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A life cycle assessment of the effect of intensification on the environmental impacts and resource use of grass-based sheep farming

D. O'Brien [a,*], A. Bohan [b], N. McHugh [b], L. Shalloo [a]

[a] Livestock Systems Research Department, AGRIC, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland
[b] Animal & Bioscience Research Department, AGRIC, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland

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ABSTRACT

Intensification is a strategy that is reported to increase the productivity and environmental performance of livestock farms, but most life cycle assessments (LCA) of livestock (particularly sheep) only consider greenhouse gas (GHG) or carbon footprint (CF). The goal of our LCA study was to assess the effect of intensification on several measures of environmental impact and resource use for grass-based sheep farms. The impacts we considered in addition to CF were acidification and eutrophication. The resource use measures we assessed were fossil fuel energy demand, land occupation and land use efficiency in terms of human digestible protein (HDP) production. Both environmental and resource use measures were expressed per kg of sheep live weight (LW) produced. The sheep production systems we assessed were Irish case study farms that represented average lowland, average hill, intensive lowland mid-season (IMS) and intensive early-season (IES) systems. Our results showed that the food-related environmental impacts and resource use of the average lowland sheep farm could be improved by intensifying grass and animal production. In addition, there was significant potential to increase production within area-based regulatory limits on nitrogen and phosphorus. However, increasing animal production by feeding more concentrate was less efficient and increased environmental impacts compared to increasing grass production, because concentrate required significantly more resources than pasture to produce and generated more emissions. There was limited potential to produce meat from the average hill farm that was located on marginal land. This generally led to the average hill farm having the highest product-related environmental impacts, but this system had the lowest nutrient surpluses per unit area. Modeling assumptions regarding carbon sequestration by grassland had a large effect on farm carbon footprints. The average hill farm had the highest carbon footprint when sequestration was excluded, but the opposite was the case when it was included. Therefore, we recommend clearly documenting the contribution of uncertain carbon sinks such as grassland sequestration to carbon footprints of sheep production systems. Additionally, we suggest that the assessment of land use efficiency should not be confined to HDP production and instead an index or scoring system should be used that accounts for the textile products and ecosystem services (e.g., landscape conservation) of sheep farms. The latter can be quantified using data from agri-environmental schemes or farm surveys and would provide additional important information on the environmental benefits of sheep farming.

1. Introduction

Sheep farms play a crucial role in supporting rural livelihoods throughout developing and developed regions. Meat is typically the primary function of sheep farms, but sheep are multi-purpose animals that also produce milk, skins and wool (Zygoyiannis, 2006). The demand for sheep meat grew by 1.7% per year between 1983 and 2013, and this is expected to continue as the global population continues to increase and become more affluent (LEAP, 2015). The production of sheep meat, however like all foods generates unwanted environmental side effects e.g., greenhouse gas (GHG) emissions, which policymakers and consumers are increasingly concerned is leading to irreversible environmental damage as production grows. This issue has stimulated retail initiatives to report the environmental performance of livestock products (Flysjö et al., 2011). Thus, the sheep sector increasingly needs to monitor its environmental performance and develop strategies to improve it.

Internationally, the majority of sheep meat is produced from seasonal grazing systems (Ledgard et al., 2011). While pasture has multiple environmental benefits including enhancing biodiversity and the natural landscape, grazing of pasture is also a key source of emissions and nutrient loss from sheep production systems (Ripoll-Bosch et al., 2013). Several technologies have been identified under laboratory or research farm conditions to reduce emissions from grassland farms such as the

* Corresponding author.
E-mail address: donal.mobrien@teagasc.ie (D. O'Brien).

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application of urease inhibitors (Dobbie and Smith, 2003). It is imperative, however that strategies to reduce emissions from farming systems are not viewed in isolation, as attempts to reduce emissions from a single source may affect another (pollution swapping). For example, feeding diets containing high levels of cereal may reduce enteric methane (CH_4); but emissions associated with the production of these feeds may actually increase the emissions from the overall production system (de Boer et al., 2011). Thus, to improve the environmental performance of sheep farms, the entire production system should be considered.

Whole farm nutrient balances and life cycle assessment (LCA) are the most widely used methods to evaluate the environmental performance of livestock systems, because measuring of actual emissions or nutrient surpluses is physically difficult and expensive. The LCA methodology is internationally standardized and specific guidelines are available for the livestock sectors (BSI, 2011; IDF, 2015; LEAP, 2015). In general, LCA studies of livestock farms such as Thomassen et al. (2008) and Peters et al. (2010) assess on-farm and off-farm environmental impacts (e.g., mining of limestone) associated with livestock until the main product(s) is sold from the farm. This stage of LCA is known as the "cradle to farm-gate stage", but has rarely been evaluated for sheep production systems (LEAP, 2015).

Various strategies have been assessed via LCA to reduce the environmental impact and resource use of dairy and beef systems including adopting new farm management practices and changing farming systems (e.g., conventional and organic farms). The outcomes of several of these studies indicate that intensification can improve environmental performance while at the same time increasing production (Capper et al., 2009; Foley et al., 2011). However, some studies have reported that intensification has the opposite influence on environmental measures of water quality (Haas et al., 2001; Basset-Mens et al., 2009). Similarly, of the small number of LCA studies that have assessed sheep farms of differing intensities Ripoll-Bosch et al. (2013) showed that extensive systems can have a lower carbon footprint than more intensive systems.

The objectives of this study were twofold. First, we aimed to develop an LCA model for grass-based sheep farms according to recognized international standards and our second goal was to analyze the effect of intensification on the environmental impact and resource use of sheep farming systems across a range of environmental and resource use categories (e.g., water quality and land use). For this study, we selected Ireland as the national location for the evaluation of sheep farms given that the majority of producers allow sheep graze pasture for most of the year. Furthermore, few, if any studies have applied LCA to evaluate environmental and resource impacts from this important national producer of sheep meat.

2. Materials and methods

2.1. Description of sheep farming systems

In Ireland, meat is the main product of sheep farms, with wool production only sufficient to cover the cost of shearing (O'Mara, 2008). Irish sheep farmers operate seasonal grazing systems, which are broadly divided into lowland and hill farms. The predominant breeds used on lowland farms are the Suffolk, Texel, Belclare and Charollais. For hill farms, the Blackface Mountain and Cheviot breeds are the most common. Lowland farms are the dominant system and account for 85% of national sheep meat production. Most lowland farmers aim to maximize profit from this system by optimizing meat production from grazed grass. To realize this goal sheep farmers typically breed ewes between late October and November and lamb ewes in spring (mid-March) to synchronize lamb growth with grass growth. Generally, ewes are housed in the weeks coming up to lambing and are fed conserved forages (grass silage, hay or both) and supplementary concentrate. After lambing, ewes and their progeny are turned out to pasture and supplemented with concentrate for a short period (<2 weeks). Lambs are typically weaned at 12 weeks and usually sold for slaughter between 4 and 6 months at a live weight (LW) of about 45 kg (O'Mara, 2008).

