	2ml dose	2ml	500ml at £155 + VAT £31 = £186 (Carrs Billington invoice 17/8/16)
	Ectoparasiticides pour-on	Lambs - CLiK	£ 181.20	5Lt	0.0362	1ml	10-20kg - 20ml, 21-30kg - 25ml, 31-50kg - 30ml	Clik Pour on 5Lt at £151 + VAT £30.20 = £181.20 (Carrs Billington invoice 23/6/16)
	Ectoparasiticides pour-on	Lambs - Crovect	£ 78.00	5Lt	0.0156	1ml	Up to 25kg-20ml, 25-40kg - 30ml, >40kg-40ml	Crovect Pour-on for sheep 5L at £65 +VAT £13 = £78 (Carrs Billington invoice 19/10/16)
July - Milk-clip	Anthelmintic oral drench	Lambs - Depidex	£ 118.80	12.5Lt	0.0095	1ml	2.5ml per 10kg	Depidex Drench 12.5L at £99 + VAT £19.8 = £118.8 (Carrs Billington invoice 23/6/16)
	Immunological vacination	Lambs - Heptavac	£ 186.00	500ml	0.7440	2ml dose	2ml	500ml at £155 + VAT £31 = £186 (Carrs Billington invoice 17/8/16)
Aug - Weaning	Anthelmintic oral drench	Lambs - Depidex	£ 118.80	12.5Lt	0.0095	1ml	2.5ml per 10kg	Depidex Drench 12.5L at £99 + VAT £19.8 = £118.8 (Carrs Billington invoice 23/6/16)
Throughout year, individual antibiotic injection		Ultrapen	£ 21.98	100ml	0.2198	1ml		Ultrapen LA 100ml at £18.32 + VAT £3.66 = £21.98 (Oban vets invoice 1/6/16)
		Alamycin	£ 26.84	100ml	0.2684	1ml		Alamycin LA 100ml at £22.37 = VAT £4.47 = £26.84 (Oban vets invoice 6/9/16)

Appendix 11 Significant relationships between two sets of explanatory variables (continuous variables in italics) with two response variable (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6

		R-EMC				R-LmWt			
		2013 *P*-value[c]	**2014 *P*-value[c]**	**In Initial models, *P*<0.1**	**In Reduced models[a]**	**2013 *P*-value[c]**	**2014 *P*-value[c]**	**In Initial models, *P*<0.1**	**In Reduced models[a]**
Visual Appearance Assessment (E-VAA)	Size	**0.005**	0.339	✓	✓	**0.003**	**0.003**	✓	✓
	Flatness of back	0.251	**0.000**	✓	✓	**0.013**	0.136	✓	✓
	Soundness of feet	0.441	0.123			0.173	0.367		
	Legs and motion	0.839	**0.025**	✓	✓	0.587	0.402		
	Teeth present	0.396	**0.004**	✓	✓	0.694	0.677		
	Jaw position	0.123	**0.000**	✓	✓	0.727	0.018	✓	✓
	Tooth angle	0.827	0.081	✓	✓	0.874	0.023	✓	✓
	Tooth length	**0.004**	**0.005**	✓	✓	**0.007**	0.866	✓	✓
	Teat size	0.360	0.524			0.103	0.051	✓	✓
	Udder attachment	**0.012**	0.683	✓	✓	**0.001**	0.923	✓	✓
	Udder damage	0.695	0.307			0.926	0.179		
	Face colour	0.111	0.195			0.912	0.417		
	Face shape	0.626	0.340			0.330	0.085	✓	✓
	Fleece colour	0.455	0.440			0.356	0.209		
	Fleece length	0.325	0.223			0.281	0.369		
	Retention decision	**0.032**	**0.004**	✓		0.199	0.093	✓	
E-EBV	*Litter size*	**0.000**	0.218	✓		**0.000**	**0.017**	✓	
	Maternal ability	**0.000**	0.145	✓	✓	**0.000**	**0.028**	✓	✓
	Eight week weight	**0.039**	0.301	✓		**0.015**	**0.044**	✓	
	Scan weight	**0.005**	0.116	✓		**0.015**	0.051	✓	
	Ultrasound muscle depth	**0.008**	0.992	✓	✓	**0.026**	0.683	✓	✓
	Ultrasound fat depth	0.103	0.794			0.318	0.396		
	Mature size	**0.012**	0.159	✓		**0.019**	0.157	✓	
	Carcass lean weight	**0.002**	0.555	✓		**0.008**	0.304	✓	
	Carcass fat weight	**0.029**	0.402	✓	✓	0.114	0.435		
	Index	**0.000**	0.167	✓		**0.000**	**0.032**	✓	

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 12 Significant relationships between two sets of explanatory variables (continuous variables in italics) with response variable R-LmNo (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6.

