Agricultural Systems 191 (2021) 103155

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

A comparison of farm labour, profitability, and carbon footprint of different management strategies in Northern European grassland sheep systems

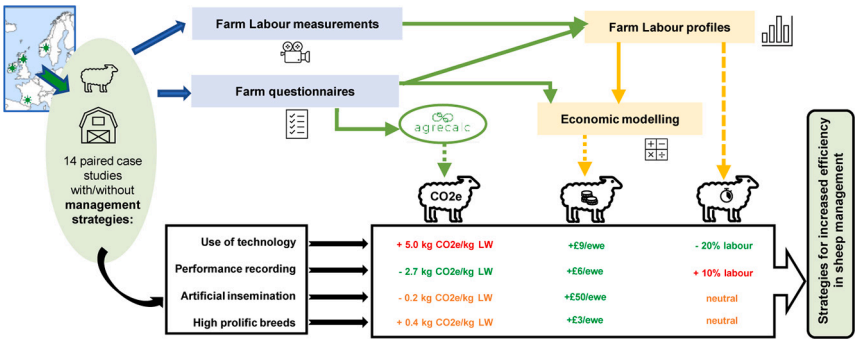
C. Morgan-Davies [a,*], J. Kyle [a], I.A. Boman [c], H. Wishart [a], A. McLaren [a], S. Fair [d], P. Creighton [b]

[a] Scotland's Rural College (SRUC), South & West Faculty, Hill & Mountain Research Centre, Kirkton farm, Crianlarich, FK20 8RU Scotland, UK
[b] Teagasc, Athenry, Co. Galway, Ireland
[c] NSG, P.O. Box 104, N-1431 Aas, Norway
[d] Department of Biological Sciences, Biomaterials Research Cluster, Bernal Institute, Faculty of Science and Engineering, University of Limerick, Ireland

HIGHLIGHTS

- European grassland sheep production must be carbon and resource efficient to meet environmental, rural and societal needs.
- Labour, carbon and economic data were collected for farm case studies modelling of different sheep management strategies.
- Sheep performance recording and artificial insemination are strategies beneficial to farm carbon efficiency and economics.
- Prolific breeds increased economics with no extra labour or carbon, and technology reduced labour and increased economics.
- Ewe prolificacy, breeding management and/or technology adoption can improve carbon and farm labour efficiency.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Dr Guillaume Martin

Keywords:
Sheep management
Efficiency
Precision livestock farming
Artificial insemination

ABSTRACT

CONTEXT: Sheep production systems need to become more carbon efficient to meet growing public demands on climate change. Some of the ways postulated to achieve this is to implement new technologies and management strategies such as precision livestock farming (PLF), increased use of high genetic merit animals with estimated breeding values through artificial insemination (AI) where practical, and the use of prolific breeds. However, the carbon footprint impact of these strategies has not to-date been quantified. Additionally, international experience indicates that uptake of such strategies is low due, in part, to the perception of increased workload especially during busy periods of the sheep year.

OBJECTIVES: This trans-European study investigates the impact of differing sheep management strategies on farm labour input, carbon footprint as well as the on-farm profitability, to address these concerns.

* Corresponding author.
E-mail addresses: claire.morgan-davies@sruc.ac.uk (C. Morgan-Davies), jenna.kyle@sruc.ac.uk (J. Kyle), iab@nsg.no (I.A. Boman), harriet.wishart@sruc.ac.uk (H. Wishart), ann.mclaren@sruc.ac.uk (A. McLaren), Sean.fair@ul.ie (S. Fair), Philip.creighton@teagasc.ie (P. Creighton).

https://doi.org/10.1016/j.agsy.2021.103155
Received 13 January 2021; Received in revised form 14 April 2021; Accepted 16 April 2021
Available online 24 April 2021

METHODS: Four management strategies were considered i) use of technology (PLF), ii) use of performance recording for higher genetic merit, iii) use of AI for higher genetic merit and iv) and use of prolific breeds, in 14 case study flocks located in areas typical of Northern European grassland sheep production systems across Scotland, France, Ireland and Norway. For each management strategy, paired case study flocks were identified. Labour was assessed at key handling events using video recording, farmers' diaries, and questionnaires, which were later quantified and classed into key tasks to create normalised labour profiles for each case study flock. The carbon footprint was quantified using a carbon calculator tool (www.agrecalc.com). Financial net margins were calculated.

RESULTS AND CONCLUSIONS: Results highlighted that introducing PLF technology on extensive farms reduced labour by 20% and increased economic margins by £9/ewe but with a concurrent increase in carbon emissions (kg CO2e/ kg of meat produced). Using performance recording on sheep farms for achieving higher genetic merit increased economic margins by £6/ewe, and reduced carbon emissions (kg CO2e) per kg of meat produced but resulted in 10% extra labour. AI on farms increased economic margins by £50/ewe, did not incur extra labour and increased carbon efficiency in terms of kg CO2e/kg meat produced. Finally, high prolific breeds did not significantly increase labour input at key handling events and resulted by higher economic margins (+£3/ewe), without a change in terms of kg CO2e/kg meat produced.

SIGNIFICANCE: These novel case studies clearly illustrate it is possible to increase carbon and labour efficiency by adopting technology, changing breeding management or ewe breed on sheep farms.

1. Introduction

There are approximately 86 million sheep on 850,000 sheep farms, in the European Union (EU), representing 14% of livestock farms (Eurostat, 2019). Many of these farms are found in challenging climatic and topographical environments, often referred to as 'Less Favoured Areas' (LFAs), which are unsuitable for any alternative type of agriculture (LFA - Article 2 of EU Council Directive No. 75/268/EEC). Additionally, sheep farms in these areas are very much part of the landscape, traditions, and cultural heritage, and can be an important source of employment (Morgan-Davies et al., 2015). The high-quality traditional products they yield are broadly recognised as the result of developing a sustainable and multifunctional form of agriculture that contributes to preserving the environment and social cohesion in rural areas (Rossi, 2017).

However, despite its predominant role, the sheep population in Europe has been in steep decline since the 2000s (Eurostat, 2019) and the industry faces many challenges. Along with the increasing focus on the impact that livestock has on the environment in terms of GHG emissions, the industry must also find solutions to a) increase production efficiency and profitability and b) speed up the rate of technology development and adoption in order to compete successfully in the future (Montossi et al., 2013). Labour and production efficiency are therefore crucial areas for consideration. Although sheep farms employ around 1.5 million people on a regular basis, representing 7% of the 22 million people working regularly on EU farms, the level of income per annual labour unit is lower than for other types of livestock farms (Rossi, 2017). Livestock farming is also becoming less attractive to the younger generation or new entrants (Madelrieux and Dedieu, 2008). As such, the lack of skilled labour available to manage larger flocks is becoming a common theme in many areas.

The EU plans a long-term strategy to reach the goal of carbon neutrality by 2050 (EU Commission, 2019). The successful management of agricultural Greenhouse Gas (GHG) emissions presents a substantial challenge to the scientific, commercial and policy sectors (Jones et al., 2014a). Changes in management strategies and production intensity are often stated as potential methods to reduce the GHG emissions from small ruminants to mitigate climate change (Kumar et al., 2014; Marino et al., 2016). The ability to identify sheep production systems and strategies with the lowest carbon footprint, to offset any future policy changes whilst maintaining farm efficiency and profitability, is essential. Amongst these strategies, research has shown that the profitability and efficiency of sheep production systems can be increased through the use of prolific breeds (Swan, 2009; Bohan et al., 2018), genetic selection indices (Lambe et al., 2014; Gibbons et al., 2019), and Precision Livestock Farming (PLF) tools (Morgan-Davies et al., 2018). However, the impact that these strategies can have on a farm's carbon footprint are, to date, relatively unknown.

One of the major impediments to the implementation of these strategies on-farm is the lack of suitably skilled labour and its optimisation. The quantification of workloads on livestock farms has been studied previously and various methods have been proposed (Dedieu et al., 2000; Dieguez et al., 2010), but few have considered those associated with different sheep production management systems. There is therefore an opportunity for on-farm labour requirements to be rationalised and for farm performance to be improved by quantifying the implementation of new management strategies. Further, some impacts of climate change could be mitigated by applying the scientific knowledge and technological capabilities included in these management strategies. Such quantification would be invaluable for the sheep production industry and wider society.

This paper presents results from a transnational project investigating the impacts on farm labour input, farm profitability and carbon footprint of four differing management strategies: i) use of technology/PLF tools, ii) use of performance recording for higher genetic merit, iii) use of Artificial Insemination (AI) for higher genetic merit and iv) use of prolific breeds. Case studies in Scotland, Ireland, France and Norway were carried out, as sheep farming systems in these areas are typical of Northern European grassland sheep production systems, where the majority of the utilised agricultural areas are classed as grassland and used for livestock grazing (80%, 78%, 44% and 80% for Scotland, Ireland, Norway and French Basque region, respectively; Eurostat, 2019; Guicheney and Ballan, 2015).

