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Evaluation of the effect of accounting method, IPCC *v.* LCA, on grass-based and confinement dairy systems' greenhouse gas emissions

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Life cycle assessment (LCA) and the Intergovernmental Panel on Climate Change (IPCC) guideline methodology, which are the principal greenhouse gas (GHG) quantification methods, were evaluated in this study using a dairy farm GHG model. The model was applied to estimate GHG emissions from two contrasting dairy systems: a seasonal calving pasture-based dairy farm and a total confinement dairy system. Data used to quantify emissions from these systems originated from a research study carried out over a 1-year period in Ireland. The genetic merit of cows modelled was similar for both systems. Total mixed ration was fed in the Confinement system, whereas grazed grass was mainly fed in the grass-based system. GHG emissions from these systems were quantified per unit of product and area. The results of both methods showed that the dairy system that emitted the lowest GHG emissions per unit area did not necessarily emit the lowest GHG emissions possible for a given level of product. Consequently, a recommendation from this study is that GHG emissions be evaluated per unit of product given the growing affluent human population and increasing demand for dairy products. The IPCC and LCA methods ranked dairy systems' GHG emissions differently. For instance, the IPCC method quantified that the Confinement system reduced GHG emissions per unit of product by 8% compared with the grass-based system, but the LCA approach calculated that the Confinement system increased emissions by 16% when off-farm emissions associated with primary dairy production were included. Thus, GHG emissions should be quantified using approaches that quantify the total GHG emissions associated with the production system, so as to determine whether the dairy system was causing emissions displacement. The IPCC and LCA methods were also used in this study to simulate, through a dairy farm GHG model, what effect management changes within both production systems have on GHG emissions. The findings suggest that single changes have a small mitigating effect on GHG emissions (<5%), except for strategies used to control emissions from manure storage in the Confinement system (14% to 24%). However, when several management strategies were combined, GHG emissions per unit of product could be reduced significantly (15% to 30%). The LCA method was identified as the preferred approach to assess the effect of management changes on GHG emissions, but the analysis indicated that further standardisation of the approach is needed given the sensitivity of the approach to allocation decisions regarding milk and meat.

Keywords: greenhouse gas, life cycle assessment, Intergovernmental Panel on Climate Change method, confinement, grass-based

Implications

Reducing greenhouse gas (GHG) emissions and increasing milk production is a major challenge facing the global dairy industry. However, to reduce GHG emissions per unit of milk, it is incorrect to consider only components of the dairy system relevant for policy reporting such as that used by the Intergovernmental Panel on Climate Change. Instead, approaches such as life cycle assessment, which consider on and off-farm GHG emissions should be used. This holistic approach ensures that emissions are reduced and not transferred to another location. Thus, reform of the present policy framework is needed to enable quantification of the impact of mitigation strategies on global GHG emissions.

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Introduction

Globally, the dairy industry is currently faced with the challenge of increasing production to satisfy growing demand

(Food and Agriculture Organisation (FAO), 2006), while meeting an international obligation to reduce greenhouse gas (GHG) emissions, which are the primary cause of global warming (Intergovernmental Panel on Climate Change (IPCC), 2007). This issue has led to an increasing interest in investigating and reducing the GHG emission intensity (kg of GHG per unit of product) of dairy production. In particular, the focus has been on improving the GHG emission intensity of primary dairy production, because the main sources of GHG from the dairy sector are emitted during this stage, for example, methane (CH_4) from enteric fermentation (Hospido *et al.*, 2003; Steinfeld *et al.*, 2006; Gerber *et al.*, 2010).

An accepted method to assess the GHG emission intensity of primary dairy production is life cycle assessment (LCA; Thomassen *et al.*, 2008b). LCA is a holistic systems approach that aims to quantify the potential environmental impacts (e.g. climate change, non-renewable energy use) generated throughout a product's life cycle, from raw-material acquisition through production, use, recycling and final disposal (International Organisation for Standardisation (ISO), 2006a). Thus, for primary dairy production, LCA quantifies GHG emissions from all processes associated with the dairy farm up to the point milk is sold from the farm (Cederberg and Mattsson, 2000; Casey and Holden, 2005). The general framework and requirements of LCA are internationally standardised (ISO, 2006a and 2006b). In addition, specific guidelines based on international standards have recently been developed for applying LCA to assess the GHG emission intensity of milk production (Carbon Trust, 2010; International Dairy Federation (IDF), 2010). However, LCA is not the recognised method for reporting the dairy sectors contribution to GHG emissions on a national basis. The standard method for reporting GHG is the IPCC guidelines (IPCC, 1996 and 2006). The IPCC method, unlike LCA, quantifies GHG emissions using a national sector-based approach (Schils *et al.*, 2005). The approach estimates emissions from the production and consumption of goods within defined national boundaries and emissions from the production of goods exported from a nation, but does not consider emissions from the production of goods imported into a country (Peters, 2008).

