A nationally representative Bio-economic modelling of sheep production systems: Modelling the carbon footprint and economic performance of Irish sheep flocks

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1. Introduction

With world food demand being increasingly driven by the shift of diets towards animal-based products such as meat, milk and dairy (FAO, 2016), demand for meat will continue to grow and is expected to exceed population growth over the next decade and in particular due to dietary changes in developing countries (Havlík et al., 2014). This is creating a number of challenges and opportunities for the agricultural industry and in particular those temperate regions where ruminant based meat and dairy is the major product output. Changing land-use patterns and the increasing policy pressure to address climate change and reach GHG emissions reduction targets have the potential to alter the future farm level profitability and sustainability of farming systems in these regions (Morris, 2009). Emerging environmental and resource use policy pressures are often in contrast to national industry production targets which set out growth and sustainable intensification goals into the future.

The distortionary impact of production based subsidies under previous EU Common Agriculture Programmes (CAP) is well documented in the literature (Breen et al., 2005; Goodwin et al., 2006; Serra et al., 2006; Weber et al., 2012). These policy signals altered producer priorities and consequently agricultural output and input allocation decisions, environmental externalities and income distribution. The CAP has provided high product prices and encouraged systems with high inputs of concentrate feed, fertiliser, and machinery and associated labour inputs, particularly in the beef and dairy sectors (Dillon, 2007). Sheep production on the other hand has in general continued to remain relatively extensive. In response recent EU Common Agricultural Policy (CAP) reforms have sought to reduce these distortionary policy effects and make EU agriculture more environmentally sustainable whilst having a greater market orientation. This has been particularly evident with: the decoupling of subsidy payments in 2005 under the Agenda 2000 Mid-Term Review; introduction of external convergence of Direct Payments (DP) across Member States (MS) and internal convergence of DPs within MSs under the 2013 reforms and continuation of the process of bringing average levels of payments in EU countries closer together in the 2023 reforms (); the move towards "greening" measures as announced in the 2013 reform and subsequent in introduction of Eco-Schemes ("Enhanced Greening") in the 2023 reforms (Louhichi et al., 2015).

With European and national policy focus evolving to foster the competitiveness and sustainability of farming systems in Europe (e.g. EIP-AGRI, Food Harvest 2020, Food Wise 2025, Food Vision 2030) there is an increasing demand for micro level analysis of the environmental, financial and social performance of agricultural systems. In response, a growing number of studies are based on farm-level models aimed at gaining a better understanding of the decision making process of farms across the distribution of farming systems, agronomic and environmental conditions (Louhichi et al., 2015; Jones et al., 2017). In the context of a growing population, emerging market trends for meat products and potentially conflicting policy challenges this paper provides a case study of Irish sheep flocks aimed at investigating the sustainability of these ruminant meat production systems from an environmental and economic perspective (Garnett et al., 2013; Bhatt et al., 2023).

Ireland represents a significant producer and exporter of sheep meat on the European Market and has a clear national sectoral growth strategy for sheep meat (DAFM, 2010, 2015, 2021). These strategy reports propose significant growth targets for the value of the agri-food industry whilst emphasising agricultural sustainability. At the same time, international marketing initiatives and eco labels are increasingly being used to promote the sustainability of production systems and certify the environmental impacts of value chains based on initiatives to improve the environmental performance of products (Chen et al., 2017; Bord Bia, 2022). However, it has been highlighted that the level of agricultural production envisioned under national sectoral strategies will pose environmental challenges particularly in the context of Ireland achieving its national emission reduction targets set down under the EU "Effort Sharing Decision" (42% by 2030 relative to 2005) and binding agriculture sectoral reduction targets of 25% by 2030 relative to 2018 as set out in the Climate Act 2022 (Government of Ireland, 2021). This ensure that continued monitoring and analyse is required to ensure that these plans are implemented in an environmentally sustainable manner (Wall et al., 2016).

This study explores these issues by comparing the farm level economic and environmental performance of Irish sheep farms based on bioeconomic model of sheep production system using data nationally representative farm accountancy panel data (Dillon et al., 2023) and biological information linked to livestock. NFS data enables the evaluation of the farm level Carbon Footprints (CF) and land occupation for the range of Irish sheep flocks. The environmental performance of distinct sheep farming systems operating at different levels of production intensity and input use is presented and compared with key financial and technical performance outcomes. Sheep farming in Ireland is generally considered to be pasture-based and extensive, but large differences in production intensity, and land and input use exist. The application of a farm level modelling approach in this study means the variation in environmental outputs and financial performance across individual (real) farms can be described (Louhichi et al., 2015).

The purposed of this study is to:

- To develop a nationally representative modelling framework to estimate the farm level carbon footprint and land occupation on ruminant grazing farms in Ireland.
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2. Background to Irish sheep farming

Sheep farming is the second most common enterprise on Irish farms and is often undertaken alongside cattle production in a mixed farming system (CSO, 2023b). Whilst Ireland does not exhibit the same stratified crossbreeding structure as the UK, sheep farming can be most readily classified into hill or lowland production (Pollott et al., 2006). A portion of upland ewe lambs are used for crossbreeding in the lowland sector but most are reared on rough hill grazing ground or improved uplands and sold for fattening and finishing on lowland farms. Lowland sheep production is predominantly grass based, with most ewes lambing in the spring with the onset of grass growth and most lambs going for slaughter before the end of the grazing season (Keady et al., 2009). The lowland sector accounts for the bulk of the sheep flock and meat production and can be divided into a number of sub systems.