2. Material & methods

2.1. Case studies and focus flocks

A large proportion of sheep production systems in Europe is grassland-based, often found at the periphery or in mountainous areas (Eurostat, 2019). In Northern Europe in particular, sheep systems are located on permanent grasslands of various quality, with similar climatic (temperate and oceanic) or geographical (mountainous) conditions. They rely on seasonal and skilled labour and are embedded in the social and cultural fabric of these often very rural or remote areas. In this context, our case studies were conducted in three northern European areas (West of Ireland, Scotland and Norway) and one western mountain area (Eastern Pyrenees – French Basque region). Whilst the Scottish, Irish and Norwegian sheep flocks were associated with meat production, the French Pyrenees case study focussed on milk production for PDO cheese making. All case study flocks were grassland-based, with the Norwegian and French flocks relying on seasonal summer grazing in the

mountains.

The four differing sheep management strategies were associated with 1) the use (or not) of PLF; 2) the use (or not) of performance recording (PR); 3) the use (or not) of AI; and 4) the use (or not) of prolific breeds (PB). For each strategy, case studies were conducted in different countries (Table 1) with paired case study flocks.

The case study flocks were on commercial farms. They were selected through the authors' professional networks, using the following criteria for selection: i) management strategies in place on the farm, ii) similar geographical locations for the paired farms, iii) similar husbandry conditions (e.g., flock size, buildings and pasture use, breed, etc.), and iv) willingness of the farmer to engage in the project for the duration. Using a paired flocks or sites approach has been used in other studies (Pollock et al., 2013) and is useful to gauge the impact of management strategies at farm level.

The characteristics of the case study flocks are presented in Table 1. The Scottish flocks were situated in the West of Scotland, in the southern Highlands. They were extensive (600 to 1470 ha) with a low stocking density (between 0.5 ewe/ha and 1 ewe/ha) and grazed outside throughout the year. The Irish flocks were situated in Western Ireland and were semi-intensive (38 to 45 ha) with a higher stocking density (between 7.1 and 12.0 ewe/ha). Animals grazed outside for part of the year and were only housed for 3 months around lambing time (January to March). The Norwegian flocks, situated in the North West of Oslo, were a mixture of extensive and semi-intensive (130 to 520 ha) with a lower stocking density (between 0.3 and 1.5 ewe/ha). However, animals were housed during winter and were sent away for 3 months in the mountains for summer grazing (transhumance) on large areas (7000 ha). The French flocks were situated in the south of France, in the Basque region. Although the French flocks were milking flocks, they were a mixture of intensive and semi-extensive. The farm areas varied between 26 and 31 ha, with some access to summer grazing (up to 100 ha). The stocking density was around 10 ewes/ha (9.6 to 10.3 ewe/ha). Animals were housed during the winter and sent away in the mountains for summer grazing (transhumance).

In Scotland, flocks using PLF had access to an auto-drafter weigh crate with an electronic identification (EID) reader, which was used for flock management and animal drafting at the major handling events. The non-PLF flocks used manual weigh crates at handling events and did not utilise any EID information. Ewes in the PLF flocks were retained based on their individual performance, whilst ewes in the non-PLF were replaced after 4 lambings (at 5.5 years old, a traditional practice in Scottish mountain type flocks). PR flocks in Scotland used rams with Estimated Breeding Values (EBV) in single-sire mating groups, recorded lamb pedigrees at lambing, and collected live weights and ultrasound back-fat and muscle information when required during the year. The non-performance recording (Non-PR) flocks used multiple-sire mating groups, and did not individually record lamb information at lambing, nor did they perform ultrasound scanning to assess back-fat and muscle information. They did, however, collect ewe weights at key handling points. In France, the flocks using AI were part of a large-scale breeding scheme using fresh ram semen (Centre Départemental de l'Elevage Ovin – CDEO), with technicians coming onto the farms to perform cervical insemination to a synchronised oestrus. These flocks were also milk recording. The non-AI flocks used natural mating. For the prolific breeds, the Norwegian and Irish flocks were either using High Prolific breeds or Medium Prolific breeds. The degree of prolificacy also varied by country (the Norwegian flocks had higher prolificacy than the Irish). Both Norwegian flocks in which breed prolificacy was compared used shot-in-the-dark AI with frozen-thawed semen, performed by the farmers themselves to a natural oestrus. This is a routine practice in Norway, with acceptable pregnancy rates due to the breed of the ewes used in Norway compared to elsewhere (Fair et al., 2019). Irish flocks used natural mating for high and medium prolific breeds.

2.2. Carbon efficiency measurement

The management strategies have been evaluated for their carbon footprint using a carbon calculator tool developed by the SAC Consulting division of Scotland's Rural College (www.agrecalc.com).

There are various models for measuring carbon footprint, which range in complexity and emissions considered (Rotz, 2018). They often include constant emission factors, variable process-related emission factors (Rotz et al., 2014), empirical or statistical models, mechanistic process simulations, and life cycle assessment (Rotz and Thoma, 2017). Life cycle assessments need a defined reporting methodology and may require a higher level of input data compared to GHG calculators (Whittaker et al., 2013). Moreover, to fully characterise farm emissions, models representing the various emission sources must be integrated to capture the combined effects and interactions of all-important components. One such method is the 'agricultural resource efficiency calculator' (AgRECalc©) which shows the quantity of GHG emissions produced from routine farm activities, highlighting areas where changes can be made that, when implemented, could reduce emissions (Sykes et al., 2017). This calculator was developed using Intergovernmental Panel on Climate Change (IPCC, 2006) Tier II calculations and Tier I

Table 1
Case study flock characteristics across 4 northern European countries. The management strategies were: with or without the use of: Precision Livestock Farming (PLF; Scotland), performance recording (PR; Scotland), Artificial Insemination (AI; France) and prolific (Medium or High) ewe breeds (Ireland and Norway).

Case study flock	Country	Number of sheep	Main sheep breed[$]	Type of farm	Area (ha)	Weaning rate[*] (%)/Milk yield (l/ewe/year)	Number of. permanent/casual labour (persons)
PLF1	Scotland	620	SBF	mountain	600	90	1/1
PLF2	Scotland	450	SBF	mountain	630	78	3/1
Non-PLF	Scotland	450	SBF	mountain	630	83	3/1
PR1	Scotland	1450	SBF	mountain	1470	85	1/3
PR2	Scotland	200	SBF	mountain	630	107	3/1
Non-PR	Scotland	360	SBF	mountain	670	47	3/1
AI1	France	630	MTN	upland	64	308	4/1
AI2	France	250	MTR	mountain	26	210	2.5/0
Non-AI1	France	290	MTR	mountain	28	280	2/0
Non-AI2	France	300	MTN	mountain	31	170	1/0
HP-IR	Ireland	320	BxS	lowland	45	170	1/5
MP-IR	Ireland	455	Sx	lowland	38	150	2/3
HP -NO	Norway	200	NW	mountain	7130	220	1/0
MP-NO	Norway	165	Sp	mountain	7520	190	2/1

PLF = Precision Livestock Farming; PR = Performance Recording; HP-IR = High Prolific Ireland; MP – IR = Medium Prolific Ireland; HP – NO = High Prolific Norway; MP – NO = Medium Prolific Norway; AI = Artificial Insemination.

[$] SBF=Scottish Blackface; BxS = Belclare x Suffolk; Sx = Suffolk cross; NW = Norwegian White; Sp = Spaelsau; MTN = Manech Tête Noire; MTR = Manech Tête Rousse.

[*] Weaning rate for the French flocks is not shown as the milking flocks do not focus on or record lamb production indicators, but milk yield is presented instead.

methodology, and emission factors from Kool et al. (2012).

AgRECalc© determines on-farm emissions per unit of output (SAC, 2019), which is one of the most meaningful comparisons when considering food production. AgRECalc© is industry focused and well suited to comparisons of farm management changes such as those investigated. Input data for AgRECalc© calculations were collected from farmer questionnaires for each flock under study, covering the breeding year between November 2016 to November 2017. The questionnaire was translated into French for the case studies in France. For the Norwegian farmers, the questionnaire was kept in English, as they understood the language.

Data collected covered:

- Land and crops, grass and forage (area, productivity, fertiliser applied)
- Livestock numbers, weights and fate (sold, dead)
- Energy used, renewable energy produced, and waste produced.

2.3. Labour measurement

2.3.1. Farm labour questionnaire

To explore the labour input for each case study flock, a questionnaire covering the whole farm activities was devised and adapted to each country. Two main areas were covered: 1) labour profile for the farm for the whole year, and 2) farm characteristics.

