A life cycle assessment case study of the carbon footprint of high performance Irish, UK and USA dairy farms

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Abstract: Life cycle assessment (LCA) is the accepted approach to simulate and compare carbon footprint (CF) of milk. The objective of this study was to apply LCA to compare CF of high performance confinement and grass-based dairy farms. Physical performance data from research herds were used to quantify CF of a high performance Irish grass-based dairy system and a top performing UK confinement dairy system. For the USA confinement dairy system, data from the top 5% of herds of a national database were used. Life cycle assessment was applied using the same dairy farm greenhouse gas (GHG) model for all systems. The model estimated all on and off-farm GHG sources associated with dairy production until milk is sold from the farm in kg of carbon dioxide equivalents (CO_2-eq) and allocated emissions between milk and meat. The CF of milk was calculated by expressing GHG emissions attributed to milk per t of energy corrected milk (ECM). The comparison showed the CF of milk from the Irish grass-based system (837 kg of CO_2-eq/t of ECM) was 5% lower than the UK confinement system (884 kg of CO_2-eq/t of ECM) and 7% lower than the USA confinement system (898 kg of CO_2-eq/t of ECM) when no GHG emissions were allocated to meat. However, without grassland carbon sequestration, the grass-based and confinement dairy systems had similar CF per t of ECM. Additionally, using different emission algorithms or methods to allocate GHG emissions between milk and meat affected the relative difference and order of dairy system CF. This indicates that further harmonization of several aspects of the LCA methodology is required to compare CF of divergent dairy systems. Relative to recent reports that assess the CF of milk from average Irish, UK and USA dairy systems, this case study indicates that top performing herds of the respective nations have CF about 30% lower than average systems. Although, differences between studies are partly explained by methodological inconsistency, the comparison suggests that there is potential to reduce the CF of milk in each of the nations by implementing practices that improve productivity.

Keywords: CF, grass, confinement, milk production

Introduction

Dairy production is an important source of the dominant GHG emissions, methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) and responsible for about 3% of global GHG emissions (Opio et al., 2013). Recent studies suggest that annual global GHG emissions will have to be cut by up to 80% (relative to 1990 levels) before 2050 in order to prevent the worst effects of climate change (Fisher et al., 2007). However, demand for milk is expected to grow by 1.1% per annum from 2006 to 2050 (Opio et al., 2013). Therefore, reducing GHG emissions or carbon footprint (CF) per unit of milk is becoming a pre-requisite. Life cycle assessment (LCA) is the preferred method to quantify CF of milk. The methodology entails quantifying GHG emissions generated from all stages associated with a product, from raw-material extraction through production, use and disposal (ISO, 2006). Several studies have applied LCA to compare CF of milk from confinement and grass-based dairy farms (Belflower et al., 2012; O'Brien et al., 2012). Generally, LCA studies not biased by the farms selected to represent grass-based and confinement dairy systems have reported that grass-based systems produce milk with a lower CF (Leip et al., 2010; Flysjö et al., 2011). However, such studies have only considered average performing dairy systems. Thus, there is a need to evaluate the CF of high performing dairy systems to determine how to fulfill production and GHG requirements. To achieve this goal, we compared CF of milk from case study farms located in regions accustomed to grass and confinement based milk production, namely the USA and UK for confinement systems and Ireland for grass-based milk production. A secondary goal of this study was to assess the effect different LCA methodologies have on the CF of these contrasting milk production systems.

Materials and Methods

Description of dairy systems

Data (Table 1) for quantifying CF of milk of a grass-based Irish dairy system and a UK confinement dairy system were obtained from research herds (McCarthy et al., 2007; Garnsworthy et al., 2012); and data for the USA confinement dairy system from the top 5% of herds recorded by the DairyMetrics database. Performance of these herds was assessed relative to national statistics, which confirmed that the input data used to model the Irish, UK and USA represented top performing herds.