		R-LmNo					
		2013 *P*-value[d]	**2014 *P*-value[d]**	**2013 *P*-value GLM**	**2014 *P*-value GLM**	**In Initial models, *P*<0.1**	**In Reduced models[a]**
Visual Appearance Assessment (E-VAA)	Size	**0.003**	**0.031**	**0.000**	**0.004**	✓	✓
	Flatness of back	0.056	0.294	**0.004**	0.218	✓	✓
	Soundness of feet	0.320	0.792	0.105	0.521		
	Legs and motion	0.898	0.892	0.632	0.539		
	Teeth present	0.855	0.556	0.616	0.395		
	Jaw position	0.570	**0.013**	0.642[b]	**0.004[b]**	✓ ✓	✓
	Tooth angle	0.632	0.098	0.736	**0.005**		
	Tooth length	**0.009**	0.810	**0.004**	0.816	✓	✓
	Teat size	0.068	**0.022**	**0.023[b]**	**0.008[b]**	✓	✓
	Udder attachment	**0.001**	0.503	**0.000**	0.823	✓	✓
	Udder damage	0.534	0.378	0.416	0.205		
	Face colour	0.711	0.482	0.908	0.220		
	Face shape	0.612	0.155	0.211	0.072		
	Fleece colour	0.493	0.076	0.712[b]	0.135[b]	✓	✓
	Fleece length	0.484	0.620	0.197	0.491		
	Retention decision	0.259	0.108	0.046[b]	0.070[b]		
E-EBV	*Litter size*	**0.000**	0.122	**0.000**	0.075	✓	
	Maternal ability	**0.002**	0.352	**0.000**	0.145	✓	✓
	Eight week weight	**0.019**	0.369	**0.012**	0.142	✓	
	Scan weight	**0.010**	0.410	**0.021**	0.175	✓	
	Ultrasound muscle depth	0.050	0.437	**0.026**	0.333	✓	✓
	Ultrasound fat depth	0.355	0.355	0.556	0.265		
	Mature size	**0.005**	0.570	**0.026**	0.441	✓	
	Carcass lean weight	**0.039**	0.952	**0.006**	0.673	✓	
	Carcass fat weight	0.393	0.742	0.204	0.631		
	Index	**0.001**	0.343	**0.000**	0.164	✓	

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 13 Significant relationships between two sets of explanatory variables (continuous variables in italics) with response variable R-ES (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6.

		R-ES					
		2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models, *P*<0.1	In Reduced models[a]
Visual Appearance Assessment (E-VAA)	Size	**0.023**	0.760	**0.048**	0.701	✓	✓
	Flatness of back	0.777	**0.001**	0.710	**0.005**	✓	✓
	Soundness of feet	1.000	1.000	0.831	0.390		
	Legs and motion	0.096	**0.027**	0.172	0.101	✓	✓
	Teeth present	0.539	**0.008**	0.543[b]	**0.044[b]**	✓	✓
	Jaw position	0.160	0.148	0.169	0.217		
	Tooth angle	1.000	1.000	0.836	0.610		
	Tooth length	1.000	0.067	0.990	0.064	✓	✓
	Teat size	0.530	**0.003**	0.309[b]	**0.004[b]**	✓	✓
	Udder attachment	0.430	0.757	0.284	0.767		
	Udder damage	1.000	1.000	0.857	0.427		
	Face colour	0.112	0.468	**0.018[b]**	0.402[b]		
	Face shape	0.164	0.359	0.270	0.378		
	Fleece colour	0.954	0.641	0.977	0.683		
	Fleece length	1.000	0.372	0.954	0.385		
	Retention decision	0.266	0.190	0.262	0.263		
E-EBV	*Litter size*	0.636	0.495	0.636	0.492		
	Maternal ability	0.446	0.888	0.446	0.887		
	Eight week weight	0.850	0.351	0.850	0.349		
	Scan weight	0.424	0.949	0.423	0.949		
	Ultrasound muscle depth	**0.004**	0.298	**0.004**	0.294	✓	✓
	Ultrasound fat depth	**0.012**	0.078	**0.011**	0.075	✓	✓
	Mature size	0.353	0.834	0.351	0.834		
	Carcass lean weight	0.058	0.876	0.058	0.876	✓	
	Carcass fat weight	0.132	0.505	0.127	0.503		
	Index	0.233	0.830	0.233	0.829		

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 14 Significant relationships between E-RP set of explanatory variables (continuous variables in italics) with two response variables (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6.