Hill sheep farmers operate a similar grazing system as lowland farmers, but generally lamb ewes in mid-April given that grass growth commences later in spring. Hill farmers usually bring ewes from upland areas to lowland areas in the weeks prior to lambing to provide conserved forages and concentrate feeding. Generally, a couple of weeks post lambing, ewes are returned to the upland (O'Mara, 2008). Nationally 72% of sheep meat was exported in 2014, which made Ireland the largest net exporter of sheep meat in the northern hemisphere (FAOSTAT, 2015).

To model the environmental performance of an average Irish sheep farm, we used the national farm survey (NFS) dataset of Hennessy et al. (2014). The NFS is collected as part of the farm accountancy data network (FADN) of the EU, providing a representative national sample of Irish farms. The NFS classify farms as sheep enterprises when at least 66% of the standardized gross margin of the farm comes from sheep meat and greasy wool. A wide spectrum of data are collected on 115 lowland sheep farms through the NFS, including financial, farm infrastructure data, animal husbandry data and production information. However, less physical data (e.g., N fertilizer rate) was available on hill farms in the NFS and the number of farms is substantially smaller ($n = 26$) than lowland farms. Therefore, to evaluate hill farms we supplemented data from NFS with information from the web-based profit monitor tool administered by Teagasc (2014). This tool is applied nationally to hill farms ($n = 17$) and collects detailed physical farm data.

The main inputs and outputs used to model lowland and hill sheep farms from the NFS and profit monitor datasets are summarized in Table 1. The table shows that on average in 2013 lowland sheep farms carried 107 ewes, were stocked at 7.5 ewes/ha, weaned 1.3 lambs/ewe mated and produced 419 kg LW/ha. The average level of concentrate fed on lowland farms was 50 kg/ewe per year and N fertilizer application was approximately 73.5 kg N/ha. In contrast to lowland farms, on hill farms the grazing area was generally shared among farms. The average stocking rate of hill farms (2 ewes/ha) was substantially lower than lowland farms, but the average flock size was greater (131 ewes) than lowland farms. On average hill farms fed 60 kg of concentrate/ewe and spread 13 kg of N/ha. Hill farms typically weaned 0.9 lambs/ewe and produced 66 kg LW/ha.

The influence of intensification on the environmental performance of sheep meat production was estimated by modeling intensive lowland mid-season (IMS) and early-season (IES) sheep farms. The data used to

Table 1
Technical summary of the average Irish lowland, average hill, and intensive mid-season (IMS) and early (IES) lowland sheep systems.

Item	Average lowland	Average hill	IMS	IES
Number of farms	115	26	19	7
Ewes	107	131	341	429
Rams	2.4	3.0	7.8	9.9
Stocking rate (ewes/ha)	7.5	2.0	9.5	11.8
Lambing period	March	April	March	January
Lamb mortality (%)	9	10	10	10
Weaning rate (lambs/ewe)	1.3	0.9	1.4	1.4
Replacement rate (%)	25	15	20	20
Grazed grass (% of diet)	87%	84%	87%	66%
Conserved forage (% of diet)	7%	7%	8%	17%
Grass utilized (t DM[a]/ha)	6.5	1.9	8.9	8.8
Concentrate (kg DM/ewe)	50	60	38	142
N fertilizer (kg/ha)	73.5	13	85	103
Electricity (kWh/ewe)	1.6	1.9	1.1	1.3
Farm fuel use (l/ha)	46	2	32	40
Greasy wool yield (kg/ha)	27	5	32	39
Lamb LW[b] (kg/ha)	419	66	546	637
Lamb CW[c] (kg/ha)	189	30	246	293
Digestible protein (kg/ha)	36	6	50	61

[a] DM = Dry matter.
[b] LW = Live weight.
[c] CW = Carcass weight.

model IMS and IES (Table 1) was sourced from Bohan et al. (2015). The IMS farm lambed ewes in the same period as the average lowland sheep farm (March) and turned out ewes to pasture after lambing. Sheep were stocked at 9.5 ewes/ha and the N fertilizer rate was 85 kg N/ha. The level of concentrate supplementation was 38 kg/ewe and the weaning rate was 1.4 lambs/ewe. The meat yield was 546 kg of LW/ha. The IES system lambed ewes in December and January and sold lambs at Easter. The quantity of concentrate fed was 142 kg/ewe. The stocking rate of IES was 12 ewes/ha and 103 kg N fertilizer was applied per ha. The meat output per unit area in IES was 637 kg of LW/ha.

2.2. Life cycle assessment

The LCA methodology was carried out using the United Nations Food and Agriculture (FAO) LCA guidelines for small ruminants (LEAP, 2015). The LEAP guidelines are consistent with the International Organization for Standardization (ISO) 14,040:2006 and 14,044:2006 standards for LCA. The LCA concept consists of 4 main phases: (1) goal and scope definition (2) life cycle inventory, (3) life cycle impact assessment and (4) interpretation. The details of each phase are described herein.

2.2.1. Goal and scope definition

The goal and scope of our analysis was to evaluate the cradle to farm-gate environmental impact and resource use of Irish sheep farms varying in intensity. The system boundary included foreground processes such as sheep rearing and feeding and background processes of manufacture and transport of various imports e.g., pesticides, fertilizer and concentrate feedstuffs (Fig. 1). Buildings and machinery were excluded from the analysis because of their small impact for grass-based livestock systems (Thomassen et al., 2008). Furthermore, some inputs (e.g., disposable syringes) were not included due to lack of relevance.

In addition to defining the goal and scope, functional unit(s), method(s) of allocation for multifunctional systems and environmental measures are selected in this phase of an LCA. Functional units relate the main function(s) of a farming system to environmental impacts. Generally, LCA studies of ruminant systems select the dominant food product in terms of economic value as the functional unit (de Vries and de Boer, 2010). Thus, the functional unit we related environmental performance measures was kg of sheep LW sold. Agricultural systems, however, have a local and global effect on the environment. Consequently, we also related local environmental impacts (e.g. eutrophication) to the on-farm land area occupied.