Table 1: Annual technical description of a high performance Irish grass-based dairy system and top performing UK and USA confinement dairy systems

Item	Unit	Irish	UK	USA
On-farm size	ha	40	85	93
Off-farm size[1]	ha	3	97	82
Permanent grassland	ha	40	21	-
Milking herd	# milking cows	92	220	153
Milk production	kg milk/cow	6,262	10,892	12,506
ECM[2] production	kg ECM/cow	6,695	10,602	11,650
Replacement rate	%	18	34	38
Average body weight	kg	543	613	680
Stocking rate	LU[3]/on-farm ha	2.53	3.74	2.79
Concentrate	kg DM/cow	320	2,905	3,355
Grass	kg DM/cow	4,099	-	-
Alfalfa hay	kg DM/cow	-	-	2,570
Grass silage	kg DM/cow	849	1,142	-
Maize silage	kg DM/cow	-	1,862	2,155
Whole crop wheat silage	kg DM/cow	-	825	-
Rape straw	kg DM/cow	-	219	-
Total intake	kg DM/cow	5,270	6,953	8,079
On-farm N fertilizer	kg N/on-farm ha	250	106	53
Manure exported	%	-	33	-

1 Land area required to produce purchased forage and concentrate feedstuffs.
2 ECM = Energy corrected milk. 3 LU = Livestock unit equivalent to 550 kg BW.

The aim of the Irish dairy system was to maximize grass utilization through a combination of extended grazing (early February to late November), tight calving patterns in early spring and rotational grazing of pasture. Grass silage was harvested in the Irish system when grass growth exceeded herd feed demand and fed during the housing period with supplementary minerals and vitamins. Concentrate feed was purchased onto the farm and fed when forage intake was not sufficient to meet nutritional requirements. In the UK and USA dairy systems cows calved throughout the year, were housed full time and fed total or partial mixed rations (TMR or PMR). The diet offered in the UK system was based on data from Garnsworthy et al. (2012) where cows had ad libitum access to PMR, and concentrates were given to cows during milking. In the USA dairy system, the composition of the diet was based on the survey of Mowrey and Spain (1999). Diets fed in the UK and USA dairy systems were formulated to maximize milk production per cow.

Greenhouse Gas modeling

Dairy systems GHG emissions were calculated using the same LCA model (O'Brien et al., 2012). The model used "cradle to gate" LCA to quantify all on and off-farm GHG sources associated with milk production until milk is sold from the farm and operates in combination with Moorepark Dairy System Model (MDSM; Shalloo et al., 2004). The LCA model calculates GHG emissions by combining input data (e.g. feed intakes) from the MDSM with literature GHG emission algorithms. On-farm emission algorithms were obtained from Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). However, enteric CH_4 emissions were calculated using country specific approaches (Brown et al., 2012; Duffy et al., 2012; US EPA, 2012). As well as generating emissions, dairy farms can also remove emissions via soil sequestration. Generally, most studies report that soils have a limited capacity to sequester carbon (Jones & Donnelly, 2004), but recent reports suggest that permanent grasslands soils are an important long-term carbon sink (Soussana et al., 2010). Thus, we tested the effect of including carbon sequestration by assuming an average rate of sequestration by permanent grassland of 1.19 t/CO_2 per ha per annum. Off-farm GHG emissions associated with production of non-agricultural products (e.g. pesticides) were estimated using emission factors from Ecoinvent (2010) and data from literature sources. Emissions from land use change were estimated for South American soybean and Malaysian palm fruit by dividing the total land use change emissions for a crop by the total crop area to estimate the average land use change emissions per crop (Ecoinvent, 2010). For Megalac, which is a calcium salt, land use change emissions were not included, because the feedstuff is produced from existing forest plantations (Volac, 2011). The output of the LCA model was a static account of annual on and off-farm (total) GHG emissions in CO_2 equivalents (CO_2-eq). The IPCC (2007) global warming potentials (GWP) were used to convert GHG emissions into kg of CO_2-eq. The model expresses total GHG emissions as the CF of milk in kg of CO_2-eq per t of energy corrected milk (ECM), which per kg of milk is equivalent to 4% milk fat and 3.3% milk protein.

Co-product allocation

In addition to producing milk, dairy farms may export crops, manure and produce meat from culled cows and surplus calves. Thus, the CF of dairy systems should be distributed between these outputs. Generally, LCA standards recommend to avoid allocation (e.g. ISO, 2006), but this was only possible for exported crops by delimiting the LCA model to consider only emissions from crops grown for dairy cattle reared on-farm. For exported manure, the avoided burdens system expansion method was used to attribute emissions. The method assumes exported manure displaces synthetic fertilizer emissions, but allocates no storage emissions to exported manure. The following allocation methods were evaluated to distribute GHG emissions between milk and meat:

1. Milk – All GHG emissions attributed to milk.
2. Mass – Emissions were allocated based on mass of milk and meat sold.
3. Economic – Allocation was based on revenue received for milk and meat.
4. Protein – Protein content of milk and meat was used to allocate GHG emissions.
5. Biological – Allocated was based on nutritional energy required for producing milk and meat.
6. Emission – The emissions generated by surplus calves, heifers <24 months and finishing culled cows were allocated to meat and the remaining emissions assigned to milk.
7. System expansion – Meat from culled cows and surplus dairy calves reared for meat was assumed to displace meat from traditional cow-calf (suckler) beef systems.

