Relating the carbon footprint of milk from Irish dairy farms to economic performance

D. O'Brien,^{*1} T. Hennessy,[†] B. Moran,[†] and L. Shalloo^{*}

^{*}Livestock Systems Research Department, Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland

[†]Rural Economy Research Centre, Teagasc, Athenry, Co. Galway, Ireland

ABSTRACT

Mitigating greenhouse gas (GHG) emissions per unit of milk or the carbon footprint (CF) of milk is a key issue for the European dairy sector given rising concerns over the potential adverse effects of climate change. Several strategies are available to mitigate GHG emissions, but producing milk with a low CF does not necessarily imply that a dairy farm is economically viable. Therefore, to understand the relationship between the CF of milk and dairy farm economic performance, the farm accountancy network database of a European Union nation (Ireland) was applied to a GHG emission model. The method used to quantify GHG emissions was life cycle assessment (LCA), which was independently certified to comply with the British standard for LCA. The model calculated annual on- and off-farm GHG emissions from imported inputs (e.g., electricity) up to the point milk was sold from the farm in CO₂-equivalent (CO₂-eq). Annual GHG emissions computed using LCA were allocated to milk based on the economic value of dairy farm products and expressed per kilogram of fat- and protein-corrected milk (FPCM). The results showed for a nationally representative sample of 221 grass-based Irish dairy farms in 2012 that gross profit averaged €0.18/L of milk and €1,758/ha and gross income was €40,899/labor unit. Net profit averaged €0.08/L of milk and €750/ha and net income averaged €18,125/labor unit. However, significant variability was noted in farm performance across each financial output measure. For instance, net margin per hectare of the top one-third of farms was 6.5 times higher than the bottom third. Financial performance measures were inversely correlated with the CF of milk, which averaged 1.20 kg of CO₂-eq/kg of FPCM but ranged from 0.60 to 2.13 kg of CO₂-eq/kg of FPCM. Partial least squares regression analysis of correlations between financial and environmental performance indicated that extending the length of the grazing season and increasing milk

production per hectare or per cow reduced the CF of milk and increased farm profit. However, where higher milk production per hectare was associated with greater concentrate feeding, this adversely affected the CF of milk and economic performance by increasing both costs and off-farm emissions. Therefore, to mitigate the CF of milk and improve economic performance, grass-based dairy farms should not aim to only increase milk output, but instead target increasing milk production per hectare from grazed grass.

Key words: milk, carbon footprint, profit, greenhouse gas, life cycle assessment

INTRODUCTION

Milk plays an important role in providing high-quality protein essential for human diets. In recent decades, global milk output has increased significantly from 482 million tonnes in 1982 to 754 million tonnes in 2012 (FAOSTAT, 2014). The cattle sector is by far the most important source of dairy products, producing about 600 million tonnes or 83% of total milk production in 2010 (Opio et al., 2013). However, the production of milk by ruminants also generates greenhouse gas (GHG) emissions (~3% annual global emissions; Opio et al., 2013), which, from an environmental perspective, is a serious source of concern. Anthropogenic GHG emissions are the main driver of climate change, which, as reported by the fifth assessment report of the IPCC (2014), rose to their highest level between 2000 and 2010.

Without action, GHG emissions from dairy production are unlikely to decline. In fact, emissions are expected to increase, given that the demand for milk is forecasted to grow at a rate of 1.1% per annum until 2050 (Opio et al., 2013). Thus, reducing GHG emissions per unit of milk or the carbon footprint (CF) of milk has become an important sustainability measure for the dairy sector. Several developed nations have evaluated the CF of milk, including Ireland (e.g., Casey and Holden, 2005). Unlike most countries where the dairy sector is a key source of GHG emissions (~10% of Irish national emissions, O'Brien et al., 2014b), Ireland has

Received December 10, 2014.

Accepted June 18, 2015.

¹Corresponding author: donal.o'brien@teagasc.ie

agreed to ambitious binding targets to reduce emissions from the non-emissions trading sector (includes dairy production) by 20% relative to 2005 levels by 2020 (European Council, 2009). Over the same period, national milk output in Ireland is expected to grow by over 50% following the removal of the milk quota system, further exacerbating the GHG situation.

On-farm processes (e.g., CH₄ emissions from cattle digestion) and the manufacture and transport of external farm inputs such as fertilizer are the main sources of GHG emissions from dairy production (94%; Opio et al., 2013). An experimental assessment of this phase of the dairy supply chain, generally referred to as the cradle-to-farm gate stage, is very complex and expensive. Therefore, mathematical models are used to compute the CF of primary dairy systems. Life cycle assessment (LCA) is the preferred approach to quantify GHG emissions from milk production, because the methodology adopts a holistic systems approach to assess cradle-to-farm gate GHG emissions (Gerber et al., 2010). Furthermore, international guidelines have been developed to apply the method across industry in general (BSI, 2011; WRI/WBCSD, 2011) and specifically for the livestock and dairy sectors (IDF, 2010; LEAP, 2014).

The majority of studies that have used LCA to assess the CF of milk have compared contrasting dairy systems (e.g., organic and conventional), assessed mitigation strategies, or analyzed LCA computation decisions (Pirlo, 2012). Typically, these studies aim to evaluate the environmental performance of dairy systems and often consider extra environmental measures such as fossil fuel depletion (e.g., van der Werf et al., 2009; O'Brien et al., 2012). However, as well as environmental performance, the profitability of milk production is important because dairy farms that are not economically viable are unlikely to be sustainable. Thus, some LCA studies of the CF of milk also assess economic performance indicators (Thomassen et al., 2008), but these studies have only considered regions where cows do not graze for an extended period (e.g., >6 mo). Therefore, to better understand the influence of economic performance on the CF of milk of grazing dairy systems, a need exists to evaluate regions or nations (e.g., Ireland) where cows normally graze for a long period (e.g., 9–10 mo).

To assess relationships between the CF of milk and economic performance measures, a large number of farms should be assessed (Thomassen et al., 2009), but performing an LCA study of milk production requires large amounts of data, which can be difficult and time consuming to collect (Yan et al., 2011; Zehetmeier et al., 2014). Thus, most LCA studies are limited to a relatively small sample of farms (<30) or based on

a simulated representative average farm for a region (Basset-Mens et al., 2009; Pirlo, 2012). However, Thomassen et al. (2009) did show that it was possible to carry out an LCA study for 119 Dutch dairy farms using the Farm Accountancy Data Network (FADN). The FADN is a European Union (EU)-wide network of data collectors that conduct surveys on a large group of farms in every EU member state to determine the financial position of European farms. Thus, Thomassen et al. (2009) also showed that the FADN can be used to relate farm economic and environmental measures.

The National Farm Survey (NFS) of Ireland fulfills the member states FADN requirement and has been used to assess the influence of farm profitability on environmental performance measures such as nutrient use efficiency (Buckley and Carney, 2013). Thus, the NFS allowed us to carry out an economic analysis of a large sample of grass-based dairy farms and quantify their CF of milk. The objectives of our study were 2-fold. First, to quantify relationships between the CF of milk and economic performance measures of grazing dairy farms using the NFS; second, to identify the underlying factors (e.g., biophysical and demographic farm characteristics) that influence these relationships.

MATERIALS AND METHODS

Irish NFS

The main data source employed in this analysis was the NFS data set of Hennessy et al. (2013) for the year 2012. The NFS was established in 1972 and has been published on an annual basis since then. Overall, depending on the size of the annual farm population, 900 to 1,100 farms are included in the NFS. Since 2012, the minimum threshold for inclusion of a farm in the sample was a standard gross output per farm of €8,000 or more. Many farmers stay in the NFS for several years, but after a certain period farms drop out and new farms are introduced to keep the sample representative. The farms included in the survey were weighted according to farm area (size) using annual aggregation factors from the national census (CSO, 2013) to ensure the survey was nationally representative for different farm sizes.