		R-EMC				R-LmWt			
		2013 *P*-value[c]	2014 *P*-value[c]	In Initial models, *P*<0.1	In Reduced models[a]	2013 *P*-value[c]	2014 *P*-value[c]	In Initial models, *P*<0.1	In Reduced models[a]
Recorded performance (E-RP)	Age	0.805	**0.036**	✓	✓	0.176	0.092	✓	✓
	Dam age	0.071	0.727	✓	✓	0.086	0.877	✓	✓
	First pre-mating BCS	0.096	0.066	✓		0.310	0.073	✓	✓
	PY pre-mating BCS	0.072	0.251	✓	✓	0.519	0.134		
	PY mid-pregnancy BCS	**0.025**	0.674	✓		0.323	0.630		
	PY weaning BCS	**0.002**	0.162	✓	✓	**0.000**	0.103	✓	✓
	Current pre-mating BCS	**0.000**	0.204	✓		**0.002**	0.230	✓	
	PY lambs born dead or alive	**0.018**	0.177	✓		**0.004**	**0.022**	✓	
	PY lambs born alive	**0.003**	0.180	✓		**0.001**	**0.007**	✓	
	PY lambs at 8 weeks	**0.014**	0.234	✓		**0.010**	**0.005**	✓	
	PY lambs at weaning	**0.048**	0.358	✓		**0.027**	**0.025**	✓	
	Ewe birth date	0.540	0.830			0.849	0.764		
	Ewe birth liveweight	**0.005**	0.606	✓	✓	**0.011**	0.994	✓	✓
	Ewe wean liveweight	**0.042**	0.215	✓	✓	**0.005**	0.128	✓	✓
	First pre-mating liveweight	**0.036**	0.989	✓		0.280	**0.011**	✓	
	PY pre-mating liveweight	0.092	0.553	✓	✓	**0.010**	**0.029**	✓	✓
	PY early pregnancy liveweight	0.087	0.477	✓		**0.003**	0.149	✓	
	PY mid-pregnancy liveweight	0.067	0.483	✓		**0.006**	**0.009**	✓	
	PY weaning liveweight	**0.001**	0.297	✓	✓	**0.000**	**0.000**	✓	✓
	Current pre-mating liveweight	**0.000**	**0.034**	✓		**0.000**	**0.000**	✓	
	PY liveweight change pre-mating to early pregnancy	0.778	0.908			0.827	0.091	✓	✓
	PY liveweight change pre-mating to mid-pregnancy	0.872	0.893			0.797	0.360		
	PY liveweight change pre-mating to weaning	0.078	0.038	✓		**0.004**	**0.002**	✓	
	PY percentage liveweight change pre-mating to early pregnancy	0.768	0.878			0.699	0.110		
	PY percentage liveweight change pre-mating to mid-pregnancy	0.910	0.986			0.636	0.400		
	PY percentage liveweight change pre-mating to weaning	0.125	**0.031**	✓	✓	**0.009**	**0.008**	✓	✓
	PY liveweight of lambs at birth	**0.001**	0.522	✓	✓	**0.008**	0.571	✓	✓
	PY liveweight of lambs at 8 weeks	**0.004**	0.904	✓		**0.012**	0.239	✓	
	PY liveweight of lambs at weaning	**0.012**	0.934	✓		**0.040**	0.347	✓	

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 15 Significant relationships between E-RP set of explanatory variables (continuous variables in italics) with R-LmNo response variable (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6.