Scenario modeling

Scenario modeling was used to evaluate variation in the emissions of the base dairy farm system described. The scenarios tested were:

S1: Enteric CH_4 emissions were estimated according to the default IPCC (2006) guidelines, which estimate enteric CH_4 emissions as 6.5% of GEI.

S2: Country specific emission algorithms from national GHG inventories and literature sources were used to estimate emissions from agricultural activities. Emissions from non-agricultural activities were estimated using national literature sources.

Results

Carbon profiles and footprints of milk

CF of ECM was lowest for the Irish system, was 6% greater for the UK system, and was 7% greater for the USA system, when no GHG emissions were attributed to meat (Table 2). Enteric CH_4 (47%), N_2O emissions from manure deposited by grazing cattle (15%), emissions from fertilizer application (12%) and production (8%), and emissions from managed manure (8%) were the main sources of emissions from the Irish system. The key sources of GHG emissions from the UK system were enteric CH_4 (42%), CH_4 emissions from manure storage (13%), GHG emissions from imported concentrate feed (12%), N_2O emissions from manure storage and spreading (9%), CO_2 emissions from electricity and fuel (7%) and emissions from land use change (6%). The main sources of GHG emissions from the USA system were enteric CH_4 (42%), N_2O emissions from manure storage and spreading (17%), CH_4 emissions from manure storage (14%), GHG emissions from imported concentrate feed (12%), and emissions from electricity and fuel (8%).

Table 2: Carbon profiles and footprints of energy corrected milk (kg of CO_2-equivalent/t of ECM) for a high performance Irish grass-based system and top performing UK and USA confinements system. All GHG emissions from surplus calves and culled cows were attributed to milk.

	Baseline			S1[1] % change			S2[2] % change		
Emission sources	Irish	UK	USA	Irish	UK	USA	Irish	UK	USA
Enteric fermentation	431	376	374	0.8	10.4	11.6	-	-	-
Manure management	77	201	275	-	-	-	-25.4	-24.9	-22.1
Manure excreted on pasture	140	5	0	-	-	-	-46.3	-26.0	-
Fuel combustion	14	22	34	-	-	-	-	-	-
Lime application	1	0	1	-	-	-	-	-	-
Carbon sequestration	-78	-11	0	-	-	-	-	-	-
Fertilizer application	106	20	18	-	-	-	-0.9	34.3	-3.1
Fertilizer production	76	20	15	-	-	-	-	-	-25.6
Concentrate production	30	111	106	-	-	-	-0.3	9.8	-22.6
Land use change	2	58	0	-	-	-	-	-	-
Electricity and other inputs[3]	38	82	75	-	-	-	-	-1.2	3.5
Carbon footprint (CF) of ECM	837	884	898	0.4	4.4	4.8	-10.4	-4.1	-9.4

1 S1 = Emission algorithms from the IPCC (2006) guidelines were applied to estimate emissions from agricultural GHG sources.
2 S2 = Country specific emission factors were applied to estimate emissions from the manufacture of non-agricultural inputs and from agricultural GHG sources.
3 Emissions from the production of purchased forage, milk replacer, fuel, pesticides and lime.

The carbon profiles show that sequestration by grassland soil had no effect on GHG emissions of the UK and USA dairy systems, but had a large effect on the Irish dairy system. Thus, without carbon sequestration the dairy systems emitted similar CF per t of ECM.