Once they had been selected, farmers were interviewed by the authors at the start of the project to explore their labour input. The farm labour questionnaire was not applied at the same time as the AgRECalc© questionnaire.

The labour profile listed i) each key sheep year activity or event and covered seasonal tasks (namely mating, winter feeding, mid-pregnancy scanning, lambing, marking, shearing, weaning, post-weaning, ewe selection, lamb sales) rather than daily tasks; the only exception being milking, ii) the number of people required for these activities, and iii) the type of tasks undertaken during these key activities (e.g. weighing, sorting animals, feeding, recording, gathering, etc.). The key events varied according to country and the management strategy (Table 2). Further description of the key activities is presented in Table 3.

The farm characteristics covered the farm itself (area of the farm, the number and type of animals and the facilities), the labour available (number of permanent, casual, family labour at different times of the year), and the animals (breeds, numbers and performance data).

2.3.2. Sample days

Once the questionnaire had been completed, sample days for recording were chosen, in agreement with the farmer. The main criteria for choosing the sample days was a typical key handling day or event. The days for labour recording at each key event was decided by the farmer. For example, at lambing, between 2 and 5 sample days were chosen, to cover the start, middle and end of lambing, to represent the variation in the number of lambs being born during the whole period (Table 4).

Small video action cameras (GoPro HERO™, GoPro, Inc. USA) were used to record labour on these sample days (either attached to the farmer or attached to a vantage point in the sheep shed). All the farmer's tasks were recorded, even if not related to sheep management. Sample day paper diaries were also used as back up. A social science ethics protocol covering General Data Protection Regulation (GDPR) issues, image property and privacy rights was established, with consent forms given to each participating farmer prior to the sample days recording.

Recordings were collected throughout the sheep year, covering the 2017/2018 period. In the case of the French case studies, recordings were collected over the 2018/2019 sheep year, due to their sheep year starting in June with AI. When a key handling day was missed, another day (covering the same handling event) during the same year or the following year, was chosen. Any missing data for these sample days was estimated and scaled using SRUC Hill & Mountain Research Centre existing labour data (Morgan-Davies et al., 2018).

2.3.3. Data classification

Video footage was analysed, and the labour categorised into tasks and sub-tasks following methods presented by Kirwan (2009) and Morgan-Davies and Robertson (2016). This was to determine total quantities and proportion of time spent on different tasks throughout each key event. The number of workers for each task or sub task was taken into account for labour quantification and scaled to 1 worker. Footage was classified into 12 main tasks (AI, driving, ewe tasks, feeding/watering, lamb tasks, non-sheep tasks, opening/shutting gates, preparation, shearing, shed tasks, walking, others) and within these task groups were sub-tasks (Supplementary Table 1). Total time spent was quantified by recording the start and finish time of each task and/or sub-task to obtain its duration. Each duration was then subsequently combined by adding them together by task. Activities involving ewes and lambs at lambing were categorised into the 'ewe' task group.

2.3.4. Labour profile

Once tasks were identified and quantified, they were modelled to create full labour profiles at key events over the year for each management strategy (Morgan-Davies et al., 2018). Information available from the farm labour questionnaire and the timings gathered on sample day videos were combined and then scaled up, to create an individual labour profile for each case study flock. Labour profiles were scaled to represent the man-hours for a flock of 100 ewes over one year, thus allowing meaningful comparisons to be made between flocks.

The labour profiles at key handling events were completed for all case study flocks, except at lambing, when recording issues arose for the video footages of PLF1, MP-NO, non-AI2 and AI2. Consequently, those four case study flocks did not collect actual number of hours spent at lambing. Comparisons of these lambing events were therefore not possible and is not included in the results.

2.4. Economic impacts

To evaluate the economic impacts of the different management strategies, financial margins for each case study flock were calculated. A combination of data collected from the AgRECalc© questionnaire and the SAC farm management handbook 2016–17 (SAC Consulting, 2017) was used to create net margins for each management strategy.

Data included variable costs (feeds quantity, fertilisers, market costs etc) and outputs (number of animals sold, wool produced etc). Support payments and fixed costs such as building and electricity were not included in the calculations, to ensure a fair comparison and avoid bias towards some systems or countries. Labour was the only fixed cost included. The labour costs were calculated from each labour profile and related to the duration of the tasks in that profile. A standardised cost/h of £12/h was used (SAC Consulting, 2017). All market prices (including lamb prices) and costs were kept in £GBP to keep the case studies comparable. They were taken from the SAC farm management handbook (SAC Consulting, 2017) and covered the same time-period. As the farm management handbook distinguishes animal prices and costs per sub-type of farming system, that distinction was applied to reflect the different management conditions under study in each country. The 'extensive hill ewe' values were thus used for the PLF and PR Scottish case study flocks, whilst the 'crossbred ewe' values were applied to the French, Irish and Norwegian case study flocks.

2.5. Analysis

A sensitivity analysis approach was used on the results from the economic impact. The following variables were explored: i) lamb, ewe and milk price, ii) labour cost, iii) weaning rate and iv) feed, AI and ram costs.

Table 2
Key handling events and associated tasks for all four management strategies, and the associated labour (man-hours) scaled up to a 100-ewe flock. Precision Livestock Farming (PLF; Scotland), performance recording (PR; Scotland), Artificial Insemination (AI; France) and prolific (Medium or High) ewe breeds (Ireland and Norway).

Handling events and tasks	Non-PLF	PLF1	PLF2	Non-PR	PR1	PR2	Non-AI1	AI1	Non-AI2	AI2	MP-IR	HP-IR	MP-NO	HP-NO
Mating														
Gather	1.8	0.3	1.8	1.8	2.1	1.8		0.1			0.1	0.1		
Manually read tag, weigh, condition score & sort into mating groups	1.8				1.1		0.8	0.8	0.8					
Automatically read EID tag, weigh, condition score ewe & sort into mating groups		0.7	0.8	0.8		0.8					0.6	0.6		
Footbath							0.3				0.3	0.3		
Dose ewe	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2		0.2	0.2	0.2	0.2	0.2
Condition score ewe								0.1					0.1	
AI ewes								1.1		1.2				
Mating of ewes with ram on leash													0.1	0.8
TOTAL (man-hours)	**3.8**	**1.2**	**2.7**	**2.7**	**3.4**	**2.7**	**1.3**	**2.3**	**0.8**	**1.4**	**1.2**	**1.2**	**0.4**	**1.0**
Scanning/pre-lambing														
Gather	1.4	0.3	1.4	1.4	2.5	1.4								
Ultrasound scanning	1.4	0.5	1.4	1.4	0.5	1.4	0.6	0.6		0.6	1.4	1.4	1.1	0.6
Manually sort into feeding and pregnancy groups	0.1	0.1			0.1		0.1	0.1		0.1		0.1	0.1	0.1
Manually read ID tag, weigh and condition score	1.9						0.1	0.1	0.1	0.1				
Automatically read EID, weigh, condition score & sort into pregnancy groups			0.8	0.8		0.8					0.8			
Vaccinate/treat ewes	0.4	0.1	0.4	0.4	0.4	0.4	0.2	0.2		0.2	0.4	0.4		
Footbath							0.3				0.3	0.3		
Neckband ewes						1.5								
TOTAL (man-hours)	**5.3**	**1.0**	**4.1**	**4.1**	**3.4**	**5.5**	**1.2**	**0.9**	**0.1**	**0.9**	**2.9**	**2.3**	**1.1**	**0.7**
Lambing (TOTAL man-hours)	**63.6**	**n/av**	**63.6**	**63.2**	**41.6**	**63.6**	**19.4**	**23.0**	**n/av**	**n/av**	**45.6**	**67.3**	**n/av**	**129.0**
Marking														
Gather	3.0	0.1	3.0	3.0	0.1	3.0					0.1	0.1	12.6	12.6
Worm, ear-notch, castrate & vaccinate lambs	8.8	0.6	8.8	5.0	0.8	8.4	0.1	0.3	0.1	0.4				
Automatically read EID tag and weigh ewes			0.8	0.8		0.8					0.3			
Manually read ID tag and weigh animals	6.1							0.6						
Condition score ewe									0.1		0.3		0.1	0.1
Automatically read EID tag and weigh lambs		0.3	2.0	1.1		1.9					0.5	0.5	1.5	1.8
Dose/treat/vaccinate lambs		0.5									0.5	0.6	0.6	0.7
Footbath					0.6						0.8	0.9		
Dose ewes	0.2		0.2	0.2	0.1	0.2					0.2			
Bell on ewes													0.8	0.8
FEC lambs									0.1		0.7			
TOTAL (man-hours)	**18.1**	**1.4**	**14.8**	**10.0**	**1.6**	**14.2**	**0.1**	**0.9**	**0.2**	**0.4**	**3.5**	**2.1**	**15.6**	**16.0**
Shearing														
Gather	3.0	0.3	3.0	3.0	2.9	3.0		0.1	0.1	0.4	0.1	0.1		
Automatically read EID, weigh and sort lambs into worming groups			0.7	0.4	0.2	0.7					0.3			
Manually read ID, weigh and sort into worming groups	4.5													
Worm lamb based on weight assessment				0.2		0.4								
Dose/treat lambs based on FEC	0.7	0.1			0.1					0.04				
FEC lambs	0.4	0.4			0.4				0.1		0.7			
Footbath		1.2			0.6		0.3	0.4	0.4		0.8	0.9		
Dose ewes									0.2	0.2				
Shear ewes	7.6	3.2	7.6	7.6	1.7	7.6	1.6	1.5	1.6	1.8	7.6	7.6	4.1	4.1
TOTAL (man-hours)	**16.2**	**5.3**	**11.3**	**11.2**	**6.0**	**11.6**	**2.0**	**2.0**	**2.3**	**2.4**	**9.6**	**8.6**	**4.1**	**4.1**
Weaning														
Gather	1.5	0.3	1.5	1.5	0.3	1.5					0.1	0.1	12.6	12.6
Split ewes and lambs using manual shedder		0.1			0.1			0.1	0.1	0.1	0.8	0.8	0.2	0.2
Automatically read EID, weigh and sort animals			1.6	1.2		1.5					1.1	0.5	1.5	1.8
Manually read ID, weigh and sort animals	6.4								2.0					
Dose/treat lambs	0.4	0.1	0.1	0.2	0.5	0.3		0.1		0.04	0.3	0.4	0.6	0.7
Back-fat scan lambs		1.5			1.4	1.4								
Footbath		1.2			0.6				0.4		0.8	0.9		
FEC lambs		0.4			0.4						0.7	0.8		
Treat ewes	0.3	0.3	0.3	0.3	0.2	0.3					0.3		0.2	0.2