In 2012, 922 farms participated in the NFS representing a population of 79,292 farms or 93% of the sector's gross output. Within the sample, farms are classified into 6 farming systems, based on the dominant farm enterprise, which was calculated on a standard gross margin basis. For dairy farming, the NFS collected data from 256 dairy farms in 2012, which represented the population of specialist Irish dairy farms (15,500). In addition, the sample only included specialist dairy

farms that produced milk for dairy manufacturing, because suppliers of liquid or fresh milk produce less than 10% of the nation's milk pool (CSO, 2013). Dairy farms were classified as specialist producers when at least 66% of the standardized gross margin of the farm came from dairy production.

All dairy farms included in the NFS operated spring-calving grazing systems and were assumed to aim to maximize profitability per unit of milk quota. In brief, farmers typically tried to achieve this goal by maximizing milk output from grazed grass (Kennedy et al., 2005). Thus, calving was usually synchronized with the onset of grass growth in early or mid-spring. Generally, calved cows remained on pasture until late autumn or early winter. In summer, when grass growth exceeded feed demand, surplus grass was harvested as grass silage, hay, or both and fed to cows indoors from early winter to early spring. Cows were supplemented with purchased concentrate feeds when grass growth was insufficient to meet herd feed requirements.

As described by Hennessy et al. (2013), a wide spectrum of data are collected on dairy farms through the NFS, including farm financial information, farm infrastructure data, animal husbandry information, and

data on the demographic profile of the farm household (Table 1). Despite the wealth of data already available through the NFS, it was necessary to supplement this with an additional survey to collect sufficient information to quantify the CF of milk according to the LCA method. The additional data required included information on the length of the grazing season, manure spreading methods, timing of manure application, use of agricultural contractors, and electricity provider (Table 1). These extra data were collected for the first time in the autumn of 2012 and spring of 2013. The additional survey was carried out on all dairy farms in the NFS, but 35 farms were excluded from the analysis because of insufficient data. Overall, 221 dairy farms were analyzed, which when weighted by farm size represented 75% of the national population.

Computing Carbon Footprint of Milk

The dairy farm GHG model of O'Brien et al. (2014a) was applied to the NFS data set to calculate the CF of milk. The model estimates the principal GHG emissions from primary dairy production: CO₂, N₂O, CH₄, and fluorinated gases using an attributional (status

Table 1. Descriptive statistics of key financial, technical and demographic farm data collected in 2012 by Hennessy et al. (2013) for a sample of 221 specialized Irish dairy farms weighted to represent a national population of 11,563 farms

Item	Mean	SD	CV (%)	Q ₁ ¹	Median	Q ₃ ¹
Milk price, c/L	32.1	1.8	6	31.0	32.0	33.0
Cull cow price, €/head	988	937	94	710	913	1075
Calf price, €/head	185	42	23	160	182	200
Dairy farm area, ha	35.5	17.9	50	25.9	32.9	44.8
Land converted to arable, ha	0.02	0.01	74	0.01	0.02	0.02
Milking cows, number	67	36	54	48	63	87
Culled cows, %	17	13	78	8	16	23
Stocking rate, cows/ha	1.89	0.44	23	1.63	1.87	2.17
Soil class ² (1 = yes)	59%	49%	83	NA ³	NA	NA
FPCM ⁴ yield, kg/cow	5,181	1,006	20	4,331	4,962	5,566
Fat, %	3.94	0.19	4.8	3.82	3.93	4.04
Protein, %	3.40	0.14	4.1	3.31	3.38	3.45
FPCM yield, kg/ha	9,776	3,150	33	7,526	9,396	11,517
Milk solids yield, ⁵ kg/cow	387	74	21	315	384	398
Concentrates, kg of DM/cow	906	379	42	667	848	1049
Pasture, kg of DM/cow	2,801	1,428	39	2,262	2,781	3,241
Total intake, kg of DM/cow	4,769	1,287	27	3,987	4,715	5,556
Grazing days	239	33	14	222	245	262
N fertilizer, kg/ha	196	83	43	133	188	250
Purchased fuel, L/ha	110	26	24	97	106	118
Electricity, kWh/cow	182	72	40	126	168	218
Age of farmer, yr	52	10	19	45	53	60
Agricultural training (1 = yes)	80%	40%	50	N/A	N/A	N/A
Discussion group (1 = yes)	55%	50%	91	N/A	N/A	N/A
Household members, number	3.7	1.6	43	2	4	5
Total labor units, number	1.7	0.7	41	1.2	1.5	2.0

¹Q₁ = first quartile; Q₃ = third quartile.

²Soil class 1 are very good soils that are classified as having no or minor limitations for use.

³NA = not applicable.

⁴FPCM = fat- and protein-corrected milk standardized to 4% fat and 3.3% true protein per kilogram.

⁵Milk solids yield = annual yield of milk fat and protein.

quo) cradle-to-farm gate LCA approach. The LCA method was applied according to the British Standards Institute (BSI, 2011) publicly available specification 2050:2011 (**PAS 2050**) standard for the assessment of GHG emissions from goods and services. The PAS 2050 standard was the first attempt to create a uniform basis for the assessment of CF and has been used on a wide array of products (Sinden, 2009). To achieve PAS 2050 certification all LCA procedures must be verified. Therefore, to comply with the standard an independent third party, the Carbon Trust (2014), certified our LCA calculations. The Carbon Trust are leaders in measuring the CF of organizations and products and are accredited by the BSI (2011) to verify compliance with PAS 2050.

The cradle-to-farm gate LCA method was applied by embedding the dairy farm GHG model within the NFS database. The model calculated GHG emissions by combining input data from the NFS with GHG emission algorithms from the literature and Carbon Trust (2013) database. However, the NFS did not contain all the information required to estimate GHG emissions given that it was too difficult to collect some data on a large scale, for example N content of manure. Therefore, where necessary, farm data were estimated using mathematical equations from O'Brien et al. (2012, 2014a) and default values from national and international literature sources (e.g., IPCC, 2006, O'Mara, 2006). Examples of key farm data that were calculated include pasture consumption by cattle and manure excretion.

Pasture intake by cattle was estimated by calculating net energy (**NE**) requirements for milk production, maintenance, pregnancy, and BW change (Jarrige, 1989). Subsequently, NE provided by purchased feedstuffs were estimated using recorded data and typical feedstuff NE values from O'Mara (1996). The NE provided by purchased feedstuffs was subtracted from cattle NE requirement and then divided by the NE value of grass to estimate pasture intake by cattle. Actual and computed cattle feed intakes were also used to estimate manure and N excretion. Manure excretion was estimated by calculating the indigestible fraction of cattle diets using feed intakes and OM digestibility data for feedstuffs from O'Mara (2006). Nitrogen excretion was estimated as the difference between total N intake and N output in meat and milk. The N content of milk was based on measured CP values, but default values were used for meat and feedstuffs (IPCC, 2006; O'Mara, 2006).

O'Brien et al. (2014a) previously described the emission factors applied within the dairy farm GHG model in detail. Briefly, on-farm emission algorithms for CH₄, N₂O, and CO₂ emissions from sources such as fertilizer application were predominately obtained from

the IPCC (2006) guidelines (Supplementary Table S1; <http://dx.doi.org/10.3168/jds.2014-9222>). However, for enteric CH₄, NO₃⁻, and NH₃ emissions, equations from the Irish national GHG inventory were used instead (Duffy et al., 2012). For example, enteric CH₄ emissions were estimated using a fixed value of 6.5% of gross energy intake when cattle grazed pasture, but for cattle consuming grass silage and concentrate the following equation from Yan et al. (2000) was used:

$$\text{Enteric CH}_4 \text{ (MJ/d)} = \text{DEI} \times (0.096 + 0.035 \\ \times S_{\text{DMI}}/T_{\text{DMI}}) - (2.298 \times \text{FL}) - 1,$$

where DEI = digestible energy intake (MJ/d); S_{DMI} = silage DMI; T_{DMI} = total DMI; and FL = feeding levels above maintenance energy.