3. Data and Methods

3.1Data

In order to estimate emissions and financial performance at a farm level this study employs National Farm Survey data. The survey collects detailed production information required in this study including data on animal activities and associated costs, the area, yields and input costs of home-grown crops, and pasture inputs and costs. This information is collected for the full sample of farms and results are scalable to the national level through the application of representative weighting factors. Weights used to make the NFS representative of the Irish farming population are based on the sample number of farms and the population number of farms (from the Census of Agriculture) in each farm system and farm size category.

The current study modelled the full sample of 3235 sheep farm enterprises (farm year records) over the period 2010 to 2019. 506 were classified as hill farms and 2729 lowland farms. Key technical performance indicators for the sample of farms are summarised for hill and lowland in Table 1. The average farm size was 50 hectares for hill farms and 42 hectares for lowland farms. On average, lowland farms demonstrate higher levels of technical performance across the range of parameters analysed. Hill farms are typically managed on upland rough grazing, have lower lambing and stocking rates than lowland breeds managed on higher quality pasture (Hanrahan, 2010). Sheep farmers can be seen to represent, on average, the oldest cohort of farmers when compared to other farming systems with an upward trend over the period of the study. This trend raises questions about generational renewal and the long term sustainability of the sector (Cush et al., 2016).

Hill farms are, on average, larger than lowland farms with larger flocks but are relatively more extensive. Average stocking rates recorded were 7.1 and 8.9 ewes/ha for hill and lowland farms respectively. Weaning rates were .9 lambs/ewe and 1.2 lambs/ewe respectively. In terms of inputs, hill farms are shown to exhibit slightly higher direct costs per unit output compared to lowland farms. In line with their more extensive nature, these farms get a higher proportion of DM intake in the form of grazed grass compared to lowland farms. Lowland farms on average spread more nitrogen fertiliser (92.4kg/ha vs 67.2 kg/ha) and use more fuel (34.6L/ha vs 26.7L/ha) per unit area than hill farms.

Table 1 Technical Summary of the average Lowland and Hill enterprise

	Hill	Lowland	^{d}P-Value	All Farms
Number of farms[1]	506	2729	**0.00**	3235
Farm Size	50	41	**0.00**	43
Age of Farmer	57	55	**0.0057**	55
Weaning rate (lambs/ewe)	0.9	1.2	**0.00**	1.16
Stocking Rate (ewes/ha)	7.1	8.9	**0.00**	8.6
Lamb carcass kg/ha[2]	124	219	**0.00**	200
Dir costs €/kg carcass	1.6	1.5	**0.00**	1.5
Breeding ewe numbers	147	92	**0.00**	102
Concentrate (kg DM/ewe)	46.8	62.6	**0.00**	59.8
N fertilizer (kg/ha)	67.2	92.4	**0.00**	88.8
Farm fuel use (l/ha)	26.7	34.6	**0.00**	33.4
Breakdown of Feed sources				
Grazed Grass (%of the diet)	81.2%	75.5%	**0.00**	76.4%
Concentrate (kg DM/ewe)	12.3%	12.4%	**0.00**	12.3%

Home grown crops feed (% of the diet)[3]	4.1%	11.0%	**0.00**	9.9%
Purchased bulk feed (%of the diet)	2.4%	1.0%	**0.00**	1.3%

[d]ttest; Test that difference between the mean value (each summary variable) of the two groups (hill or upland) is not equal to 0, significant results highlighted in bold (P<0.05).

[1]NFS Sheep enterprise data

[2]Assuming an average carcass weight of 20kg

[3]Includes conserved forage, hay and silage

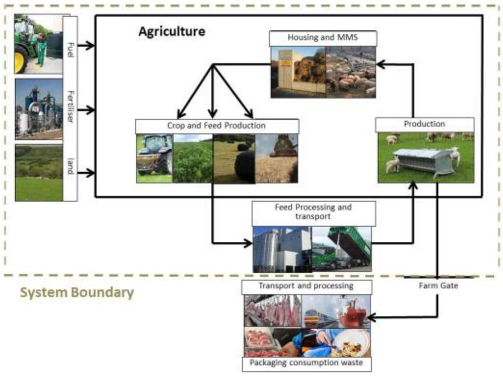
3.2Life Cycle Assessment

This study performs a Life Cycle Assessment (LCA) of the environment outputs from Irish sheep farms. LCA is an established and standardised method to evaluate environmental impacts across the life cycle of a production system and has been widely applied to livestock production systems, in particular the carbon foot printing of agricultural outputs (Edwards et al., 2008; Yan et al., 2011). While the analysis presented in this study follows the ISO standard layout, the Carbon Footprint calculations represent a partial LCA. This approach to calculating a carbon footprint of sheep farms without undertaking a full LCA as has been applied in a number of previous related studies of UK sheep production, (Saunders et al., 2006; Williams et al., 2006; Jones et al., 2009). In this context, a carbon footprint (CF) analysis represents a single-issue LCA which can be extended to account for a multitude of additional environmental outputs, such as water use, land use, acidification, energy use, eutrophication, etc. (Murphy et al., 2017; Schmidinger et al., 2012; Thomassen et al., 2008).