The production of sheep yields more than one output (meat and wool). Additionally, concentrates that are fed to sheep can themselves be co-products of multifunctional systems (e.g., barley grain and straw). The products of multifunctional agricultural systems are difficult to separate. Therefore, allocation between products is usually required. Generally, LCA studies of agricultural systems allocate environmental impacts and resources between co-products based on their economic value (de Vries and de Boer, 2010). Thus, we used this method to allocate environmental impacts or resources to concentrate co-products and sheep outputs (Tables 1 and 2). The resource measures and

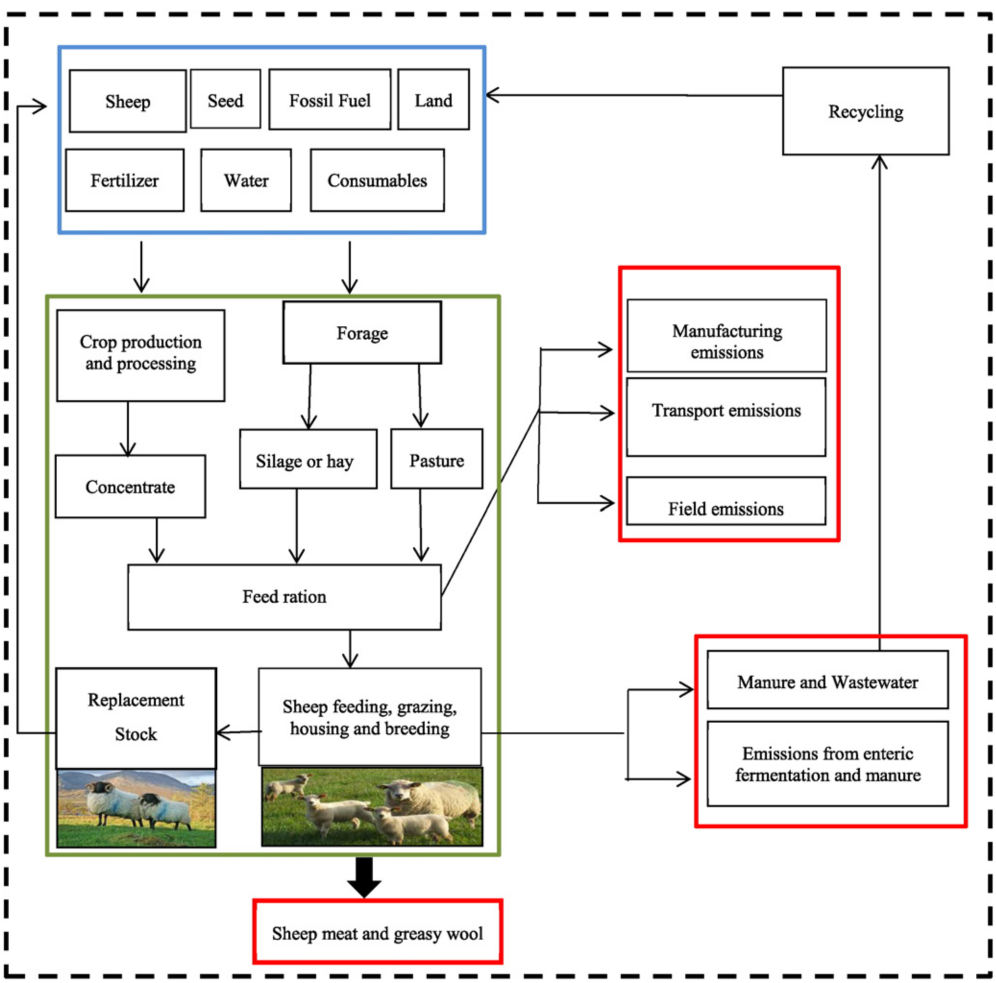

Fig. 1. Cradle to farm-gate system boundary for sheep production. Note: The dotted box represents the system boundary of the LCA study. The blue box represents raw materials, the green box represents feed and animal production and the red boxes represent system outputs and losses.

Table 2
Composition of 3 types of concentrate feeds in g/kg dry matter for sheep production systems.

Feed ingredients	Ewe 18% CP[a]	Lamb 16% CP	Lamb 17% CP	HDP[b] (%)	Economic allocation factor[c] (%)	Origin
Citrus pulp	–	50	70	–	1	USA
Maize grain	–	160	150	7	95	Germany
Dried distillers grains solubles	–	90	–	5	1	USA
Maize gluten	–	80	–	4	6	USA
Molasses	30	60	30	1	5	Cuba
Soy hulls	–	120	40	–	2	USA
Rape meal	–	100	–	7	26	Germany
Soybean meal	190	–	150	37	66	South America
Wheat grain	–	170	100	8	95	Ireland
Sunflower meal	–	–	40	6	23	France
Barley grain	430	100	200	8	92	Ireland
Beet pulp	325	–	170	1	4	Germany
Palm kernel oil	–	20	–	–	17	South east Asia
Minerals and vitamins	25	50	50	–	100	Netherlands

[a] Crude protein.
[b] Human digestible protein content of feed ingredient.
[c] An economic allocation factor was derived based on the share of revenue generated by a feed ingredient. For example, 92% of the revenue generated by 1 ha of Irish barley was derived from grain and the remainder from straw.

environmental impact categories we chose to assess were acidification, eutrophication, climate change (carbon footprint), fossil fuel energy demand and land occupation. We also computed the efficiency of land use in terms of human-edible food. Other common categories included in LCA (e.g., ecotoxicity) were not taken into account, because detailed data on inputs such as pesticides was not available. The temporal coverage of the LCA model was a period of 1 year and the mode of our LCA was attributional or descriptive.

2.2.2. Inventory analysis

The resources used and emissions related to each process were quantified in the inventory analysis stage via a sheep farm systems model constructed in Microsoft Excel by Bohan et al. (2015). The data collected by the NFS (Hennessy et al., 2014) and Teagasc profit monitors were used to determine the quantity of materials used directly on farm (e.g., lime usage). The quantity of resources used on-farm was calculated for operations that farmers decided to contract to various service providers (e.g. fossil fuel required by contractors for carrying out major field operations such as silage harvesting). These were estimated using the report of Teagasc (2011). For minor farm operations (e.g., hedge cutting) carried out by contractors, fuel use was estimated using data from Nemecek and Kägi (2007).

Agricultural soils are important carbon (C) reservoirs (Soussana et al., 2010). Generally, soils lose or gain C following a change in soil management. For instance, soil loses C following the conversion of grassland to cropland, but gains C when the opposite occurs. The rate of soil C loss or increase declines over time and begins to reach a plateau after 20 to 100 years (IPCC, 2006). The potential of permanent managed grassland soil to continue removing C via sequestration, however, can occur for periods much longer than 100 years (Soussana et al., 2010). Additionally, Schulte et al. (2013) reported that permanent grassland soils are presently sequestering C to reach a new equilibrium with elevated CO_2 concentrations in the atmosphere. Thus, we assessed GHG emissions with and without C sequestration. Based on Leip et al. (2010) and Schulte et al. (2013) the annual rate of C sequestration by grassland was estimated as 0.89 t of CO_2/ha for lowland farms and 0.57 t of CO_2/ha for hill farms.