(*continued on next page*)

Table 2 (*continued*)

Handling events and tasks	Non-PLF	PLF1	PLF2	Non-PR	PR1	PR2	Non-AI1	AI1	Non-AI2	AI2	MP-IR	HP-IR	MP-NO	HP-NO
TOTAL (man-hours)	**8.6**	**3.9**	**3.5**	**3.2**	**3.6**	**5.0**	**n/av**	**0.1**	**2.4**	**0.1**	**4.1**	**3.5**	**15.1**	**15.4**
Post-weaning														
Automatically read EID, weigh and sort lambs into groups			0.8			0.8					0.5	0.5		
Manually read ID, weigh and sort lambs into groups	4.5							0.04	0.03				0.3	0.4
Footbath					0.3						0.5	0.6		
FEC lambs					0.4						0.7	0.8		
Dose/treat lambs	0.0	0.2	0.2	0.2	1.0	0.3					0.3	0.4		
2nd tag lambs					1.4									
Dose ewe												0.3		
TOTAL (man-hours)	**4.6**	**0.2**	**1.0**	**0.2**	**3.1**	**1.1**	**N/A**	**0.04**	**0.03**	**N/A**	**2.0**	**2.5**	**0.3**	**0.4**
Lamb sales														
Manually read ID and weigh lambs	4.6								0.1				1.5	
Automatically read EID and weigh lambs		0.3	0.7		0.2	0.6					0.6	0.7		1.8
TOTAL (man-hours)	**4.6**	**0.3**	**0.7**	**0.0**	**0.2**	**0.6**	**N/A**	**0.0**	**0.1**	**N/A**	**0.6**	**0.7**	**1.5**	**1.8**
Ewe Selection														
Manually read ID and weigh ewes	1.9													
Condition score		0.1			0.1		0.1		0.1		0.3		0.1	
Footbath											0.3			
Automatically read EID and weigh ewes			0.8	0.8		0.8					0.3			
Treat ewes		1.1			1.1									
TOTAL (man-hours)	**1.9**	**1.2**	**0.8**	**0.8**	**1.2**	**0.8**	**0.1**	**N/A**	**0.1**	**N/A**	**1.0**	**n/av**	**0.1**	**n/av**
Milking														
Milking ewes							88.7	88.7	73.1	76.6				
Milking control							1.9	2.1	1.9	2.1				
TOTAL (man-hours)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**90.6**	**90.8**	**75.0**	**78.7**	**N/A**	**N/A**	**N/A**	**N/A**
Grand total with lambing (man-hours)	**126.6**	**14.5**	**102.3**	**95.3**	**64.1**	**105.1**	**114.8**	**120.0**	**81.1**	**83.9**	**70.4**	**88.2**	**38.3**	**168.3**
Grand total without lambing (man-hours)	**63.0**	**14.5**	**38.7**	**32.1**	**22.5**	**41.5**	**95.4**	**97.0**	**81.1**	**83.9**	**24.8**	**21.0**	**38.3**	**39.3**

EID = electronic identification.
FEC = Faecal Eggs Counts for anthelminthic treatment decision.
ID = identification.
N/A = not applicable.
n/av = not available.

Table 3
Description of the key activities during the sheep year, for all four management strategies.

Key activity	Description
Mating	Ram(s) introduced with the ewes for 1 to 3 cycles
AI	Artificial insemination of the ewes – either with fresh semen (French systems) or frozen-thawed semen (Norwegian systems). Include synchronisation of ewes with insertion/removal of sponges (France) or to a natural oestrus (Norway).
Mid-pregnancy scanning	Ultrasound scanning of ewes to determine pregnancy and the number of lambs carried.
Lambing	Lambing period (from 3 to 6 weeks) - e.g. monitoring and assisting ewes lambing if necessary, taking care of the ewes and lambs up to 1 week after lambing, taking care of orphan lambs, moving ewes and lambs from sheds to pastures.
Marking	Weighing, counting, tagging and worming lambs ~8 weeks after birth.
Shearing	Shearing the animals to obtain the wool.
Weaning	Lambs taken off their dams.
Post-weaning	Feeding/fattening lambs in shed or on pasture.
Back -fat scanning	Ultrasound scan image collected at the third lumbar vertebra of a lamb to collect fat and muscle depth measurements.
Ewe selection	Decide which ewes to keep for another year, which ewe to sell on, which ewe lambs to keep for replacements.
Lamb sales	Select lambs ready to be sent to slaughter.
Milking	Daily milking - includes preparing/cleaning milking parlour.
Milking control	Controlling milk quality and quantity - not daily.

Being case studies with a relatively small number of farms, the labour profiles were not analysed using statistical tests. However, at lambing, the ranking of the different sub-tasks durations was analysed using non-parametric ranking (Mann-Whitney U) test. All statistical analyses were performed using the Genstat 16th edition software (VSN International, 2013).

Table 4
Sample days per handling event for each case study flock.

Handling events	Non-PLF	PLF1	PLF2	Non-PR	PR1	PR2	Non-AI1	AI1	Non-AI2	AI2	MP-IR	HP-IR	MP-NO	HP-NO
Mating	1	1	1	1	1	1	1	2	0	1	1	0	1	1
Pre-lambing/scanning	2	2	2	2	1	2	1	0	0	0	2	0	1	0
Lambing	5	3	5	5	3	5	2	1	0	0	2	3	0	4
Marking	1	4	1	1	1	1	1	1	0	0	1	1	0	0
Shearing	1	1	1	1	1	1	1	1	1	1	1	0	1	0
Weaning	1	1	1	1	1	1	0	0	0	0	1	1	0	1
Lamb sales	1	0	1	1	1	1	0	0	0	0	1	0	0	1
Ewe selection	1	0	1	1	1	1	0	0	1	0	0	0	0	0
Milking	N/A	N/A	N/A	N/A	N/A	N/A	0	2	1	1	N/A	N/A	N/A	N/A
Milking control	N/A	N/A	N/A	N/A	N/A	N/A	1	1	1	1	N/A	N/A	N/A	N/A
Transhumance/summer grazing	N/A	N/A	N/A	N/A	N/A	N/A	1	1	1	1	N/A	N/A	0	1
Total sample days	**13**	**12**	**13**	**13**	**10**	**13**	**8**	**9**	**5**	**5**	**9**	**5**	**3**	**8**

3. Results

3.1. Labour measurements

3.1.1. Labour profiles

The labour profiles (Table 2) were modelled for a 100-ewe flock across key handling events (based on sample days and labour questionnaires) for each management strategy. Although the location and environment of the farms as well as the farmer's approach and speed during tasks, can explain some of the differences, the labour profiles allowed to pinpoint in more detail where the differences lay.

The PLF management strategy showed that PLF1 and PLF2 both used less labour than the non-PLF (48.5 man-hours/year and 24.3 man-hours/year less, respectively) across the key handling events. The main differences concerned the manual handling versus the automatic handling of the animals. There was no direct video footage for lambing on PLF1 farm, so comparison with non-PLF was not feasible. However, with lambing the total time spent at key handling events on 100 ewes was 102.3 man-hours/year and 126.6 man-hours/year for PLF2 and non-PLF respectively. The amount of time spent at lambing was similar (63.6 man-hours per 100 ewes), as the PLF was not used at lambing.