Goal and scope definition

The goal of this analysis was to estimate and compare Carbon Footprint of the full distribution of Irish sheep farms as describe by the nationally representative farm business survey, the Teagasc National Farm Survey (NFS). The CFs for sheep farms were calculated in this study according to a cradle to farm gate system boundary. Figure 1 provides a schematic representation of this system boundary which follows the British Standards Institute (BSI, 2011) approach with emissions estimates based on a Life-cycle assessment (LCA) methodology. This is a holistic systems approach that aims to quantify the potential environmental impacts e.g. GHG emissions, generated throughout a product or processes life cycle within a defined boundary. Thus the analysis accounts for all GHG emissions from the farm up to the point of product sale from the farm (cradle to farm gate).

Figure 1 Schematic representation of the system boundary for Irish Sheep Production



The functional unit (FU) is taken as an attribute of the main product being analysed which enables comparison of farm emissions on a standardised per unit basis. For sheep production systems, the main product is sheep meat, and the FU for this study is expressed as the environmental impact per unit production of 1kg of liveweight equivalent.

3.3 Inventory Analysis

The resources used and emissions related to sheep enterprises were quantified in the inventory analysis stage through a sheep farm systems model crops sub model briefnly described here. This crops sub model was developed to estimate emissions from crops used for livestock feed. While the NFS provides detailed farm level data on the quantity of inputs used in feed crops and pasture production as well as the quantities and cost of purchased feed, additional data were required for a number of inputs for which there was insufficient information. Emissions factors were calculated based on this input information gathered from national research and Teagasc production specialists (CSO, 2023a; DAFM, 2012; Phelan, 2022; Teagasc, 2011), IPCC (2006) guidelines and the international LCA literature (O'Brien et al., 2016; Nemeck et al., 2007).

The farm (cradle to farmgate) LCA analysis includes the emissions from livestock (enteric fermentation), inputs used on-farm (pesticides, fuel, phosphorus (P) and potassium (K) and ammonia nitrate fertilisers) along with the inputs used in the production of purchased feeds produced off-farm (pesticides, fuel, P,K and ammonia nitrate fertiliser) and the emissions released in the manufacturing process of these same inputs (off-farm production processes). The emissions factors for these inputs and their respective sources are detailed in appendix 1).

The Land Use change emissions for a representative sheep ration (0.23kg CO_2 per kg Concentrate dry matter fed) (appendix 2) are estimated here by computing the land use change emissions associated with the production of relevant constituent feed ingredients based on the associated crop information for source countries (Vellinga et al., 2013) and emissions factors from the Carbon Trust (2013) and are in line with O'Brien et al. (2016). Land area was quantified in hectares, including land required to produce home-grown forage and crops and land for imported feedstuffs (Appendix 1).

3.4 Impact assessment

The climate change impact of GHG emissions from sheep production was calculated in terms of CO_2 equivalents using 100 year global warming potential (GWP) The Global Warming Potential (GWP) factors are a relative measure of how much heat a greenhouse gas traps in the atmosphere and was developed to allow comparisons of the global warming impacts of different gases. In this study (IPCC, 2013) (AR5) GWP values are applied to determine the overall contribution of CO_2, CH_4 and N_2O to total emissions. Accordingly, all GHG emissions calculated are estimated in terms of the reference gas CO_2 equivalents where the GWP of 1 kg CO_2 is 1, 1 kg CH_4 is 28, and 1 kg N_2O is 265, assuming a 100-year time horizon.

The other resource use measure examined in this study is the equivalised land area occupied by sheep production systems. Land occupation was quantified in m_2/kg of LW and included land required to produce homegrown forage (grass and grass silage or hay) fodder crops used for the sheep enterprise, and the equivalised land footprint of purchased bulkfeeds and imported feedstuffs (presented in hectare equivalents).

3.5 Economic Performance and Feed Costs

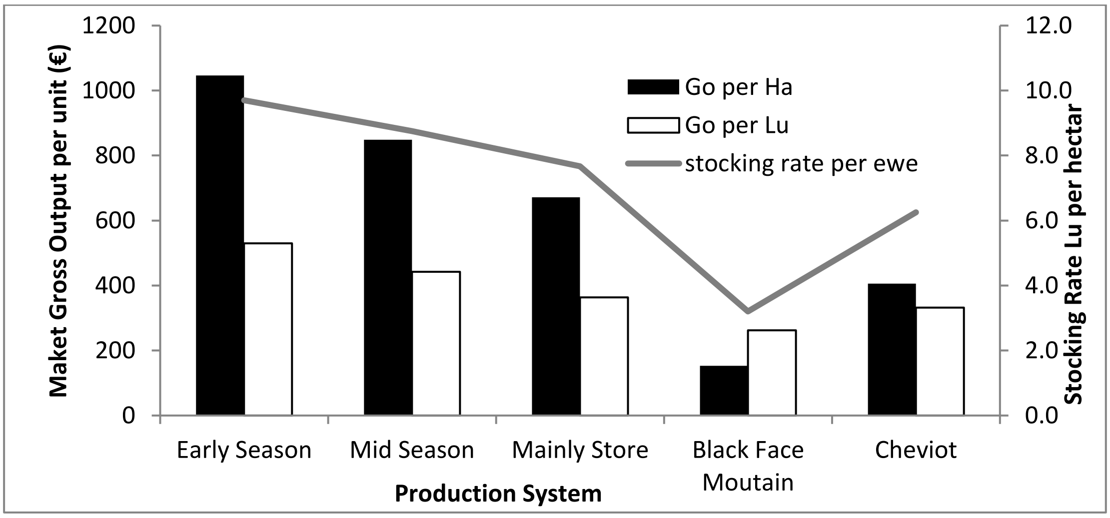
The economic performance of sheep farms was analysed using the NFS panel dataset which provides a time series of key financial records for sheep farms including farm gross output and variable costs (Dillon et al., 2023). Analysis is performed at the enterprise level and broken down by hill and lowland enterprises, taking into account their differential production systems. To benchmark the different sheep farming systems, a gross margin analysis is performed. Financial results are presented for the average of lowland, hill and all farms. Lowland farms are further ranked on the basis of gross margin per hectare, and grouped into three categories; the top third, middle third and bottom third of performing farms. The average levels of output, direct costs and gross margin per hectare across these groups and the key indicators of technical performance, can then be compared.

