Agricultural Systems 201 (2022) 103467

Contents lists available at ScienceDirect

Agricultural Systems

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

Modelling the production, profit, and greenhouse gas emissions of Irish sheep flocks divergent in genetic merit

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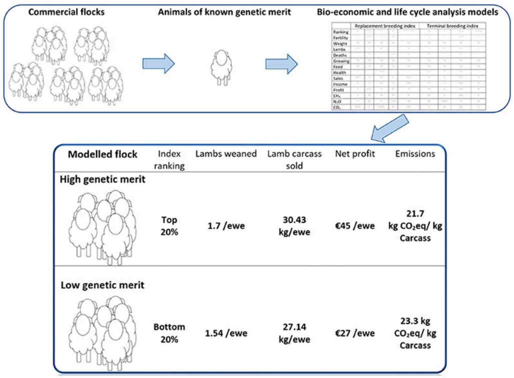
HIGHLIGHTS

- Field data from animals divergent in genetic merit was input to bio-economic and life-cycle analysis models.
- The flock of high genetic merit had net profit €18/ewe higher than the flock of low genetic merit.
- Higher ranking on the replacement index had larger increases in profit than from the terminal index.
- GHG emissions intensity was 6.9% lower for the flock of high genetic merit.
- Farmers can improve profitability while reducing GHG emissions intensities through selection using the national indices.

GRAPHICAL ABSTRACT



Modelled flock	Index ranking	Lambs weaned	Lamb carcass sold	Net profit	Emissions
High genetic merit	Top 20%	1.7 /ewe	30.43 kg/ewe	€45 /ewe	21.7 kg CO_2eq/ kg Carcass
Low genetic merit	Bottom 20%	1.54 /ewe	27.14 kg/ewe	€27 /ewe	23.3 kg CO_2eq/ kg Carcass

ARTICLE INFO

Editor: Kairsty Topp

Keywords:
Life cycle assessment
Bio-economic
Terminal
Replacement
Breeding
Validation

ABSTRACT

CONTEXT: Sheep production industries face the challenge of increasing farm production and profit while reducing environmental impacts.

OBJECTIVES: Genetic selection using multi-trait breeding indices can be used to improve flock productivity, profitability, and greenhouse gas (GHG) emissions intensities (kg CO_2-eq /kg of product), however validation of the improved performance of animals ranked higher on breeding indices at a flock level is required.

METHODS: Phenotypic data from 387,580 production records of animals born between 2018 and 2020 of known genetic merit in commercial flocks were inputted to an established bio-economic model. Two contrasting flocks were compared, a flock of ewes ranked *High* (top 20%) on the Irish replacement Index bred with rams ranked *High* on the replacement and terminal indices, and a flock of ewes ranked *Low* (bottom 20%) on the Irish replacement Index bred with rams ranked *Low* on the replacement and terminal indices. The two flocks were then simulated using life cycle assessment to estimate the GHG emissions profile for both systems.

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https://doi.org/10.1016/j.agsy.2022.103467
Received 27 March 2022; Received in revised form 17 July 2022; Accepted 18 July 2022

RESULTS AND CONCLUSION: Flock weaning rates were 1.70 and 1.53 lambs weaned per ewe presented for breeding for the *High* and *Low* genetic merit flocks, respectively. The flock of *High* genetic merit ewes sold 0.17 more lambs per ewe, equating to 3.29 kg more lamb carcass per ewe, than the flock of *Low* genetic merit ewes; lambs from the *High* genetic merit flock were also sold at an earlier age. The greater production of the *High* genetic merit flocks resulted in an additional €18/ewe net profit than the *Low* genetic merit flock. Although total flock GHG emissions were higher for the *High* genetic merit flock, GHG emissions intensities were lower at 21.7 and 23.3 kg CO_2-eq /kg lamb carcass sold for the High and *Low* genetic merit flocks, respectively. The lower emissions intensity of the *High* genetic merit flock was due to the dilution effect of higher lamb production and lambs being drafted for slaughter ealier.

SIGNIFICANCE: The results suggest Irish sheep producers can make substantial profit gains through selection according to the national breeding indices while also reducing their environmental impact, and farmers should consider genetic merit when purchasing their rams, particularly sires of replacement ewe lambs.

1. Introduction

Improvements in flock productivity and profitability can be achieved through a multitude of factors including through genetic selection using multi-trait breeding indices (James, 1980). Breeding indices for sheep systems focusing on meat production can be broadly categorised as either replacement (emphasis on maternal traits important for replacement ewe lambs such as number of lambs born, ewe mature liveweight, lamb survival, etc.), terminal (emphasis on traits important for lambs destined for slaughter such as lamb growth and carcass characteristics (Santos et al., 2015), or hill (emphasis on traits important to hill sheep systems such as ewe longevity and lamb survival; Lambe et al., 2014). Production traits previously identified to differ by genetic merit in Irish flocks (Fetherstone et al., 2021; McHugh et al., 2022) include traits recognised as drivers of farm production and profit, such as number of lambs born (Bohan et al., 2019; Farrell et al., 2020) and days for lambs to reach slaughter liveweight (Farrell et al., 2020). Analysis of data from 1131 commercial Irish dairy farms showed that higher productivity and profitability was achieved by herds ranked higher on the Irish total merit index (Ramsbottom et al., 2012). It is therefore logical to assume that improving the genetic merit of a ewe flock may improve farm profit, however, to date no published study has used field data from commercial flocks to quantify the impacts on whole farm profit from farming a sheep flock of higher genetic merit.

The Intergovernmental Panel on Climate Change has stated a global warming of 1.5 °C should not be exceeded in order to mitigate the severity of climate change impacts (IPCC, 2021). Therefore, as well as improving farm profit, the Irish sheep production industry also needs to reduce greenhouse gas (GHG) emissions to support national targets of reducing agricultural GHG emissions to 18–21% below 2018 levels by 2030 (Government of Ireland, 2021). Previous review and modelling studies of pastoral sheep production systems have predicted reductions in GHG emissions intensity (GHG emissions per kg of product) of up to 10% through improvements in genetic merit (Marino et al., 2016; Harrison et al., 2014). Increasing genetic merit through selection according to the national breeding indices may thus provide opportunities to simultaneously increase farm profitability and reduce GHG emissions intensity. However, no study has yet modelled both the potential economic and environmental benefits of improved genetic merit in ewe flocks using field data from a national database.