The IPCC (2006) guidelines, and Nemecek and Kägi (2007) were used to estimate on-farm emissions from lime and urea application, and fossil fuel combustion (Table 3). The Irish national GHG inventory (Duffy et al., 2014) was followed to estimate CH_4 emission from ruminants and manure. Enteric CH_4 loss for ewes, hoggets and rams was estimated as 6.5% of gross energy intake (GEI) depending on the digestibility of the diet. For lambs, no enteric CH_4 emission were estimated for the first month post lambing, because milk was largely sufficient to sustain lamb growth. From week 5, enteric CH_4 emission was estimated as 6% of lambs GEI.

The GEI and dry matter intake (DMI) of ruminants was estimated according to the net energy (NE) required for animal growth, milk production and maintenance (Jarrige, 1989). Animal weights, growth rates, activity, pregnancy, feed digestibility, milk production and composition data required to estimate total NE requirements were based on NFS data, McDonald (2002) and research carried out on feed requirements by O'Mara (1996). The concentrate feedstuffs fed to sheep along with their ingredients are listed in Table 2. The quantity of forage fed was estimated by subtracting the NE provided by concentrate from sheep's total NE requirement and then dividing the NE required from forage by its NE value. The consumption of feed was also used to estimate animal manure production by multiplying feed digestibility and DMI estimates. The number of days animals spent housed was related to manure production to estimate the quantity of manure requiring storage.

Methane emission from manure storage were computed as a proportion of the maximum CH_4 potential (B_o) of manure (Table 3) using the method described by the IPCC (2006) and data from Duffy et al. (2014). Methane was also released from manure after spreading, but the quantities are negligible (IPCC, 2006) and was excluded. Nitrogen excreted in manure was estimated by subtracting N outputs in animal products from total N intake in feed. The manure N emissions of NH_3, N_2O, NO_x and NO_3^- were quantified using a mass flow approach based on the annual quantity of N or total ammoniacal N (TAN) excreted. The TAN content of sheep manure was estimated as 60% of N excreted (Duffy et al., 2015). N emissions were calculated for different manure management stages (housing, storage, spreading) using emission factors from Duffy et al. (2014, 2015) detailed in Table 3 and subtracted from the total pool to calculate the N or TAN available for the next stage.

The NH_3 emissions from the application of inorganic N fertilizer were estimated as 13% of N applied in urea and 1% for other fertilizer compounds (Duffy et al., 2015). Emissions of N_2O and NO_x from N fertilizer were estimated as 1% and 0.2% of N applied, respectively, and NO_3^- loss was estimated as 10% of N fertilizer spread. Indirect N_2O emissions from manure and fertilizer application were estimated as 0.75% of N leached and 1% of NH_3 emissions (Duffy et al., 2014). Potential loss of P was computed using a farm-gate balance approach, where the P surplus was quantified as total P input in purchased feed, fertilizer, manure and livestock minus P exported in animals, greasy wool, feed and manure. The same approach was used to estimate the farm N balance. The P lost to waterways was estimated as 0.5 kg P/ha when the P surplus/ha was between 1 and 5 kg, 1.5 kg P/ha when the surplus was between 5 and 10 kg, and 2.5 kg P/ha when the surplus/ha was >10 kg (Schulte et al., 2010).

The data for external farms imports (e.g., electricity) were combined with emission factors from Howley et al. (2014) and the Carbon Trust (2013) to estimate off-farm CO_2, CH_4 and N_2O emissions (Table 4). Soil CO_2 emissions from land use change were included for the production of some imported feedstuffs (e.g., South East Asia palm). Land use change emissions were directly attributed to arable crops and estimated according to BSI (2011) recommendations. For instance, average land use change emissions from South American soy were estimated as 7.5 t CO_2/ha per annum (BSI, 2011). The land area occupied by imported feedstuffs was calculated using the feedprint database of Vellinga et al. (2013). The human-edible content of feedstuffs imported onto farms and for home-grown feeds was estimated using digestibility data from

Table 3
Key on-farm emission and energy factors applied in a cradle to farm-gate life cycle assessment sheep model.

Emission or energy source	Emission or energy factor	Unit	Reference(s)
Carbon dioxide (CO_2)			
Lime	0.44 × lime application	kg/kg lime	IPCC (2006)
Urea	0.73 × urea application	kg/kg urea	IPCC (2006)
Diesel	2.63 × diesel use	kg/l	IPCC (2006)
Gasoline	2.30 × gasoline use	kg/l	IPCC (2006)
Kerosene	2.52 × kerosene use	kg/l	IPCC (2006)
Grassland carbon sequestration	0.57–0.89[a] × grassland area	t/ha	Leip et al. (2010), Schulte et al. (2013)
Methane (CH_4)			
Enteric fermentation			
Ewes, hoggets and rams	0.065 × GEI[b]	MJ/d	Duffy et al. (2014)
Lambs	0.06 × GEI	MJ/d	Duffy et al. (2014)
Manure storage and excretion on pasture	Manure VS[c] excreted × 0.19 × 0.67 × MS[d] × MCFe	kg/year	Duffy et al. (2014)
Nitrous oxide (N_2O-N)			
Solid manure storage	0.005 × solid manure N stored	kg/kg N	Duffy et al. (2014)
Manure excreted on pasture	0.01 × N excreted on pasture	kg/kg N	Duffy et al. (2014)
Synthetic N fertilizer	0.01 × N fertilizer applied	kg/kg N	Duffy et al. (2014)
Solid manure application	0.01 × N in manure spread	kg/kg N	Duffy et al. (2014)
Crop residues	0.01 × N crop residues	kg/kg N	Duffy et al. (2014)
Nitrate leaching	0.0075 × N leached	kg/kg NO_3^--N	Duffy et al. (2014)
Ammonia (NH_3) re-deposition	0.01 × sum of NH_3 loss	kg/kg NH_3-N	Duffy et al. (2014)
Nitrogen oxides (NO_x)			
Solid manure storage	0.01 × solid manure TAN[f] stored	kg/kg TAN	Duffy et al. (2015)
Solid manure application	0.002 × N in manure spread	kg/kg N	Duffy et al. (2015)
Manure excreted on pasture	0.0035 × TAN excreted on pasture	kg/kg TAN	Duffy et al. (2015)
Synthetic N fertilizer	0.002 × N fertilizer applied	kg/kg N	Duffy et al. (2015)
Diesel	0.025 × diesel use	kg/l	Nemecek and Kägi (2007)
Gasoline	0.030 × gasoline use	kg/l	Nemecek and Kägi (2007)
Kerosene	0.001 × kerosene use	kg/l	Nemecek and Kägi (2007)
Ammonia (NH_3-N)			
Housing	0.22 × manure TAN stored	kg/kg TAN	Duffy et al. (2015)
Solid manure storage	0.35 × solid manure TAN stored	kg/kg TAN	Duffy et al. (2015)
Solid manure application	0.68–0.004 × TAN in solid manure spread	kg/kg TAN	Duffy et al. (2015)
Manure excreted on pasture	0.06 × TAN excreted on pasture	kg/kg TAN	Duffy et al. (2015)
Synthetic N fertilizer	(0.01–0.13)[g] × N fertilizer applied	kg/kg N	Duffy et al. (2015)
Nitrate (NO_3^--N)			
Solid manure storage	0.12 × solid manure TAN stored	kg/kg TAN	Duffy et al. (2015)
Field N leaching	0.1 × (N applied – NH_3 loss – N_2O loss)	kg/kg N	Duffy et al. (2014)
Phosphorus (P)			
P runoff and leaching	(0–2.5)[h] × farmland area	kg/ha	Schulte et al. (2010)
Sulphur dioxide (SO_2)			
Diesel	2.0 × diesel use	g/l	Nemecek and Kägi (2007)
Gasoline	0.5 × gasoline use	g/l	Nemecek and Kägi (2007)
Kerosene	1.1 × kerosene use	g/l	Nemecek and Kägi (2007)
Non-renewable energy			
Diesel	36.2 × diesel use	MJ/l	Ecoinvent (2010)
Gasoline	32.7 × gasoline use	MJ/l	Ecoinvent (2010)
Kerosene	35.5 × kerosene use	MJ/l	Ecoinvent (2010)