4 Results

4.1Economic Performance and Feed Costs

Figure 1 describes this distribution of gross output across sheep enterprises over the sample period. The average value of gross output per hectare for the sample of sheep flock subsystems is measured relative to their forage area (hectares) and number of sheep livestock unit. The difference between the two measures is largely due to the difference in the average stocking rate across systems. Early season enterprises have the highest gross output in both unit measures (€1047/ha €530/lu). The higher per livestock output from the early season system is facilitated through indoor housing and a greater emphasis on more expensive, concentrate based diets required to meet the nutritional requirements of ewes lambing earlier in the season, when grass is in short supply (Flanagan et al., 2001). The predominant mid-season system has the second highest output per LU and per hectare (€849/ha, €442/lu) with farms typically lambing down in the spring with the onset of grass growth (Keady et al., 2009). Later lambing or mainly store lamb production systems (also includes farms that buy in store lambs for fattening and later finishing) have lower margins (€672/ha, €363/lu) and lower stocking rates (7.7ewes/ha). The hill sheep systems have the lowest output per hectare output as would be expected given their extensive nature and upland grazing. Blackface Mountain systems exhibit the lowest stocking rates (0.6ewes/ha) and output per unit (€153/ha, €262/lu) of all the systems analysed.

Figure 2 Distribution of Gross Output and Stocking Rates by sheep Sub-System



A breakdown of financial performance at the enterprise level for hill, lowland and midseason lowland farms is presented in table 2. Lowland farms exhibit higher gross margins driven by significantly higher gross output per unit hectare. Hill farms are much more dependent on direct income support: of the €206/ha gross margin earned on hill farms over the period €110/ha or 54% of this is attributable to subsidy payments, whilst on lowland farms almost 80% is earned from the market. Analysing midseason lowland farms, the top performing group earned an average gross margin of €937 per hectare; farms in the bottom group earned an average gross margin of only €198 per hectare. This means that the top producers earned, on average, almost 5 times more per hectare than their counterparts in the bottom group whilst a breakdown of the trend in gross margin highlights that the gap between the top and bottom third of mid-season lowland lamb producers has been growing. The best performing farms can be seen to achieve significantly higher levels of output while simultaneously keeping a control over direct cost. Higher output levels are achieved through better technical performance and reflected in higher stocking rates and weaning rates.

In terms of direct costs per hectare, feed costs represent the major cost item. Over the sample period, feed costs contributed on average over 73% of total direct costs across all sheep farming enterprises. If feed costs are broken down into its components, concentrate costs are the single largest expense item, contributing on average over 44% of direct costs across all enterprises for the same period. The share of expenditure attributable to concentrates is lowest in the top performing farms (41%) and highest in the bottom third of farms (45%) while the opposite is true for pasture costs (33% vs 29%). In line with the findings from Kilcline et al. (2014), results highlight the importance of maximizing output and returns from well managed pasture and simultaneously controlling concentrate input as means of improving margins (Figure 3). A more detailed breakdown of the key sources of forage and feed crops fed to sheep is detailed in Table 2 along with their relative costs on a per unit energy basis and contribution to total flock energy requirements.

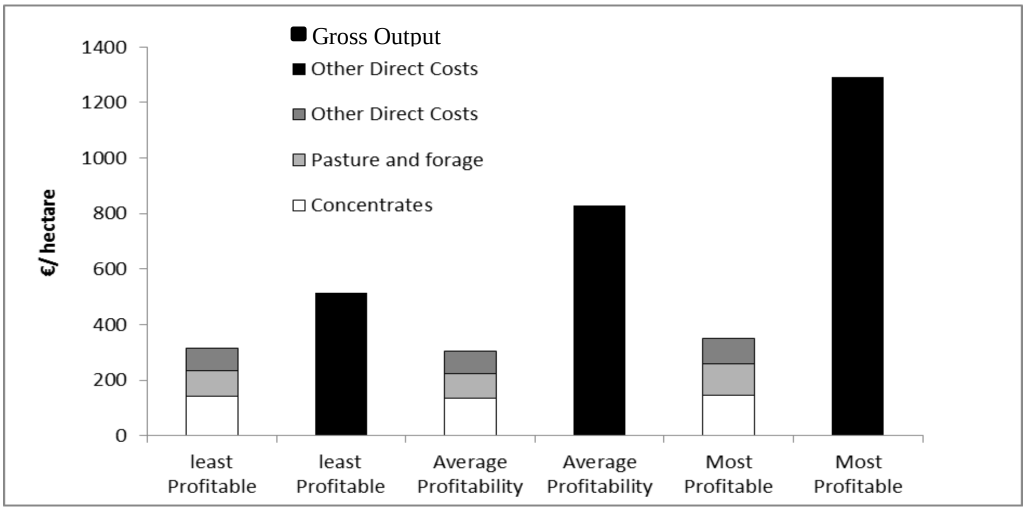
The list of feeds presented in Table 2 can be seen to contribute on average over 99% of animal feed supplied to sheep over the reference period. In line with expectations, grass represents the most important and cheapest feed on a cost per unit energy basis, contributing over 76% of energy supply to livestock and at a cost of little over 1 cent per unit energy across all farms. Concentrates is the second most important feed source, supplying 12.3% of energy to livestock at a cost of 24 cent per UFL. This makes concentrate feed the most expensive feed source.