The objectives of this study were, therefore, to model production data from sheep divergent in genetic merit for the Irish replacement and terminal breeding indices and to quantify differences in farm production, profit, and GHG emissions. Results of these analyses will provide useful information on the economic value of selection for improved genetic merit according to national breeding indices and implications for GHG emissions released by sheep production systems.

2. Methods

2.1. Bio-economic model

An established bio-economic model of Irish lowland sheep flock, the Teagasc Lamb Production Model (TLPM; Bohan et al., 2016), was utilised to predict the production and profit of *High* and *Low* genetic merit flocks in two scenarios. Detailed model descriptions can be found in Bohan et al. (2016). Briefly, the TLPM is operated in Microsoft Excel with sheep numbers, production, feed budget, income, expenses, and net

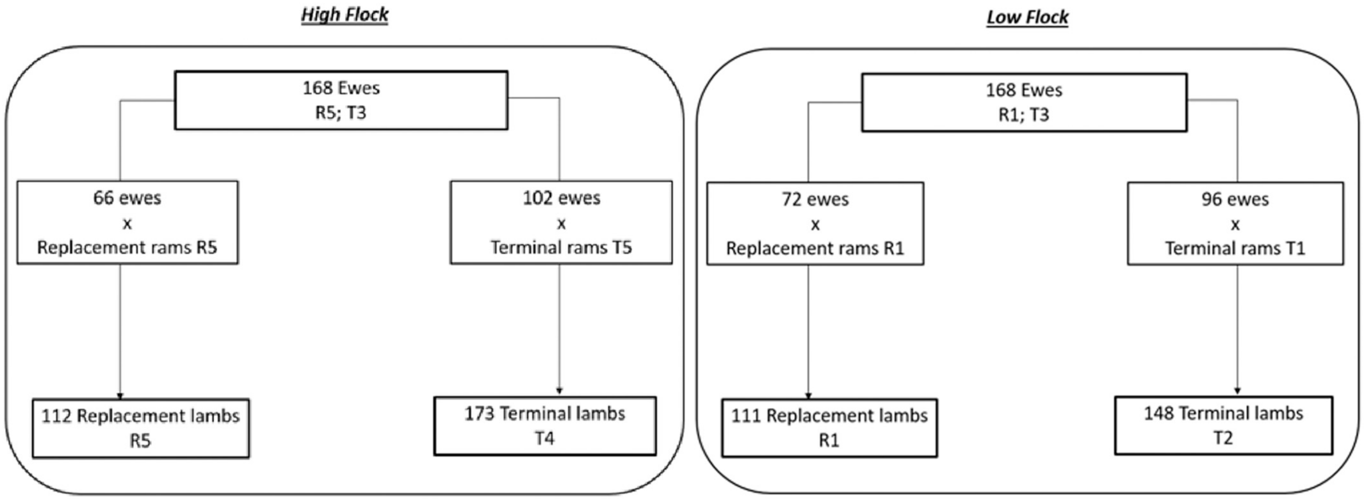

Fig. 1. Simplified diagram of the two modelled scenarios, showing the genetic merit of animals (*High or Low*) in each flock where ewes were bred with replacement and terminal rams of varying genetic merit. Where R = replacement index ranking, T = terminal index ranking, 1 = ranked in bottom 20% of index, 2 = ranked in top 20% to 40% of index, 3 = ranked in top 40% to 60% of index, 4 = ranked in top 60% to 80% of index, and 5 = ranked in top 20% of index.

profit estimated monthly in a 12-month production cycle commencing at mating (Bohan et al., 2016). The flock included lambs from birth until sale or retention as replacement females, nulliparous replacement females, primiparous and multiparious ewes, and breeding rams. Changes in animal numbers due to birth, death, sale, and culling were modelled each month, with lambs not retained as replacements drafted for slaughter when the target liveweight (20 kg carcass weight) was reached. A monthly feed budget was estimated based on flock net energy demand and feed supply from pasture, with feed surpluses conserved as silage and feed deficits requiring diet supplementation with silage and/or concentrates depending on time of year and stock class (Bohan et al., 2016). Key model inputs included animal production data, market prices for sheep and wool sales, market prices for variable and fixed costs, stocking rate, and fertiliser use. Key model outputs included stock inventories, production at a whole farm level, total income and expenses, farm gross margin, and net profit expressed on either a whole farm, per ha, per ewe, or per lamb born basis.

2.2. Scenarios investigated

Production values assumed for animals divergent in genetic merit in this study were derived from the Irish national sheep production database, using 387,580 production records from animals born between 2018 and 2020 in commericial flocks in the Irish Central Progeny Test programme (McHugh et al., 2022). The divergence of the animals in genetic merit potential was based on the national breeding indices, which are generated by the body responsible for the national sheep genetic evaluations in Ireland, Sheep Ireland (www.sheep.ie). For the purpose of the study, the genetic merit and the corresponding phenotypic differences of both dams and sires in the production database were divided separately into five strata of equal size: *High* (top 20% of animals), above-average (top 60% to 80%), average (top 40% to 60%), below-average (top 20% to 40%), and *Low* (top bottom 20%). Two scenarios based on the genetic merit of the parents were investigated, with each modelled flock purchasing two groups of rams to produce offspring suited either for flock replacement or for slaughter (terminal; Fig. 1). In the first modelled scenario (hereon referred to as *High* flock) dams within the top 20% of animals for the replacement index were assumed to be bred with terminal sires within the top 20% of animals on the terminal index. The *High* flock represented producers selecting all rams for high genetic merit. In the second modelled scenario (*Low* flock), dams within the bottom 20% of animals for the replacement index were assumed to be bred with terminal sires within the bottom 20% of animals for the terminal index. This *Low* flock was chosen for modelling to represent the spread in genetic merit and performance occurring in Irish sheep flocks. The genetic merit of ewes, rams, and lambs for each scenario are shown in Fig. 1, all ewes in the flock were assumed to be ranked as 'Average' on the terminal index. Offspring were assumed to be ranked based on their parental average values for the genetic indices, for example a lamb bon to a dams and a sire ranked in the third and fifth quintile, respectively, was ranked in the fourth quintile.