		R-LmNo					
		2013 *P*-value[d]	2014 *P*-value[d]	2013 *P*-value GLM	2014 *P*-value GLM	In Initial models, *P*<0.1	In Reduced models[a]
Recorded performance (E-RP)	Age	0.568	0.093	0.145[b]	0.128[b]	✓	✓
	Dam age	0.295	0.399	**0.030**	0.552		
	First pre-mating BCS	0.521	0.346	0.190[b]	**0.009[b]**		
	PY pre-mating BCS	0.436	0.073	0.335[b]	0.059[b]	✓	✓
	PY mid-pregnancy BCS	0.624	0.696	0.245	0.412		
	PY weaning BCS	**0.000**	0.258	**0.002[b]**	**0.017[b]**	✓	✓
	Current pre-mating BCS	**0.009**	0.109	**0.000[b]**	0.450[b]	✓	
	PY lambs born dead or alive	**0.001**	**0.041**	**0.000[b]**	**0.009[b]**	✓	
	PY lambs born alive	**0.001**	**0.024**	**0.000[b]**	**0.003[b]**	✓	
	PY lambs at 8 weeks	**0.002**	**0.012**	**0.002[b]**	**0.001[b]**	✓	
	PY lambs at weaning	0.055	**0.048**	**0.012[b]**	**0.007[b]**	✓	
	Ewe birth date	0.638	0.985	0.866	0.964		
	Ewe birth liveweight	0.060	0.884	**0.007**	0.946	✓	✓
	Ewe wean liveweight	**0.026**	0.421	**0.008**	0.169	✓	✓
	First pre-mating liveweight	0.194	**0.005**	0.366	**0.019**	✓	
	PY pre-mating liveweight	**0.004**	**0.001**	**0.007**	0.056	✓	✓
	PY early pregnancy liveweight	**0.004**	**0.031**	**0.002**	0.316	✓	
	PY mid-pregnancy liveweight	**0.001**	**0.001**	**0.008**	**0.026**	✓	
	PY weaning liveweight	**0.000**	**0.000**	**0.000**	**0.000**	✓	✓
	Current pre-mating liveweight	**0.000**	**0.000**	**0.000**	**0.000**	✓	
	PY liveweight change pre-mating to early pregnancy	0.634	**0.017**	0.788	0.063	✓	
	PY liveweight change pre-mating to mid-pregnancy	0.915	0.672	0.965	0.493		
	PY liveweight change pre-mating to weaning	**0.004**	**0.002**	**0.001**	**0.001**	✓	
	PY percentage liveweight change pre-mating to early pregnancy	0.869	**0.019**	0.657	0.078	✓	✓
	PY percentage liveweight change pre-mating to mid-pregnancy	0.586	0.671	0.814	0.560		
	PY percentage liveweight change pre-mating to weaning	**0.010**	**0.002**	**0.003**	**0.003**	✓	✓
	PY liveweight of lambs at birth	**0.009**	0.609	**0.003**	0.847	✓	✓
	PY liveweight of lambs at 8 weeks	0.075	0.473	**0.015**	0.302	✓	
	PY liveweight of lambs at weaning	0.228	0.482	0.056	0.497		

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 16 Significant relationships between E-RP set of explanatory variables (continuous variables in italics) with R-ES response variable (statistical significance, *P<0.5, shown in bold). Also shown are explanatory variables included in Initial (P<0.1) and Reduced models (✓). Extension for Table 9.6.