Scenario analysis

S1 (Table 2) showed that estimating enteric CH_4 as 6.5% of GEI increased CF of ECM of the confinement systems by 4-5% compared to the baseline scenario. However, using this approach to estimate enteric CH_4 emissions had little effect on CF per t of ECM (<1%) of the grass-based system, because enteric CH_4 emissions was estimated as 6.45% of GEI in the baseline scenario. Thus, the difference between grass-based and confinement systems CF was greater in S1. Country specific emission algorithms of S2 reduced emissions from manure relative to the baseline. In addition, S2 estimated lower emissions from concentrate and fertilizer production for the USA system. However, the scenario had no effect or increased emissions from these sources for the Irish and UK systems. This resulted in the country specific emission algorithms of S2 reducing the CF of the UK system by 4% relative to the baseline, but by 9-10% for the Irish and USA systems. Thus, the order of CF per t of ECM of dairy systems in S2 was not consistent with the baseline scenario.

Allocation of GHG emissions between milk and meat

Excluding attributing all GHG emissions to milk, mass allocation attributed the most GHG emissions to milk followed by protein, economic, biological, emission allocation and system expansion (Table 3). System expansion led to a greater difference between the CF of grass-based and confinement dairy systems compared to the other methods analyzed. The approach showed that the Irish system had a CF per t of ECM 19% lower than the UK system and 22% lower than the USA system.

Table 3: The effect of different methods to allocate greenhouse gas emissions between milk and meat on carbon footprint of energy corrected milk (kg of CO_2-equivalent/t of ECM) of a high performance Irish grass-based system and top performing UK and USA confinement systems.

Allocation method	Irish	UK	USA
Milk	837	884	898
Mass	820	865	879
Economic	759	789	838
Protein	789	827	844
Biological	739	772	787
Emission	715	740	727
System expansion	497	613	636

Discussion

Comparison of GHG emissions and carbon footprint of milk

Congruous with reports by Belflower et al. (2012) the key source of GHG emissions, enteric CH_4, was greater per cow from the confinement systems than the grass-based system, but lower per unit of milk. The greater milk yield per cow and higher replacement rate within the confinement systems explained the greater enteric CH_4 emissions per cow, because these factors increase feed intake, which is a key determinant of enteric CH_4 emissions. Milk yield per cow was greater in the confinement systems given the greater genetic selection for milk yield and higher levels of concentrate feeding. These factors also explained the lower enteric CH_4 emissions per unit of milk of the confinement systems, because concentrate rich diets contain less fiber than forage diets and improving genetic merit facilitates the dilution of maintenance effect (Capper et al., 2009).

The findings of Garnsworthy (2004) also agreed with this finding, but showed that at similar annual milk yields, improving the fertility of dairy cows decreases enteric CH_4 emissions per unit of milk. This was because improving cow fertility reduces the number of replacement heifers required to maintain herd size for a given milk volume, which reduces enteric CH_4 emissions. Thus, the results of Garnsworthy (2004) partially explain why the lower replacement rate of the UK system resulted in similar enteric CH_4 emissions per unit of milk as the USA system, even though milk yield per cow was 10% greater in the USA system. Another reason that explained the similar enteric CH_4 emissions of the confinement systems was the different diets fed. Unlike the USA system, the diet of cows in the UK system included protected lipids, which compared to most feeds reduce enteric CH_4 emissions, because protected lipids are not fermentable in the rumen (Martin et al., 2010). In addition, they slightly increased the feed efficiency (kg feed/unit of milk) of the UK system relative to the USA system, which partly led to these systems emitting similar enteric CH_4 emissions per unit of milk.

The greater feed efficiency of the UK confinement system in part reduced GHG emissions from manure storage and on-farm feed production, which resulted in lower on-farm GHG emissions per unit of milk relative to the USA system. In addition, manure from all animals was managed in a liquid system for the UK system, but for the USA system, manure from replacements was managed in a dry lot. This caused the USA system to emit greater N_2O emissions and therefore greater GHG emissions per unit of milk from manure storage. On-farm GHG emissions per unit of milk were also greater from the USA system relative to the UK system, because the USA system recycled all manure on-farm, but the UK system exported a third of manure produced. The UK and USA confinement systems were more feed and N efficient compared to the Irish grass-based system, but used more arable land. Thus, the confinement systems sequestered less carbon compared to the Irish system. As a result, on-farm GHG emissions per unit of milk of the Irish system were lower than the USA system. However, carbon sequestration of the UK system was greater than the USA system, which led to the UK system emitting the lowest on-farm GHG emissions per unit of milk.