2.3. Physical parameters

A mid-season lowland flock, representing a typical Irish lowland sheep farm (Teagasc, 2020), consisting of 168 ewes farmed on 20 ha, stocked at 7.91 ewes/ha (hectare) was simulated in the TLPM. Ewes were mated for the first time at 19 months of age to lamb at two years old and all sold lambs were sold direct to slaughter, i.e. finished on-farm. Each modelled ewe flock had a replacement rate of 22%, requiring 37 replacement ewe lambs annually. Sufficient proportions of the flocks were bred with replacement sires in order to produce 150% of replacement ewe lamb requirements, from which replacement ewe lambs were selected. The remaining ewes were bred with terminal sires with all resultant offspring destined for slaughter. With a higher flock weaning rate, the *High* genetic merit flock produced the required replacement ewe lambs from fewer ewes, leaving more ewes available for breeding with terminal sires compared with the *Low* genetic merit flock; 61% and 57% of ewes for the modelled flocks of *High* and *Low* genetic merit were mated to terminal sires, respectively.

Table 1
Input parmeters, along with the data source for two flocks divergent in genetic merit, where the *High* flock consisted of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisted of animals representing those ranked in the bottom 20% of the breeding indices.

Input Parmeter	*High*	*Low*	Source
Farm size (ha)	20	20	
Stocking rate (ewes/ha)	7.91	7.91	
Total ewes joined (head)	168	168	
Ewes lambing (head)	159	159	
Replacement ewe lambs (head)	37	37	Teagasc, 2020
Ewe mature liveweight (kg)	73.08	73.08	
Scanning rate (% of ewes joined)	1.87	1.70	
Flock litter size[1]	1.91	1.74	
Lamb survival (%)	93.48	92.87	
Lamb pre-weaning weight[2,3] (kg)	18.11	17.66	
Lamb weaning weight (kg)	31.52	30.65	
Lamb post-weaning weight[3,4] (kg)	39.24	38.29	McHugh et al., 2022, under review
Average days to slaughter	190	203	
Nitrogen applied (kg/ha)	100	100	
Phosphorus applied (kg/ha)	10	10	
Potassium applied (kg/ha)	20	20	Teagasc, 2020

[1] Lambs born per ewe lambing.

[2] Lamb liveweight at 40 days of age.

[3] Lamb liveweights and days to slaughter are weighted averages for all lambs in the flock, from both replacement and terminal sires.

[4] Lamb liveweight at 120 days of age.

Phenotypic performance parameters to populate both flock scenarios (Fig. 1) in the TLPM were taken from the Irish national sheep production database, which included animal rankings on the breeding indices as validated by McHugh et al., 2022, with performance parameters outlined in Table 1. Values shown in Table 1 were weighted averages for animals in the modelled flock, for example, lamb birth weight was a weighted average for lambs differing in sire (replacement or terminal) and birth (single or multiple) type. Only production traits that were shown to be significantly different ($P < 0.05$) by genetic merit (McHugh et al., 2022) were varied between both modelled scenarios in the present study; where a production trait was not significantly different, the averaged performance merit was included across both modelled scenarios (Table 1). Total flock production, profit, and GHG emission profiles were calculated separately for both modelled scenarios.

Flock feed demand was estimated monthly according to sheep numbers, and physiological state (growth, lactation, etc.) according to equations and methodology described in Bohan et al. (2016). Fertiliser inputs were assumed consistent across both scenarios for nitrogen (100 kg/ha), phosphorus (10 kg/ha), and potassium (20 kg/ha; Table 1). Ewes were housed over winter from 1 December and offered grass silage and supplemented with concentrates pre-lambing. An average lambing date of 1st March was assumed across both modelled scenarios and ewes and lambs were returned to pasture within 48 h post lambing. Lambs were drafted for slaughter once reaching a target liveweight of 43 kg in June; to account for reductions in carcass kill out rate the target liveweight increased by one kg for each subsequent month thereafter. To coincide with the reduction in grass growth (Earle et al., 2017), lambs not drafted by 1st October were offered concentrate supplementation until a target slaughter weight was achieved.

Profit indicators (represented in euros €) used in this analysis were gross margin, as total income minus total variable costs, and net profit, as gross margin minus fixed costs and overdraft loan interest costs. Farm income was generated from sheep and wool sales, with average market prices from 2017 to 2021 utilised (BordBia, 2020). Variable and fixed costs were based on market values from 2017 to 2020, with sources the same as those described in detail by Bohan et al. (2016).

2.4. Economic sensitivity analysis

An economic sensitivity analysis was conducted to assess the effect of variation in key input and output prices on farm net profit. The key variables assessed were lamb carcass price, concentrate price, and fertiliser price, each of which are critically important to the economic viability of Irish sheep production systems and have been shown to vary across time. This analysis highlighted the robustness of both the *High* and *Low* genetic merit flocks when faced with price variability. Each of the three aforementioned variables were increased and decreased by 10% to quantify their impact on net profit and the resilience of each modelled flock to price volatility.

2.5. Secondary economic analysis

In a secondary analysis the same two flocks with ewes and replacement sires of either *High* or *Low* genetic merit were modelled. However, the terminal sires used by both flocks were of *Average* genetic merit, representing animals ranked in the top 40% to 60% of the Irish terminal breeding index. By using terminal sires of the same genetic merit, the secondary analysis allowed for quantification of the potential economic benefits from genetic divergence on the replacement index only.

