Animal 16 (2022) 100640

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Bio-economic modelling of sheep meat production systems with varying flock litter size using field data

L. Farrell [a,*], P. Creighton [a], A. Bohan [b], F. McGovern [a], N. McHugh [c]

[a] Teagasc Animal & Grassland Research and Innovation Centre, Mellows Campus, Athenry, Co. Galway, Ireland
[b] Sheep Ireland, Ballincollig, Co. Cork, Ireland
[c] Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland

ARTICLE INFO

Article history:
Received 18 April 2022
Revised 28 August 2022
Accepted 1 September 2022

Keywords:
Ewe age
Lambing rate
Profit
Simulation
Weaning rate

ABSTRACT

Sheep meat producers derive the majority of income from sales of weaned lambs, determined by flock conception rates, litter size, and lamb survival. Field data from commercial flocks can inform sensitivity analyses of the effect of litter size on flock productivity, feed demand, and gross margin. This study adapted an established bio-economic model of a flock of breeding ewes informed by statistical relationships (from linear models) between flock litter size (lambs born per ewe lambing) and production factors (such as flock barren rate, litter birth type and lamb birth weight) identified using 156 145 animal records from the Irish national sheep breeding database. Sensitivity analyses were undertaken to investigate the effects of flock litter size on flock production, feed demand, and gross margin. Results showed that as flock litter size increased, the proportion of lambs born as multiples increased, with 14 % of lambs born as singles when flock litter size was 2.2 lambs born per ewe lambing. Flock gross margin increased from €2 205 to €7 730 as litter size increased from 1.0 to 2.0 lambs born per ewe lambing. As litter size increased from 1.0 to 2.2 lambs born per ewe lambing, flock gross margin increased linearly by, on average, €52 per 0.01 increase in litter size. At a litter size of > 2.2 lambs born per ewe lambing, flock gross margin increased on average €12 per 0.01 increase in litter size. At a litter size of 2.2 lambs born per ewe lambing, flock efficiency (at 65.0 kg of lamb weaned per ewe presented for breeding), weaning rate (at 1.5 lambs weaned per ewe presented for breeding; not including excess lambs from large litters sold within a week after birth and thus not weaned on-farm), and gross margin (at €8 500) began to plateau. The results indicate lower marginal returns in gross margin at very high flock litter size, due to the lower value of additional lambs born as triplets and quadruplets compared with single- and twin-born lambs. However, the diminishing economic returns occurred at higher flock litter size than are currently biologically achieved in most flocks. Quantification from this analysis demonstrates how the value of increasing the number of lambs born changes at very high flock litter size, which can inform the priorities and performance benchmarking for international sheep meat production industries.

Implications

Litter size is a major determinant of flock lamb production and income. This study used a bio-economic model informed by a large database of records from commercial flocks to investigate the effects of a large range of flock litter sizes on productivity, feed demand, and gross margin. Our results provide insight for sheep meat production industries on the marginal economic returns from increasing flock litter size to very high levels. Publication of these outputs indicate potential outcomes from improving flock litter size, an important production metric for the industry, informing producers of appropriate levels of spending to increase flock litter size and informing decision-making around production priorities.

Introduction

Sales of lambs generate the majority of income for sheep meat producers internationally (Young et al., 2014; Farrell et al., 2021, Teagasc, 2021). **Flock litter size** (lambs born per ewe lambing) is a key factor in the annual lamb production per flock and, when combined with flock conception and lamb survival rates, determines flock weaning rate. Previous bio-economic modelling of lamb production systems has confirmed flock weaning rate as a driver

* Corresponding author at: DairyNZ, Private Bag 3221, Hamilton 3240, New Zealand.

E-mail address: lydia.farrell@dairynz.co.nz (L. Farrell).

https://doi.org/10.1016/j.animal.2022.100640
1751-7311/

of profitability in Ireland (Bohan et al., 2018), New Zealand (Amer et al., 1999; Morel and Kenyon, 2006; Farrell, 2020), and Australia (Young et al., 2014). Numerous interconnected factors affect flock production of weaned lamb, including flock genetics (SanCristobal-Gaudy et al., 2001) and farm management factors such as nutrition and health (Montossi et al., 2013; Young et al., 2014).

Previous studies modelling the profitability of lamb production have generally used a combination of experimental data and averages from industry survey data to inform assumptions of flock production levels. In contrast, Shorten et al. (2021) used field data from nine commercially farmed New Zealand ewe flocks to model lamb production, however, their analysis did not extend to changes in flock feed demand, weight of lamb sold, or profitability. The Irish national sheep breeding organisation Sheep Ireland (https://www.sheep.ie) collects production data from commercial flocks providing detailed information on parameters contributing to lamb production. These data can be used to explore relationships between factors contributing towards lamb production, for example between the rate of lambs born per ewe lambing (flock litter size) and lamb birth type or between ewe age and prolificacy. Examination of field data from commercial flocks has already provided insight into phenotypic factors for flock lambing (McHugh et al., 2016) and lamb growth (McGovern et al., 2020) traits. Bio-economic modelling informed by field data can quantify changes in flock production, sheep feed demand, and flock profitability with varying flock litter size, providing useful information for sheep meat production enterprises. Therefore, the objectives of this research were to a) identify relationships in field data between key factors contributing towards weaning rate and production of lamb carcass for sale, b) incorporate these relationships into a bio-economic model of a ewe flock, and c) use the bio-economic model for sensitivity analyses exploring changes in production, feed demand, and gross margin with changes in flock litter size.

Material and methods

Production data from commercial flocks in the Irish national sheep breeding database were analysed to determine relationships between factors contributing towards the production of weaned lambs. An existing bio-economic model of a breeding ewe flock (Farrell et al., 2019) was adapted to incorporate these relationships identified in the field data. The flock was then simulated in sensitivity analyses with varying flock litter size to quantify changes in animal production, feed demand, and gross margin.

Field data

Field data from 156 145 records of animals born from 2014 to 2020, inclusive of 974 lowland commercial flocks, were extracted from the national database maintained by Sheep Ireland (https://www.sheep.ie). Data utilised in the present analysis included the following: flock of origin, birth year, birth and genetic dam, ewe weight, ewe age, number of foetuses at ultrasound pregnancy scanning, lamb birth and rearing type, birth and death dates, and lamb weights.

Key variables already included in the bio-economic model (Farrell et al., 2019) were chosen for exploration. These key variables were litter size (number of lambs born per ewe lambing in the flock), dam age at lambing (2, 3, 4, 5, or ≥ 6 years of age), lamb birth type (single, twin, triplet, or quadruplet), and lamb rearing type (single or twin). Litter size was the main measure of flock reproduction level, expressed as the rate of lambs born per ewe lambing. It was assumed lambs were reared as either singles or twins, in accordance with industry practice (Bohan et al., 2017); excess lambs born as triplets and quadruplets were sold within a week after birth without within-flock cross-fostering. Data edits for both the key variables and production factors have been described previously (McHugh et al., 2016; McGovern et al., 2020). Production factors considered in the present analysis at flock level included the following: barren rate and proportions of lambs born of each birth type. Flock barren rate data were defined based on the number of ewes per flock recorded as barren at pregnancy scan recording around early January for spring lambing, with records retained for analysis for flocks that recorded ≥ 1 barren ewe. Flock litter size was calculated from lamb records with valid birth weights (between 2 and 9 kg) included, and proportions of lambs born of different birth types (1 to 4) were calculated. Animals born in litters of five lambs were observed at very high flock litter sizes outside of the range explored in this study and were therefore not considered in the subsequent analysis. After editing, there were 99 flock-year records for barren rate and 306 flock-year records for proportions of lamb birth type.