The PR management strategies showed that, excluding lambing, PR2 required 9.4 man-hours/year more than the non-PR, whilst PR1 needed 9.6 man-hours less per year than the non-PR. Once lambing was included in the profiles, the PR2 system took 9.8 man-hours more than the non-PR, mostly due to the task of neck-banding the ewes and back-fat scanning the lambs. However, the PR1 system took 31.2 man-hours less than the non-PR. Whilst PR1 also back-fat scan its lambs, they seem to spend much less time with the lambs at marking. Farmer's organisation would therefore be a major factor for differences in that case.

For a 100-ewe flock across the key handling events (excluding lambing), the non- AI French case study flocks required on average 2.2 man-hour/year less than the AI case study flocks, giving a total number of hours of 95.4, 97.0, 81.1 and 83.9 man-hour/year for the non-AI1, AI1, non-AI2, and AI2, respectively. At mating, the AI tasks were the major difference. Additionally, the AI1 was weighing and recording its animals more frequently, thus causing the difference.

In total (excluding lambing), the time spent on 100 ewes across key events in the Norwegian medium prolific case study flock was 38.3 man-hours/year, compared to 39.3 man-hours/year in the Norwegian high prolific case study flock. Some of the differences were observed at mating and at marking and weaning, when the HP-NO spent more time handling its animals. However, differences at lambing could not be accounted for as the footage was missing for one of the Norwegian case study flocks. In the Irish case study flocks, the total time spent on 100 ewes across key handling events including lambing was 70.4 man-hours/ year in the medium prolific case study flock, compared to 88.2 man-hours/year for the Irish high prolific case study flock, a difference of 17.8 man-hours/year. The lambing task caused most of the difference between the flocks. Without it, the MP-IR spent more time handling animals than the HP-IR.

3.1.2. Labour profiles at lambing

The labour profiles at lambing were further investigated for the Scottish performance recording (PR) and Irish prolific breeds

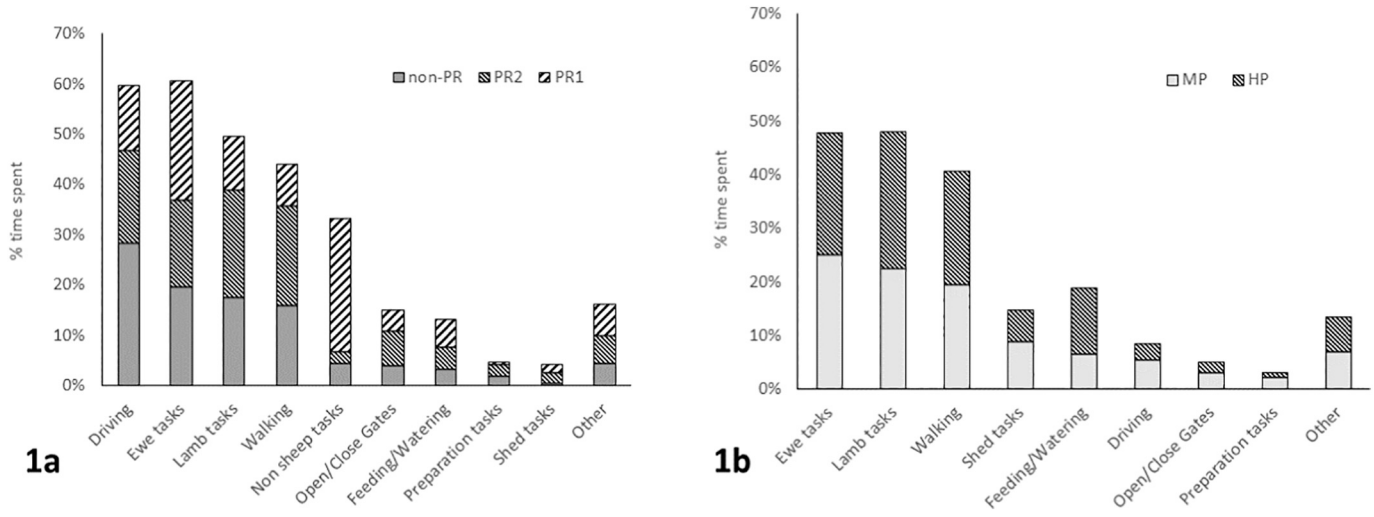


Fig. 1. Time spent (%) on main tasks on an average lambing day per 1a) performance recording (PR) management strategies in two Scottish flocks and 1b) in the medium prolific (MP) and high prolific (HP) management strategy in two Irish flocks.

management strategies (Fig. 1). Due to the missing footage, the Norwegian and French lambing labour profiles are not presented.

The time spent on an average lambing day (in percentage) per task in all PR management systems is presented in Fig. 1a.

The four main tasks across the PR management strategies related to driving and walking as well as tasks associated with the ewes and the lambs (Supplementary Table 1). Driving took 28, 13 and 18% of the farmers' time in the non-PR, PR1 and PR2 flocks, respectively. The ewe tasks took 20, 23 and 17% of the farmers' time (non-PR, PR1 and PR2 flocks, respectively). Interestingly, whilst the lamb tasks took 17 and 21% of the farmers' time in the non-PR and PR2 flocks, respectively, the farmer in PR1 only devoted 10% of their time to lamb tasks. Likewise, farmers in non-PR and PR2 flocks spent 16 and 19% of their time walking, whilst the farmer in PR1 flock only spent 8% of their time walking. Conversely, the farmer in PR1 flock spent a quarter of their time (26%) doing tasks related to the on-farm cattle herd.

However, once the tasks were subdivided in sub-tasks (Supplementary Table 1), there were differences in the sub-tasks' durations between PR2 and non-PR ($P < 0.05$), and between PR1 and PR2 ($P < 0.001$). The main differences (Supplementary Fig. 1) were linked to sub-tasks relating to the lambs (e.g. recording/weighing the lambs (absent in non-PR)) and the ewes (e.g. moving ewes and lambs from the field to the shed or from one field to another).

In the prolific breeds management strategy (Fig. 1b), the high prolific (HP) flock appeared to spend more time, in an average lambing day, on ewe and lamb tasks, and on walking, compared to the medium prolific flock (MP). The three main tasks undertaken were related to the ewes (25 and 23% of the farmer's time in the MP and HP, respectively), and the lambs (23 and 25% of the farmer's time for MP and HP, respectively). Walking was the third most important task undertaken in terms of farmer's time (19 and 21% for MP and HP, respectively).

When the lambing tasks were subdivided into sub-tasks (Supplementary Table 1), the HP flock spent 30% of its time checking the animals, whilst the MP spent 36% of its time doing so. Equally, both HP and MP spent 18% of their time feeding lambs, whilst the HP spent 21% of its time preparing milk for lambs, compared to only 12% of the farmer's time in MP case study flock (Supplementary Fig. 2).

3.2. Carbon footprint

The carbon footprints calculated for each management strategy are shown in Table 5.

In the PLF management strategy, the difference between non-PLF to PLF ranged from 3.5 and 6.7 kg CO2e per kg of liveweight and from of 14.2 and 7.8 kg CO2e per kg of deadweight, with the PLF having a higher carbon footprint. Conversely, both PR management strategies had a lower carbon footprint, compared to the non-PR (3.5 and 1.8 kg CO2e per kg of liveweight for PR1 and PR2 respectively, 8.1 and 3.2 kg CO2e per kg of deadweight for PR1 and PR2, respectively).

In the French AI management strategy, the difference between the non-AI and AI was minimal in terms of kg of CO2 per kg liveweight. AI1 management strategy had a slightly lower carbon footprint compared to non-AI1 (a difference of 1.8 kg of CO2e per kg of liveweight), whilst AI2 had a higher carbon footprint compared to non-AI2 (1.5 kg CO2e per kg of liveweight). However, in terms of kg CO2e per kg of deadweight, both paired case study flocks showed opposite results. Non-AI1 has a much higher carbon footprint to AI1 (18.3 kg of CO2e) while Non-AI2 has a lower carbon footprint to AI2.

Finally, in the Irish prolific breeds management strategy, the high prolific breeds had a slightly higher carbon footprint compared to the medium prolific (a difference of −0.4 kg CO2e per kg of liveweight and of 0.29 kg CO2e per kg of deadweight).