The IPCC (2006) guidelines assume all C absorbed by temporary C sinks (e.g., animals and manure) to be quickly released back to the atmosphere through respiration, burning, and decomposition. Short-term biogenic sources and sinks of CO₂ were therefore considered neutral with respect to GHG emissions. To comply with PAS 2050, long-term C sinks, for instance permanent grassland soils, were assumed to reach saturation after 20 yr. Thus, on-farm cropland recently converted to grassland (<20 yr) was estimated to remove (sequester) 6 t of CO₂/ha per year (IPCC, 2006). The PAS 2050 standard follows the IPCC (2006) guidelines regarding C removal or sequestration, but the standard assumes soil C levels reach equilibrium at the lower end of the IPCC (2006) time range (20–100 yr). Recent reports by Soussana et al. (2007, 2010), suggest that managed permanent grassland soils can sequester C for significantly longer than 20 yr. Thus, we also tested the effect of including C sequestration by assuming that permanent Irish grassland soils sequester 1.36 t of CO₂/ha per year based on the review of Soussana et al. (2010).

In addition to removing C, soils can also lose C when a change in land use occurs (e.g., forestland or grassland to cropland). Land use-change emissions were directly attributed to arable crops and estimated as 6.7 t CO₂/ha per annum, where grassland was converted to cropland <20 yr prior on-farm (BSI, 2011). The production of specific imported feeds, for instance Malaysian palm kernel, were also estimated to cause land use-change emissions by computing the average land use-change emissions for that crop in that country using data from the Carbon Trust (2013). Emission factors from the Carbon Trust (2013) database were primarily used to estimate off-farm GHG emissions associated with the manufacture and delivery of imported farm inputs, for instance purchased feedstuffs, fertilizer, and pesticides (Supplementary Table S2; <http://dx.doi.org/10.3168/>

jds.2014-9222). National literature sources were used to estimate off-farm GHG emission sources (e.g., electricity generation) when sufficient data were available. The Carbon Trust (2013) database and national literature sources, however, did not provide emission estimates for some inputs (e.g., pesticide manufacture); therefore, international databases were also used (e.g., Ecoinvent, 2010).

All GHG emissions calculated were estimated in terms of CO₂ equivalents (**CO₂-eq**) using 100-yr global warming potential factors from the IPCC (2013). The global warming potential factors for key GHG emissions were 1 for CO₂, 28 for CH₄, and 265 for N₂O. The temporal coverage of the LCA method in the GHG model was a period of 1 yr. Thus, the model generated a static account of the dairy systems' annual on-farm and total (on and off-farm) GHG emissions. To estimate the CF of milk from the dairy farms examined, total GHG emissions were allocated between the animal products sold, milk, and meat (culled cows and surplus calves). Some dairy farms also sold crops, but the model only quantified emissions from crops grown for dairy cattle, which avoided allocation between crop and animal products. In addition, none of the farms assessed sold manure. Thus, allocation of GHG emissions was only carried out between milk and meat.

The economic method of allocation was used to distribute GHG emissions between milk, culled cows, and surplus calves. Economic allocation was chosen instead of other widely used methods, for example biophysical allocation, because this method is favored by PAS 2050 when allocation cannot be avoided. The economic value or revenue from milk, culled cows, and surplus calves varied among farms (Table 1) and was quantified using the NFS database (Hennessy et al., 2013). The CF of milk was calculated by expressing GHG emissions attributed to milk per kilogram of fat- and protein-corrected milk (**FPCM**). Fat- and protein-corrected milk was standardized to 4% fat and 3.3% true protein per kilogram using the following equation from the IDF (2010):

$$\text{FPCM (kg/yr)} = \text{milk production (kg/yr)} \times (0.1226 \times \text{fat\%} + 0.0776 \times \text{true protein\%} + 0.2354).$$

Economic Analysis

Economic performance or financial output measures of specialist dairy farms were calculated from measurements of farm gross output, variable costs, and fixed (overhead) costs from the NFS (Hennessy et al., 2013). Gross output consisted of revenue from selling dairy farm products, such as milk and livestock. Variable

costs included charges for purchases of raw materials, such as feedstuffs, fertilizer, livestock, medicines, and seeds, and included service expenses for various providers of raw materials and skills (e.g., veterinarians and AI technicians). Fixed costs comprised running charges for farm machinery, maintenance costs for buildings, land and equipment, hired labor charges, telephone, electricity, insurance, and sundry charges.

The gross profit or margin of dairy farms was estimated as the difference between gross output and variable costs. Net profit was calculated by subtracting variable and fixed costs from gross output. The gross and net profit of dairy farms were expressed per unit of land and milk. In addition, farm profitability was expressed per unit of labor (paid and unpaid) to assess labor income. One labor unit was defined as at least 1800 h worked per year on the farm for a person over 18 yr of age. Labor input on the farm included hired labor and paid and unpaid family labor.

Statistical Analysis

Relationships between the CF of milk and economic performance measures of dairy farms were tested using the correlation (PROC CORR) and stepwise multiple regression analysis (PROC REG) methods of the SAS software package (SAS, 2008). The financial output measures included in the correlation and stepwise multiple regression analyses were gross and net profit per hectare and per liter, and gross and net income per labor unit. Farm milk footprints were also grouped based on their economic performance for the bottom, middle, and top third of farms. Differences between farm groups CF of milk were tested using general linear models (PROC GLM, SAS, 2008).

Partial least squares regression (**PLSR**) modeling was used to determine factors that influenced relationships between the CF of milk and measures of economic performance. The aim of PLSR was to predict correlated variables from a combination of orthogonal factors extracted from a set of independent variables. The dependent or response variables included in the PLSR model were milk CF and economic performance measures that were moderately or strongly correlated with CF ($-0.3 < r < 0.3$). Independent variables included in the PLSR model were technical and demographic farm measures such as annual milk yield per hectare and per cow, purchased fertilizer (kg of N/ha), length of the grazing season, concentrate feeding (kg/cow), stocking rate, diesel use, soil type, and farmer age, sex, and family size.

The importance of each independent farm variable in fitting the PLSR model for the orthogonal prediction factors and response variables was assessed using

Table 2. The mean economic costs and returns for specialized Irish dairy farms and the financial results for the bottom, middle, and top third of farms ranked in terms of gross margin/ha

Item	Mean (SD)	Bottom third (SD)	Middle third (SD)	Top third (SD)
Milk revenue, €/ha	3,125 (1,060)	2,241 (792)	2,997 (734)	4,205 (822)
Livestock and forage revenue, €/ha	88 (200)	30 (186)	85 (149)	176 (227)
Gross output, €/ha	3,212 (1,096)	2,271 (718)	3,082 (623)	4,381 (794)
Concentrate costs, €/ha	584 (319)	511 (361)	557 (282)	693 (322)
Pasture and forage costs, €/ha	448 (163)	401 (131)	400 (145)	503 (182)
Other variable costs, €/ha	422 (235)	330 (258)	404 (220)	521 (199)
Total variable costs, €/ha	1,454 (586)	1,241 (616)	1,361 (446)	1,716 (581)
Gross margin, €/ha	1,758 (744)	1,030 (395)	1,721 (433)	2,666 (475)
Gross margin, €/L	0.18 (0.05)	0.14 (0.06)	0.19 (0.03)	0.21 (0.03)
Gross income, €/labor unit	40,889 (22,609)	25,109 (17,358)	41,154 (22,542)	54,347 (18,889)
Energy and fuel, €/ha	216 (79)	180 (72)	209 (78)	242 (77)
Hired labor, €/ha	44 (128)	24 (83)	30 (88)	89 (177)
Other fixed costs, €/ha	749 (325)	601 (313)	726 (263)	880 (346)
Total fixed costs, €/ha	1,009 (421)	805 (411)	965 (389)	1,211 (444)
Total costs, €/ha	2,462 (918)	2,046 (925)	2,326 (501)	2,927 (939)
Net margin, €/ha	750 (651)	225 (517)	756 (411)	1,454 (526)
Net margin, €/L	0.08 (0.06)	0.03 (0.07)	0.08 (0.05)	0.11 (0.04)
Net income, €/labor unit	18,125 (16,740)	5,759 (12,905)	18,390 (14,599)	28,945 (14,321)

regression coefficients and the variable importance for projection (VIP) statistic (Wold, 1994). Based on Wold (1994), independent farm variables that had relatively small regression coefficients and VIP values less than 0.8 were deleted from the analysis. The PLSR model was refitted when independent farm variables were removed. The number of orthogonal prediction factors obtained from PLSR was determined by the absolute minimum predictive residual sum of squares. Independent farm variables that had an effect on the correlation analyzed were selected based on their PLSR loading values for each extracted orthogonal prediction factor.