[a] Dependent on location of grassland.
[b] GEI = Gross energy intake.
[c] VS = Volatile solids.
[d] MS = Percentage of manure volatile solids managed in a specific storage system or percentage of manure excreted on pasture.
[e] MCF = Methane conversion factor for manure volatile solids managed in a particular storage system or excreted on pasture. The MCF values were 0.01 for manure excreted on pasture and 0.02 for solid manure system (DM >20%).
[f] TAN = Total ammoniacal nitrogen.
[g] Dependant on fertilizer compound.
[h] Dependant on farm P surplus.

Wilkinson (2011) and calculated on a DM and energy basis. Ecoinvent (2010) database was used to calculate additional emissions associated with the production and transport of farm imports.

2.2.3. Impact assessment

The resources used by sheep farms and emissions were grouped and converted into environmental impacts or measures using various characterization factors. The eutrophication potential of sheep systems was calculated using conversion factors from Guinee et al. (2002) in kg PO_4-equivalents (eq), $NH_3 = 0.35$, $NO_3^- = 0.1$, $NO_x = 0.13$ and $PO_4 = 1$. Acidification potential was estimated using factors recommended by Huijbregts (1999) in kg SO_2-eq, $NH_3 = 1.6$, $NO_x = 0.5$ and $SO_2 = 1.2$. The climate change impact of GHG emissions was calculated in terms of CO_2-eq using 100-year global warming potential (GWP) factors from the IPCC (2013). The GWP factors for key GHG emissions were 1 for CO_2, 28 for CH_4 and 265 for N_2O. Fossil fuel energy demand was quantified in MJ using the lower heating values of the cumulative energy demand method from Guinee et al. (2002).

Land occupation was quantified in m^2/kg of LW and included land required to produce homegrown forage and crops, and land for imported feedstuffs. The efficiency of land use was calculated by dividing the human digestible protein (HDP) output in sheep meat by the HDP input from crops fed to sheep. Data from Young and Pellett (1994) was used to estimate the digestible protein content of sheep meat and crops. A land use ratio (LUR) of <1 implied that sheep meat yielded more HDP than directly consuming the human-edible crops fed to sheep. The potential efficiency of land use was also estimated using the method proposed by van Zanten et al. (2015). In this

Table 4
The resources used[a] and emissions[b] released during the manufacture and transport of key purchased farm inputs.

Item	Energy use (MJ)	Land use (m^2)	CO_2 (kg)	CO_2 LUC (kg)	CH_4 (g)	N_2O (g)	SO_2 (g)	NH_3 (g)	NO_x (g)	NO_3 (g)	PO_4 (g)	P (g)
Electricity[c], kwh	11.4	–	0.58	–	0.71	0.02	0.73	0.01	0.53	–	–	–
Diesel, l	8.2	–	0.38	–	1.51	–	3.45	–	1.13	0.01	–	–
Pesticide, kg active ingredient	212.5	–	8.40	–	0.71	0.41	32.92	0.04	12.14	0.13	0.37	–
Ammonium nitrate, kg N	54.0	–	3.63	–	2.84	11.45	4.02	8.85	13.98	–	–	–
Urea, kg N	63.9	–	2.89	–	3.70	0.62	3.13	3.49	3.21	0.01	–	–
Limestone, kg	0.4	–	0.15	–	0.12	–	0.03	0.01	0.08	0.01	–	–
Triple super phosphate, kg P_2O_5	27.3	–	1.77	–	3.72	0.01	28.16	0.04	8.62	0.10	22.84	0.03
Ewe 18% CP[d], kg	3.1	1.5	0.11	0.29	0.27	0.35	0.42	0.71	0.42	4.30	0.67	0.03
Lamb 16% CP, kg	4.8	0.8	0.17	0.00	0.19	0.46	0.43	2.54	0.64	19.14	0.31	0.02
Lamb 17% CP, kg	2.8	1.2	0.14	0.23	0.21	0.45	0.40	1.61	0.55	12.53	0.67	0.04

[a] Data related to energy use was sourced from Ecoinvent (2010) and data regarding land use was obtained from Vellinga et al. (2013).
[b] Carbon dioxide, CO_2 from land use change (LUC), CH_4 and N_2O emissions data was sourced from the Carbon Trust (2013). Sulphur dioxide, NH_3, NO_3, PO_4 and P emissions data was sourced from Ecoinvent (2010).
[c] Carbon dioxide emissions for electricity were sourced from Howley et al. (2014).
[d] CP = Crude protein.

approach, the HDP of meat from sheep farms was divided by the maximum amount of HDP that could be obtained from land suitable to grow feed crops.

To compute the potential of land to grow food crops we quantified the area of grassland occupied on sheep farms that could be cultivated using data on soil type and location in the NFS (Hennessy et al., 2014). Different crops can be grown on the land identified as suitable for cultivation, but as recommended by van Zanten et al. (2015) we focused on the major global food crops i.e. potatoes, wheat, maize, rice and soybean. Where grassland could be cultivated on Irish sheep farms, potatoes were selected as the potential food crop. The potential food crop yield for off-farm land required by concentrate feedstuffs was estimated based on the maximum yielding major global food crop. Off-farm major food crop yields were country specific and sourced from FAOSTAT (2015). On and off-farm potential food crop yields were summed and multiplied by their digestible protein content to quantify the maximum potential quantity of HDP that could be derived from food crops.