Table 2 Financial Performance Indicators (€) and Feed constituent costs (€/UFL)

				Bottom, middle, and top third of Midseason lowland farms ranked by GM/Ha		
	Hill	Lowland	Total	Bottom 1/3	Middle 1/3	Top 1/3
Key Financial Performance Indicators (€/ha)						
Gross output[1]	400	854	774	516	830	1291
Total Direct Costs	194	322	299	318	308	354
Concentrates expenditure	84	144	133	142	134	146
Winter Forage expenditure	16	28	26	31	27	32
Pasture Expenses	37	65	60	62	61	78
Other Direct Costs	57	83	79	81	84	95
Gross Margin	206	532	474	198	522	937
Unit Energy Costs of main feed sources (€/UFL)				% energy contribution to diet (All farms)		
Grass	0.008	0.011	0.0108	76.4%		
Concentrates	0.245	0.242	0.242	12.3%		
Fodderbeet	0.120	0.084	0.084	0.4%		
Hay	0.058	0.051	0.052	3.2%		
Silage	0.093	0.077	0.079	4.7%		
Barley	0.129	0.121	0.122	0.6%		
Oats	0.125	0.137	0.136	0.2%		
Purchased hay	0.177	0.153	0.160	1.1%		
Purchased Silage	0.173	0.158	0.163	0.1%		
				99.2%		

[1] Includes subsidy payments

Figure 3 Variation in Gross Output Direct Costs and Gross Margin-Mid-Season farms



4.2GHG Emissions and Land Occupation

Whilst sheep farms produce wool, on average the return from wool sales is only sufficient to cover the cost of shearing. This study thus presents the CF of sheep farms, expressed in terms of the main production output, sheep liveweight (Table 3). GHG emissions from sheep farms are expressed in terms of the Carbon Dioxide (CO_2) equivalent per kg of live weight equivalent of sheep produced, unlike previous LCAs of sheep farms which allocated emissions between products based on economic allocation (Casey et al., 2006a; O'Brien et al., 2016).

The average CF of lowland farms was estimated at 9.8kg of CO_2-eq/kg LW, which was 13% lower than the average CF estimated for hill farms. The average CF of lowland farms was within the range previously estimated by O'Brien et al. (2016) whilst the CF of hill farms diverged significantly. This reflects the alternative data source used by O’Brien et al. (2016) to construct an average hill farm representation based on mean e-profit monitor financial benchmarking data. The e-profit monitor is a financial analysis tool that is available to all Teagasc clients that when completed provides a detailed financial breakdown of the business. However the results generated are not nationally representative as the farms in the sample are self-selecting and do not proportionally represent the farming population (Teagasc, 2016).

All sheep farms analysed in this study operate grass based grazing systems. Estimates of the breakdown of energy supply from the range of feed stuffs support this and show that on average across all farms grass contributed 76.4% of flock energy demands (Table 2). As would be expected, given their more extensive nature, grass supplied a greater proportion of energy to livestock on hill farms (81%) when compared to lowland farms (75.5%), Appendix 3. Taking into account the carbon sequestration value of grassland reduces the carbon footprints on hill farms to 9.99kg of CO_2-eq/kg LW (12% reduction) and lowland farms to 8.6kg of CO_2-eq/kg LW (10% reduction). In line with O'Brien et al. (2016), the carbon sequestration rate had a relatively larger impact on reducing emissions for more extensive farms. This is evident when comparing the average of hill to the average of lowland farms or average top and bottom performing midseason farms to the bottom performing one.

Table 3 Carbon footprint (CF) of sheep meat production (kg of CO_2 /kg LW)

				Midseason Farms ranked by GM/ha		
	All farms	Hill	Lowland	Bottom	Middle	Top
Carbon Footprint	9.88	11.33	9.84	10.47	8.44	7.47
Carbon Footprint excluding Land use change[1]	9.52	11.04	9.12	10.03	8.13	7.18
Carbon Footprint with Carbon Sequestration[2]	8.89	9.99	8.58	9.13	7.54	6.49

[1] Nonrecurrent LUC emissions - conversion of grassland to arable land and cultivation of South American soybean and southeast Asian palm concentrate feedstuffs

[2] Grassland soil carbon storage estimates are based on a review Soussana et al. (2010) of the literature and LEAP (2015)

Looking at the breakdown of emissions across all sheep farms (Table 4), animal activities represent the largest source, with Tier I estimates of enteric fermentation and manure management comprising (64%) and (6%) of total emissions respectively. Other emissions include those emissions from soils (14%) and total emissions associated with feed production (16%). A detailed breakdown of emission from feed production included emissions associated with inputs used in the feed production process (field processes, transport, manufacturing and processing of feed grains, mixed rations and forage) and land use change are presented in (Table 4).