The IPCC and LCA methods are frequently used to evaluate measures to reduce GHG emissions from dairy production. LCA studies of dairy systems have in particular assessed the effect of production system (e.g. conventional or organic dairy production) on GHG emissions (Cederberg and Mattsson, 2000; Haas *et al.*, 2001; Van der Werf *et al.*, 2009). In contrast, the IPCC approach has mainly been used to evaluate the effect that farm-management practices, such as nutrient management or feed additives, have on GHG emissions (Smith *et al.*, 2008). Few studies, to our knowledge, have applied the IPCC method to evaluate GHG emissions from different systems of production (Schils *et al.*, 2005), because the structure of the method is not conducive to a full appraisal of emissions from farming systems (Crosson *et al.*, 2011). However, the dairy sector can only achieve recognition for a reduction in GHG emissions when using the IPCC method.

The primary objective of this paper was to test the effect of applying the IPCC and LCA methodologies to compare GHG emissions from different systems of dairy production (conventional seasonal calving grass-based dairy system and a confinement dairy system). A secondary objective of this study was to determine what effect farm-management changes within both production systems would have on GHG emissions.

Material and methods

Dairy farm systems

The study quantified GHG emissions from a seasonal calving grass-based dairy system (Grass) and a confinement dairy system (Confinement) based on the work of Patton *et al.* (2009) and Olmos *et al.* (2009). Patton *et al.* (2009) investigated the effect that grass and confinement dairy farms had on the annual milk performance of Holstein–Friesian cows, and Olmos *et al.* (2009) examined the effect these dairy systems had on reproductive welfare.

The two studies were based on the same trial conducted at Moorepark Research Centre, Fermoy, Co. Cork, Ireland (52°16′N, 8°25′W) from December 2006 to January 2008 (Table 1). Spring-calving Holstein–Friesian cows were blocked based on genetic merit (Irish Economic Breeding Index €60, s.d. = €17.3), parity number (2.5, s.d. = 1.49), expected calving date (6 March, s.d. = 27.9 days), body condition score (3.0, s.d. = 0.69) and predicted annual milk yield (98 kg, s.d. = 123.4 kg) and assigned randomly from within pairs to either the Grass or Confinement system.

Holstein–Friesian cows were housed full time in the Confinement system and fed total mixed ration (TMR). However, replacement heifers were only indoors during the winter period and grazed pasture during the growing season. Grass silage was harvested on-farm. The remaining feed was imported. Cows were offered specific TMR diets during the dry period (dry cow TMR) and lactation (lactation cow TMR; Table 2). The TMR diets offered were comparable in chemical composition to TMR fed in other studies (Kolver and Muller, 1998; Grainger *et al.*, 2009), apart from dry matter (DM) content, which was lower than that in other studies (Bargo *et al.*, 2002; Vibart *et al.*, 2008). The low DM content was mainly due to the low DM of the maize and grass silages offered. The maize silage used was typical of maize produced in Ireland during a poor growing season with low DM content, poorly developed cobs and low starch content (Fitzgerald and Murphy, 1999).

The aim of the Grass system was to maximise the utilisation of grazed grass in the diet of lactating Holstein–Friesian dairy cows. This was accomplished by targeting calving to commence in early spring (mean calving date 14 February), which generally is the onset of the grass-growing season (Dillon *et al.*, 1995). Grass silage was harvested on-farm when grass growth exceeded herd feed demand. The system was self-contained for forage. The N fertiliser input was 260 kg/ha and the total concentrate offered was 370 kg of DM per cow. Concentrate was offered mainly at the

Table 1 *Technical description of the seasonal grass-based (Grass) and confinement dairy farms (Confinement) investigated*[a]

Item	Unit	Grass	Confinement
On-farm size	ha	40	20
Off-farm size[b]	ha	5	49
Milking cows	No.	90	90
Total FPCM[c] production	kg FPCM/cow per year	6639	8040
Delivered FPCM	kg FPCM/cow per year	6538	7942
Milk fat	%	4.31	4.15
Milk protein	%	3.49	3.37
Length of lactation	days	305	305
Replacement rate	%	18	18
Cull rate	%	18	18
Average BW	kg	567	609
Stocking rate	LU/ha	2.54	5.10
Concentrate	kg DM/cow per year	370	2865
Grass[d]	kg DM/cow per year	4093	0
Grass silage	kg DM/cow per year	1063	1497
Maize silage	kg DM/cow per year	0	1746
Barley straw	kg DM/cow per year	0	499
Concentrate	t DM/herd per year	42	249
Grass	t DM/herd per year	381	34
Grass silage	t DM/herd per year	103	143
Maize silage	t DM/herd per year	0	147
Barley straw	t DM/herd per year	0	43
N fertilizer	kg N/ha per year	260	85
Annual manure exported	%	0	23