3.3. Economic margins

The net margins calculated for all management strategies, based on a 100-ewe flock, are given in Table 6. The averaged results show that adopting PLF, PR, prolific breeds and/or AI management strategies resulted in an increased net margin per ewe of £9.14, £6.25, £3.26 and £51.05, respectively, even when the labour costs were included. These results are however farm-dependant. It also demonstrated the profitability of the French dairy systems compared to the meat-based systems in the other countries. There were nonetheless farm differences for PLF and PR management strategies. PLF2 and non-PLF only showed a margin difference of £2.90/ewe, whilst the PLF1 and non-PLF difference was much higher (£15.40/ewe), due to husbandry decisions not linked to the management strategy (no hay, bedding straw or off-wintering costs for PLF1). Similarly, PR2 is slightly worse off than non-PR (£2.04/ewe), whilst PR1 showed a positive difference of £14.5/ewe compared to non-PR. Most of the differences are due to finishing the lambs in shed (finishing feeds and bedding straw).

There were large differences between the milk production incomes for the French dairy farms, leading to large variation between the average gain with the AI management strategy (£91.58 between non-AI1 and AI1, and £10.53 between non-AI2 and AI2, giving an average of £51.05).

The sensitivity analysis (Supplementary Table 2) showed that the management strategies were not very sensitive to changes in inputs (ram, AI, feed and labour costs), prices (lamb, ewe and milk prices) and weaning rate. Changes between 5% and 10% did not have a strong effect. However, the variables most likely to affect the margins were the lamb price and the weaning rate (a change of 19% in both cases affected the high prolific flock margins), whilst the variables with the least effect were the ewe price and the AI cost. For the AI management strategy, it would require an increase of 527% in the cost of AI (from £9.70/ewe to £60.82/ewe) for it to be less financially attractive than the non-AI. Likewise, for the PLF management strategy, even if the labour was free, there would still be a gain of £4.10/ewe between the PLF and the

Table 5
kg CO2e per kg of liveweight and deadweight, in the Scottish, Irish, Norwegian and French case study flocks and the differences (Δ = non-PR minus PR; MP-IR minus HP-IR; non-PLF minus PLF; non-AI minus AI)) for each strategy. The difference for the Norwegian flocks is not shown (N/A) as values for MP-NO were unavailable.

	Non-PLF	PLF1	PLF2	Non-PR	PR1	PR2	Non-AI1	AI1	Non-AI2	AI2	MP-IR	HP-IR	MP-NO	HP-NO
kg CO_2e / kg liveweight	16.17	22.75	19.62	19.81	16.28	18.03	25.10	23.27	30.44	31.89	10.35	10.75	N/A	13.42
kg CO_2e / kg deadweight	36.33	50.56	44.09	44.02	35.95	40.85	70.05	51.71	67.65	70.87	24.18	23.89	N/A	53.96
Δ kg CO_2e / kg liveweight		−6.59	−3.46		3.52	1.78		1.82		−1.45		−0.40		N/A
Δ kg CO_2e / kg deadweight		−14.23	−7.77		8.07	3.17		18.34		−3.22		0.29		N/A

Δ = non-PLF minus PLF; non-PR minus PR; non-AI minus AI; MP-IR minus HP-IR for each strategy.
AI = Artificial Insemination.
HP-IR = High prolific – Ireland.
HP-NO = High prolific - Norway.
MP-IR = Medium prolific – Ireland.
PLF = Precision Livestock Farming.
PR = performance recording.

Table 6
Gross and net margins (in GBP £ sterling) per 100-ewe flock for all management strategies.

	Non-PLF	PLF1	PLF2	Non-PR	PR1	PR2	MP-IR	HP-IR	MP-NO	HP-NO	Non-AI1	AI1	Non-AI2	AI2
Lambs reared	91%	90%	91%	51%	85%	86%	150%	170%	190%	220%	24%	26%	16%	26%
Lamb income	£2170	£2310	£2345	£770	£3736	£4135	£10,500	£11,900	£13,300	£15,400	£1714	£2520	£1750	£1610
Ewe income	£1624	£1334	£1334	£1344	£1624	£1334	£1241	£1241	£1241	£1241	£1314	£1387	£949	£1022
Wool income	£150	£150	£150	£96	£150	£150	£354	£354	£354	£354	£354	£354	£354	£354
Milk income											£16,896	£30,796	£12,333	£14,000
Less: ram replacement (net)	£450	£450	£450	£400	£450	£450	£542	£542	£542	£542	£542		£542	
Less: gimmers purchased / AI costs							£2662	£2662	£2662	£2662		£970		£970
Total output	£3494	£3344	£3379	£1810	£5060	£5169	£8891	£10,291	£11,691	£13,791	£19,736	£34,087	£14,844	£16,016
Winter feed	£950	£1034	£950	£412	£220	£950	£1393	£1833	£1833	£2308	£3234	£7084	£968	£1056
Finishing feed					£1344	£1488								
Hay	£336		£336	£33		£336						£370	£739	£672
Off-wintering costs	£522		£432	£522	£522	£432								
Health costs	£495	£495	£495	£474	£495	£495	£606	£621	£640	£676	£606	£606	£606	£606
Bedding straw	£128		£128		£75	£128	£503	£503	£450	£450	£300	£750	£623	
Other costs	£682	£682	£682	£489	£682	£682	£1188	£1320	£1452	£1650	£1188	£1188	£1188	£1188
Forage costs	£228	£135	£228	£228	£108	£811	£1344	£968	£2066	£2066	£112	£246		£239
Total variable costs	*£3341*	*£2346*	*£3251*	*£2159*	*£3446*	*£5321*	*£5034*	*£5245*	*£6441*	*£7149*	*£5440*	*£10,244*	*£4124*	*£3761*
GROSS MARGIN	**£153**	**£997**	**£128**	**-£349**	**£1614**	**-£152**	**£3857**	**£5046**	**£5250**	**£6641**	**£14,297**	**£23,843**	**£10,720**	**£12,255**
Labour costs	£1591	£896	£1278	£912	£1421	£1312	£2925	£3888	£3152	£4116	£5168	£5557	£5061	£5543
GROSS MARGIN MINUS LABOUR COSTS	**-£1438**	**£101**	**-£1150**	**-£1260**	**£193**	**-£1464**	**£932**	**£1158**	**£2098**	**£2526**	**£9128**	**£18,286**	**£5659**	**£6712**
Per ewe	-£14.38	£1.01	-£11.50	-£12.60	£1.93	-£14.64	£9.32	£11.58	£20.98	£25.26	£91.28	£182.86	£56.59	£67.12
difference		*£15.39*	*£2.88*		*£14.53*	*-£2.04*		*£2.25*		*£4.27*		*£91.58*		*£10.53*
Average gain (£) with management (PLF, PR, HP, AI) strategies		**£9.14**			**£6.25**			**£3.26**				**£51.05**		

non-PLF. The labour costs would need to be negative (−£10.14/h) for the PLF to become less financially attractive than the non-PLF. Regarding the PR management strategy, the cost of a performance recorded ram would need to increase by 139% (from £450 to £1075.50) for it not to have a financial benefit compared to the non-PR, even with the extra labour costs (due to performance recording) included. Likewise, the cost of labour would need to increase by 138% (£29.4/h) for the PR management strategy to become less attractive than the non-PR. Finally, amongst the four management strategies, the PR and high prolific breeds were the most likely to be affected by changes in variables.

4. Discussion

These results are from case study flocks and as such, are country and farm dependant, and only provide indications of what could be achieved in terms of labour, economics and carbon footprint. However, some key messages can be identified.

4.1. Labour input and economic margin

Similar to Carson et al. (2004), this study highlights differences between the different sheep farming systems with differing management strategies. As already demonstrated by Morris et al. (2012) and Morgan-Davies et al. (2018), this study reinforces the fact that labour savings could be achieved through the use of technology (between 24 and 49 man-hours per 100 ewes per year). Although the initial outlay for technology may be onerous, the averaged subsequent savings in labour time were shown to be around ~£9 per ewe. An auto-drafter can cost up to ~£10,000 (Gautier et al., 2019), so the return on investment for a 500-ewe flock could be about 2.5 years (rising to 11 years for a 100-ewe flock). Targeted subsidies for modernisation are available in Ireland (40% grant aid; DAFM, 2020) and Scotland (Scottish Government, 2020), making such an investment more affordable. Additionally, the labour saved can be used for other on-farm diversifications or off-farm working. This labour flexibility (Bernués et al., 2011) can be another sustainability strategy for sheep farmers.

Although flock genetic improvement via the use performance recording schemes or AI can bring financial rewards (Conington et al., 2006), there is slow uptake of this technology. Our study showed that the averaged financial reward for performance recording could be up to £6/ewe. It would require an increase of 138% in labour prices for such strategy to stop being cost-effective, as shown by the sensitivity analysis. Performance recording of animals can be rewarding for the profitability of the farm, provided the labour input is planned. Our findings also highlighted that more time is spent attending lamb tasks (e.g. writing/recording/weighing lamb) than ewe tasks in the PR case study flocks. Once farmers are aware of such differences, they can rationalise or organise in advance their labour. Cournut et al. (2018) emphasised this need to understand work organisation in livestock farms to better respond to the diversity of the work situation and consider the evolutions of livestock farming systems.