The GHG emissions associated with the cultivation, processing, and transport of concentrate feed (but excluding non-recurrent land use change emissions) were the largest, contributor of emissions associate with feed input provision 49% (7.8% of total emissions). The off-farm emissions from land use change (LUC) associated with the production of Brazilian soybean meal (protein ingredient in representative concentrate feed) accounted for the next largest proportion of emissions from feed inputs at 20% (3.2% of total farm emissions), followed by on-farm emissions from artificial N fertiliser application at 11% (2.5% of total). While the overall proportion of direct cost expenditure on fertiliser and pasture costs was shown to be higher on the most profitable midseason farms (Table 2), the proportion of GHG emissions coming from fertiliser application and production per unit output is lower, reflecting the relative efficiency of fertiliser input use per unit of output.

Table 4 GHG emissions profiles of Irish sheep flock Diets

					Bottom, middle, and top third of Midseason lowland farms ranked by gross margin/ha		
GHG emssions and source as CO_2 equivalent	**Emissions Location**	**All Sheep Farms**	**Lowland**	**Hill**	**Bottom Third**	**Middle Third**	**Top Third**
Methane (CH_4) Livestock Activities							
Enteric Fermentation	On-Farm	64.4%	62.4%	70.7%	58.7%	62.2%	64.1%
Manure Management and excretion		6.2%	6.1%	6.3%	5.7%	6.2%	6.3%
Nitrous oxide (N_2O-N) Livestock Activities							
Manure storage and spreadings, & excretion on pasture		13.6%	14.8%	10%	14.4%	14.7%	15.2%
Nitrous oxide (N_2O-N)							
Synthetic N fertilizer application	On-farm	2.5%	2.8%	1.5%	4.1%	2.9%	2.2%
N leaching		0.2%	0.2%	0.1%	0.3%	0.2%	0.2%
Atmospheric deposition(6)		0.1%	0.1%	0.0%	0.1%	0.1%	0.1%

Carbon Dioxide (CO_2)							
Fuel Use (Diesel)	On-farm	0.7%	0.7%	0.7%	1.1%	0.6%	0.5%
Fertiliser Application (Urea applied)	On-farm	0.1%	0.1%	0.0%	0.2%	0.1%	0.1%
Lime application	On-farm	0.4%	0.4%	0.3%	0.6%	0.4%	0.2%
LUC from on-farm arable land (home-grown feeds)[1]	On-farm	0.5%	0.6%	0.1%	0.5%	0.5%	0.8%
Fertiliser Production (Urea, P, K, and Ammonia Nitrate fertiliser applied)	Off-farm	0.6%	0.6%	0.3%	0.9%	0.7%	0.5%
Concentrate production[2]	Off-farm	7.8%	8.1%	6.7%	8.5%	7.8%	7.0%
Carbon dioxide, CO_2 from land use change LUC[3]	Off-farm	3.2%	3.3%	2.7%	3.5%	3.2%	2.8%
Other Inputs[4]	Off-farm	0.5%	0.4%	0.8%	0.5%	0.3%	0.4%

[1] Nonrecurrent land use change emissions from the conversion of grassland to arable land.

[2] The GHG emissions associated with the cultivation, processing, and transport of concentrate feed, but excluding nonrecurrent land use change emissions.

[3] Nonrecurrent land use change emissions from the cultivation of South American soybean feedstuffs used as a constituent in concentrate ration.

[4] Emissions from the production of purchased forage, milk replacer, fuel, pesticides and plastic.

The average land occupation for the various sheep systems analysed in this study is presented in (Table 5). Average land occupation levels are broken down into key feed categories and aggregated to on-farm and off-farm area totals (hectares). Results highlight the grass based nature of sheep production, with diets supplemented in winter and particularly around lambing season (O'Mara, 2008). The vast majority of land occupied by sheep farms is used for home produced forage in the form of pasture grazing and conserved forage, hay and silage. The proportion of the total equivalised land area used for on-farm forage production ranged from 92% for the average of the poorest performing group of midseason lowland farms to 98.8% for the average of hill farms. The next most important land area occupied by sheep enterprise was off-farm land used in the production of supplementary concentrate feeds.

Table 5 Land Occupation - Feed crops and pasture on Sheep Enterprises Ha

	Hill	Lowland	All Farms	Bottom third	Middle third	Top Third
Purchased concentrate	1.08	0.91	0.94	1.08	1.11	0.79
Purchased bulkfeeds	0.29	0.09	0.13	0.08	0.04	0.18
Off farm land occupation [1]	1.37	1.00	1.07	1.16	1.15	0.97
Pasture	38.69	12.67	17.29	14.35	14.23	11.05
Conserved forage area[2]	0.43	0.75	0.69	0.93	0.95	0.61
Homegrown feed crop	0.03	0.25	0.21	0.27	0.19	0.19
On farm land occupation[3]	39.16	13.66	18.19	15.55	15.37	11.85
Total Equalized Land area allocated to sheep feed crops and pasture	40.53	14.67	19.26	16.70	16.52	12.82

[1] Land occupation representing the area required to grow purchased Bulk Feed and Concentrates fed to sheep

[2] Land occupation representing the area of required to grown hay and silage crops

[3] Land occupation representing the area of pasture and home-grown crops allocated to sheep livestock

5 Discussion and Conclusion

5.1 Discussion of results

In the context of sheep farming, there are a number of differential production systems which provide a significant range of both market and non-market outputs, all of which must be taken into account when comparing the relative sustainability of systems (Ripoll-Bosch et al., 2013; Plieninger et al., 2006). In this analysis both financial and economic performance indicators were estimated and analysed to provide insight into the relative sustainability of Irish sheep farms.