3. Results and discussion

3.1. Nutrient balances

Farm-gate N balances (Table 5) showed that artificial fertilizer was the primary N input (58%–77%) followed by concentrate feedstuffs or N deposition (11%–28%). In agreement with Ledgard (2001), the total N input/ha increased as farm stocking rate increased. The total input of N/ha was lowest for the average hill farm followed by the average lowland, IMS and IES farms. The production of LW was the main N output of farms (61%–74%) followed by wool. The total N input/ha was greater than the total N output/ha and the difference increased with stocking rate. Therefore, similar to Schils et al. (2006) the N surplus/ha was greatest for the most intensive farm (IES) and the lowest for the least intensive farm (average hill farm). The average hill farm, however, had the poorest grass growth response to N fertilizer, which is a key determinant of N efficiency for pasture-based systems (Ledgard, 2001). The N efficiency of IES (15%) was higher than the average hill farm (12%), but lower than IMS, which was the most N efficient (18%).

Artificial fertilizer was the key P import onto the average lowland farm and IMS (63%–64%), but for the average hill farm and IES, concentrate was the most important P input (64%–75%). Apart from IES, all farms were heavily reliant on grass (91%–95%). Thus, the P input from concentrate was low. Consequently, similar to Haygarth et al. (1998), the P surplus of IMS, the average lowland and average hill farms was low (0.1–0.4 kg P/ha). The P input was greatest for IES, because IES fed 3–4 times more concentrate/animal than the other systems. On average, concentrate feed contains 25%–30% more P/kg of DM than grass (Gouldings, 2002). Therefore, increased concentrate supplementation without a concomitant reduction in artificial P fertilizer in IES resulted

Table 5
Sheep production systems nitrogen and phosphorus balances, and acidification and eutrophication emissions per ha per year.

	Unit	Sheep systems N balance				Unit	Sheep systems P balance			
		Average lowland	Average hill	IMS[a]	IES[b]		Average lowland	Average hill	IMS	IES
Input										
Deposition	kg N/ha	5.1	4.9	4.8	5.1	kg P/ha	–	–	–	–
Fixation	kg N/ha	10.9	1.1	8.8	5.2	kg P/ha	–	–	–	–
Animals	kg N/ha	0.1	0	0.1	0.2	kg P/ha	0	0	0.1	0.1
Concentrate	kg N/ha	11.2	3.5	10.9	43.6	kg P/ha	1.9	0.6	2.3	8.4
Artificial fertilizer	kg N/ha	73.5	13.3	82.7	102.9	kg P/ha	3.3	0.2	4.2	4.6
Total input	kg N/ha	100.8	22.8	107.3	157	kg P/ha	5.2	0.8	6.6	13.1
Output										
Animals	kg N/ha	11.1	1.7	14.6	17.5	kg P/ha	5	0.8	6	7.9
Greasy wool	kg N/ha	4.2	1.1	5.1	6.5	kg P/ha	0.1	0	0.1	0.1
Total output	kg N/ha	15.3	2.8	19.7	24	kg P/ha	5.1	0.8	6.1	8
NUE[c]	%	15	12	18	15	%	98	98	92	61
Surplus or deficit	kg N/ha	85.5	20.0	87.6	133.0	kg P/ha	0.1	0.1	0.4	5.1
NH_3 emission	kg N/ha	20.1	5.3	26	35					
N_2O emission	kg N/ha	2.9	0.6	3.6	4.4					
NO_3^- emission	kg N/ha	24.9	4.8	31.1	36.8					
P loss						kg P/ha	0.1	0.1	0.4	1.5
Acidification	kg SO_2-eq/ha	41.1	10.6	52	69.8					
Eutrophication						kg PO_4-eq/ha	20.4	5.2	26.7	33.2

[a] IMS = Intensive mid-season lowland sheep production system.
[b] IES = Intensive early-season lowland sheep production system.
[c] NUE = Nutrient use efficiency (total nutrient output/total nutrient input).

in a P surplus of 5.1 kg P/ha and the lowest level of P efficiency. Farm P efficiency was substantially greater than farm N efficiency, which resulted in lower P losses than N emissions (Table 5).

3.2. Acidification

Congruous with Williams et al. (2006) and Peters et al. (2010), NH_3 was the main contributor to sheep on-farm acidification (95%–96%). Ammonia was emitted from artificial N fertilizer and manure applied to grow forage (80%–85%) and from sheep housing and manure storage (15%–20%). Intensification increased NH_3 emissions/ha from sheep farms, because the application of fertilizer and manure increased per ha.

On-farm acidification/ha was greatest for IES and lowest for the average hill farm, but the average hill farm produced 90% less LW/ha (Table 1). Thus, food-related on-farm acidification was 55% greater for the average hill farm than IES (Table 6). Similarly, total acidification/kg of LW was greater for this system, because on-farm acidification was the dominant contributor to total acidification (83%–91%). The production of concentrate ingredients (cereal and protein feeds) was the largest source of off-farm acidification (57%–75%). Greater concentrate feeding increased off-farm acidification and meat production, but did not improve farm N efficiency. Similar to Van der Werf et al. (2009) increasing output by feeding less forage did not necessarily result in lower food-related acidification. Increasing the amount of lamb produced off grazed grass, however, did improve N efficiency, which resulted in more farm output then on and off-farm acidification. Thus, IMS had the lowest total acidification/kg of LW followed by the average lowland farm.

3.3. Eutrophication

The majority of sheep farms total eutrophication was generated on-farm (86%–94%). Nitrate loss was the main contributor to on-farm eutrophication for lowland sheep farms (45%–54%) followed by NH_3 emission (41%–42%), but for the average hill farm the contribution of NH_3 (48%) was slightly greater than NO_3 (45%). In contrast to LCA studies of intensive dairy systems by Thomassen et al. (2008) and Belflower et al. (2012), the P balance of sheep farms excluding IES was almost in balance. As a result, P loss was a minor contributor to on-farm eutrophication for IMS and the average sheep farms (2%–5%), but was important for IES (13%). The main source of on-farm NO_3 and P loss was artificial and organic fertilizer applied for on-farm forage production. Increasing forage and animal production increased NO_3 and P loss from farms, which increased on-farm eutrophication/ha (Table 5).

Consistent with the reports of Arsenault et al. (2009) and Van der Werf et al. (2009), N and P loss from growing imported cereal and protein feeds was the main source of off-farm eutrophication (80%–89%). Increasing the stocking rate of lowland grass-based sheep farms and feeding less concentrate/animal resulted in the lowest food-related on and off-farm eutrophication (Table 6). Therefore, total eutrophication/kg of LW was greater for IES than the average lowland and IMS farms. The N efficiency and LW output of IES, however, was substantially greater than the average hill farm. As a result, food-related on-farm and total eutrophication was greatest for the average hill farm.