While the AI management strategy case study flocks were somewhat different from the other three case study flock, being sheep dairy farms, similar trends were observed. The use of AI, despite the costs of synchronisation and insemination, brought an averaged additional £51.05 per ewe, mostly due to a higher milk production. This increase in milk productivity is most likely due to the genetic merit of the rams providing the semen. However, similar increases could perhaps also have been achieved through purchases of rams with higher genetic merit and used naturally. The initial technological investment in the management system needs to be accounted for (Gibbons et al., 2019), as well as access to the skilled labour necessary for the procedure and additional facilities when a high percentage of ewes lamb in a short period. It should also be noted that in this study, the French case study flocks used cervical AI with fresh liquid semen. This technique is widely used in French dairy

sheep and yields acceptable pregnancy rates. However, in Norway, cervical AI with frozen-thawed semen is used routinely but not elsewhere due to unacceptably low (<30%) pregnancy rates. This is due to the breed of the ewes used in Norway (Fair et al., 2019).

The use of prolific breeds has been identified as a key driver for the profitability of meat-based sheep systems (Diskin and McHugh, 2012; Bohan et al., 2018). Our study demonstrated that lambing was the main key event affecting labour costs between flocks of differing prolificacy level. Having high prolific breeds increased labour by ~18 man-hours per 100 ewes per year in the Irish flocks. Interestingly, the repartition of tasks varied between the two Irish case study flocks. In the high prolific flock, more time was spent on checking animals, feeding lambs, preparing milk and lambing ewes. As in the PR management strategy, once the farmer is aware of the sort of tasks that will be required at lambing, they can organise their lambing accordingly. Moreover, in terms of profitability, the high prolific breeds management strategy brought an additional £3.30 per ewe (£2.30 and £4.30 for the Irish and Norwegian case study flocks, respectively. It would take a 19% decrease in either weaning rate or lamb prices for it to become non-profitable.

4.2. Carbon footprint

This study assessed the efficiency in terms of labour and carbon footprint. Numerous studies on the carbon footprint of the livestock sector, and particularly the sheep sector, have been conducted on dairy sheep (Jones et al., 2014b; Sabia et al., 2020), meat sheep (Dougherty et al., 2019; Toro-Mujica et al., 2017) as well as pastoral sheep (Mansard et al., 2018). Most of these studies have used an LCA approach. This present study is using a different tool, AgRECalc© which is, to a greater extent, a farmer-friendly benchmarking tool (MacLeod et al., 2016; Sykes et al., 2017). Our study highlighted management strategies that were more efficient in terms of carbon efficiency than others.

Increasing animal efficiency (by increasing the number of lambs produced, either with performance recording or by using AI) is one strategy to decrease emissions on a kg liveweight or deadweight basis (Toro-Mujica et al., 2017). By using the PR management strategy, this study found that the carbon footprint could be on average, 5.6 kg CO2e/kg deadweight produced (meat) less when compared to the non-PR management. Likewise, the AI management strategy was more carbon efficient in terms of CO2e/kg deadweight produced, especially in one of the case studies. Conversely, in both case studies, the PLF management strategy produced a higher carbon footprint. This could be due to the ewe retention strategy in the PLF case study flocks, where older (heavier) ewes are kept for longer, whilst more lambs (lighter) are sold, thus affecting the overall amount of deadweight produced by the flocks. This is counterintuitive and could be an artefact of the AgRECalc© calculations. Indeed, keeping ewes longer means a lower replacement rate, which should reduce the carbon footprint of that flock. Finally, the high prolific breeds management strategy only shows a minimal impact on kg CO2e/kg liveweight or deadweight produced (meat). The small difference could be due to the higher amount of concentrates feed and fertiliser used in the high prolific breeds flock, causing a higher amount of direct and indirect emissions of CO2 from energy use in the AgRECalc© calculations.

Ripoll-Bosch et al. (2013) found similar values of kg CO2e/kg lamb liveweight in Spanish meat-sheep farming systems (between 19.5 and 25.9 kg CO2e). They also found that the highest values belonged to the more extensive, pastoral systems, which is also reflected in our study (the Scottish case study flocks have a higher carbon footprint than the Irish more intensive ones). However, these authors also argue that carbon efficiency should also take into account the multifunctionality of these sheep systems, by accounting for cultural and social ecosystem services. By doing so, the ranking of emissions of these sheep systems was reversed. Similarly, by accounting for labour input and economic margin, as well as carbon efficiency, this present study concurs with the findings of Ripoll-Bosch et al. (2013). For instance, although the PLF management strategy was found to be less carbon efficient, it provided the most labour savings. However, the values presented in this study did not consider the farm as a whole, and only focused on the sheep flock component of these farms.

Finally, it should be stressed that the present study was based on case studies and farm-specific focus flocks and data, with shown individual farm effects. Although not representative of the whole sheep industry in each country, it nonetheless can provide trends and pointers, especially regarding labour tasks and farm labour organisation. Rolling out a wider study based on video recording the sheep year labour at key events was beyond the scope of this study. This study pinpoints the key events affecting labour, carbon and financial efficiencies, and thus could further guide more detailed and representative studies. Additionally, whilst we used a labour tasks accounting system, as described by Kirwan (2009), it could also be interesting to use a different approach, such as the QuaeWork (Hostiou and Dedieu, 2012) which analyses interactions between livestock management, workforce and equipment facilities using productivity and flexibility-based work criteria, to compare and contrast the methods and further the knowledge regarding labour on sheep farms.

5. Conclusion

These case studies are a unique insight into sheep farm efficiency that consider and combine carbon footprint, farm labour and economics for four sheep management strategies. The study has highlighted that using performance recording on sheep farms for gaining higher genetic merit could increase economic margins and reduce GHG emissions per kg of meat produced, with incurring up to 10% extra labour. Although high prolific breeds increased labour input on farms mostly at lambing time, this increase was compensated for by higher economic margins, with a small change in terms of kg CO2e/kg meat produced. Introducing PLF technology on extensive farms could reduce greatly labour and increase economic margins but may also be associated with a concurrent increase in GHG emissions. Finally, using AI on farms increased economic margins, did not incur extra labour, with a small change in carbon efficiency in terms of kg CO2e/kg meat produced. However, the milk production effect, which could not be entirely captured with the AgRECalc© software in this study, needs to be modelled.

To conclude, these unique case studies suggest it could be possible to improve carbon and labour efficiency by introducing changes associated with ewe prolificacy, breeding management and/or by adopting precision livestock tools. Although this work was conducted on a small number of case studies based in Northern Europe, the results could help to inform where future studies should be concentrated to ensure sheep production systems and strategies aim for the lowest environmental footprint whilst maintaining farm efficiency and profitability worldwide.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103155.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the financial support from the European Research Area Network, on Sustainable Animal Production. National funding was provided in Ireland by the Department of Agriculture, Food and the Marine (DAFM - 16/RD/SusAn/ERA-Net/1) as well as Teagasc (ERA-NET SusAn, 0299), in France by the Agence Nationale de la Recherche (ANR-16-SUSN-0001), in Norway by The Research Council of Norway (NFR 272338 / E50) and the Norwegian Association of Sheep

and Goat Breeders (NSG) and in Scotland by the Department of Environment, Food and Rural Affairs (DEFRA - ERA-NET SusAn, SCF0210). Additionally, SRUC receives financial support from the Scottish Government's Rural and Environment Science and Analytical Services Division to collect research flock data. We also gratefully acknowledge SAC Consulting and G. Inman for their advice and access to the SAC AgRECalc software. Finally, many thanks to the UK Maternal Sheep Group, to the French CDEO, and to all farmers who accepted to take part in this project.

References

Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., Casasús, I., 2011. Sustainability of pasture-based livestock farming systems in the European Mediterranean context: synergies and trade-offs. Livest. Sci. 139, 44–57.

Bohan, A., Shalloo, L., Creighton, P., Earle, E., Boland, T.M., McHugh, N., 2018. Investigating the role of stocking rate and prolificacy potential on profitability of grass based sheep production systems. Livest. Sci. 210, 118–124.

Carson, A.F., Dawson, L.E.R., Irwin, D., Kilpatrick, D.J., 2004. The effect of management system at lambing and flock genetics on lamb output and labour requirements on lowland sheep farms. Anim. Sci. 78, 439–450.

Conington, J., Bishop, S.C., Lambe, N.R., Bünger, L., Simm, G., 2006. Testing selection indices for sustainable hill sheep production–lamb growth and carcass traits. Anim. Sci. 82 (4), 445–453.