RESULTS

Economic Performance

The financial results for Irish dairy farms in 2012 showed that the mean gross margin or profit per liter of milk was €0.18 (SD = €0.05) and €1,758 (€744) per hectare (Table 2). Average gross income was €40,889 (€22,609) per labor unit. The mean net margin per liter of milk was €0.08 (€0.06) and €750 (€651) per hectare. Per labor unit, net income averaged €18,125 (€16,740). Ranking dairy farms in terms of gross margin per hectare showed large differences in milk sales, gross output, costs, and profitability between the bottom, middle, and top third of farms (Table 2). Revenue from milk sales per hectare from the top third of farms was 40% greater than the middle third and 88% more than the bottom third. This can be explained by greater milk (fat and protein) solids yield per hectare for the top group (918 kg/ha) compared with the middle (665 kg/

ha) and bottom group (507 kg/ha). Thus, the total revenue per hectare for the top group was also considerably higher than the other groups, given that milk sales were the main component of gross output (range = 74–97%). Variable costs per hectare, however, were 26 to 38% higher and fixed costs per hectare were 25 to 50% greater for the top group compared with the middle and bottom groups.

Dairy farm costs per hectare were greater for the upper third of farms mainly for 2 reasons. First, the stocking rate of the top farm group (2.24 cows/ha) was greater than the middle group (1.88 cows/ha) and bottom group (1.59 cows/ha). Second, the top group used more inputs, such as feed per hectare, than the other groups. For instance, the upper third of farms fed 26% more concentrate than the middle third of farms (1.90 t/ha) and 40% more than the bottom third (1.71 t/ha). However, when evaluated per unit of milk, the top farm group was more productive than the other groups, because this group produced more milk solids per hectare and per cow and used more grass (9.5 t/ha) than the middle group (7.6 t/ha) and bottom group (6.6 t/ha). The top group also used concentrate feed more efficiently and yielded more milk solids for the same level of feed offered. Thus, the total cost per liter of milk for the top group was €0.02 less than the middle group and €0.04 less than the bottom group. Consequently, net margin per liter of milk of the top third was €0.03 above the middle third and €0.08 greater than the bottom third.

Higher farm productivity and grass utilization also resulted in the top group returning the highest gross and net margins per hectare. Gross margin per hectare of the top farm group was about 1.6 times greater than

the middle group and 2.6 times higher than the bottom group. On a net margin basis, profit per hectare of the top third of farms was 1.9 times greater than the middle third and 6.5 times higher than the bottom third of farms. Across all farm groups, the total labor input (paid and unpaid) was similar (1.7–1.8 labor units/farm). Thus, gross and net income per labor unit was substantially greater for the top group relative to the other groups.

CF of Milk

Based on the economic value of farm outputs, the majority of the dairy system's total GHG emission was allocated to milk (mean = 86%, SD = 5%) and the remainder to the co-products culled cows and surplus calves. The mean on-farm GHG emission per kilogram of FPCM was 0.90 (0.19) kg of CO₂-eq, but on-farm GHG emission per kilogram of FPCM varied widely across farms from 0.46 to 1.76 kg of CO₂-eq. Consequently, a large range was observed in the CF of milk (0.60–2.13 kg of CO₂-eq/kg of FPCM), which averaged 1.20 (0.25) kg of CO₂-eq/kg of FPCM when nonrecurrent land use-change emissions were included according to the PAS 2050 standard.

Excluding nonrecurrent land use-change emissions reduced individual farm footprints or had no effect. The mean CF of milk without nonrecurrent land use-change emissions was 8% lower or 1.11 kg of CO₂-eq/kg of FPCM. Including C sequestration by grassland soils reduced individual farm footprints across the entire sample because all farms were grass-based. The mean CF of milk with grassland C sequestration and land use-change emissions included was 12% lower or 1.06 kg of CO₂-eq/kg of FPCM. The variability in farm footprints, however, was similar when land use-change emissions were excluded (SD = 0.26; range = 0.52–1.99 kg of CO₂-eq/kg of FPCM) or when grassland C sequestration was included (SD = 0.26; range = 0.50–1.97 kg of CO₂-eq/kg of FPCM).

The GHG emission profiles of Table 3 for the bottom, middle, and top third of dairy farms ranked in terms of gross margin per hectare highlighted that CH₄ accounted for the majority of total GHG emissions across farm groups (51–52%) followed by N₂O (25–28%). Fluorinated gases were the least important contributor to total farm GHG emissions (0.1%), followed by CO₂ (21–24%). Enteric fermentation was the chief source of all farm groups' total GHG emissions (44–45%). The second largest source of total GHG emissions for the bottom, middle, and top farm groups were off-farm emissions (including nonrecurrent land use-change emissions) from concentrate production (13–16%), followed by GHG losses from manure excreted by grazing

cattle (10–12%). For all farm groups, the remaining GHG emissions were primarily generated from N fertilizer manufacture (8–9%) and application (6–7%), manure storage and spreading (6–7%), and from electricity and fuel use (3–4%).

Relating Economic Performance and CF of Milk

The CF of milk for the bottom, middle, and top third of farms ordered in terms of gross margin per hectare are detailed in Table 4. The results show the CF of milk generally decreased (with or without land use change emissions or grassland C sequestration) as economic performance improved. For instance, the top group CF of milk was 12 to 15% lower than the bottom third of farms ($P < 0.05$) and the middle group CF of milk was 10 to 13% lower than the bottom group ($P < 0.05$). In addition, the variability in the CF of milk declined as economic performance improved. For instance, variability in the CF of milk as measured using the 90% confidence interval was lowest for the top group (0.84–1.50 kg of CO₂-eq/kg of FPCM), followed by the middle (0.87–1.66 kg of CO₂-eq/kg of FPCM) and bottom (0.94–1.89 kg of CO₂-eq/kg of FPCM) groups (Figure 1). Furthermore, Figure 1 shows that ranking farms using an alternative economic output measure (gross margin per liter of milk) did not alter the relationship between the CF of milk and economic performance.

Correlations between CF of milk and economic performance were moderately negative ($r = -0.3$ to -0.5 , $P < 0.001$), irrespective of the inclusion or exclusion of land use-change emissions or grassland C sequestration. The economic performance measure that had the strongest beneficial association with the CF of milk was net margin per liter of milk ($r = -0.45$), followed by gross margin per liter of milk ($r = -0.43$). Per hectare, the strength of the relationship between CF of milk and gross margin ($r = -0.40$) was slightly greater than the association with net margin ($r = -0.38$). Net income per labor unit was moderately correlated with the CF of milk ($r = -0.34$), but the association between gross income per labor unit and CF of milk was weak ($r = -0.27$). Multiple regression analysis of economic performance measures showed that variability in the CF of milk was best explained by net margin per liter of milk ($R^2 = 0.22$), but the relationship was nonlinear (Figure 2).