Production factors considered in the present analysis at animal level included the following: lamb survival, lamb weight at birth, preweaning, weaning and postweaning, ewe weight, and ewe age. Lamb survival was defined as the number of lambs recorded as alive within 24 h of birth and alive at weaning, separated by birth type. Only lamb weight records from flock-year records for which at least half of lambs with a birth weight also had a postweaning weight recorded were retained. Birth weight was defined as the live weight of the lamb taken within 24 h of birth; only lambs with a birth weight between 2 and 9 kg were retained. Weaning weight was the weight taken > 65 and ≤ 120 d of age and weighing between 20 and 50 kg. Postweaning weight was the weight measured > 120 and ≤ 365 days of age and weighing between 25 and 65 kg. Pre- and postweaning lamb growth rates were also calculated. Preweaning lamb growth rate was calculated as weaning weight less birth weight divided by the age of lamb at preweaning weight; postweaning lamb growth rate was calculated as the postweaning weight less the weaning weight divided by the difference in days between weight recording at weaning and postweaning. For pre- and postweaning, only growth rate records between 50 and 650 g/d were retained. Ewe age at lambing was categorised as 2, 3, 4, 5, and ≥ 6 years, and ewe weight records at lambing between 50 and 100 kg were retained. Litter size per ewe and ewe weight for varying age classes were compared within flock-year records. Following all data edits, the remaining data for analysis were as follows: 1 139 flock-year-birth type lamb survival, 36 839 birth weight, 25 099 preweaning weight, 19 106 postweaning weight, 25 099 ewe litter size, and 4 075 ewe weight records.

Statistical analysis

The association between the key variables for litter size, ewe age at lambing, birth type, and rearing type and production factors (such as lamb survival, lamb birth weight, etc.) were analysed using linear mixed models in PROC MIXED (SAS Inst. Inc., Cary, NC) in a series of analyses (described below), where P = 0.01 was used as the threshold significance levels for entry and exit of variables from the model.

For flock traits, the model employed was as follows:

$Y_{ijk} = \mu + LitterSize_i + Flock_j + Year_k + e_{ijk}$.

where Y_{ijk} is the dependent variable of barren rate or proportions of lambs of different birth type, μ is the population mean, LitterSize$_i$ is the litter size of the ewe (i = 1, 2, 3, or 4), Flock$_j$ is the random effect of flock of recording (j = 1,. . .., 93), Year$_k$ is the year of recording (k = 2014,. . .. . ., 2020), and e_{ijk} is the residual term.

For the lambing traits, the model employed was as follows:

$Y_{ijklm} = \mu + EweAge_i + BirthType_j + BirthWeight_k + Flock_l + Year_m + e_{ijklm}$.

where Y_{ijklm} is the dependent variable of lamb birth weight or lamb survival, μ is the population mean, $EweAge_i$ is the age category of the ewe (i = 2, 3, 4, 5, or ≥ 6), $BirthType_j$ is the birth type of the litter (j = 1, 2, 3, or 4), $BirthWeight_k$ is the lamb birth weight and was only included when lamb survival was the trait under investigation (k = 2 to 9 kg), $Flock_l$ is the random effect of flock of birth (l = 1,…., 256), $Year_m$ is the year of birth (m = 2014,…….. , 2020), and e_{ijklm} is the residual term.

For lamb performance traits, the model employed was as follows:

$Y_{ijklm} = \mu + EweAge_i + BirthType_j + RearType_k + Flock_l + Year_m + e_{ijklm}$.

where Y_{ijklm} is the dependent variable of lamb weight at preweaning, weaning or postweaning or postweaning growth rates, μ is the population mean, $EweAge_i$ is the age category of the ewe (i = 2, 3, 4, 5, or ≥ 6), $BirthType_j$ is the birth type of the litter (j = 1, 2, 3, or 4), $RearType_k$ is the rearing type of the litter (k = 1 or 2), $Flock_l$ is the random effect of flock of birth (l = 1,…., 92), $Year_m$ is the year of birth (m = 2014,……., 2020), and e_{ijklm} is the residual term.

For ewe performance traits, the model employed was as follows:

$Y_{ijk} = \mu + LitterSize_i + Flock_j + Year_k + e_{ijk}$.

where Y_{ijk} is the dependent variable of ewe weight or litter size at lambing, μ is the population mean, $LitterSize_i$ is the litter size of the ewe (i = 1, 2, 3, or 4), $Flock_j$ is the random effect of flock of recording (j = 1,…., 93), $Year_k$ is the year of recording (k = 2014, ……., 2020), and e_{ijk} is the residual term.

Bio-economic model

The bio-economic model used in this analysis is an existing model previously validated by Farrell et al. (2019) and used to simulate New Zealand ewe flocks investigating physical and economic changes from various breeding and management strategies (e.g. in Farrell et al., 2021). Full workings, including all parameters and equations for the base model, are available online (Farrell, 2020), and the flock dynamics module was further developed for the current analysis using field data as explained in this materials and methods section. The model is a system-dynamics model developed using STELLA v.1.8 (https://www.iseesystems.com/store/products/stella-architect.aspx), and component modules used in this analysis were flock dynamics (including sheep sale numbers), feed demand, and economics (Fig. 1). The model included sheep as stocks according to sex and age, with flows between stocks according to birth, ageing, death, and culling (detailed further in Supplementary Material S1). The feed demand module was informed by sheep numbers from the flock dynamics module, production levels from field data, and energy demand equations (detailed further in Supplementary Material S1) from Commonwealth Scientific and Industrial Research Organisation (2007) and Nicol and Brookes (2007). Energy demand (in megajoules of metabolisable energy; **MJ ME**) was estimated on a fortnightly basis for maintenance, weight gain and loss, gestation, lactation, and wool growth for all applicable sheep classes on-farm, which were summed to estimate annual feed demand. The economics module was informed with sheep sale numbers from the flock dynamics module and with concentrate feeding levels from the feed demand module as well as market values for prices and costs.

Flock

The modelled flock was a self-replacing lowland flock lambing annually in spring, grazing pasture from lambing (March) until mid-gestation (December), and spending the winter months indoors feeding on grass silage and concentrate. Average values from the Irish National Farm Survey (**NFS**) data (Teagasc, 2021) informed the main characteristics of the flock, consisting of 75 breeding ewes at a stocking rate of 7.86 ewes per ha. The ewe flock was comprised of weaned lambs until sale or reaching one year old, nulliparous one-year-old females, bred two- to six-year-old ewes, and rams on-farm at a rate of one ram per 35 ewes (Bohan et al., 2017). The ratio of deaths:culling in ewes ≥ two years old was maintained at a ratio of 24:76 for all replacement rates (25 % replacement rate for the main sensitivity analysis), consistent with NFS data (Teagasc, 2021).

Gross margin

Flock gross margin was used in this analysis as an indicator of profit, as no assumptions were made around farm financial structure. Gross margin for the flock was estimated as total income from sales of sheep and wool less total direct costs. Sheep sales included cull ewes and lambs sold directly to slaughter (Table 1). Prices received for cull ewes were on a per head basis and based on average values from NFS data on self-replacing, finishing lowland flocks from 2016 to 2020 (Teagasc, 2021). Prices received for lamb sales were based on weekly published values per kg of carcass, with values averaged each calendar week across June 2016 to June 2020 (BordBia, 2021), and carcass weights of 20 kg (Earle et al., 2017a) were assumed. In typical Irish lowland sheep meat production systems, ewes rear a maximum of two lambs each and farmers work in off-farm employment with limited time resource for cross-fostering or artificially rearing excess triplets and quadruplets. Thus, excess lambs born as triplets and quadruplets were assumed to be sold within 1 week of birth for €20 per head for rearing on another farm, with ewes each rearing a maximum of two lambs (Gottsetin, 2017). Income from wool sales was estimated from a price received of €0.66 per kg of greasy wool, the average price from the period of 2016 to 2020 during which the wool price fell from €1.03 to €0.17 per kg (Teagasc, 2021), and annual wool production of 3.5 kg per mature ewe was assumed (Teagasc, 2021). Total direct costs per hectare were sourced from the NFS data (Teagasc, 2021) at €423 per ha (Table 1), for an average stocking rate of 7.86 ewes per ha (ewes ≥ two years old), resulting in a base level of total direct costs of €3 325. Concentrate feeding levels were 19, 24, and 32 kg DM per ewe (Teagasc, 2017) for late gestation feeding of ewes carrying one, two, or ≥ three lambs, respectively, and concentrate feed had a cost of €0.32 per kg DM (Teagasc, 2021).