2.6. Greenhouse gas emissions

2.6.1. Goal and scope

Farm physical parameters input to the model (i.e., stock numbers, fertiliser use) and model output (i.e., total production, feed supply profile, income) were input to a life cycle assessment (LCA) model to predict the modelled flocks' GHG emissions profiles. Key input values for animal production and fertiliser use are shown in Table 1, with output from the bio-economic modelling (shown in the results section of this study) also input to the LCA model. The LCA model used was developed by O'Brien et al. (2016), operating on a monthly time step with a temporal range of one production year. The LCA adopted a cradle-to-farm gate system boundary which included all life cycle stages up to the point where animals and by-products were sold from the system, enabling upstream environmental burden embodied in farm inputs to also be included in the LCA. These included production of concentrate feed, synthetic fertiliser, electricity, fossil fuels, chemicals, and purchased stock (i.e. rams). The environmental impact of capital goods (i.e. farm machinery and infrastructure) were excluded as they did not differ between the two scenarions investigated in the present study. The production of medicines was excluded due to the lack of data and small contribution to GHG emissions (Saunders and Barber, 2007). To enable comparison between scenarios and production systems, GHG emissions were expressed on per kg carcass weight (kg CW) sold, per ha, and total flock bases. Economic allocation was applied to disaggreate the environmental burden between co-products (meat and wool).

2.6.2. Life cycle inventory

Consistent with the TLPM bio-economic model, the LCA model estimated dry matter intake based on the energy content of feed (unité fourragère lait per kg dry matter, UFL per kg DM) offered to animals and net energy requirements for maintainance, liveweight gain, pregnancy and milk production (O'Mara, 1996). The energy provided by concentrate feed was calculated using the net energy content of concentrate feed (UFL/kg DM) and the specified concentrate feeding rate (kg DM/day). The remaining energy requirements were fulfilled by either fresh forage while grazing or conserved forage during winter housing. Nitrogen (N) intake was calculated from dry matter intake and the crude protein content of the diet. The quantity of volatile solid excreted was the difference in total organic matter intake and the quantity of digestible organic matter in dry matter intake. The quantity of manure requiring storage and management wihin a manure system was based on volatile solid excretion rates for each month of housing and the number of days housed in each month. All animals were housed in a soild floor (i.e., straw bedding) system. Nitrogen excretion was calculated by subtracting N partitioned towards animal products and total N intake. Emissions factors and coefficients applied in the LCA modelling are shown in Table S1 in the supplementary material. Methane (CH_4) emissions from enteric fermentation were calculated using gross energy intake, derived from dry matter intake and gross energy content of diet. In accordance with IPCC (2019) guidelines, 7.0%, 6.7% and 6.5% of gross energy intake was lost as CH_4 emissions when dry matter intake was less than 0.6 kg DM per day, between 0.6 and 0.8 kg DM per day, and over 0.8 kg DM per day, respectively. Methane emissions from lambs in their first month of life were excluded as their diet consisted solely of milk. IPCC (2019) Tier 2 methodology was used for CH_4 emissions from manure storage and manure excreted at pasture.

Nitrous oxide (N_2O), ammonia (NH_3), nitrogen oxide (NO_x) and nitrate (NO_3) from managed and unmanaged manure were calulcated using the N mass flow approach outlined by Webb and Misselbrook (2004) and used in the Irish informative inventory report (EPA, 2021a). As N flows through each stage of manure management N emissions are calculated and removed from the total ammonical nitrogen (TAN) pool. IPCC (2019) Tier 2 methodology was used for direct N_2O emissions from manure storage, manure application, and manure excreted at pasture. Ammonia emissions from manure were calculated using regional specific emission factors reported by Misselbrook and Gilhespy (2020) and applied in the national informative inventory report (EPA, 2021a). Country specific emission factors were used for direct N_2O emissions from synthetic fertiliser application (Harty et al., 2016). Ammonia emission from synthetic fertiliser application were derived using emission factors provided by EMEP/EEA (2019). Nitriate leaching rate was estimated as 10% of N applied (EPA, 2021b).

On-farm carbon dioxide (CO_2) emissions from the decomposition of agricultural lime applied to agricultural soil, and the hydrolysis of urea fertiliser following application were calculated using IPCC (2019) Tier 1 emission factors. Greenhouse gas emissions from the on-farm combustion of fossil fuel were calculated using the national inventory methodology (EPA, 2021b). For off-farm sources, emission factors reported in national inventory report (EPA, 2021b) and electricity energy flow data (SEAI, 2020) were used to determine GHG emissions released during the production of electricity. Greenhouse gas emissions generated from the production of synthetic fertilisers were calculated using recent region specific emission factors (Hoxha and Christensen, 2019). Remaining life cycle inventory data (i.e. concentrate feed, chemicals and production of fossil fuels) were sourced from SimaPro (Pré Sustainability, 2021).

2.6.3. Life cycle impact assessment

For ease of interpretation and direct comparison of the two scenarios investigated in the present study, the results of the life cycle inventory stage were transformed into the climate change mid-point environmental indicator. The IPCC (2013) 100 year time horizion global warming potential characterisation factors (excluding climate change feedback) were applied.

2.6.4. Uncertainty analysis

Inherent uncertainty exists in the calculation of greenhouse gas emissions from agicultural sytems due to spatial and temporal factors. To account for this uncertainty, stochastic simulation was conducted. Probabilty distributions were applied to the emission factors associated with the main GHG emission sources identified in the deterministic simulation using the Palisade @Risk 7.5 software (Table S2, in supplementary material). All stochastic parameters were simulated simultaneously and assumed to be independent. A series of monte carlo simulations (10,000 iterations) were conducted for each of the *High* and

Low flocks.

Table 2
Flock lamb production, lamb sales, and feed demand for modelled flocks divergent in genetic merit, where the *High* flock consisted of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisted of animals representing those ranked in thebottom 20% of the breeding indices.

Scenario	*High*	*Low*
Ewes bred with terminal sire (%)	61	57
Flock weaning rate[1]	1.70	1.53
Lambs sold (head)	248	220
Lambs sold per ewe joined (lamb/head)	1.48	1.31
Carcass sold per ewe joined (kg/head)	30.43	27.14
Average carcass per lamb (kg)	20.50	20.48
Average price per lamb (€)	111.85	111.97
Lambs drafted in June (%)	9	7
Lambs drafted in July (%)	12	9
Lambs drafted in August (%)	23	18
Lambs drafted in September (%)	22	23
Lambs drafted in October (%)	21	23
Lambs drafted in November (%)	11	16
Lambs drafted in December (%)	2	4
Grass grown (kg DM[2]/ha)	7650	7650
Total fresh grass demand (kg DM)	114,278	109,825
Total silage demand (kg DM)	26,693	26,012
Total concentrates fed (Kg FW[3])	4916	5109

[1] Lambs weaned per ewe presented for breeding.
[2] Dry matter.
[3] Fresh weight.