Further analysis of the associations between economic output measures moderately correlated with the CF of milk using PLSR showed that 3 orthogonal factors were significant in predicting the correlation between these response variables ($R^2 = 0.51$, $P < 0.05$). The variation accounted for in both economic performance measures

Table 3. Cradle to farm-gate greenhouse gas (GHG) emission profiles for the bottom, middle, and top third of Irish dairy farms ranked in terms of gross margin/ha

Greenhouse gas and source	Location	Gross margin/ha (%)		
		Bottom third	Middle third	Top third
Methane as CO ₂ equivalent				
Enteric fermentation	On-farm	44.2	45.1	44.4
Manure storage and spreading	On-farm	4.4	4.2	3.9
Manure excreted on pasture	On-farm	0.4	0.5	0.5
Fertilizer production	Off-farm	0.1	0.1	0.1
Concentrate production ¹	Off-farm	1.2	1.2	1.2
Other inputs ²	Off-farm	0.3	0.4	0.4
Nitrous oxide as CO ₂ equivalent ³				
Fertilizer application	On-farm	5.3	5.9	6.3
Manure storage and spreading	On-farm	2.2	1.8	1.6
Manure excreted on pasture	On-farm	9.7	10.7	11.0
Indirect loss from ammonia and nitrate	On-farm	3.1	3.2	3.2
Fertilizer production	Off-farm	3.2	3.6	3.8
Concentrate production	Off-farm	1.5	1.4	1.4
Other inputs	Off-farm	0.2	0.5	0.5
Carbon dioxide as CO ₂ equivalent				
Fuel use	On-farm	2.5	2.1	1.7
Fertilizer application	On-farm	0.3	0.4	0.4
Lime application	On-farm	1.3	1.2	1.5
LUC from on-farm arable land ⁴	On-farm	0.1	0.1	0.1
Fertilizer production	Off-farm	4.5	5.0	5.3
Concentrate production	Off-farm	2.4	2.3	2.3
LUC ⁵ from soybean and palm concentrate feedstuffs	Off-farm	10.5	7.7	7.8
Electricity	Off-farm	1.5	1.4	1.4
Other inputs	Off-farm	1.0	1.1	1.1
Fluorinated-gases as CO ₂ equivalent				
Refrigerant losses	On-farm	0.1	0.1	0.1

¹The GHG emissions associated with the cultivation, processing, and transport of concentrate feed, but excluding nonrecurrent land use change emissions.

²Emissions from the production of purchased forage, milk replacer, fuel, pesticides and plastic.

³Nitrous oxide emissions from redeposition of on-farm ammonia emissions and nitrous oxide losses following nitrate leaching to waterways.

⁴Nonrecurrent land use change emissions from the conversion of grassland to arable land.

⁵Nonrecurrent land use change emissions from the cultivation of South American soybean and southeast Asian palm concentrate feedstuffs.

and CF of milk by orthogonal prediction factor 1 was 34%. Factors 2 and 3 explained 10 and 7%, respectively, of the variability in the response variables (CF of milk and economic output measures). Farm measures that loaded high on each orthogonal factor included FPCM yield per hectare, the length of the grazing season, and FPCM yield per cow (Figure 3). The VIP statistic (Table 5) of the prediction factors and response variables ranked FPCM yield per hectare, the length of the graz-

ing season, and concentrate feeding per cow as the most important farm variables in fitting the PLSR model.

DISCUSSION

Quantifying the CF of milk and economic performance of commercial farms is difficult given the uncertainty in modeling various GHG sinks and sources (e.g., land use change). To reduce uncertainty in our

Table 4. The carbon footprint (CF) of milk (kg of CO₂-equivalent/kg of fat- and protein-corrected milk¹) for the bottom, middle, and top third of Irish dairy farms in terms of gross margin/ha

Item	Bottom third	Middle third	Top third	<i>P</i> -value
CF of milk	1.32 ^a	1.15 ^b	1.12 ^b	0.004
CF of milk excluding LUC ²	1.18 ^a	1.06 ^b	1.04 ^b	0.004
CF of milk with grassland sequestration	1.18 ^a	1.05 ^b	1.03 ^b	0.002

^{a,b}Means with different superscripts within the same row are significantly different ($P < 0.05$).

¹Fat and protein corrected milk standardized to 4% fat and 3.3% true protein per kg.

²Nonrecurrent land use change emissions from the conversion of grassland to arable land and from the cultivation of South American soybean and southeast Asian palm concentrate feedstuffs.

Figure 1. Box plots of the carbon footprint (CF) of milk (kg of CO₂-equivalent/kg of FPCM) for the bottom, middle, and top third of Irish dairy farms ranked in terms of gross margin/liter of milk. The gray shaded area represents 90% of the distribution of the CF of milk for each farm group. FPCM = fat- and protein-corrected milk standardized to 4% fat and 3.3% true protein per kg.

GHG computations, we applied an LCA model that was independently certified to the PAS 2050 (BSI, 2011) standard by an accredited third party (Carbon Trust) using the Irish NFS. The advantages of using this particular data set was that the sample of farms was nationally representative and thus can be used to draw conclusions about the CF of the national milk pool. The outcomes of the analysis showed, consistent with most international studies (Leip et al., 2010; Gerber et al., 2011; Hagemann et al., 2012), that the CF of Irish milk in 2012 was in the lower range of global estimates. However, it is important to note that the weather of 2012 was unusually poor. For instance, summer rainfall levels were 1.75 to 3 times greater than the 30-yr average for most regions (Met Éireann, 2013). Thus, the farms we assessed were less productive, using more inputs per unit of milk relative to similar recent national studies (Teagasc, 2011; O'Brien et al., 2014a), which resulted in a 6 to 9% higher CF of milk and caused total farm costs to reach their highest national average level (Donnellan and Hennessy, 2014).

The high dairy farm costs in 2012 were primarily driven by significant decreases in pasture growth, which increased concentrate cost by over a third compared with the short-term (2007–2011) average (Donnellan and Hennessy, 2014). Thus, the average economic performance of dairy farms in terms of profitability and

labor income was also below the 5-yr average, but the decline was somewhat mitigated by a 4% increase in average milk price relative to the 2007 to 2011 mean. Congruous with previous studies (Ramsbottom et al., 2012; O'Brien et al., 2014a), profitability and the CF of milk varied significantly between dairy farms in 2012. However, despite the inclement weather conditions, the variability in farm economic performance and CF of milk was similar to previous years. Thus, this suggests that other factors, for instance farm management practices (e.g., grassland management), were more important in explaining the variation in economic performance and CF of milk.

Economic performance measures were inversely correlated with the CF of milk, which agrees with previous reports for grass-based farms (Lovett et al., 2008; Beukes et al., 2010; O'Brien et al., 2010). However, most studies that have evaluated the economic performance and the CF of milk have been limited to a small group of research farms. Furthermore, comparable large-scale studies have only assessed specialized dairy farms where cows were fed a concentrate-rich diet (e.g., mean 1.8 t of concentrate/cow per year; Thomassen et al., 2009). As a result, such studies have reported that on-farm GHG emission per kilogram of FPCM increased as gross margin per liter of milk increased, but found no correlation or reduction in CF of milk as farm income increased. Therefore, this implies that associations between economic performance and the CF of milk can vary between farming systems (e.g., extensive and intensive grass-based dairy farms). Nevertheless, most studies agree that the goal of improving dairy farm profitability does not adversely affect the CF of milk.

Beneficial associations between milk CF and economic performance were predominately influenced by farm feeding practices, the length of the grazing season, and annual milk production per hectare and per cow. Congruous with several previous studies (Moss et al., 2000; Benchaar et al., 2001; Lovett et al., 2005), higher concentrate feeding was generally associated with lower enteric CH₄ emissions and greater milk production per cow. Higher milk yield per cow facilitates the dilution of maintenance effect described by Capper et al. (2009), which reduced enteric CH₄ emission per unit of milk and on-farm emissions. However, greater concentrate feeding was associated with higher off-farm emissions per kilogram of FPCM and higher direct and total farm costs. Consequently, higher concentrate supplementation typically reduced farm profit and labor income and tended to increase the CF of milk, despite improving milk production per hectare and per cow.