Modelling sensitivity analyses

The flock was modelled as 75 breeding ewes and 25 one-year-old ewes which were not bred, i.e. with a flock replacement rate of 25 % of ewes aged ≥ one year old. The sensitivity analysis was undertaken to explore the effect of flock litter size on the production of weaned lamb, lamb for sale, and flock gross margin. Flock litter size was varied from 1.00 to 2.45 at increments of 0.05 lambs born per ewe lambing. A litter size of 2.45 was assumed to be the biological limit based on the field data.

While varying litter size, flock replacement rate and therefore flock age structure remained constant, with a replacement rate of 25 % to match the average replacement rate of flocks in the NFS data (Teagasc, 2021). Ewe age has previously been identified to affect lamb production (Keady et al., 2014; Farrell et al., 2019; Shorten et al., 2020) and was explored in the field data. Therefore, as a secondary analysis, flock replacement rate was modelled at 20 %, 25 %, 30 % and 35 %, in combinations with litter sizes of 1.30, 1.80, and 2.30 to represent flocks with a range of replacement rates and lamb production levels. Flock replacement rate was considered as the proportion of the flock as nulliparous one-year-old

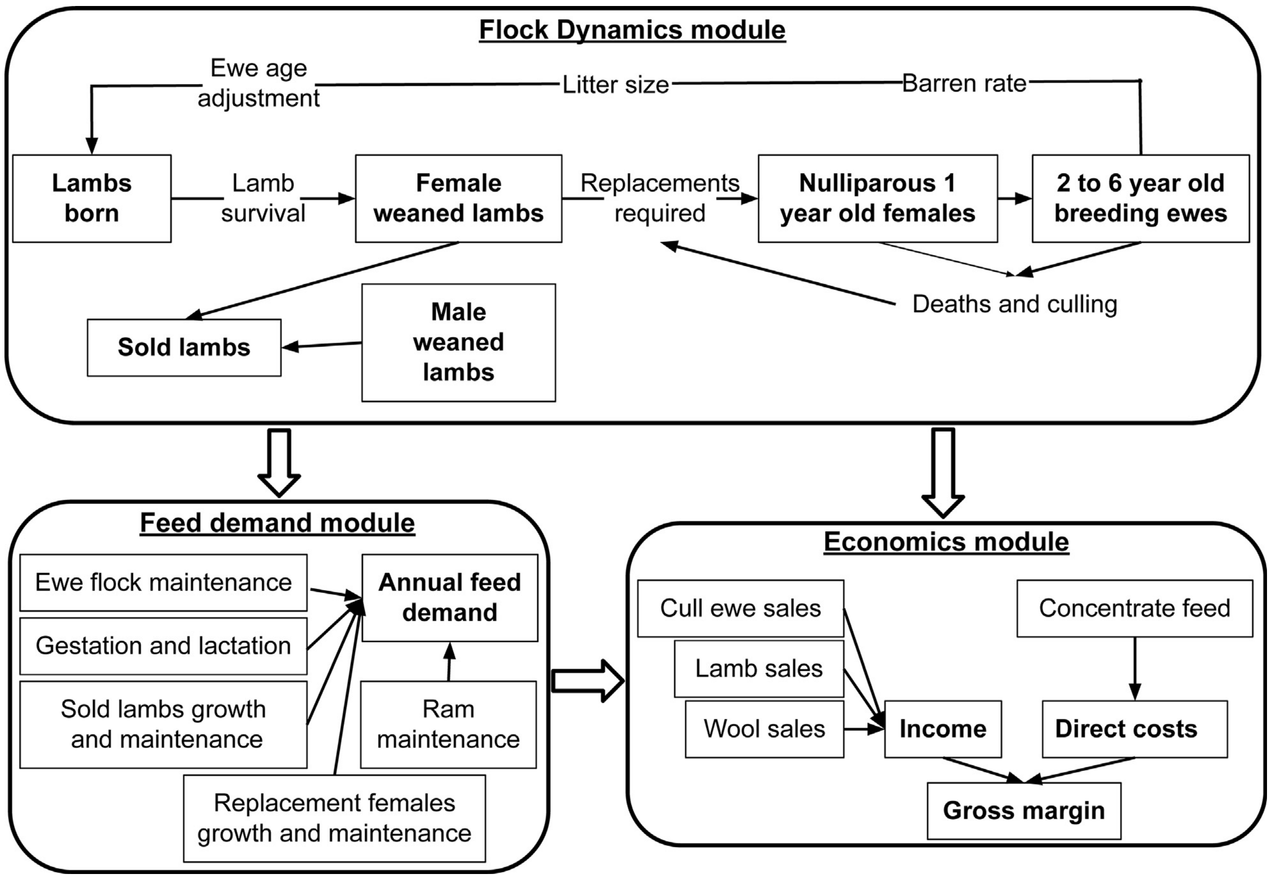

Fig. 1. Simplistic diagram of the bio-economic model of a ewe flock in a sheep enterprise, including the flock dynamics, feed demand, and economics component modules.

Table 1
Values used to predict ewe flock income and costs for a sheep enterprise, with all cull ewes and lambs sold direct to slaughter.

Item	Value	Units	Source
Sales			
Cull ewe	88.06	€ per head	Teagasc, 2021 [1]
Single-reared lamb	4.71	€ per kg carcass	BordBia, 2021 [2]
Twin-reared lamb	4.72		
Excess lambs [3]	20.00	€ per head	Gottsetin, 2017
Wool	0.66	€ per kg greasy	Teagasc, 2021
Costs			
Direct costs	423.00	€ per ha	Teagasc, 2021
Concentrates	0.32	€ per kg DM	

[1] Survey data averaged for 2016 to 2020 inclusive.
[2] Weekly published lamb prices averaged per week from June 2016 to June 2020.
[3] Excess lambs born as triplets and quadruplets were sold within a week after birth.

ewes in this analysis, with replacement females bred to lamb as two year olds.

Results

Only key variables (flock litter size, lamb birth and rearing types, and ewe age) identified as statistically significant for production factors were included in the model as linear equations or in look-up tables as shown in Table 2. Losses of foetuses between pregnancy scanning and lambing were less than 1 % in flock records and were not input to the bio-economic model. Lamb survival decreased at higher birth types (Supplementary Table S1),

Table 2
Bio-economic model inputs (as multivariate linear equations) derived from analysis[1] of field data from Irish commercial sheep flocks.

Factor and key variable	Equation parameters in model	
Flock barren rate (%)		
Intercept		13.47
Litter size		−4.37
Birth weight (kg)		
Intercept	3.80	
Birth type	1	1.87
	2	1.03
	3	0.35
	4	−0.11
Dam age	2	−0.39
	3	−0.12
	4	−0.02
	5	0.01
	6	0.00
Preweaning growth (g/day)		
Intercept		268.6
Rearing type	1	45.4
	2	5.8
Dam age	2	−14.2
	3	2.9
	4	8.2
	5	6.2
	6	0.0
Postweaning growth (g/day)		
Intercept		200.9
Rearing type	1	−2.4
	2	−3.0

[1] Association determined using linear mixed models in PROC MIXED ($P < 0.01$).

while lamb weights and growth rates decreased with higher birth and rearing type (Table 2). Lamb survival was included in the model in a look-up table as least-square means of 84.9, 83.2, 75.8, and 74.8 % for lambs born in litters of 1, 2, 3, and 4, respectively (Supplementary Table S1). Relative ewe reproductive rate and weight increased to a ewe age of 4 years. The relative litter size adjustments were 0.94, 1.00, 1.05, 1.06, and 1.05 for ewes aged 2, 3, 4, 5, and ≥ 6 years, respectively. The relative live weight adjustments were 0.92, 1.02, 1.06, 1.05, and 1.07 for ewes aged 2, 3, 4, 5, and ≥ 6 years, respectively.