Results of financial performance and feed analysis highlight that sheep farms operate grass-based production systems and that the best performing lowland flocks are focused on the production and use of grazed grass as the cheapest feed source. Supplementary concentrate feed on the other hand is shown to be the most expensive feed per unit energy with poorer financial performing farms more reliant on it as a key source of nutrition. The more profitable lowland enterprises are characterised by higher technical performance, stocking and weaning rates, greater production intensity and greater emissions efficiency on a per unit basis and is in line with previous studies in comparable production settings (Hyland, 2016; Jones et al., 2014a; O'Brien et al., 2016). Improved technical performance is reflected in the average carcass output per hectare of 332 kilos on the top third of lowland mid-season farms, versus 167 kilos on the bottom third of farms. This higher level of lamb output per hectare, combined with tighter control of direct costs is reflected in higher enterprise profitability.

The results of the analysis of carbon footprints and land occupation in this study are not directly comparable with previous studies of sheep production systems. Previous carbon CF studies used alternative methodologies applied to different farm samples, locations, or production settings. Estimates are thus model specific and while broadly inline with previous published studies based on similar production settings, Ireland (Brien et al., 2016), UK (Jones et al., 2009; Jones et al., 2014b) they are not compared in detail. In contrast to most other studies this study enables the application of nationally representative panel data (Dillon et al., 2023) results in farm level estimation which is scalable and representative at a national level and thus more suitable for agronomic and policy recommendations. Including estimates of carbon sequestration by soils reduces the enterprise CFs across the entire sample of sheep farms. However carbon sequestration of grassland soils is an emerging area of research and a range of estimates are provided in the literature. Accordingly, estimates of grassland soil carbon storage are excluded from many LCA and CF studies of grazing production systems (Jones,

2014) while estimates provided here are based on a review Soussana et al. (2010) of the literature and LEAP (2015) and subject to revision.

In line with previous studies (Jones et al., 2014b), extensive hill production systems demonstrated lower overall emissions, lower production efficiency and higher GHG emissions per unit output. However, there are a range of other environmental sustainability measures that are not analysed in this study. O'Brien et al. (2016) also analysed nutrient surpluses, acidification and eutrophication as part of an LCA and found more intensive sheep farms had the greatest negative environmental impact for these factors. This highlights the potential conflict between carbon efficiencies and other environmental objectives not analysed here (Jones et al., 2009; Maier et al., 2001). Sheep farming has also been shown to provide an important range of ecological services and public goods, including landscape management, preservation of biodiversity, clean water supplies, flood mitigation, and recreation opportunities, traditional farming systems and cultural heritage (Ripoll-Bosch et al., 2013; Buckley et al., 2009; Osoro et al., 2016; Plieninger et al., 2006; Reed et al., 2009). Sheep production is highly embedded in the rural economy and supports downstream economic activity and employment. (Grealis et al., 2015) have previously estimated high economic and employment multipliers for sheep and cattle production systems. Therefore, when assessing the overall sustainability and contribution of production systems, the range of economic, environmental and social sustainability indicators should be taken into account. Many of these are not readily quantifiable or easily comparable across different production settings (Buckley et al., 2012; Dillon et al., 2010).

5.2 Conclusions

The farm level modelling framework developed in this study was used to analyse the GHG emissions from the range of sheep production systems consistent with IPCC reporting standards. Additionally, the emissions from upstream input production were estimated to provide a CF of sheep farms. This framework can be readily extended to estimate CFs for cattle and dairy production systems as recorded in the NFS. Furthermore, the use of a consistent panel dataset stretching back to 1972 and before Ireland's accession to the EU means the environmental impact associated with the evolution of farming management practice in response to market and policy stimulus can be investigated. The NFS captures information on farmer participation in agri-environmental schemes which have emerged in line with the general "greening" of the CAP. This study can be developed to compare the emissions profiles of participating and non-participating farms in agri-environmental schemes.

Emissions factors applied in this paper are currently calculated based on IPCC (2006) reporting guidelines and are currently being updated in accordance with IPCC (2019) refinement for National Greenhouse Gas Inventories. There is also the potential to develop the analysis in this study to produce a full LCA of sheep farms. This would require a Tier II estimate of Enteric Fermentation emissions in line with LCA protocols. Given the structure of NFS data, additional assumptions around animal performance, growth rates, and dry matter intake (DMI) would need to be made in conjunction with livestock specialists and in order to more accurately describe the farm level variability in livestock performance and related emissions.