		R-ES					
		2013 *P*-value[d]	**2014 *P*-value[d]**	**2013 *P*-value GLM**	**2014 *P*-value GLM**	**In Initial models, *P*<0.1**	**In Reduced models[a]**
Recorded performance (E-RP)	Age	0.264	**0.015**	0.226[b]	0.098[b]	✓	✓
	Dam age	0.240	0.166	0.178	0.117		
	First pre-mating BCS	0.203	0.358	0.220	0.134		
	PY pre-mating BCS	0.113	0.127	0.244	0.104		
	PY mid-pregnancy BCS	**0.005**	0.206	**0.011[b]**	0.217[b]	✓	✓
	PY weaning BCS	0.389	0.285	0.414	0.440		
	Current pre-mating BCS	**0.002**	0.621	**0.002[b]**	0.436[b]	✓	✓
	PY lambs born dead or alive	0.316	0.760	0.348	0.887		
	PY lambs born alive	0.153	1.000	0.179	0.977		
	PY lambs at 8 weeks	0.279	1.000	0.290	0.989		
	PY lambs at weaning	0.192	1.000	0.198	0.990		
	Ewe birth date	0.435	0.378	0.427	0.387		
	Ewe birth liveweight	**0.033**	0.582	**0.029**	0.579	✓	✓
	Ewe wean liveweight	0.829	0.123	0.829	0.118		
	First pre-mating liveweight	0.351	0.330	0.348	0.328		
	PY pre-mating liveweight	0.794	0.310	0.793	0.315		
	PY early pregnancy liveweight	0.745	0.761	0.744	0.761		
	PY mid-pregnancy liveweight	0.202	0.155	0.194	0.159		
	PY weaning liveweight	0.649	0.180	0.647	0.181		
	Current pre-mating liveweight	**0.046**	0.336	**0.043**	0.337	✓	✓
	PY liveweight change pre-mating to early pregnancy	0.979	**0.000**	0.979	0.214	✓	
	PY liveweight change pre-mating to mid-pregnancy	0.229	0.429	0.231	0.427		
	PY liveweight change pre-mating to weaning	0.751	0.542	0.750	0.543		
	PY percentage liveweight change pre-mating to early pregnancy	0.886	**0.000**	0.885	0.159	✓	✓
	PY percentage liveweight change pre-mating to mid-pregnancy	0.375	0.486	0.372	0.487		
	PY percentage liveweight change pre-mating to weaning	0.853	0.760	0.852	0.761		
	PY liveweight of lambs at birth	**0.024**	0.641	**0.026**	0.640	✓	✓
	PY liveweight of lambs at 8 weeks	0.077	0.975	0.071	0.975	✓	
	PY liveweight of lambs at weaning	0.061	0.937	0.056	0.936	✓	

[a]Further selection for Reduced models involved considering and removing associated variables; [b]factors where levels have been grouped as a result of sparse data;
[c]*P*-values from Pearson's correlation coefficient and ANOVA, Linear Modelling carried out on these but same *P*-values as those shown;
[d]*P*-values from Chi-squared test and ANOVA.
E-: explanatory variables; EBV: Estimated Breeding Values; BCS: Body Condition Score; PY: previous year (year prior to stockdraw); GLM: Generalized Linear Models; R-: response variable; EMC: Ewe Marginal Contribution; LmWt: Total liveweight of lambs weaned; LmNo: Total number of lambs weaned; ES: Ewe survival to weaning.

Appendix 17 Receive Operating Characteristic (ROC) curves

Receiver Operator Characteristic (ROC) curves were all produced for each model for the binomial response measures (R-LmNo and R-ES). These curves show, for all possible cut-off points, the true positive rate (sensitivity) when plotted against the false positive rate (1-specificity), and connecting the points with a line (Steensels et al., 2016; Watson and Petrie, 2010). An example ROC curve is shown in Figure a1. Figure a2 shows the E-all model fits for R-LmNo, and Figure a3 for R-ES. Even through the E-all models accounted for the greatest variation accounted for the ROC curves further demonstrate the lack of model fit.

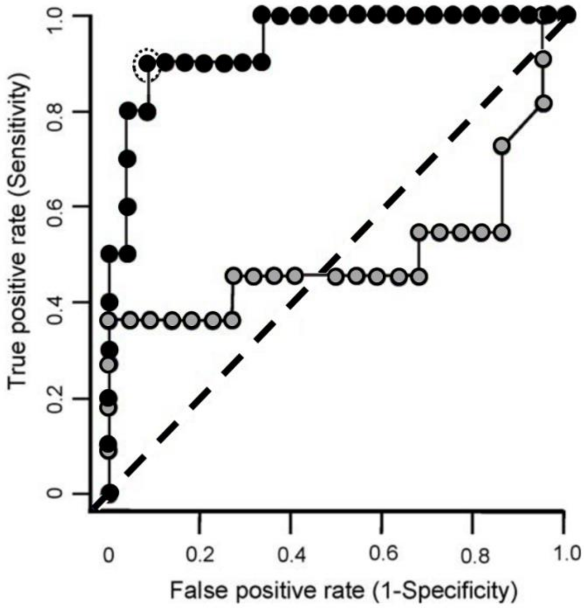


Figure a1 Example Receive Operating Characteristic (ROC) curves, where a poorly discriminating test (grey points) and a good discriminating test (black points) are shown. The dotted circle shows the optimum sensitivity and specificity point when the absolute difference between them is minimised (graph and description adapted from Watson and Petrie, 2010).