Outputs from the bio-economic model showed that the proportion of lambs born as singles decreased as flock litter size increased, while the proportion born as multiples increased with the proportion of twins peaking at 67 % of lambs with a flock litter size of 1.85 lambs born per ewe lambing (Fig. 2). Flock barren rate decreased from 9.1 % to 2.8 % as flock litter size increased from 1.00 to 2.45 and average lamb survival for the flock decreased from 85 % to 80 % due to increasing proportions of lambs born as multiples with lower survival (Fig. 3). With excess triplet and quadruplet lambs sold within a week after birth, flock weaning rate (lambs weaned per ewe presented for breeding) increased until it plateaued at approximately 1.54 with a flock litter size of 2.20. At a flock litter size of 2.20, triplet and quadruplet lambs combined accounted for 31 % of lambs born; of the 132 surviving lambs (1.76 lambs potentially weaned per ewe), 117 lambs were weaned in the flock and 15 lambs from litters of 3 or 4 were sold within a week after birth. The weight of lamb weaned per ewe presented for breeding and feed demand per kg of lamb carcass sold also plateaued at approximately 65 kg and 433 MJ ME, respectively, with a flock litter size of 2.20 (Fig. 4). Feed demand for flock maintenance including replacements was constant across litter sizes, while feed demand for reproduction and lambs destined for sale increased, therefore the proportion of feed demand accounted for by flock maintenance decreased from 76 % with a flock litter size of 1.00–70 % with a flock litter size of 2.45 (Fig. 5). Without feed demand for lactation to feed excess lambs born as triplets and quadruplets, total flock feed demand increased from 749 420 MJ ME with a flock litter size of 1.00–814 029 MJ ME with a flock litter size of 2.45, representing a 9 % increase in total annual flock feed demand.

Income from lamb sales constituted the majority of flock income, thus flock income increased as numbers of lamb weaned and sold increased with increasing flock litter size, and flock income started to plateau at €11 900 with a flock litter size of 2.20 (Fig. 6). Increases in direct costs were relatively small compared with increases in income, thus flock gross margin increased with increasing flock litter size, appearing to plateau around a flock litter size of 2.20 when the gross margin was €8 500. Gross margin increased on average €52 per 0.01 increment in litter size (per 1 % change in the rate of lambs born per ewe lambing) until litter size

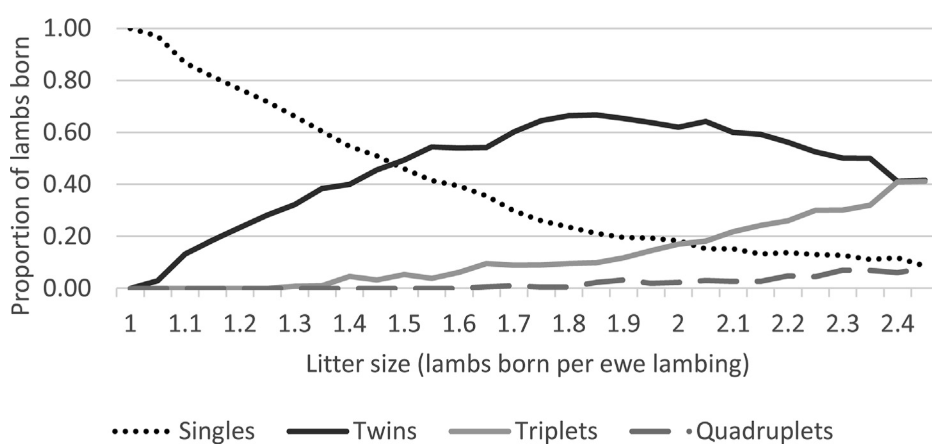

Fig. 2. Proportions of lamb born categorised as single, twins, triplets, and quadruplets in a sheep flock with increasing rate of lambs born per ewe lambing (litter size).

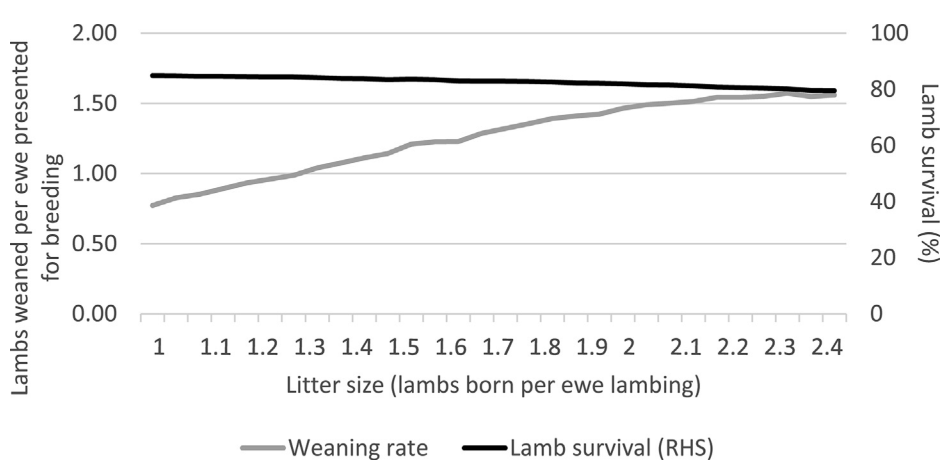

Fig. 3. Sheep flock weaning rate (lambs weaned per ewe presented for breeding) and lamb survival (right-hand side axis) with increasing flock litter size.

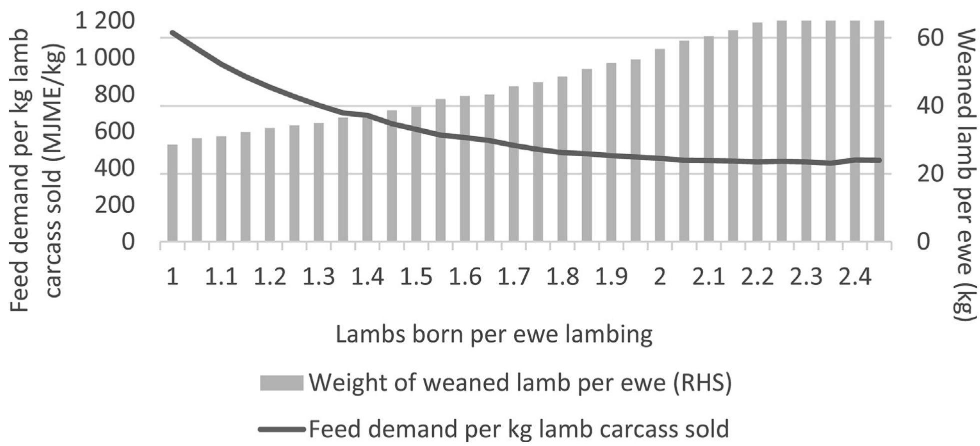

Fig. 4. Total annual sheep flock feed demand (in megajoules of metabolisable energy; MJ ME) per kg of lamb carcass sold and total flock weight of weaned lamb (right-hand side axis) with increasing flock litter size.

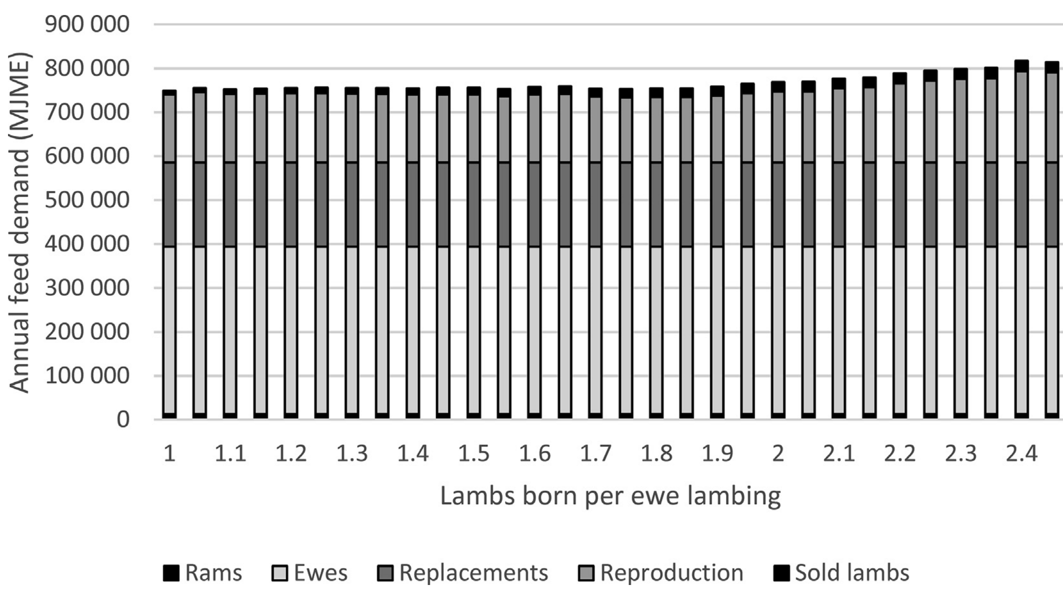

Fig. 5. Annual sheep feed demand (in megajoules of metabolisable energy; MJ ME) for rams, mature ewes, nulliparous replacements, ewe reproduction (including both lactation and gestation), and lambs destined for sale with increasing flock litter size.

was 2.20. As litter size increased above 2.20, the marginal change in gross margin was relatively small, averaging increases of €12 per 0.01 increment in litter size.