Table 3
Income, expenses, and profit (in € unless otherwise stated) and greenhouse gas emissions for modelled flocks divergent in genetic merit, where the *High* flock consisted of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisted of animals representing those ranked in the bottom 20% of the breeding indices.

Scenario	*High*	*Low*
RECEIPTS		
Wool sales	134	134
Lamb sales	27,693	24,613
Cull ewe sales	2218	2215
Surplus silage sales	131	328
TOTAL FARM RECEIPTS	**30,045**	**26,962**
Concentrates	1602	1672
Straw	2166	2166
Fertilizer	3236	3236
Lime	400	400
ReSeeding	1000	1000
Livestock purchases	373	373
Dead animal disposal	200	200
Machinery hire	650	650
Silage making	2025	1973
Vet and medicine	2587	2489
Carcass processing levies	249	224
Machinery operation and repair	1882	1882
TOTAL VARIABLE COSTS	**16,370**	**16,264**
GROSS MARGIN	**13,675**	**10,699**
Car use	1680	1680
Electricity and phone	526	525
Farm insurance	1300	1300
Buildings depreciation	554	553
Machinery depreciation	980	980
TOTAL FIXED COSTS	**5040**	**5039**
TOTAL FARM COSTS	**21,410**	**21,303**
Earnings before interest & tax (EBIT)	8635	5660
Net interest costs on overdraft	27	23
Interest payments	1077	1077
FARM NET PROFIT	**7585**	**4607**
Farm net profit (€/ha)	**379**	**230**
Farm net profit (€/ewe joined)	**45**	**27**
Farm net profit (€/lamb born)	**25**	**17**
Emissions intensity (kg CO$_2$eq/ kg carcass weight sold)	**21.7**	**23.3**
Emissions (kg CO$_2$-eq/ ha)	**6573**	**6389**
Total emissions (kg CO$_2$-eq)	**131,459**	**127,782**

3. Results and discussion

The flock of *High* genetic merit ewes sold 0.17 more lambs per ewe equating to 3.29 kg more lamb carcass per ewe joined, than the flock of *Low* genetic merit ewes (Table 2). The *High* genetic merit flock also sold 38 more lambs before 1st October, i.e. from an all-pasture diet, compared with the *Low* genetic merit flock. The *High* flock exploited the production benefits of selecting for higher genetic merit on both of the replacement and terminal breeding indices. Validation of the indices by McHugh et al. (2022) confirmed phenotypic differences in ewe and lamb production traits of commercial Irish flocks divergent in genetic merit. Previous analyses identified improved productivity of flocks in the United Kingdom with higher genetic merit according to their ranking on terminal and hill sheep breeding indices (Conington et al., 2006; Márquez et al., 2013). The current analysis has validated that the higher individual animal productivity for animals of superior genetic merit on a per trait level identified by McHugh et al. (2022), did translate to higher lamb production and total flock output.

3.1. Economics

The flock of *High* genetic merit had €3080 higher income from lamb sales, driven by the higher flock litter size and lamb liveweights compared with the flock of *Low* genetic merit (Table 3). With similar total farm costs between the two modelled scenarios, net profit was €18/ewe higher for the flock of high genetic merit (€45/ewe) than the flock of low genetic merit (€27/ewe). An eight-year study of two Scottish sheep flocks with genetic selection according to a hill breeding index consisting of both maternal and terminal ewe and lamb traits identified improved profitability with improved genetic.

merit compared with a control line, where the profit increase was driven by lamb growth rates which were heavily weighted in the indices (Lambe et al., 2014). Irish national breeding indices for dairy (Ramsbottom et al., 2012) and beef (Connolly et al., 2016; Twomey et al., 2020) cattle have previously validated production and/or profit differences at per trait, per animal, and per herd levels for animals divergent in genetic merit. The current study is novel not only in validating the Irish sheep breeding indices for improvements in production and profit at flock level, but also extending the analysis to include implications for flock GHG emissions profiles. The previous findings for the Irish dairy and beef industries as well as those of the current study indicate selection according to breeding indices to be beneficial for the production and profit of a herd or flock when consistantly applied. When selecting animals of *High* genetic merit according to the national Irish replacement and terminal breeding indices in this study, net profit per ewe was predicted to be 67% greater than the flock with *Low* genetic merit animals. The results suggest Irish sheep producers can make substantial profit gains through selection according to the national breeding indices and should consider genetic merit when purchasing their rams.

3.1.1. Economic sensitivity analysis

The three prices that were varied within the sensitivity analysis (i.e. lamb carcass price, concentrate price, and fertiliser price), all impacted net profit to a varying extent, with smaller relative changes in net profit associated with the *High* genetic merit flock compared with the *Low* genetic merit flock (results shown in Table S3 in the supplementary material). Lamb carcass price had the largest impact on net profit, as income from lamb sales had a larger overall value than costs associated with fertiliser and concentrates. Lamb price variation resulted in changes in net profit of 36.5% and 53.4% for the *High* and *Low* genetic merit flocks, respectively. Variation in fertiliser price resulted in changes in net profit of 4.3% and 7.0% for the *High* and *Low* genetic merit flocks, respectively; while variation in concentrate prices altered net profit by 2.1% to 3.6% for the *High* and *Low* genetic merit flocks, respectively.

These results indicate the net profit of the *Low* genetic merit flock was impacted greater by price volatility compared with the *High* genetic merit flock, suggesting the *Low* genetic merit flock to be less economically robust. A more profitable flock, shown here to be achievable through improved genetic merit, may experience less drastic effects on profit when market conditions change. Future analysis of effects of genetic merit on flock production and net profit could include variation in flock characteristics and system type, such as varying replacement rate or selling lambs store for anther farmer to grow to target slaughter weight.