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Appendices

Appendix 1 Key on-farm emission and energy factors for Irish Sheep flocks

Emission source		Emission or energy factor	Unit	Reference
Methane (CH_4)				
Enteric fermentation				
Ewes Lowland	On-farm	8 × livestock number	kgCH_4/animal	(Duffy et al., 2017)
Other Sheep over 1yr Lowland	On-farm	8 × livestock number	kgCH_4/animal	
Lambs Upland	On-farm	2.73 × livestock number	kgCH_4/animal	
Ewes Upland	On-farm	8 × livestock number	kgCH_4/animal	
Rams Upland	On-farm	8 × livestock number	kgCH_4/animal	
Other Sheep over 1yr Upland	On-farm	8 × livestock number	kgCH_4/animal	
Rams Lowland	On-farm	8 × livestock number	kgCH_4/animal	
Lambs Lowland	On-farm	2.73 × livestock number	kgCH_4/animal	
Ewes Lowland	On-farm	8 × livestock number	kgCH_4/animal	
Nitrous oxide (N_2O-N)				
Synthetic N fertilizer application	On-farm	0.01 × N fertilizer applied (KG N)	kg N_2O-N	(IPCC, 2006 ; Carbon Trust, 2013; Vellinga et al., 2013)
Nitrogen leaching from synthetic N application	On-farm	0.0075 × frac N applied (10% of N input to managed soils is lost through leaching)	kg N_2O-N	
Atmospheric Deposition of nitrogen (N) volatilised from synthetic N	On-farm	0.01 × frac applied volatilised (3% of synthetic fertilizer N applied to soils volatilises as NH_3 and NO_x, 8% for livestock N))	kg NH_3-N	
Solid manure storage	On-farm	0.005 × solid manure N stored	kg/kg N	(Duffy et al., 2017)
Manure excreted on pasture	On-farm	0.01 × N excreted on pasture	kg/kg N	
Solid manure application	On-farm	0.01 × N in manure spread	kg/kg	
Ammonia (NH_3) re-deposition	On-farm	0.01 × sum of NH_3 loss	kg/kg NH3-N	
Nitrogen oxides (NOx)				
Solid manure storage	On-farm	0.01 × solid manure TAN stored	kg/kg TAN	(Duffy et al., 2017)
Solid manure application	On-farm	0.002 × N in manure spread	kg/kg N	
Manure excreted on pasture	On-farm	0.0035 × TAN excreted on pasture	kg/kg TAN	
Ammonia (NH3-N)				
Housing	On-farm	0.22 × manure TAN stored	kg/kg TAN	(Duffy et al., 2017)
Solid manure storage	On-farm	0.35 × solid manure TAN stored	kg/kg TAN	
Solid manure application	On-farm	0.68–0.004 × TAN in solid manure spread	kg/kg TAN	
Manure excreted on pasture	On-farm	0.06 × TAN excreted on pasture	kg/kg TAN	

Carbon Dioxide (CO_2)				
Diesel	On-farm	2.63 × diesel use (litres)	kg CO_2/l	(IPCC, 2006)
Gasoline	On-farm	2.30 × gasoline use (litres)	kg CO_2/l	
Kerosene	On-farm	2.52 × kerosene use (litres)	kg CO_2/l	
Urea application	On-farm	0.733× urea application (KG Urea)	kgCO_2/kg urea	
Lime application	On-farm	0.44 × lime application (Kg Lime)	kgCO_2/kg lime	
LUC from on-farm arable land[1]	On-farm	6.7 × crop area (Ha)	kgCO_2/Ha	(BSI, 2011)
Grassland carbon sequestration[2]		0.57–0.89 × grassland area (Ha)	tCO_2/Ha	(Leip et al., 2015)
[1] Arable land used for the production of home-grown feeds [2] Grassland carbon sequestration estimated at 0.89 t of CO_2/ha for lowland farms and 0.57 t of CO_2/ha for lowland farms				

Appendix 2 Key off-farm emission and energy factors for Irish Sheep flocks

		Emission or energy factor	**Unit**	**Reference(s)**
Diesel	Off-farm	.38 × diesel use (litres)	kg CO_2/l	
Lime application	Off-farm	0.15 × lime application (Kg)	kgCO_2/kg lime	(Carbon Trust, 2013)
Urea	Off-farm	2.89 × urea application (KG N)	kg CO_2/kg N	(Carbon Trust, 2013
P fertilizer	Off-farm	1.87 × P application (KG P)	kgCO_2/kg P	(Carbon Trust, 2013
K fertilizer	Off-farm	1.80 × K application (KG K)	kg CO_2/kg K	(Carbon Trust, 2013
Ammonia Nitrate	Off-farm	3.63× K application (KG N)	kg CO_2/kg N	(Carbon Trust, 2013
Pesticides	Off-farm	8.40 × Active Ingredient (KG)	kgCO_2/kg active ingredient	(Carbon Trust, 2013
Concentrate production[1]	Off-farm	0.161× Concentrate Fed (Kg DM)	kgCO_2/kg DM	(Carbon Trust, 2013
Concentrate (CO_2 from land use change)[2]	Off-farm	0.23 × Concentrate Fed (Kg DM)	kgCO_2/kg DM	(Carbon Trust, 2013 ; Vellinga et al., 2013)
[1] GHG emissions associated with of representative 17% CP concentrate feed (see Appendix 2 for DM formulation) [2] Nonrecurrent land use change emissions associated with of representative 17% CP concentrate feed				