Replacement rate

In this study, replacement rate was modelled as varying from 20 % to 35 % for a flock of 75 breeding ewes, thus total flock size (including nulliparous one-year-old ewes) varied from 95 to 110 total ewes (Table 3). Assuming an average flock litter size of 1.80, increasing the flock replacement rate from 20 % to 35 % resulted in the average flock age decreasing from 3.70 to 2.99 years, with reductions in average ewe weight from 74.30 to 72.20 kg and reductions in weaning rate, from 1.36 to 1.31 lambs weaned per ewe presented for breeding. The decrease in ewe weight reduced the feed demand for maintenance of the breeding ewes, however, as replacement rate increased from 20 % to 35 %, the proportion of feed demand accounted for by unproductive replacement young stock increased, such as from 22 % to 31 % with a flock litter size of 1.30, and thus, the proportions of feed used more directly for production (reproduction and sold lambs) decreased. Increased feed demand incurred by higher requirements for replacements increased total flock annual feed demand by 21 % as replacement rate increased from 20 % to 35 %. The effects of ewe age on lamb birth and weaning weights were small relative to the effect of birth and rearing type, and lamb weights decreased by < 0.5 kg as replacement rate increased from 20 % to 35 %.

With a lower lamb weaning rate and more ewe lambs retained for flock replacement requirements, numbers of sold lambs and lamb income decreased with higher replacement rates, for a given litter size (Table 3). Income from cull ewes increased with higher replacement rates, from €1 320 to €2 290 with a flock litter size of 1.30 and replacement rates of 20 % and 35 %, respectively. However, lamb income constituted the majority of total income, and thus, total income decreased from €7 450 to €6 950 as replacement rate increased from 20 % to 35 %. Total direct costs were assumed to be constant across a given litter size, therefore, flock gross margin decreased with increasing replacement rate, for example with a flock litter size of 1.30 gross margin decreased from €3 776 to €2 916 with replacement rates of 20 % and 35 %, respectively.

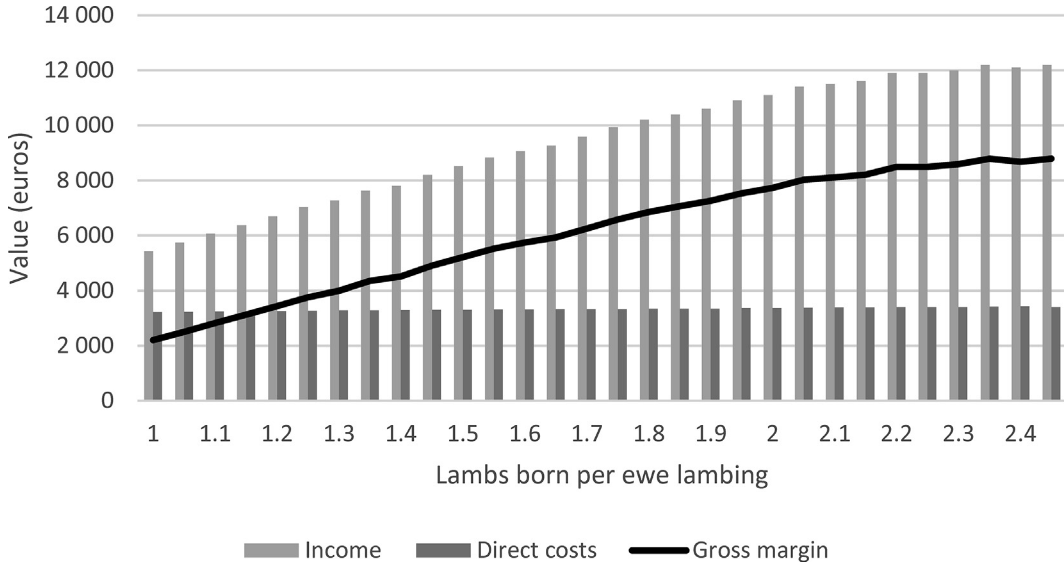

Fig. 6. Total sheep flock income, direct costs, and gross margin with increasing flock litter size.

Table 3
Model outputs for a ewe flock in a sheep enterprise with varying replacement rates and litter size.

Litter size	1.3				1.8				2.3			
Replacement rate (%)	20	25	30	35	20	25	30	35	20	25	30	35
Sheep numbers												
Total flock (head)	95	100	105	110	95	100	105	110	95	100	105	110
Breeding ewe age (years)	3.70	3.45	3.22	2.99	3.70	3.45	3.22	2.99	3.70	3.45	3.22	2.99
Breeding ewes (head)	75	75	75	75	75	75	75	75	75	75	75	75
Replacement ewe lambs (head)	20	25	30	35	20	25	30	35	20	25	30	35
Production												
Breeding ewe weight (kg)	74.3	73.7	73.0	72.2	74.3	73.7	73.0	72.2	74.3	73.7	73.0	72.2
Weaning rate (%)[1]	1.00	0.99	0.99	0.97	1.36	1.36	1.36	1.31	1.55	1.55	1.54	1.52
Weaned lambs (head)	75	74	74	73	102	102	102	98	116	116	116	114
Lamb birth weight (kg)	5.37	5.35	5.32	5.30	4.92	4.90	4.87	4.85	4.60	4.58	4.55	4.53
Lamb weaning weight (kg)	35.43	35.38	35.18	35.05	33.45	33.36	33.15	33.05	32.99	32.89	32.69	32.60
Lambs sold prime (head)[2]	55	51	45	38	83	78	72	65	97	92	86	79
Lambs sold as pets (head)[3]	0	0	0	0	4	4	4	4	18	18	18	18
Proportion of feed demand												
Mature ewes	0.51	0.50	0.50	0.49	0.52	0.50	0.50	0.49	0.48	0.47	0.47	0.46
Replacements[4]	0.23	0.25	0.28	0.31	0.22	0.25	0.28	0.31	0.21	0.24	0.27	0.31
Sold lambs	0.02	0.02	0.01	0.01	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.02
Reproduction[5]	0.22	0.21	0.19	0.18	0.21	0.20	0.18	0.17	0.26	0.24	0.21	0.20
Rams	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01
Economics (€)												
Lamb sale income	5 950	5 430	4 810	4 120	8 920	8 390	7 740	7 010	10 700	10 200	9 520	8 760
Cull ewe sale income	1 320	1 660	2 030	2 290	1 300	1 630	2 030	2 290	1 320	1 620	2 000	2 260
Wool income	180	180	180	180	180	180	180	180	180	180	180	180
Total income	7 450	7 270	7 020	6 590	10 400	10 200	9 950	9 480	12 200	12 000	11 700	11 200
Total direct costs	3 854	3 854	3 854	3 854	3 912	3 912	3 912	3 912	3 965	3 965	3 965	3 965
Gross margin	3 776	3 596	3 346	2 916	6 668	6 468	6 218	5 748	8 415	8 215	7 915	7 415

[1] Lambs weaned per ewe presented for breeding.
[2] Lambs sold directly to slaughter at target carcass weight of 20 kg.
[3] Excess triplet and quadruplet lambs sold for rearing on another farm.
[4] Female flock replacement animals, from weaning until turning two years old.
[5] Including both gestation and lactation.