3.1.2. Secondary economic analysis

With terminal sires of *Average* genetic merit used in both *High* and *Low* ewe flocks (results shown in Table S4 in the supplementary material), net profit was €16 higher per ewe for the flock of *High* genetic merit ewes (€44/ewe) than the flock of *Low* genetic merit ewes (€28/ewe). These result show the higher profit of the *High* genetic merit flock was driven by the higher rankings on both the replacement and terminal indices. Number of lambs born has a high relative emphasis in the Irish replacement index (Sheep ireland, 2021) and previous bio-economic modelling of Irish (Bohan et al., 2018), Australian (Young et al., 2011), and New Zealand (Farrell et al., 2020) flocks have shown flock income and profit increases with higher flock litter sizes. Therefore the increase in net profit in the current study from improved genetic merit on the replacement index was expected. These results suggest that increasing the ewe genetic merit into the next strata ranking (e.g., ranked in the top 20% versus the top 60% to 80%) on the replacement breeding index will on average increase net profit by €4/ewe. However, in the validation study by McHugh et al. (2022) relationships between production traits and genetic merit were not always linear.

The profitability of scenarios in the main analysis (flocks of *High* and *Low* genetic merit ewes using terminal sires of *High* and *Low* genetic merit, respectively) could be compared with the scenarios in the secondary analysis (flocks of *High* and *Low* genetic merit ewes both using terminal sires of *Average* genetic merit) to investigate the economic effects of using terminal sires divergent in genetic merit only. The results suggested that increasing the terminal sire genetic merit into the next strata ranking on the terminal breeding index will on average increase farm net profit by €1/ewe. As stated above, the increases in flock production and profit are unlikely to increase linearly with index ranking, however the results indicate the effect of improved replacement sire genetic merit to be four times as effective in increasing flock profitability compared with improving terminal sire genetic merit. Thus the secondary analysis from the current study demonstrates using replacement and terminal sires of higher genetic merit to both increase farm net profit, with improvements on the replacement index yielding greater economic gains. While the current economic analysis included effects on feed balance and proportions of ewes bred to different types of rams, it did not include the difference in breeding costs when using *High* and *Low* genetic merit rams which would affect the net profit of the explored scenarios and could be investigated in future analyses. The breeding ewe contribute half of lamb performance and their genetic merit could be increased from *Low* to *High* over multiple years through use of *High* genetic merit replacement rams given the flock replacement rate of 22%. Further, prices for rams of a given genetic merit vary widely in Ireland with breed and market factors. The results provide an indication of the value of using rams ranked higher on the replacement and terminal indices, which can inform producers of appropriate levels of spending on rams of superior genetic merit.

Net profit per lamb born was €25 and €17 for the modelled flocks of *High* and *Low* genetic merit, respectively (Table 3). The validation analysis which informed the production data used in this modelling study (Table 1) identified the difference in economic breeding values between animals ranked as *High* and *Low* on the replacement and terminal indices to be €3.28 and €1.97, respectively (McHugh et al., 2022). The relatively smaller difference in profit per lamb born (potentially €5.25 when considering both indices) identified by McHugh et al. (2022) compared with the current study (€8) may reflect the older, lower lamb prices used in the current genetic evaluations in McHugh et al. (2022) The results of this analysis suggest the Irish genetic evaluations are under-predicting the potential increase in profit from improving sheep genetic merit and indicate the current evaluations need to be updated to more accurately reflect the value of superior genetics in the national flock.

3.2. Greenhouse gas emissions

The LCA results predicted the flock of *High* genetic merit ewes to have a 6.9% lower GHG intensity (at 21.7 kg CO_2-eq/kg CW) than the *Low* genetic merit flock (23.3 kg CO_2-eq/kg CW; Table 3). The reduction in GHG intensity with superior genetic merit is ascribed to the increase in quantity of carcass sold per ewe (3.29 kg) and the reduction in average days to slaughter (13 days; Table 2). Increasing the quantity of carcass sold per ewe diluted the GHG emissions generated per ewe and replacements over one production year. Despite selling an additional 28 lambs (578 kg lamb CW), the *High* genetic merit flock consumed 193 kg less concentrate feed than the *Low* system. The *High* genetic merit flock drafted lambs at an earlier age at slaughter, increasing the proportion of lambs grown to target liveweight from a pasture-based diet thus reduced reliance on imported feed and subsequently the quantity of GHG emissions generated over the lambs' lifespans (Waghorn et al., 2002).

Similar to the current modelling analysis, previous studies have identified improvement in flock genetic merit to reduce GHG emissions intensity while simultaneously improving productivity and profitability (Wall et al., 2010; Lambe et al., 2014; Morgan-Davies et al., 2021). Modelling by Wall et al. (2010) predicted selection according to crossbred and terminal sheep breeding indices in Scotland could improve profitability while reducing GHG emissions intensity and per ewe, while case study analysis by Morgan-Davies et al. (2021) predicted performance recording to improve sheep genetic merit in Scottish flocks to improve profit and reduce GHG emissions intensity. Further, an Irish modelling study based on farmlet trial data estimated dairy cows in the top 5% of a national breeding index to have 10% lower GHG emissions per kg of fat and protein corrected milk produced compared with cows ranked as the national average on the economic index (Lahart et al., 2021). Chilean (Toro-Mujica et al., 2017) and Australian modelling studies (Harrison et al., 2014) predicted flocks with higher reproductive rates to have lower GHG emissions intensities, and case study analysis by Morgan-Davies et al. (2021) predicted an Irish flock of higher prolificacy to have higher profit and lower GHG emissions intensity. The number of lambs born per ewe has a high weighting in the Irish replacement breeding index (Bohan et al., 2019), therefore the reduction in GHG emissions intensity with the increase in number of lambs born for the flock of *High* genetic merit ewes estimated in the current analysis agrees with the citied studies.

Ewes in a Scottish hill sheep flock were selected for eight years according to a breeding index comprising of ewe and lamb traits for improved production and profitability (Lambe et al., 2014). Although profit was greater for the selection line ranked higher on the index, the associated selection for higher ewe mature liveweight resulted in increased GHG emissions, on both a per ewe and intensity basis (Lambe et al., 2014). Replacement rate and mature liveweight of ewes within the *High* and *Low* systems did not differ from each other ($P < 0.05$) in the current analysis (Table 1), and lower replacement rate and lighter ewe liveweight would both contribute to reductions in GHG emissions intensities (Lanigan et al., 2018). Future adjustments to the Irish national breeding indices could focus on these traits (ewe longevity and GHG emissions) to further reduce GHG emissions intensities. Potential effects of the weighting of individual traits within breeding indices may impact on the ability to reduce GHG emissions intensity through improvements in flock genetic merit, this should be considered during breeding index development given global and national GHG reductions targets.