The quantity of concentrate fed was strongly influenced by the length of the grazing season. Similar to

O'Brien et al. (2014a), farms that grazed cows longer used less concentrate and more forage per cow; however, unlike Thomassen et al. (2009), this did not adversely affect milk yield per cow or per hectare because extending the grazing season replaced grass silage with grazed grass, which, in agreement with Dillon et al. (2002), improved the digestibility of forage in the diet. Consequently, the practice reduced enteric CH_4 emission, which agrees with the analysis of Lovett et al. (2008), but disagrees with the findings of Schils et al. (2005, 2007). However, in contrast to our analysis, Schils et al. (2005, 2007) and Thomassen et al. (2009) generally assessed farms that fed maize silage or cereal silages or both to cows indoors in addition to feeding grass silage. Thus, these studies did not report that extending the grazing season reduced enteric CH_4 because maize silage is typically a higher-quality feed than grass silage

and less conducive to methanogenesis (Beauchemin et al., 2008; Grainger and Beauchemin, 2011).

Similar to Schils et al. (2005, 2007), grazing cows on pasture rather than feeding animals grass silage reduced fossil fuel consumption and decreased manure storage requirements. This reduced GHG emissions and direct costs from fuel use and manure storage and spreading, but, in agreement with Flechard et al. (2007) and Luo et al. (2010), increased N_2O emission from agricultural soils. However, congruous with O'Brien et al. (2014a), the increase in on-farm N_2O emissions caused by extending the grazing season was generally less than the reduction in CH_4 emissions from enteric fermentation and manure. Therefore, extending the length of the grazing season reduced on- and off-farm GHG emissions and, in contrast to greater concentrate feeding, decreased variable and total farm costs. As a result,

Figure 2. Relationship between net margin (€/L of milk) and carbon footprint of milk (kg of CO_2 -equivalent/kg of FPCM). The regression line was fitted using multiple regression ($R^2 = 0.22$). FPCM = fat- and protein-corrected milk standardized to 4% fat and 3.3% true protein per kilogram. Color version available online.

Table 5. Variable importance for projection (VIP¹) statistics and regression coefficients of a partial least squares regression (PLSR) model fitted to economic farm performance measures and carbon footprint (CF) of milk (kg of CO₂-equivalent/kg of FPCM² milk) using technical and demographic farm predictor variables

Farm predictor variable	VIP Statistic	Response variables regression coefficients					
		Gross margin/ L of milk	Gross margin/ha	Net margin/ L of milk	Net margin/ha	Net income/ labor unit	CF of milk
FPCM yield, kg/ha	1.08	0.09	0.79	0.12	0.44	0.20	0.11
FPCM yield, kg/cow	0.95	0.50	0.22	0.45	0.31	0.37	-0.58
Grazing days	1.06	0.12	-0.13	0.07	-0.10	0.13	-0.17
Concentrate fed, kg/cow	1.01	-0.67	-0.41	-0.59	-0.56	-0.39	0.23

¹The VIP statistic represents the value of each farm variable in fitting the PLSR model to the predictor and response variables. Farm predictor variables were retained in the model when VIP values were 0.8 or greater.

²FPCM = fat-and protein-corrected milk standardized to 4% fat and 3.3% true protein per kilogram.

similar to Lovett et al. (2008), the farm practice had a win-win effect whereby it simultaneously mitigated the CF of milk and increased labor income and farm profitability.

The capacity to extend the grazing season of dairy farms is constrained by climatic and biophysical conditions. Nevertheless, Lpple et al. (2012) showed that farmer education and participation in farmer discussion groups were equally important contributing factors. Thus, this implies that, other things being equal, there is still scope to extend the grazing season via farmer education. Furthermore, the farm practice can be combined with increasing the total genetic merit of the dairy herd via the economic breeding index (EBI), which O'Brien et al. (2010) reported positively influenced dairy farm profitability and the CF of milk. The EBI of dairy herds however was not recorded in the NFS. Therefore, herd total genetic merit was not considered in this analysis, but herd EBI is recorded nationally by the Irish Cattle Breeding Federation (Ramsbottom et al., 2012). Thus, the influence of herd EBI on CF of milk could be analyzed in the NFS in the future.

In general, individual improvements in farm management that increase farm profit have a minor influence on the CF of milk, but applying several improvements together has significant mitigation potential. For instance, Beukes et al. (2010) reported for a Waikato grass-based dairy farm in New Zealand that improving nutrient, feeding, and breeding management practices increased profitability and reduced GHG emissions per unit of milk by 27%. Similarly, Schulte et al. (2012) reported Irish agriculture could avoid a projected 7% rise in GHG emissions and increase milk output by 50% following the removal of the EU milk quota system via adopting a suite of farm practices that increase farm productivity and profit (e.g., improving herd EBI). Schulte et al. (2012) also assessed the potential of agriculture to meet EU GHG emission targets and concluded that improving farm management was key to

meeting 2020 GHG obligations, but reported for longer term 2050 targets additional mitigation measures must be developed.

Figure 3. Loading values for orthogonal factors of a partial least squares regression (PLSR) model that was fitted to economic performance measures and carbon footprint (CF) of milk (kg of CO₂-equivalent/kg of FPCM) using technical and demographic farm predictor variables. Loading values of orthogonal factors describe which farm variables influenced the correlation(s) between the dependent variables (economic performance measures and CF of milk). The orthogonal factors 1, 2, and 3 accounted for 34, 10, and 7% of the variation in the dependent variables. The economic measures included in the analysis were gross and net profit per hectare and per liter, and net income per labor unit. FPCM = fat- and protein-corrected milk standardized to 4% fat and 3.3% true protein per kilogram. Color version available online.

Examples of additional GHG-mitigation strategies that have relevance for grass-based farms include the development of enteric CH₄ vaccines, the selection of ruminants for low enteric CH₄, increasing soil C sequestration, and nitrification inhibitors. Of these strategies, the IPCC (2007) report that increasing soil C sequestration has the greatest potential to reduce agricultural GHG emissions and tends to enhance farm productivity. Thus, some LCA studies have included soil C sequestration in their analysis (e.g., Leip et al., 2010), which results in a 10 to 20% lower CF of milk. The results of our analysis support these findings and indicate that soil C sequestration does not alter the relationship between CF of milk and economic performance for grass-based farms. However, verifying soil C sequestration is difficult because it is a decadal process with small C inputs (<1 t of C/ha) being input into a large soil C pool (>100 t of C/ha). Furthermore, there is large uncertainty regarding the capacity of grassland soil to store C and the period it takes these soils to reach C saturation (Jones and Donnelly, 2004). Thus, this implies more research needs to be carried out before C sequestration by grassland can be accurately included in CF evaluations.

Assessing the relationship between economic performance and the CF of milk was the focus of our study, but it is important to note that GHG emissions and CF are only one aspect of environmental performance. For instance, dairy farms can also cause eutrophication and acidification of waterways and loss of wildlife habitats. Thus, developing strategies to only reduce the CF of milk may cause undesirable changes in other aspects of environmental performance (pollution swapping). Furthermore, improvements in economic and environmental sustainability might negatively influence social issues such as animal welfare, work-life balance, or consumer perception (Thomassen et al., 2009; Dillon et al. 2010). Therefore, to improve the sustainability of primary milk production, all pertinent economic, environmental, and social issues need to be evaluated. The NFS has recently been expanded to assess social measures of farming systems and additional environmental measures (e.g., whole-farm nutrient balances; Hennessy et al., 2013), but does not cover all relevant sustainability measures. Therefore, it is envisaged that the database will be further developed to carry out such an analysis based on relevant international guidelines (e.g., ISO, 2010; LEAP, 2014).