Cournut, S., Chauvat, S., Correa, P., Dos Santos Filho, J.C., Dieguez, F., Hostiou, N., Pham, D.K., Servière, G., Sraïri, M.T., Turlot, A., Dedieu, B., 2018. Analyzing work organization on livestock farm by the work assessment method. Agron. Sustain. Dev. 38 (6), 58.

DAFM (Department of Agriculture, Food and the Marine), 2020. Targeted Agricultural Modernisation Scheme. DAFM - TAMS. agriculture.gov.ie. accessed 14/12/2020.

Dedieu, B., Chauvat, S., Serviere, G., Tchakerian, E., 2000. Bilan travail pour l'étude du fonctionnement des exploitations d'élevage: méthode d'analyse et documents d'enquête. Collection Lignes, Institut de l'élevage.

Dieguez, F., Morales, H., Cournut, S., 2010. La Méthode Bilan Travail pour l'approche du fontionnement des élevages extensifs uruguayens. Cah. Agricult. 19, 316–322.

Diskin, M.G., McHugh, M.P., 2012. Improving the efficiency and profitability of your sheep flock. In: Technical Updates on Sheep Production, Teagasc, p. 2012.

Dougherty, H.C., Oltjen, J.W., Mitloehner, F.M., DePeters, E.J., Pettey, L.A., Macon, D., Finzel, J., Rodrigues, K., Kebreab, E., 2019. Carbon and blue water footprints of California sheep production. J. Anim. Sci. 97, 945–961.

EU Commission, 2019. European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents. Accessed 10th December 2019.

Eurostat, 2019. Agriculture, Fisheries and Forestry Statistics, 2019 edition. Publication Office of the European Union, Luxembourg.

Fair, S., Meade, K.G., Reynaud, K., Druart, X., de Graaf, S.P., 2019. The biological mechanisms regulating sperm selection by the ovine cervix. Reprod. 158 (1), R1–R13.

Gautier, J.M., Morgan Davies, C., Keady, T.W.J., Bohan, A., Lagriffoul, G., Ocak, S., Beltrán De Heredia, I., Carta, A., Gavojdian, D., Rivallant, P., Francois, D., 2019. Use of electronic identification and new technologies on European sheep farms. In: 12th EFITA International Conference, Digitizing Agriculture, pp. 234–239. Rhodes Island, Greece, June 27–29, 2019.

Gibbons, A.E., Fernandez, J., Bruno-Galarraga, M.M., Spinelli, M.V., Cueto, M.I., 2019. Technical recommendations for artificial insemination in sheep. Anim. Reprod. 16 (4), 803–809.

Guicheney, H., Ballan, S., 2015. Dynamiques agricoles au Pays Basque. (Agreste Aquitaine: agr_AQ_ter_2015_07.pdf (insee.fr)) accessed on 14/12/2020.

Hostiou, N., Dedieu, B., 2012. A method for assessing work productivity and flexibility in livestock farms. Animal 6 (5), 852–862.

IPCC, 2006. IPCC Guidelines for National Greenhouse gas Inventories. IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ (Accessed 19 June 2019).

Jones, A.K., Jones, D.L., Cross, P., 2014a. The carbon footprint of lamb: sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107.

Jones, A.K., Jones, D.L., Cross, P., 2014b. The carbon footprint of UK sheep production: current knowledge and opportunities for reduction in temperate zones. J. Agric. Sci. 152 (2), 288–308.

Kirwan, S., 2009. Best Uses of Labour for Animal Welfare and Productivity in Extensive Sheep Farming Systems in Britain. PhD thesis. School of Biological Science, Aberdeen University.

Kool, A., Marinussen, M., Blonk, H., 2012. LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization: GHG Emissions of N. P and K Fertilizer Production, Blonk Consultants.

Kumar, S., Choudhury, P.K., Carro, M.D., Griffith, G.W., Dagar, S.S., Puniya, M., Calabro, S., Ravella, S.R., Dhewa, T., Upadhyay, R.C., Sirohi, S.K., 2014. New aspects and strategies for methane mitigation from ruminants. Appl. Microbiol. Biotechnol. 98, 31–44.

Lambe, N.R., Wall, E., Ludemann, C.I., Bunger, L., Conington, J., 2014. Genetic improvement of hill sheep- impacts on profitability and greenhouse gas emissions. Small Rumin. Res. 120, 27–34.

MacLeod, M., Eory, V., Amponsah, N.Y., 2016. Benchmarking the Emissions Intensity of Scottish Livestock–Derived Agricultural Commodities.

Madelrieux, S., Dedieu, B., 2008. Qualification and assessment of work organisation in livestock farms. Animal 2, 435–446.

Mansard, L., Vigan, A., Meuret, M., Lasseur, J., Benoit, M., Lecomte, P., Eugene, M., 2018. An enteric methane emission calculator (DREEM) built to consider feed diversity: case study of pastoral and sedentary farming systems. Small Rumin. Res. 167, 6–15.

Marino, R., Atzori, Alberto Stanislao, Mariasilvia, D'Andrea, Iovane, G., Trabalza-Marinucci, M., Rinaldi, L., 2016. Climate change: production performance, health issues, greenhouse gas emissions and mitigation strategies in sheep and goat farming. Small Rumin. Res. 135, 50–59.

Montossi, F., Font-i-Furnols, M., del Campo, M., San Julián, R., Brito, G., Sañudo, C., 2013. Sustainable sheep production and consumer preference trends: compatibilities,contradictions, and unresolved dilemmas. Meat Sci. 95, 772–789.

Morgan-Davies, C., Robertson, I., 2016. Optimising Use of Labour at Lambing Time. Report to AHDB Beef and Lamb Farm Innovation Grant. SRUC, Edinburgh.

Morgan-Davies, C., Wilson, R., Waterhouse, A., 2015. Use or delight? History of conflicting hill land uses in Scotland – a review. Scott. Geogr. J. 131 (2), 98–122.

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. Livest. Sci. 208, 67–76.

Morris, J.E., Cronin, G.M., Bush, R.D., 2012. Improving sheep production and welfare in extensive systems through precision sheep management. Anim. Prod. Sci. 52, 665–670.

Pollock, M.L., Holland, J.P., Morgan-Davies, C., Morgan-Davies, J., Waterhouse, A., 2013. Reduced sheep grazing and biodiversity: a novel approach to selecting and measuring biodiversity indicators. Rangel. Ecol. Manag. 66, 387–400.

Ripoll-Bosch, R., de Boer, I.J.M., Bernués, A., Vellinga, T.V., 2013. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: a comparison of three contrasting Mediterranean systems. Agric. Syst. 116, 60–68.

Rossi, R., 2017. The sheep and goat sector in the EU. Main features, challenges and prospects. In: European Parliament Briefing. http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/608663/EPRS_BRI (2017)608663_EN.pdf Accessed 5th December 2019.

Rotz, C.A., 2018. Modelling greenhouse gas emissions from dairy farms. J. Dairy Sci. 101, 6675–6690.

Rotz, C.A., Thoma, G., 2017. Assessing carbon footprints of dairy production systems. In: Beede, D.K. (Ed.), Large Dairy Herd Management, 3rd. ed, pp. 19–31.

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 43 (4), 1143–1158.

Sabia, E., Gauly, M., Napolitano, F., Serrapica, F., Cifuni, G.F., Claps, S., 2020. Dairy sheep carbon footprint and ReCiPe end-point study. Small Rumin. Res. 185, 106085.

SAC, 2019. Welcome to SAC Consulting's AgRE Calc. Available at. http://www.agrecalc.com/.

SAC Consulting, 2017. The Farm Management Handbook 2017/2018, 38th edition, p. 514.

Scottish Government, 2020. Sustainable Agricultural Capital Grants Scheme. Sustainable Agriculture Capital Grant Scheme (SACGS). ruralpayments.org.

Swan, A., 2009. The economics of litter size in meat sheep. In: Use of the FecB (Booroola) gene in sheep-breeding programs. In: Proceedings of the Helen Newton Turner Memorial International Workshop. Australian Centre for International Agricultural Research, Canberra, pp. 170–176.

Sykes, A.J., Topp, C.F., Wilson, R.M., Reid, G., Rees, R.M., 2017. A comparison of farm-level greenhouse gas calculators in their application on beef production systems. J. Clean. Prod. 164, 398–409.

Toro-Mujica, P., Aguilar, C., Vera, R.R., Bas, F., 2017. Carbon footprint of sheep production systems in semi-arid zone of Chile: a simulation-based approach of productive scenarios and precipitation patterns. Agric. Syst. 157, 22–38.

VSN International Ltd, 2013. GenStat for Windows, 16th edition. Lawes Agricultural Trust, Hemel Hempstead, UK.

Whittaker, C., McManus, M.C., Smith, P., 2013. A comparison of carbon accounting tools for arable crops in the United Kingdom. Environ. Model. Softw. 46, 228–239.