Discussion

Production and feed demand

Overall, the model outputs based on the field data analysis shown in Fig. 2 and Table 2 were similar to previously published values, thus the simulation was assumed to be a realistic representation of a sheep meat production system. Proportions of lambs of differing birth types with increasing litter size are shown in Fig. 2 and were very similar to those previously reported for New Zealand flocks (Amer et al., 1999; Shorten et al., 2021). Flock barren rates reported in the current study were within the range of previously reported values in Irish flocks (Keady et al., 2009, 2014; Bohan et al., 2017), and lamb survival decreased with higher lamb birth types which agreed with previous findings internationally (Keady et al., 2009; Earle et al., 2017a; Shorten et al., 2021).

Although the flock average rate of survival only decreased marginally with increasing flock litter size, at a higher flock litter size, this translated to greater numbers of lambs lost. For example, 10 lambs were lost preweaning with a flock litter size of 1.00 (lamb survival was 85 %) and 37 lambs were lost with a flock litter size of 2.45 (lamb survival was 80 %; Fig. 3). Irish farmlet experiments have observed lamb mortality rates to 5 weeks old of 10.1 % to 13.8 % (Keady et al., 2009), and mortality rates to approximately 160 days old of 15.9 % (Fetherstone et al., 2022), similar to rates in the field data explored in the current study. Previous analyses have shown lamb survival to be an important factor in flock production and profitability internationally (Byrne et al., 2010; Young et al., 2011, 2014; Shorten et al., 2021), and increased rates of lambs lost before weaning also reduce the number available for sale or selection as replacement ewe lambs.

Birth and weaning weights were lighter for lambs of higher birth and rearing types, falling within the range of weights previously reported in Irish data (Keady et al., 2009; McGovern et al., 2020; Table 2). Despite higher proportions of twin-reared lambs with lower weaning weights, as flock litter size increased, the total weight of lamb weaned per ewe presented for breeding increased (Fig. 4). Further, total flock feed demand per kg of lamb carcass sold decreased with increasing flock litter size, indicating greater production efficiency. The total weights of lamb weaned per ewe presented for breeding observed in an Irish farmlet study were 47 and 51 kg of weaned lamb per ewe with flock litter sizes of 1.87 and 2.07, respectively (Earle et al., 2017a). When compared with the same weaning rates from the current sensitivity analysis, 51 and 59 kg of lamb were weaned per ewe presented for breeding with flock litter sizes of 1.85 and 2.05, respectively (Fig. 4). The greater lamb weaned per ewe in the present study compared with Earle et al. (2017a) can be explained by the heavier weaning weights reported in the current analysis. The relationship shown between flock litter size up to 1.75 lambs born per ewe lambing and total weight of lamb weaned per ewe in data from nine New Zealand flocks (Shorten et al., 2021) were also very similar to the current analysis, i.e. around 43 kg of lamb weaned per ewe with a flock litter size of 1.60 in Shorten et al. (2021) and the current study (Fig. 4). Although there was minimal (<1 g/day) difference in the postweaning growth rates of lambs reared as singles and twins in the field data (Table 2), the heavier weaning weights of single-reared lambs resulted in their sale on average 24 days earlier than twin-reared lambs. Reduced age at slaughter results in lambs consuming less feed for maintenance and their total feed demand is therefore less. However, output from the sensitivity analysis indicates a higher proportion of twin-reared lambs was more efficient in reducing both flock feed demand per kg of lamb carcass sold and the proportion of feed demand used for flock maintenance, due to the dilution effect of greater lamb production. The total weight of lamb weaned per ewe and total flock feed demand per kg of lamb carcass sold both improved with increasing litter size but plateaued at approximately 2.20 lambs born per ewe lambing (Fig. 4). This plateauing effect was driven by the additional lambs being born in large litters (i.e. triplets or quadruplets), with a third of triplets and half of quadruplets sold within a week after birth. The results indicate there may be a limit to the efficiency gains from increasing flock litter size for sheep production systems selling excess triplet and quadruplet lambs within a week of birth for a relatively low price, which in this analysis appeared to occur at 2.20 lambs born per ewe lambing. Only 14 % of flock-year records in the field data had litter sizes of $\geq$ 2.20 lambs born per ewe lambing. This flock litter size is well above the national average flock litter size in Ireland, averaging a flock litter size of 1.65 for lowland flocks (Shiels et al., 2022), and in the United Kingdom, with a national average flock litter size of 1.70 (Agriculture and Horticulture Development Board, 2022). The flock litter size of 2.20 lambs born per ewe lambing is also likely above the levels achieved by most producers in alternative sheep meat production systems such as extensive systems in New Zealand as indicated by national average weaning rate of 1.35 lambs weaned per ewe presented for breeding (Farrell, 2020). The model output from the sensitivity analysis exploring the effects of increasing flock litter size will therefore be useful for sheep meat producers internationally.

Economics

Increases in direct costs at higher flock litter sizes were assumed to be small. Irish farmlet experimental data suggest weaning rate can increase from 1.50 to 1.80 lambs weaned per ewe without large increases in purchased feed, with the incurred increase in feed demand addressed through increased pasture utilisation during spring and feeding concentrates during late gestation (Earle et al., 2017b). The flock was assumed to be stocked at 7.86 ewes/ha, approximately the national average (Teagasc, 2021). Modelling of recent trial data suggests there is scope for large production increases, such as increasing stocking rate from 10 to 14 ewes/ha, through increasing pasture growth and utilisation with relatively small increases in purchased feed (Bohan et al., 2018). Therefore, it was assumed the modelled flock stocked at 7.86 ewes/ha could meet the additional feed demand required from increased litter size through increased pasture growth and utilisation and concentrate supplementation during late gestation, thereby resulting in relatively small increases in direct costs. Gross margin per ewe was reported to average €78 for Irish flocks in 2019, with an industry average weaning rate of 1.37 (Teagasc, 2021), while the current sensitivity analysis predicted the modelled flock to have a gross margin of €91 per ewe with a weaning rate of 1.36 using economic data from 2016 to 2020 (Fig. 6). This suggests the current modelling was representative of the economic performance of lowland Irish farms and quantification of increases in gross margin with increasing litter size can inform farmers of appropriate levels of spending on breeding and labour to increase litter size.

Flock gross margin increased with increasing flock litter size, consistent with previous international research showing higher lambing rates to increase flock profitability (Young et al., 2011; Bohan et al., 2018; Farrell, 2020; Fig. 6). However, previous analyses did not model as large a range of litter sizes as in the current sensitivity analysis, which showed diminishing returns in gross margin at high litter sizes (i.e. >2.20 lambs born per ewe lambing). The excess triplet- and quadruplet-born lambs sold for rearing on another farm incurred costs for concentrate feeding of their dams during pregnancy and were sold for less than a quarter of the value of lambs grown to slaughter weight on-farm. Therefore, the added value of additional lambs was low when the additional lambs were triplets and quadruplets. The sensitivity analysis output indicates small marginal increases or even reductions in gross margin as flock litter size increased above 2.20 lambs born per ewe lambing. These results demonstrate that the value of increasing the numbers of lambs born diminished at very high litter sizes. However, with the potentially 'optimal' litter size of 2.20 lambs born per ewe lambing for sheep production systems selling excess triplet and quadruplet lambs within a week of birth being well above current industry average levels, increasing flock fecundity should be a priority for most sheep meat producers.

For sheep meat production systems such as that modelled in this study, of small scale with winter housing and farmers usually employed off-farm, the assumptions of none or minimal cross-fostering of lambs within the flock and sale of excess lambs within a week after birth were appropriate. At litter sizes of more than 2.00 lambs born per ewe lambing, it was assumed $\geq$ 10 excess triplet lambs were sold within a week after birth as there were only

11 single-bearing ewes in the flock on which to potentially foster lambs. Cross-fostering a few lambs within the flock would increase flock weaning rate compared with output from the current study; however, there are limited opportunities for cross-fostering at these high litter sizes due to timing and labour constraints during lambing. In systems similar to that modelled with ewes rearing a maximum of two lambs, there is an option to artificially rear lambs as an alternative to early sale. The cost of artificially rearing lambs has been estimated at €53 to €70 per lamb in Ireland depending on the mix of milk replacer and grass fed (Gottsetin, 2017) and €21 per lamb excluding labour costs in New Zealand (Beef + Lamb New Zealand, 2017). These costs and additional labour requirements may be justifiable to farmers with current high prices for lambs at slaughter; artificially rearing lambs for high sale prices would be expected to increase the flock litter size at which gross margin plateaus and could be modelled in future studies.