3.4. Climate change

The climate change impact or carbon footprint of sheep farms was primarily generated by on-farm GHG emissions (80%–87%). Enteric CH_4 emission from sheep was the largest source of on-farm GHG emissions (61%–68%), followed by CH_4 and N_2O emissions from manure (23%–25%) and N_2O emissions from artificial fertilizer spreading (8%–12%). Feed efficiency (kg DM/kg LW) and digestibility were the most important drivers of enteric CH_4 emission (Mills et al., 2003; Hegarty et al., 2007). Relative to lowland farms, the average hill farm used 23%–25% more feed DM/kg of LW, mainly because the hill farms weaned less lambs/ewe and grass digestibility was 15%–17% lower. Therefore, the average hill farm generated 0.11–0.13 kg more enteric CH_4/kg of LW than the lowland farms, which resulted in this farm emitting 37%–45% more on-farm GHG emission/kg of LW than the lowland farms (Table 6).

Food-related enteric CH_4 and on-farm GHG emission of the average lowland farm was 4% greater than IES and 6% more than IMS. In addition, the IMS farm emitted the lowest off-farm GHG emission/kg of LW. Off-farm GHG emission was largely generated by fertilizer for IMS and the average lowland farm (65%–68%) with the majority of the

Table 6
The cradle to farm-gate life cycle assessment results by environmental impact category for the average Irish lowland, average Irish hill, intensive mid-season (IMS) and early season (IES) sheep production systems.

Impact category	Unit		Sheep production systems				Hotspot(s)[a]
			Average lowland	Average hill	IMS	IES	
Eutrophication	g PO_4-eq/kg LW	On-farm	38.4	59.5	38.3	44.3	AF, M
		Off-farm	3.0	5.4	2.3	7.7	C
		Total	41.3	64.9	40.6	52.0	AF, M
Acidification	g SO_2-eq/kg LW	On-farm	76.8	132.5	75.2	85.2	AF, M
		Off-farm	9.6	15.8	7.5	17.0	C
		Total	86.3	148.3	82.7	102.2	AF, M
Carbon footprint	kg CO_2-eq/kg LW	On-farm	8.9	12.2	8.5	8.6	S, M, AF
		Off-farm	1.5	1.9	1.2	2.1	AF, C
		Total	10.4	14.2	9.7	10.7	S, M, AF
Carbon footprint with seq[b]	kg CO_2-eq/kg LW	Total	8.7	7.0	8.4	9.7	FA, S, M, AF
Fossil fuel energy demand	MJ/kg LW	On-farm	3.8	3.6	2.3	2.2	D
		Off-farm	11.6	17.8	9.4	17.9	AF, C
		Total	15.4	21.4	11.7	20.1	AF, C
Land occupation	m^2/kg LW	On-farm	19.0	125.7	14.5	12.2	FA
		Off-farm	1.0	2.0	0.7	2.6	C
		Total	19.9	127.7	15.2	14.8	FA
Actual land use efficiency	kg crop HDP[c]/kg LW HDP	On-farm	–	–	–	–	–
		Off-farm	0.35	0.69	0.25	1.11	C
		Total	0.35	0.69	0.25	1.11	C
Potential land use efficiency	kg crop HDP/kg LW HDP	On-farm	1.65	–	1.26	0.78	FA
		Off-farm	0.50	0.95	0.35	1.25	C
		Total	2.15	0.95	1.61	2.03	FA

[a] AF = Artificial fertilizer; C = Concentrate production; D = Diesel; FA = Farm area; M = Manure; S = Sheep.
[b] Includes sequestration of carbon by grassland.
[c] HDP = Human digestible protein.

remainder emanating from concentrate production (28%–29%). Fertilizer production was a key source of off-farm GHG emission for the average hill and IES farms (40%–42%), but less important than concentrate (51%–58%). Increasing concentrate feeding similar to Martin et al. (2010) increased off-farm GHG emission per unit of product.

The high off-farm GHG emission/kg of LW resulted in IES having a 3% greater carbon footprint than the average lowland farm even though food-related on-farm GHG emission was 5% lower for IES. This finding was similar to the results of O'Brien et al. (2012) who reported that the carbon footprint of a grazing dairy system was lower than a confinement dairy farm that generated lower on-farm GHG emission/unit of product. Our results support the conclusions of O'Brien et al. (2012) that to avoid increasing agricultural GHG emissions, strategies to mitigate on-GHG emissions should also consider off-farm emissions. In contrast to the average lowland farm, on-farm GHG emission of IMS was similar to IES. Consequently, the carbon footprint of IES was 10% greater than IMS.

The carbon footprints of the lowland farms were 9.7–10.7 kg of CO_2-eq/kg of LW, which was 24%–31% lower than the average hill farm. Including sequestration of C by grassland reduced on-farm GHG emissions of lowland and hill sheep farms. Consistent with Plassmann (2012), C sequestration per unit of product decreased with farm intensity. For instance, the average hill farm sequestered 5.4–6.1 kg more CO_2 per kg of LW than the lowland sheep farms. Thus, the average hill farm had the lowest carbon footprint when sequestration was included even though this farm was the least N and feed efficient. Including C sequestration reduced or increased the differences between lowland farms footprints, but did not affect their order.

3.5. Fossil fuel energy demand

Consistent with McChesney's (1979) evaluation of New Zealand sheep grazing systems our results showed that the majority of fossil fuel was consumed off-farm (75%–89%). Fertilizer manufacture was the main user of off-farm fossil fuel energy (57%–71%) followed by concentrate production (21%–43%) and the manufacture of fossil fuels (5%–14%). On-farm, diesel and petrol for machinery use were the largest energy consumers. Per kg of LW, on-farm fossil fuel energy demand was similar for the average lowland and hills farm, but 40%–42% lower for IMS and IES mainly because these systems used feed and diesel more efficiently. Off-farm fossil fuel energy demand increased with concentrate feeding, because cereal and protein feed ingredients require more energy to produce than pasture (Dalgaard et al., 2001). For example, the fossil fuel demand of concentrate fed to lambs was 1.7–3.9 MJ greater than pasture per kg of DM. The total fossil energy demand/kg of LW for IES was 30% greater than the average lowland farm and 71% greater than IMS. The average hill farm used more N fertilizer per unit of product than IES. Thus, the total food-related fossil fuel energy demand of the hill farm was 7% greater than IES.

3.6. Land occupation and efficiency

The total land area occupied by sheep farms was primarily composed of land used to grow on-farm forage (82%–98%). The remainder of land used by sheep was occupied off-farm and used to grow imported concentrate feeds. For the lowland systems, the IES farm required the most off-farm land/kg of LW, but used the least on-farm land, because the farm could carry more sheep/ha. As a result, total land occupation/kg of LW for IES was 3% lower than IMS and 26% lower than the average lowland farm. The stocking rate of the lowland farms was 4–6 times greater than the hill farm. Thus, similar to Williams et al. (2006) the total land occupation/kg of LW of the average hill farm was 6–9 times greater than the lowland farms.