CONCLUSIONS

The application of LCA to compute GHG emissions using the Irish NFS database demonstrated that the CF

of milk was negatively correlated with financial performance measures. The main farm factors that improved economic performance measures and reduced the CF of milk were increasing the length of the grazing season and improving annual milk production per hectare and per cow. Thus, this suggests several farm management practices can provide win-win solutions, allowing farmers to improve their economic performance while also mitigating dairy sector GHG emissions. However, increasing milk production per hectare through greater concentrate feeding had the opposite effect, because the practice significantly increased farm expenditure and off-farm emissions. Therefore, grass-based dairy farms should aim for higher levels of milk production per hectare from grazed grass. These practices should also positively influence farm sustainability, but this study did not consider all relevant aspects of sustainability such as animal welfare measures. Thus, it is envisaged that the LCA model and database we applied will be further developed to facilitate a more comprehensive analysis of practices to improve the sustainability of grass-based dairy farms.

ACKNOWLEDGMENTS

The authors express their gratitude to the farmers that participated in the National Farm Survey. We are also grateful to the staff of the National Farm Survey (Rural Economy Research Centre, Teagasc, Athenry, Co. Galway, Ireland) who carried out the recording, collection, and validation of the database and thank the anonymous reviewers for their helpful suggestions and comments.

REFERENCES

- Basset-Mens, C., F. Kelliher, S. Ledgard, and N. Cox. 2009. Uncertainty of global warming potential for milk production on a New Zealand farm and implications for decision making. *Int. J. Life Cycle Assess.* 14:630–638.
- Beauchemin, K. A., M. Kreuzer, F. O'Mara, and T. A. McAllister. 2008. Nutritional management for enteric methane abatement: A review. *Aust. J. Exp. Agric.* 48:21–27.
- Benchaar, C., C. Pomar, and J. Chiquette. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modeling approach. *Can. J. Anim. Sci.* 81:563–574.
- Beukes, P. C., P. Gregorini, A. J. Romera, G. Levy, and G. C. Waghorn. 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. *Agric. Ecosyst. Environ.* 136:358–365.
- BSI. 2011. PAS 2050:2011—Specification for the Assessment of Life Cycle Greenhouse Gas Emissions of Goods and Services. British Standards Institute (BSI), London, UK.
- Buckley, C., and P. Carney. 2013. The potential to reduce the risk of diffuse pollution from agriculture while improving economic performance at farm level. *Environ. Sci. Policy* 25:118–126.
- Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* 87:2160–2167.

- Carbon Trust. 2013. Carbon-Footprinting Software—Footprint Expert. The Carbon Trust, London, UK. Accessed Jun. 20, 2015. <http://www.carbontrust.com/software>.
- Carbon Trust. 2014. The Carbon Trust Annual Report 2013/2014. The Carbon Trust, London, UK.
- Casey, J. W., and N. M. Holden. 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. *Agric. Syst.* 86:97–114.
- CSO. 2013. Agriculture and fishing statistical products. Central Statistics Office, Cork, Ireland. Accessed Oct. 12, 2014. http://www.cso.ie/px/pxeirestat/Database/eirestat/Livestock%20and%20Farm%20Numbers/Livestock%20and%20Farm%20Numbers_statbank.asp?SP=Livestock and Farm Numbers&Planguage=0.
- Dillon, E., T. Hennessy, and S. Hynes. 2010. Assessing the sustainability of Irish agriculture. *Int. J. Agric. Sustain.* 8:1–17.
- Dillon, P., S. Crosse, B. O. Brien, and R. W. Mayes. 2002. The effect of forage type and level of concentrate supplementation on the performance of spring-calving dairy cows in early lactation. *Grass Forage Sci.* 57:212–223.
- Donnellan, T., and T. Hennessy. 2014. Review of dairy farming in 2013 and outlook for 2014. Pages 1–12 in *Outlook 2014 Economic Prospects for Agriculture*. M. Maloney, ed. Agricultural Economics and Farm Surveys Department, Teagasc, Galway, Ireland.
- Duffy, P., E. Hanley, B. Hyde, P. O'Brien, J. Ponzi, E. Cotter, and K. Black. 2012. Ireland National Inventory Report 2012. Greenhouse Gas Emissions 1990–2010 Reported to the United Nations Framework Convention on Climate Change. Environmental Protection Agency, Co. Wexford, Ireland.
- Ecoinvent. 2010. Ecoinvent 2.0 Database. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland. Accessed May 15, 2015. <http://www.ecoinvent.org/database/ecoinvent-version-2/ecoinvent-version-2.html>.
- European Council. 2009. Decision No 406/2009/EC of the European Parliament and of the council on the effort of member states to reduce their greenhouse gas emissions to meet the community's greenhouse gas emission reduction commitments up to 2020. *Official J. EU* L140, 136–148.
- FAOSTAT. 2014. United Nations Food and Agriculture Organization statistical database. Accessed Nov. 12, 2014. <http://faostat.fao.org/site/291/default.aspx>.
- Flechar, C. R., P. Ambus, U. Skiba, R. M. Rees, A. Hensen, A. van Amstel, A. P.-v. Dasselaaar, J. F. Soussana, M. Jones, J. Clifton-Brown, A. Raschi, L. Horvath, A. Neftel, M. Jocher, C. Ammann, J. Leifeld, J. Fuhrer, P. Calanca, E. Thalmann, K. Pilegaard, C. Di Marco, C. Campbell, E. Nemitz, K. J. Hargreaves, P. E. Levy, B. C. Ball, S. K. Jones, W. C. M. van de Bulk, T. Groot, M. Blom, R. Domingues, G. Kasper, V. Allard, E. Ceschia, P. Cellier, P. Laville, C. Henault, F. Bizouard, M. Abdalla, M. Williams, S. Baronti, F. Berretti, and B. Grosz. 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. *Agric. Ecosyst. Environ.* 121:135–152.
- Gerber, P., T. Vellinga, C. Opio, B. Henderson, and H. Steinfeld. 2010. Greenhouse Gas Emissions from the Dairy Sector. A Life Cycle Assessment. Food and Agricultural Organization of the United Nations: Animal Production and Health Division, Rome, Italy.
- Gerber, P., T. Vellinga, C. Opio, and H. Steinfeld. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livest. Sci.* 139:100–108.
- Grainger, C., and K. A. Beauchemin. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166–167:308–320.
- Hagemann, M., A. Ndambi, T. Hemme, and U. Latacz-Lohmann. 2012. Contribution of milk production to global greenhouse gas emissions. *Environ. Sci. Pollut. Res. Int.* 19:390–402.
- Hennessy, T., B. Moran, A. Kinsella, and G. Quinlan. 2013. National Farm Survey 2012. Teagasc Agricultural Economics and Farm Surveys Department, Athenry, Co. Galway, Ireland.
- IDF. 2010. A Common Carbon Footprint for Dairy. The IDF Guide to Standard Lifecycle Assessment Methodology for the Dairy Industry. Bulletin of the International Dairy Federation 445. International Dairy Federation, Brussels, Belgium.
- IPCC. 2006. 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Inventories. Vol. 4. Agriculture, Forestry and Other Land Use. H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, ed. Institute for Global Environmental Strategies (IGES), Hayama, Japan.
- IPCC. 2007. Climate Change 2007: Mitigation. Contribution of working group III to the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.
- IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.
- IPCC. 2014. Summary for policymakers. Pages 6–10 in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx, ed. Cambridge University Press, Cambridge, UK.
- ISO. 2010. Guidance on Social Responsibility. (ISO 26000:2010). International Organization for Standardization (ISO), Brussels, Belgium.
- Jarrige, R. 1989. Ruminant Nutrition: Recommended Allowances and Feed Tables. John Libbey Eurotext, Montrouge, France.
- Jones, M. B., and A. Donnelly. 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO₂. *New Phytol.* 164:423–439.
- Kennedy, E., M. O'Donovan, J. P. Murphy, L. Delaby, and F. O'Mara. 2005. Effects of grass pasture and concentrate-based feeding systems for spring-calving dairy cows in early spring on performance during lactation. *Grass Forage Sci.* 60:310–318.
- Läpple, D., T. Hennessy, and M. O'Donovan. 2012. Extended grazing: A detailed analysis of Irish dairy farms. *J. Dairy Sci.* 95:188–195.
- LEAP. 2014. Environmental Performance of Animal Feed Supply Chains: Guidelines for Quantification. Livestock Environmental Assessment and Performance Partnership. FAO, Rome, Italy.
- Leip, A., F. Weiss, T. Wassenaar, I. Perez, T. Fellmann, P. Loudjani, F. Tubiello, D. Grandgirard, S. Monni, and K. Biala. 2010. Evaluation of the Livestock's Sector Contribution to the EU Greenhouse Gas Emissions (GGELS)—Final report. European Commission, Joint Research Center, Ispra, Italy.
- Lovett, D. K., L. Shalloo, P. Dillon, and F. P. O'Mara. 2008. Greenhouse gas emissions from pastoral based dairying systems: The effect of uncertainty and management change under two contrasting production systems. *Livest. Sci.* 116:260–274.
- Lovett, D. K., L. J. Stack, S. Lovell, J. Callan, B. Flynn, M. Hawkins, and F. P. O'Mara. 2005. Manipulating enteric methane emissions and animal performance of late-lactation dairy cows through concentrate supplementation at pasture. *J. Dairy Sci.* 88:2836–2842.
- Luo, J., C. A. M. de Klein, S. F. Ledgard, and S. Saggar. 2010. Management options to reduce nitrous oxide emissions from intensively grazed pastures: A review. *Agric. Ecosyst. Environ.* 136:282–291.
- Met Éireann. 2013. Climate Annual 2012. Met Éireann. Accessed Jul. 25, 2015. <http://www.met.ie/climate/monthly-weather-reports.asp>.
- Moss, A. R., J. P. Jouany, and J. Newbold. 2000. Methane production by ruminants: Its contribution to global warming. *Ann. Zootech.* 49:231–253.
- O'Brien, D., P. Brennan, J. Humphreys, E. Ruane, and L. Shalloo. 2014a. An appraisal of carbon footprint of milk from commercial grass-based dairy farms in Ireland according to a certified life cycle assessment methodology. *Int. J. Life Cycle Assess.* 19:1469–1481.
- O'Brien, D., L. Shalloo, P. Crosson, T. Donnellan, N. Farrelly, J. Finnan, K. Hanrahan, S. Lalor, G. Lanigan, F. Thorne, and R. Schulte. 2014b. An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. *Environ. Sci. Policy* 39:107–118.