Imported concentrate feeds, fertilizer and electricity were the main contributors to dairy systems off-farm GHG emissions. The Irish system emitted the lowest off-farm GHG emissions per unit of milk, because of the low reliance of this system on purchased concentrate. Off-farm GHG emissions per unit of milk were greater from the UK system than the USA system, given the greater feeding of concentrate feeds associated with a high GHG emission (e.g. South American soybeans) in the UK system. However, the CF of the UK and USA dairy systems were similar, because on-farm GHG emissions were greater from the USA system. The higher off-farm GHG emissions of the confinements system, though, resulted in the UK and USA systems having a greater CF than the Irish system. The lower CF of milk from the grass-based system compared to the confinement systems agrees with some reports (Flysjö et al., 2011; O'Brien et al., 2012) but disagrees with others (Capper et al., 2009; Belflower et al., 2012). This can be explained by the performance of dairy systems compared, but also by the variation in the application of the LCA methodology.

Influence of LCA methodology on carbon footprint of milk

Although international LCA standards (ISO, 2006) have been developed, they are not consistent particularly regarding allocation. Several criteria can be used to allocate emissions between milk and meat e.g. economic value or mass basis. For instance, choosing to allocate GHG emissions between milk and meat on a mass basis for the UK system, but on an economic basis for the USA system, resulted in the UK system having a greater CF of ECM than the USA system. However, when mass or economic allocation was used for both dairy systems, the UK system had a slightly lower CF of ECM. Thus, to compare CF of milk the same allocation procedure must be used. Similar to Flysjö et al., (2011) allocation according to mass, protein or economic value resulted in a greater CF of milk relative to allocation based on physical causal relationships (e.g. biological energy). The differences between these allocation methods was explained by the high energy requirements of producing meat from dairy systems compared to the mass or value of meat produced.

Allocation was also handled in this study through system expansion. This methodology caused the greatest difference between the grass-based and confinement systems CF of ECM. This was because for a fixed farm milk output increasing milk yield per cow generally reduces meat production from a dairy system (Flysjö et al., 2012). Thus, the confinement systems displaced less meat per unit of milk from traditional beef systems, compared to the grass-based system. However, the type of meat a dairy system substitutes can significantly affect the CF of milk using system expansion. For instance, Flysjö et al. (2012) reported that conventional dairy systems had a greater CF of milk than organic dairy systems when meat from dairy systems was assumed to replace meat from traditional beef systems, but conventional systems had the opposite effect when meat from dairy systems was assumed to substitute pork. Thus, this shows that system expansion increases the uncertainty of the CF of milk. The comparison of allocation methods also showed when the same allocation method was used the percentage of GHG emissions allocated to meat varied depending dairy system. Thus, for a given dairy system there are advantages to choosing a particular allocation procedure.

Life cycle choices regarding carbon sequestration and land use change emissions also affect the CF of milk. For instance, when carbon sequestration was included, the grass-based system had the lowest CF of ECM, but omitting sequestration resulted in the grass-based and confinement systems having similar CF of ECM. However, the uncertainty associated with carbon sequestration by soil is high. Thus, more data are required to increase confidence in sequestration and CF estimates. There is also lack of consensus on how to assess land use change emissions. The direct method of Leip et al. (2010) was followed in this study, but using a different approach, such as a general emission factor for land use change, can alter the order of dairy systems CF of milk. Thus, there is need to develop a harmonized approach to assess land use change emissions.

Comparison with carbon footprint studies of milk

Relative to recent national average estimates of CF of Irish, UK and USA dairy production (Capper et al., 2009; Leip et al., 2010; Thoma et al., 2013), our findings suggest that high performance dairy systems of these countries reduce CF of milk by 27-32%, however, this comparison is partially affected by methodological differences. Furthermore, the comparison of CF of milk from high performance dairy systems in this study relative to recent reports of CF of average Irish, UK and USA dairy systems indicates that the relative difference between average and high performance dairy systems was likely to be greater than the relative difference between top performing grass and confinement dairy systems. Thus, this suggests that improving productivity has a greater effect on the CF of milk than converting from a confinement system to a grass-based system or vice versa.

Conclusions

A high performing Irish grass-based system had a lower CF of milk than top performing UK and USA confinement systems. However, the relative difference and ranking of dairy systems CF of milk were not consistent in this study when different methodologies regarding, emission algorithms, carbon sequestration and allocation decisions were used. Therefore, this implies that harmonization of the LCA method is required to compare CF of milk.

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