Human digestible crop protein was not produced on-farm, but was imported in the form of cereal and protein feeds. The LUR in terms of total actual HDP was lowest for IMS followed by the average lowland and hills farm and the LUR was <1 for all. This implies that actual land use by these farms was efficient, because more HDP was produced from sheep than human edible food crops (Mollenhorst et al., 2014). The LUR of IES was >1 given the greater reliance of IES on concentrate. The actual efficiency of land use however does not represent the total potential of land occupied by sheep (e.g., cultivable grassland) to produce human edible crops. Therefore, van Zanten et al. (2015) argue that the efficiency of land use should also be assessed based on the total potential to produce human edible crops.

The total potential to produce HDP from crops was greater than the production of HDP from sheep (LUR > 1) except for the hill farm. This means that lowland farms did not make the best potential use of land to produce HDP. The potential to till the on-farm grassland area of sheep farms mainly determined the total potential of HDP production from crops. For instance, there was potential to till 45% of the on-farm grassland area of the lowland sheep farms, but cultivation was not possible for the average hill farm given the farms soil type and topography (Hennessy et al., 2014). As a result, the on-farm and total potential HDP LUR of the average hill farm was 0.7–1.2 units lower than the lowland farms.

4. General discussion

This LCA case study of the environmental impacts and resource use of sheep farms agreed with previous reports (e.g., Capper et al., 2009; Ledgard et al., 2011) that increasing the intensity of livestock production can reduce emissions and resource use per kg of product. However, per unit of area the most intensive sheep farms had the greatest impact on the local environment in terms of nutrient surpluses, acidification and eutrophication. The large effect the unit of expression had on the order of farms local environmental impacts agreed with Topp et al. (2007) analysis of conventional and organic agriculture and highlights that it is necessary to evaluate local impacts in terms of area-based thresholds. Currently, area-based thresholds for the local effects of farms on water and air are set in terms of total N and P inputs by the EU (European council, 1991). For the sheep farms we assessed their total nutrient inputs were generally well below these area limits, which means that the local effect of farms on water and air quality measures was legislatively acceptable. This means there is scope to grow national sheep production, but the effects of nutrient surpluses on the environment should be regularly measured to verify pollution is not taking place.

Producing more sheep meat by increasing the intensity of production had a mixed effect on farm efficiency and productivity. For example, the most intensive lowland sheep farm we assessed (i.e. IES) was less efficient in terms of N, P, feed and fossil fuel than the next most intensive farm (IMS). The lower efficiency of IES was largely explained by the relatively high proportion of concentrate in the diet of sheep, which Bohan et al. (2015) also showed increased farm costs and reduced profitability compared to IMS. These findings therefore indicate to improve the food-related environmental performance and profitability of lowland sheep production; grass-based farmers should aim to increase animal production from grazed grass instead of feeding greater quantities of concentrate. This can be achieved by improving grassland and animal management on lowland and hill farms e.g., moving ewes to improved grasslands within hill farms during the breeding season (Lynch and Diskin, 2014). The strategy can also increase the productivity of hill sheep farms, but the potential is less given the natural biophysical constraints of hill farms.

The outcomes of our analysis were difficult to compare with other studies because most LCA studies of sheep farms only consider carbon footprint. In addition, LCA studies sometimes select different modeling methods and often use emission factors parameterized for specific regions (e.g., N leaching). Nevertheless, cautious comparisons between studies are useful to validate results. The result of this study for carbon footprint were within the wide range of estimates for sheep LW (8–144 kg CO_2-eq/kg of LW; Ripoll-Bosch et al., 2013) and below the global average of 11.3 kg CO_2-eq/kg of LW (Opio et al., 2013) for lowland farms. The carbon footprint for the average hill farm was also below the average when sequestration was included, but verifying soil sequestration is difficult, because it is a long-term process with small C inputs (<1 t C/ha) being inputted into a large soil C pool (>100 t C/ha). Thus, more research needs to be carried out before sequestration can be accurately included in footprint evaluations, especially for hill farms.

Unlike other sheep LCA studies, Williams et al. (2006) estimated food-related acidification and eutrophication. The results of Williams et al. (2006) were higher than our results for these impacts largely because the UK sheep farms used more N and P inputs. For land use and fossil fuel energy demand, our results were generally higher than Williams et al. (2006) and Wiedemann et al. (2015) case study of Australian, UK and New Zealand sheep farms. Differences in land and energy use between studies were primarily explained by differences in crops yields and farm feeding practices. The actual efficiency of land use in terms of HDP was not estimated by LCA studies of sheep until now, but Ledgard et al. (2011) did postulate that ruminants play an important role in turning forage unsuitable for non-ruminants into food. Our results support Ledgard et al. (2011) for sheep farms almost completely reliant on pasture, but for systems more reliant on concentrate, this was not the case.

The potential HDP efficiency of dairy and poultry farms assessed by Van Zanten et al. (2015) was similar or lower than the sheep farms assessed, except when dairy farms occupied marginal land. The production of HDP, however, does not account for differences in essential amino acids or vitamins between plants and animals. Furthermore, for some sheep farming systems meat is of secondary importance to wool. The productivity of land used by ruminants therefore cannot only be estimated in terms of HDP and should instead be based on an index or scoring system that accounts for the textile and environmental functions of sheep. Environmental services (e.g., landscape conservation) are particularly important outputs of hill and mountain farms and could be quantified using data from agri-environmental schemes or via farm surveys. This data was not collected for this study, but will be included in future to provide information on the favorable environmental aspects of sheep farming.

5. Conclusions

The food-related environmental impact and resource use of the average Irish lowland sheep farm can be improved by increasing meat production from grazed grass within area-based regulatory limits on N and P. Alternatively farms can increase animal production by feeding more concentrate, but we found this approach was less resource efficient and increased environmental impacts compared to increasing grass production. The average hill farm generally had the highest food-related environmental impacts and was the least efficient except for potential HDP production. Including carbon sequestration, however resulted in the average hill farm having the lowest carbon footprint, but sequestration of carbon by grassland is an uncertain process that requires verification. Thus, sheep LCA studies that include this sink should report carbon footprint results with and without sequestration. Furthermore, we suggest that it is not appropriate to evaluate land use efficiency only in terms of HDP for sheep farms. Instead, we recommend assessing land use using an index or scoring system that accounts for food and wool production, and the ecosystem services (e.g., landscape conservation) that these systems provide. The latter would also provide important information on the environmental benefits of sheep farming and thereby facilitate a more comprehensive evaluation of the environmental sustainability of sheep production.

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