- O'Brien, D., L. Shalloo, C. Grainger, F. Buckley, B. Horan, and M. Wallace. 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. *J. Dairy Sci.* 93:3390–3402.
- O'Brien, D., L. Shalloo, J. Patton, F. Buckley, C. Grainger, and M. Wallace. 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. *Agric. Syst.* 107:33–46.
- O'Mara, F. 1996. A Net Energy System for Cattle and Sheep. Department of Animal Science and Production, Faculty of Agriculture, University College Dublin, Belfield, Dublin, Ireland.
- O'Mara, F. 2006. Development of emission factors for the Irish cattle herd. Environmental Protection Agency, Co. Wexford, Ireland.
- Opio, C., P. Gerber, A. Mottet, A. Falcucci, G. Tempio, M. Macleod, T. Vellinga, B. Henderson, and H. Steinfeld. 2013. Greenhouse Gas Emissions from Ruminant Supply Chains—A Global Life Cycle Assessment. FAO, Rome, Italy.
- Pirlo, G. 2012. Cradle-to-farm gate analysis of milk carbon footprint: A descriptive review. *Ital. J. Anim. Sci.* 11:109–118.
- Ramsbottom, G., A. R. Cromie, B. Horan, and D. P. Berry. 2012. Relationship between dairy cow genetic merit and profit on commercial spring calving dairy farms. *Animal* 6:1031–1039.
- SAS Institute. 2008. SAS User Guide Version 9.1.3. SAS Institute Inc., Cary, NC.
- Schils, R. L. M., J. E. Olesen, A. del Prado, and J. F. Soussana. 2007. A review of farm level modeling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livest. Sci.* 112:240–251.
- Schils, R. L. M., A. Verhagen, H. F. M. Aarts, and L. B. J. Šebek. 2005. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. *Nutr. Cycl. Agroecosyst.* 71:163–175.
- Schulte, R., P. Crosson, T. Donnellan, N. Farrelly, J. Finnan, S. Lalor, G. Lanigan, D. O'Brien, L. Shalloo, and F. Thorne. 2012. A Marginal Abatement Cost Curve for Irish Agriculture. Teagasc Submission to the National Climate Policy Development Consultation. Teagasc, Oak Park, Carlow, Ireland.
- Sinden, G. 2009. The contribution of PAS 2050 to the evolution of international greenhouse gas emission standards. *Int. J. Life Cycle Assess.* 14:195–203.
- Soussana, J. F., V. Allard, K. Pilegaard, P. Ambus, C. Amman, C. Campbell, E. Ceschia, J. Clifton-Brown, S. Czobel, R. Domingues, C. Flechard, J. Fuhrer, A. Hensen, L. Horvath, M. Jones, G. Kasper, C. Martin, Z. Nagy, A. Neftel, A. Raschi, S. Baronti, R. M. Rees, U. Skiba, P. Stefani, G. Manca, M. Sutton, Z. Tuba, and R. Valentini. 2007. Full accounting of the greenhouse gas (CO₂, N₂O, CH₄) budget of nine European grassland sites. *Agric. Ecosyst. Environ.* 121:121–134.
- Soussana, J. F., T. Tallec, and V. Blanford. 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* 4:334–350.
- Teagasc. 2011. Sectoral Road Map: Dairying. Accessed Mar. 10, 2015. www.teagasc.ie/publications/2011/761/Roadmap_Dairy.pdf.
- Thomassen, M. A., M. A. Dolman, K. J. van Calker, and I. J. M. de Boer. 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. *Ecol. Econ.* 68:2278–2284.
- Thomassen, M. A., K. J. van Calker, M. C. J. Smits, G. L. Iepema, and I. J. M. de Boer. 2008. Life cycle assessment of conventional and organic milk production in the Netherlands. *Agric. Syst.* 96:95–107.
- van der Werf, H. M. G., C. Kanyarushoki, and M. S. Corson. 2009. An operational method for the evaluation of resource use and environmental impacts of dairy farms by life cycle assessment. *J. Environ. Manage.* 90:3643–3652.
- Wold, S. 1994. PLS for Multivariate Linear Modeling. *QSAR: Chemometric Methods in Molecular Design. Methods and Principles in Medicinal Chemistry*. H. Van de Waterbeemd, ed. Verlag-Chemie, Weinheim, Germany.
- WRI/WBCSD. 2011. Greenhouse Gas Protocol: Product Life Cycle Accounting and Reporting Standard. World Resources Institute and World Business Council for Sustainable Development Washington, DC.
- Yan, M.-J., J. Humphreys, and N. M. Holden. 2011. An evaluation of life cycle assessment of European milk production. *J. Environ. Manage.* 92:372–379.
- Yan, T., R. E. Agnew, F. J. Gordon, and M. G. Porter. 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.* 64:253–263.
- Zehetmeier, M., H. Hoffmann, J. Sauer, G. Hofmann, G. Dorfner, and D. O'Brien. 2014. A dominance analysis of greenhouse gas emissions, beef output and land use of German dairy farms. *Agric. Syst.* 129:55–67.