Production systems in which a proportion of triplet-bearing ewes with sufficient milk supply are allowed to rear three lambs may also increase the litter size at which gross margin plateaus. In a more intensive, housed system such as that modelled the additional concentrate feed and labour costs incurred as well as the lower per lamb production for ewes rearing- three lambs would need to have a smaller effect on gross margin than the additional income generated from the sale of the third lamb. In more extensive grazing systems without housing and with limited concentrate feeding, choice of paddock and availability of high quantity and quality of pasture at low stocking rates are essential for ewes rearing multiple lambs, where reductions in lamb survival rates with increasing proportions of triplet and quadruplet lambs may be greater than was identified in the Irish field data (Beef + Lamb New Zealand, 2017). Varying rates of success for ewes rearing three lambs have previously been observed, and there are risks incurred for subsequent years' production without careful management (Gottsetin, 2017). In pasture-based systems with limited supplementary feeding where feed supply is fixed on a per hectare basis, the increased feed demand from increasing flock litter size may necessitate reductions in breeding ewe numbers, as explored in Farrell et al. (2021) with lower litter sizes than investigated in the current analysis. As flock litter size increases, the value of producing the additional lighter lambs with lower survival relative to the opportunity cost of farming fewer ewes would affect the litter size at which gross margin plateaus.

Litter size is key to flock management for all sheep meat production systems, as ewes bearing different litter sizes are typically managed separately in late gestation and lactation. As flock litter size increases, trans-abdominal ultrasound scanning to determine the number of foetuses carried by each ewe increases in importance for all sheep production systems. Adequate feeding of ewes bearing different litter sizes is imperative for the management of lamb birth weight, ewe milk supply, and lamb survival (McGovern et al., 2015). A ewe litter size of 2.00 lambs has been cited as the most profitable situation for French farmers (SanCristobal-Gaudy et al., 2001), similar to the findings of the current study. A study of the genetic components of litter size in French ewes investigated the possibility of maintaining the occurrence of 'intermediate' size litters per ewe over 'extreme' sizes as flock fecundity increases through canalising selection (SanCristobal-Gaudy et al., 2001). Currently, farmers have limited control over the incidence of lambs born as triplets and quadruplets at very high flock litter sizes, and it would be expected for gross margin to eventually plateau with higher litter sizes in most systems due to lower lamb survival and growth rates as well as the increased management and feeding requirements. Farmers already achieving very high flock litter size could thus shift production priorities from fecundity to improving lamb survival and growth rates.

Replacement rate

The effect of ewe age was most evident in ewe weight, which decreased by 2.1 kg as replacement rate increased from 20 % to 35 % and thus reduced feed demand for maintenance of breeding ewes (Table 3). Similarly, previous studies have shown that ewe weight (Coop, 1973; McHugh et al., 2019) and litter size (Turner et al., 1968; Keady et al., 2014; Shorten et al., 2020) increase until approximately 5 years of age, although differences in litter size between ewes of differing age were larger in the previously published work than those calculated in the present study. Total annual sheep feed demand increased by 21 % as replacement rate increased from 20 % to 35 % (Table 3), a larger increase than was incurred by increased litter size from 1.00 to 2.45 lambs born per ewe lambing (feed demand increased by 9 %; Fig. 5). Similarly, an Irish farmlet experiment found proportionally larger increases in flock feed demand from increases in stocking rate compared with increasing flock prolificacy (Earle et al., 2017b). Results from Earle et al. (2017b) and the current analysis highlight the relatively smaller feed demand of increasing litter size and flock productivity compared with the inefficiencies of flocks with large proportions of unproductive replacement young stock.

The decrease in income from lamb sales with higher replacement rates was larger than the increased income from cull ewe sales (Table 3). Reductions in gross margin per 1 % change in replacement rate (averaging €62) appeared to be similar to the value of incremental increases in gross margin as litter size increased until flock litter size reached 2.20, showing replacement rate to also be important for flock economic performance. Previous bio-economic modelling has also predicted lower profitability with higher replacement rates in New Zealand (Farrell, 2020); however, the model assumptions resulted in ewe age having a larger effect on production and profit compared with the current study. Relative to published data from New Zealand and Australia (death rates of 2.7–27 %), relatively low ewe death (3–10 %) and flock replacement rates have been reported for both the United Kingdom and Ireland (Bohan et al., 2017; Flay et al., 2021). The lower death rates of Irish ewes may be due to less incidence of ewe death around lambing when lambing indoors and the NFS data suggest Irish farmers are achieving low rates of ewe attrition relative to sheep production systems internationally. This analysis focused on the impact of flock age from variation in flock replacement rates on lamb production and gross margin. Previous analysis of field data from Irish flocks highlighted the lack of detailed information on death and culling reasons (McLaren et al., 2020). Future investigation into factors driving replacement rates in Irish flocks could identify how increasing litter size might affect ewe death rate or subsequent years' production and cull rates.

Conclusions

Lamb production, production efficiency, and gross margin all increased with increasing flock litter size; however, above a litter size of 2.20 lambs born per ewe lambing marginal increases for all of these model outputs began to plateau. In accordance with typical practice for the system modelled, ewes were assumed to rear a maximum of two lambs each, with excess triplet and quadruplet lambs sold for rearing on another farm. The relatively low value of these additional lambs produced for litter sizes above 2.20 lambs born per ewe lambing was illustrated by gross margin increasing on average €52 per 0.01 increment in litter size (per 1 % change in the rate of lambs born per ewe lambing) up to a litter size of 2.20, above 2.20, the changes in gross margin averaged €12 per 0.01 increment in litter size. Results suggest the benefits of very high litter sizes to be small and quantification of implications for flock productivity, and gross margin is useful for international sheep meat production industries, including informing production priorities. The secondary analysis showed higher flock replacement rates to have lower production and gross margin, indicating the importance of replacement rate for flock economic performance, driven largely by requirements for replacement ewe lambs rather than by the effects of ewe age.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2022.100640.

Ethics approval

Not applicable.

Data and model availability statement

None of the data were deposited in an official repository; the Irish sheep breeding database is managed and held by Sheep Ireland (https://www.sheep.ie/). Full workings for the base bio-economic model including all parameters and equations are available online (https://mro.massey.ac.nz/handle/10179/16058).

Author ORCIDs

Lydia Farrell 0000-0003-1905-9515.
Philip Creighton 0000-0001-6106-4436.
Alan Bohan 0000-0001-7364-9968.
Fiona McGovern 0000-0003-4471-5078.
Noirin McHugh 0000-0002-3105-8796.

Author contributions

Lydia Farrell: conceptualisation, methodology, investigation, formal analysis, writing – original draft, and writing – review and editing. **Philip Creighton**: validation, and writing – review and editing. **Alan Bohan**: validation, and writing – review and editing. **Fiona McGovern**: validation, and writing – review and editing. **Noirin McHugh**: methodology, investigation, formal analysis, and writing – review and editing.

Declaration of interest

None.

Acknowledgements

None.

Financial support statement

This work was supported by the Irish Department of Agriculture, Food and Marine Research Fund MultiRepro (16/S/696) held by NM and supported by ERA-GAS (2019EN202; GrassToGas) held by FM.

References

Agriculture and Horticulture Development Board, 2022. Lamb: cost of production benchmarks. Retrieved on 28 February 2022 from https://ahdb.org.uk/lamb-cost-of-production-benchmarks.

Amer, P., McEwan, J., Dodds, K., Davis, G., 1999. Economic values for ewe prolificacy and lamb survival in New Zealand sheep. Livestock Production Science 58, 75–90. https://doi.org/10.1016/S0301-6226(98)00192-4.

Beef + Lamb New Zealand, 2017. Tips for managing ewes with triplets. Retrieved on 8 April 2022 from https://beeflambnz.com/knowledge-hub/PDF/tips-managing-ewes-triplets.pdf.

Bohan, A., Shalloo, L., Creighton, P., Boland, T., McHugh, N., 2017. A survey of management practices and flock performance and their association with flock size and ewe breed type on Irish sheep farms. The Journal of Agricultural Science 155, 1332. https://doi.org/10.1017/S0021859617000399.