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Appendix 17 Continued

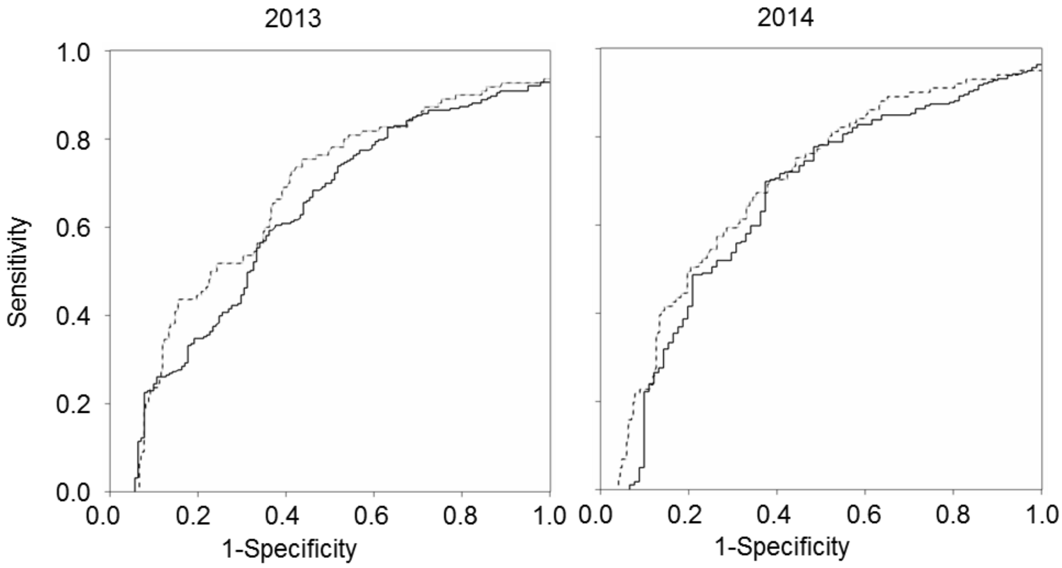

Figure a2 Receiver Operator Characteristic (ROC) curve when E-all Reduced model variables fitted for R-LmNo for two years for correctly identifying singles (solid line) and twins (dashed line), where sensitivity is the true positive rate and 1-specificity is the false positive rate.

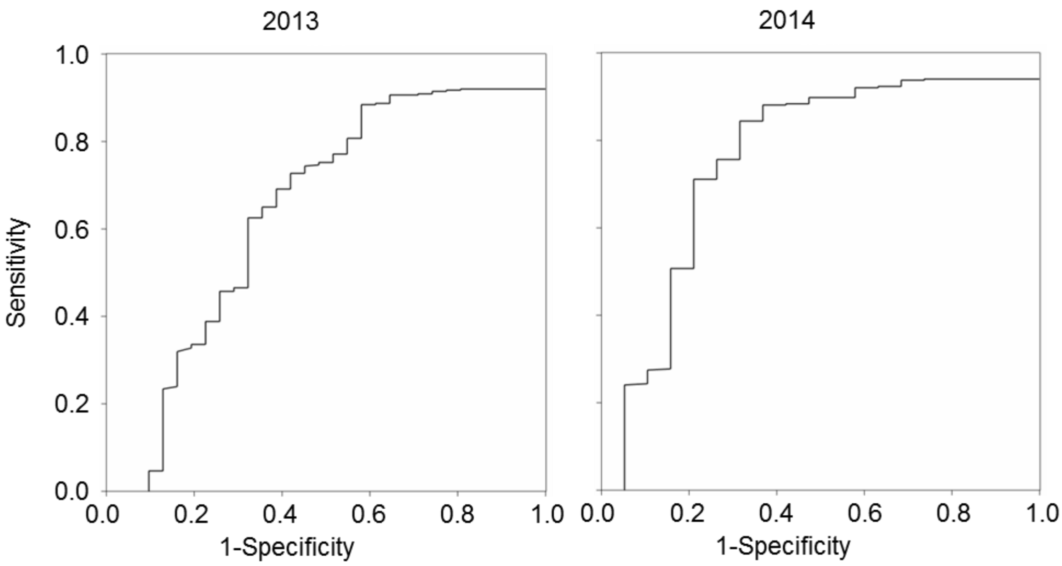

Figure a3 Receiver operator characteristic (ROC) curve when E-all Reduced model variables fitted for R-ES for two years, where sensitivity is the true positive rate and 1-specificity is the false positive rate.