Proposed mitigation strategies that improve the efficiency of a system can reduce the GHG intensity per kg product (i.e. carcass weight), however they may also allow for increased levels of productivity and potentially an increase in total system GHG emissions which may lead to an unbalanced view of their mitigation potential (Salou et al., 2017). Total on-farm area was fixed for both modelled systems in this analysis, thus any changes in GHG emissions on a per ha basis indicate proportionate changes in total GHG emissions. The paradoxical effect of improved productivity was identified in the current study where the flock of *High* genetic merit ewes produced 2.8% (184 kg CO_2eq/ha) greater GHG emissions per ha (than the *Low* genetic merit flock despite reductions in GHG intensity per kg carcass weight (Table 3). Herron et al., n.d. (under review) reported a similar effect of improved productivity from increased weaning rate for the GHG emissions of lowland sheep systems. In the current study, the number of ewes lambing in both the *High* and *Low* genetic flocks were the same, as a result the increase in total GHG emissions in the *High* flock arose from the increased lamb production and associated feed intake. If ewe numbers in the *Low* flock were increased to match the total annual feed consumption of the *High* flock, their feed surplus would be lower and GHG emissions per ha would be similar between the two flocks. The flock of *High* genetic merit ewes produced greater quantities of carcass per ha than the *Low* flock, thus potentially reducing the land area requirements for such commodities and availing land for other ecosystem services. The results suggest flocks of *High* genetic merit to have higher production, profit, and total emissions compared with the *Low* genetic merit flock at the same stocking rate. The *High* genetic merit flock was predicted to produce more lamb carcass and profit per unit of feed compared with the *Low* genetic merit flock. A flock of *High* genetic merit ewes could produce the same emissions as a flock of *Low* genetic merit ewes while farmed at a lower stocking rate, potentially maintaining flock production and net profit above that of a *Low* genetic merit flock. Earle et al. (2017) reported an interaction between stocking rate and lamb performance, therefore to investigate changes in stocking rate, the effect on lamb performance must be accounted. However, due to insuffient data the current analysis did not extend to investigate changes in stocking rate.

The LCA analysis in this study used economic allocation method to determine the proportion of GHG emissions attributed to meat and wool production and to derive the emissions intensity values on a per kg carcass weight sold basis. This approach is one of the most common method applied in sheep LCA studies (Opio et al., 2013; Jones et al., 2014; O'Brien et al., 2016) as the revenue generated provides an insight into the socioeconomic demand for co-products and therefore production systems. A key limitiation of economic allocation however is that the LCA results are subject to the volatility of market prices (Rice et al., 2017). As lamb production is the primary focus of sheep systems in Ireland, with wool considered a low value by product, the majority of GHG emissions produced by the systems simulated in this study was attributed to meat production (96%). Inversely, Wiedemann et al. (2015) reported specialised wool systems allocate 52% of GHG emissions towards wool, resulting in lower GHG emissions intensity for meat production than that of specialised meat systems. To address this anomoly Wiedemann et al. (2015) recommended using biological allocation based on protein partitioning between wool and liveweight. It is evident that a common harmonized LCA methodology for sheep systems is required to reduce inconsistencies in LCA approaches and assumptions (e.g. allocation method). A ratio of farm profit to GHG emissions has been suggested as an alternative measure of GHG emissions to allow comparison of the effectiveness of mitigation strategeis for between production systems (Young et al., 2016). In the current study the flock of *High* genetic merit ewes generated €56.61 of net profit per tonne of CO_2-eq emitted, while the *Low* genetic merit flock generated €36.42 of net profit per tonne of CO_2 (Table 3). This measure captures the benefit of farming a flock of superior genetic merit for profit and sustainability while ignoring implications of co-products.

Table 4
Modelled carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions from various sources (kg CO_2eq /kg carcass weight unless otherwise stated) for the *High* flock consisting of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisting of animals representing those ranked in the bottom 20% of the breeding indices.

	High			Low		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Enteric fermentation	–	14.33	–	–	15.19	–
Manure housing and storage	–	0.08	0.41	–	0.09	0.45
Manure spreading	–	–	0.35	–	–	0.37
Grazing	–	0.07	0.72	–	0.08	0.77
Fertiliser application	0.46	–	1.96	0.51	–	2.16
Ammonia emissions	–	–	0.29	–	–	0.31
Nitrate leaching	–	–	0.45	–	–	0.49
Concentrate feed	0.22	0.01	0.09	0.24	0.01	0.10
Fertiliser production	1.02	0.04	0.10	1.13	0.05	0.11
Fossil fuel	0.81	0.01	0.06	0.89	0.01	0.06
Purchased animals	0.03	0.08	0.04	0.03	0.09	0.04
Purchased forage/bedding	0.02	–	0.01	0.02	–	0.01
Other	0.05	–	–	0.05	–	–
Emissions intensity	2.6	14.6	4.5	2.9	15.5	4.9
Emissions (kg CO_2 eq/ ha)	791	4430	1352	767	4264	1335
Contribution (%)	12.0	67.4	20.6	12.4	66.7	20.9

Methane was the dominant GHG for both the *High* and *Low* flocks, contributing 66.7% and 67.5% of total GHG emissions, respectively (Table 4). Enteric fermentation was the dominant source of CH_4, with the *High* flock emitting less enteric CH_4 per kg carcass weight (14.33 kg CO_2-eq/kg CW) than the *Low* flock (15.19 kg CO_2-eq/kg CW) due to the dilution of ewe emissions and reduced days to slaughter of lambs. Pinares-Patiño et al. (2011) demonstrated the existence of genetic variation for enteric CH_4 emissions between animals and that these traits are both heritable (0.29) and repeatable (0.55). Further, with the exception of fleece weight, weak to no correlations were reported for CH_4/kg DMI, and investigated production and functional traits (Pinares-Patiño et al., 2013). These results were substantiated by a meta-analysis (Brito et al., 2018) which found enteric CH_4 emission traits in cattle and sheep are under moderate genetic control and that between animal variation in CH_4 emission could be exploited to breed animals for lower enteric CH_4 emissions. The studies suggest that if the traits responsible for enteric CH_4 emissions were included in breeding indices the differential between flocks of *High* and *Low* genetic merit ewes as investigated in this study could increase. Selectively breeding sheep for lower CH_4 emissions within a multi-trait selection index could potentially offer a cost-effective GHG emissions mitigation strategy that will be cumulative and permanent. However, to capture GHG mitigation due to genetic selection for reduced CH_4 emissions, LCA methodology must be updated to account for variation among ruminants.