Bohan, A., Shalloo, L., Creighton, P., Earle, E., Boland, T., McHugh, N., 2018. Investigating the role of stocking rate and prolificacy potential on profitability of grass based sheep production systems. Livestock Science 210, 118–124. https://doi.org/10.1016/j.livsci.2018.02.009.

Bordbia, 2021. Sheep trade and prices. Retrieved on 28 February 2022 from https://www.bordbia.ie/farmers-growers/prices-markets/sheep-trade-prices/deadweight-lamb-prices/.

Byrne, T.J., Amer, P.R., Fennessy, P.F., Cromie, A.R., Keady, T.W.J., Hanrahan, J.P., McHugh, M.P., Wickham, B.W., 2010. Breeding objectives for sheep in Ireland: a bio-economic approach. Livestock Science 132, 135–144. https://doi.org/10.1016/j.livsci.2010.05.013.

Commonwealth Scientific and Industrial Research Organisation, 2007. Nutrient Requirements of Domesticated Ruminants. CSIRO Publishing, Melbourne, Australia.

Coop, I., 1973. Age and live weight in sheep. New Zealand Journal of Experimental Agriculture 1, 65–68. https://doi.org/10.1080/03015521.1973.10427618.

Earle, E., Boland, T., McHugh, N., Creighton, P., 2017a. Measures of lamb production efficiency in a temperate grass-based system differing in ewe prolificacy potential and stocking rate. Journal of Animal Science 95, 3504–3512. https://doi.org/10.2527/jas.2017.1427.

Earle, E., McHugh, N., Boland, T., Creighton, P., 2017b. Effect of ewe prolificacy potential and stocking rate on ewe and lamb performance in a grass-based lamb production system. Journal of Animal Science 95, 154–164. https://doi.org/10.2527/jas.2016.0772.

Farrell, L., 2020. Bio-economic system-dynamics modelling to investigate strategic management options in New Zealand sheep farming enterprises. Massey University, Manawatu, New Zealand. PhD thesis.

Farrell, L., Tozer, P., Kenyon, P., Ramilan, T., Cranston, L., 2019. The effect of ewe wastage in New Zealand sheep and beef farms on flock productivity and farm profitability. Agricultural Systems 174, 125–132. https://doi.org/10.1016/j.agsy.2019.04.0.

Farrell, L.J., Tozer, P.R., Kenyon, P.R., Cranston, L.M., Ramilan, T., 2021. Producing Higher Value Wool through a Transition from Romney to Merino Crossbred: Constraining Sheep Feed Demand. Agriculture 11, 920. https://doi.org/10.3390/agriculture11100920.

Fetherstone, N., McGovern, F.M., Boland, T.M., McHugh, N., 2022. How does maternal genetic merit and country of origin impact lamb performance pre-and post-weaning? Small Ruminant Research 209,. https://doi.org/10.1016/j.smallrumres.2022.106642 106642.

Flay, K.J., Ridler, A.L., Compton, C.W.R., Kenyon, P.R., 2021. Ewe Wastage in New Zealand Commercial Flocks: Extent, Timing, Association with Hogget Reproductive Outcomes and BCS. Animals 11, 779. https://doi.org/10.3390/ani11030779.

Gottsetin, M., 2017. Strategies for dealing with orphan lambs in high litter size flocks. Proceedings of the Teagasc National sheep conference 2017, 31 January - 2 February 2017, Carrick on Shannon/Carlow, IE, pp. 14-18. https://www.teagasc.ie/media/website/publications/2017/National-Sheep-Conferences.pdf.

Keady, T., & McNamara, N., 2014. Effects of rearing regime of replacements on the lifetime performance of ewes differing in prolificacy. Paper presented at the National Sheep Conference 2014, 4-5 February 2014, Athlone/Letterkenny, IE. https://t-stor.teagasc.ie/handle/11019/650.

Keady, T., Hanrahan, J.P., Flanagan, S., 2009. An evaluation of two grassland-based systems of mid-season prime lamb production using prolific ewes of two genotypes. Irish Journal of Agricultural and Food Research 48, 87–101.

McGovern, F.M., Campion, F.P., Lott, S., Boland, T.M., 2015. Altering ewe nutrition in late gestation: I. The impact on pre-and postpartum ewe performance. Journal of animal science 9310, 4860–4872. https://doi.org/10.2527/jas.2015-9019.

McGovern, F.M., McHugh, N., Fitzmaurice, S., Pabiou, T., McDermott, K., Wall, E., Fetherstone, N., 2020. Phenotypic factors associated with lamb live weight and carcass composition measurements in an Irish multi-breed sheep population. Translational. Animal Science 4, txaa206. https://doi.org/10.1093/tas/txaa206.

McHugh, N., Berry, D.P., Pabiou, T., 2016. Risk factors associated with lambing traits. Animal 10, 89–95. https://doi.org/10.1017/S1751731115001664.

McHugh, N., McGovern, F., Creighton, P., Pabiou, T., McDermott, K., Wall, E., Berry, D., 2019. Mean difference in live-weight per incremental difference in body condition score estimated in multiple sheep breeds and crossbreds. Animal 13, 549–553. https://doi.org/10.1017/S1751731118002148.

McLaren, A., McHugh, N., Lambe, N.R., Pabiou, T., Wall, E., Boman, I.A., 2020. Factors affecting ewe longevity on sheep farms in three European countries. Small Ruminant Research 189,. https://doi.org/10.1016/j.smallrumres.2020.106145 106145.

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 Science 95, 772–789. https://doi.org/10.1016/j.meatsci.2013.04.048.

Morel, P., Kenyon, P., 2006. Sensitivity analysis of weaner lamb production in New Zealand. Proceedings of the New Zealand Society of Animal Production 66, 377-381. http://www.nzsap.org/system/files/proceedings/ab06075.pdf.

Nicol, A.M., Brookes, I.M., 2007. The metabolisable energy requirements of grazing livestock. In: Rattray, P.V., Brookes, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals. New Zealand Society of Animal Production Occasional Publication, Hamilton, New Zealand, pp. 151–172.

SanCristobal-Gaudy, M., Bodin, L., Elsen, J.M., Chevalet, C., 2001. Genetic components of litter size variability in sheep. Genetics Selection Evolution 33, 249–271.

Shiels, D., Loughrey, J., Dwyer, C.M., Hanrahan, K., Mee, J.F., Keady, T.W., 2022. A Survey of Farm Management Practices Relating to the Risk Factors, Prevalence, and Causes of Lamb Mortality in Ireland. Animals 12, 30. https://doi.org/10.3390/ani12010030.

Shorten, P.R., Edwards, S.J., Juengel, J.L., 2020. The effect of reproductive loss on the performance of a research flock. Journal of Animal Science 98, skaa055. https://doi.org/10.1093/jas/skaa055.

Shorten, P.R., Edwards, S.J., Juengel, J.L., 2021. The role of reproductive loss on flock performance: a comparison of nine industry flocks. Translational. Animal Science 5, txab013. https://doi.org/10.1093/tas/txab013.

Teagasc, 2017. Feeding ewes pre lambing. Retrieved on 28 February 2022 from https://www.teagasc.ie/animals/sheep/nutrition/feeding-ewes-pre-lambing/.

Teagasc, 2021. National farm survey. Retrieved on 28 February 2022 from https://www.teagasc.ie/media/website/publications/2020/NFS2019-Sheep-Enterprise-Factsheet.pdf.

Turner, H., Brown, G., Ford, G., 1968. The influence of age structure on total productivity in breeding flocks of Merino sheep. I. Flocks with a fixed number of breeding ewes, producing their own replacements. Australian Journal of Agricultural Research 19, 443–475. https://doi.org/10.1071/AR9680443.

Young, J., Thompson, A., Curnow, M., Oldham, C., 2011. Whole-farm profit and the optimum maternal weight profile of Merino ewe flocks lambing in winter and spring are influenced by the effects of ewe nutrition on the progeny's survival and lifetime wool production. Animal Production Science 51, 821–833. https://doi.org/10.1071/AN10078.

Young, J., Trompf, J., Thompson, A., 2014. The critical control points for increasing reproductive performance can be used to inform research priorities. Animal Production Science 54, 645–655. https://doi.org/10.1071/AN13269).