Nitrous oxide was the second most dominant GHG, contributing 20.9% to 20.6% of total GHG emissions (Table 4). Sythetic fertiliser

Table 5
Uncertainty analysis expressed per kg of carcass and on a per hectare basis of modelled flocks divergent in genetic merit, where the *High* flock consisted of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisted of animals representing those ranked in the bottom 20% of the breeding indices.

	Per kg carcass weight		Per hectare	
	High	Low	High	Low
Mean GWP[1] (kg CO_2eq)	22.1	23.7	6704	6518
Standard deviation	1.97	2.13	596	585
Coefficient of variance	9%	9%	9%	9%
2.5th percentile (kg CO_2eq)	18.3	19.5	5541	5372
97.5th percentile (kg CO_2eq)	26.0	27.9	7880	7658
Iterations	10,000	10,000	10,000	10,000

[1] GWP, Global warming potential.

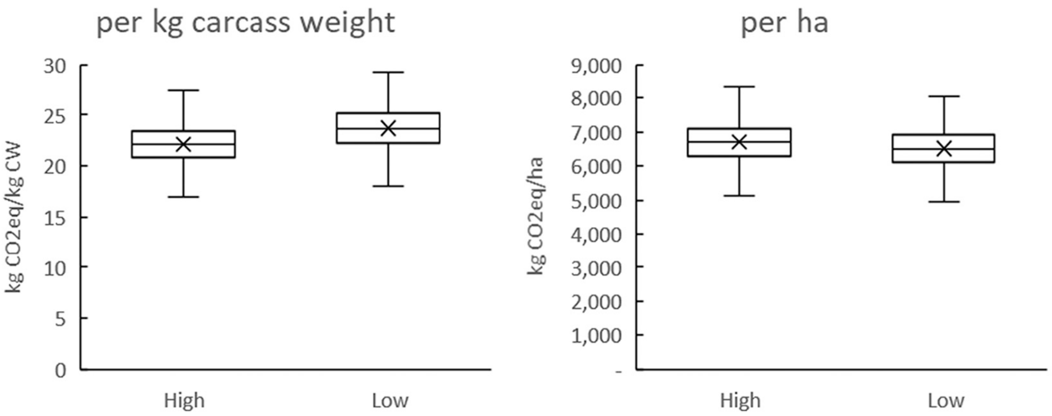

Fig. 2. Global warming potential (kg CO_2-eq) per kg carcass weight and per hectare for the *High* flock consisting of animals representing those ranked in the top 20% of the breeding indices and the *Low* flock consisting of animals representing those ranked in the bottom 20% of the breeding indices.

application was the main source of N_2O, followed by managed manure and manure excreted during grazing. Dietary manipulation has been proposed as a potential mitigation strategy for manure derived N_2O emissions which are driven by nitrogen (N) intake and excretion (Dijkstra et al., 2013). However, both Gregorini et al. (2016) and Dijkstra et al. (2011) highlighted potential trade offs between N excretion and enteric CH_4 emissions when diets are manipulated. Further, dietary manipulation in pasture based systems is difficult due to grazed forage comprising approximately 78% of total DM intake and the temporal variability of fresh forage throughout a grazing season. While N efficiency could be selectively bred in dairy cows using milk urea N as an indicator (Lopez-Villalobos et al., 2018; Beatson et al., 2019), alternative indicators correlated to N efficiency need to be identified before selection in sheep will be possible.

The mean GHG emissions on both per kg of carcass weight and per ha bases were greater in the LCA uncertainty analysis (Table 5; Fig. 2) compared with the deterministic LCA results (Table 4). The increase in GHG emission in the uncertainty anaylsis can largely be attributed to the non-normal right skewed distribution assigned to N_2O emissions from the application of CAN based fertiliser (Table 5). An analysis of contribution of variance identified enteric fermentation as the largest contributor, followed by synthetic fertiliser application. The current IPCC (2019) enteric CH_4 conversion factor is a notable source of uncertainty for GHG emitted from pasture-based sheep production, having a coeffient of variation of 13.4% and being the dominant GHG source (Table 4). This study highlights the requirement for the measurent of enteric CH_4 emissions from sheep in pasture-based systems and the development of a country specific methodology with improved accuracy and precision. Further, collection and analysis of enteric CH_4 emissions data from sheep divergent in genetic merit on the Irish breeding indices may identify existing correlations between genetic merit and CH_4 emissions which would affect the results of this LCA analysis, particularly if CH_4 emissions are included in future development of the indices. A limition of the current analyisis was the omission of possible covariance among paramaters investigated due to insufficient data. This warrants research into establishing correlations between emission sources.

4. Conclusions

The current analysis validated the higher productivity for animals of superior genetic merit previously identified (McHugh et al., 2022) translated to higher production and profit at a flock level. The sale of more lambs and at a younger age from a pasture diet by the *High* genetic merit flock contributed to the lower GHG emission intensity compared with the *Low* flock. Flock genetic merit could further reduce GHG emissions, on per kg of carcass weight and total farm system bases, through future development of the breeding indices to increase focus on ewe longevity and liveweight, or through inclusion of a breeding value for enteric CH_4 emissions. Overall, the modelling output has validated genetic selection according to the current Irish replacement and terminal breeding indices will improve the productivity, profitability, and environmental impact of the Irish national flock. Quantification of the economic benefits can also inform the industry of the value of purchasing rams of higher genetic merit.

Funding

Funding from the Irish Department of Agriculture, Food and Marine Research Fund GREENBREED (17/S/235) and Grass2Gas (2019/EN/202) is gratefully acknowledged.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103467.

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