FPCM = fat and protein corrected milk; BW = body weight; LU = livestock unit, equivalent to one dairy cow; DM = dry matter.
[a]Data based on research of Patton *et al.* (2009) and Olmos *et al.* (2009).
[b]Off-farm land area required to produce purchased forage and concentrate. The land area was calculated using average yields from Central Statistics office (CSO, 2010) and Ecoinvent (2010).
[c]FPCM = (0.337 + 0.116 × %fat + 0.06 × %protein) × kg milk (Thomassen and de Boer, 2005).
[d]Forage intakes were estimated with the Moorepark Dairy System Model (Shalloo *et al.*, 2004) using milk production, animal BW, concentrate supplementation and feed-ration composition data from Patton *et al.* (2009) and Olmos *et al.* (2009).

beginning and end of lactation. Grass silage was fed predominately during the dry period with minerals and vitamins included in the diet (Table 2).

The Moorepark Dairy System Model (MDSM; Shalloo *et al.*, 2004), a whole-farm simulation model, was used with milk production data, body weight (BW), concentrate supplementation data and the composition of the feed ration to predict the total dry matter intake (DMI) of animals. Data from Patton *et al.* (2009) was used to check the accuracy of predicted feed intakes. The overall pregnancy rate was not significantly different between the two systems (Olmos *et al.*, 2009); therefore, the replacement rate was the same for both systems (Table 1). Both farms investigated were specialised milk production systems, which meant that bull calves were sold from the farm as soon as practically possible.

GHG emissions

GHG emissions were calculated using a dairy farm GHG model (O'Brien *et al.*, 2011). The model estimates the principal GHG emissions from primary dairy production: carbon dioxide (CO_2), nitrous oxide (N_2O) and CH_4. The GHG model operates in combination with the MDSM (Shalloo *et al.*, 2004), which defines key input parameters (land area; animal inventory; milk production; feed intakes; herbage quality; grazing-season length; manure, fertiliser and lime application) required for the GHG model to quantify emissions.

In this study the model used two approaches, LCA and the IPCC method, to quantify GHG emissions from two dairy systems. The subsequent sections summarise how the LCA and IPCC methodologies were applied in the GHG model.

LCA methodology. The LCA approach was used to quantify emissions from all processes associated with the dairy production system up to the point that milk is sold from the farm. The approach was implemented in the GHG model by combining input data from the MDSM with specific LCA GHG emission factors in Microsoft Excel (Tables 3 and 4). The LCA emission factors for on-farm sources of CH_4 and N_2O emissions were obtained from the agricultural section of the Irish GHG national inventory (Duffy *et al.*, 2011b). On-farm sources of CO_2 were estimated using emission factors from the IPCC (2006) guidelines and data from Nemecek and Kägi (2007). The LCA emission factors for off-farm GHG sources (GHG emissions associated with the production and supply of purchased farm inputs, e.g. synthetic fertiliser) were obtained mainly from European literature (Table 4) and databases included with the LCA software, SimaPro (Pré Consultants, 2008). The LCA approach did not consider GHG

Table 2 *Ingredient composition, DM and net energy of confinement dairy system (Confinement) dry and milking cow total mixed ration diets, seasonal grass-based dairy system (Grass) dry cow diet and concentrate offered to lactating cows at pasture*

	Confinement		Grass	
Ingredient (g/kg DM)	Dry	Lactation	Dry	Lactation
Maize silage	247	267	–	–
Grass silage	247	223	999	–
Barley straw	416	20	–	–
Rolled barley	–	126	–	–
Citrus pulp	–	82	–	280
Soya bean meal	80	142	–	120
Maize gluten feed	–	70	–	20
Molasses	–	55	–	30
Maize grain	–	–	–	100
Rapeseed meal	–	–	–	80
Palm kernel meal extract	–	–	–	160
Rolled wheat	–	–	–	200
Vegetable oil	–	10	–	10
Mineral and vitamin premix[a]	10	5	1	–
Net energy (UFL[b] kg/DM)	0.70	0.98	0.81	1.11

DM = total dry matter; UFL = unit feed lactation.
[a]Vitamin A, 250 000 IU; vitamin D, 50 000 IU; vitamin E, 2000 IU; Se, 60 mg/kg; I, 700 mg/kg; Cu, 4000 mg/kg; Zn, 5000 mg/kg.
[b]1 UFL is 7.11 MJ of net energy.

removals, because farm sinks (e.g. C sequestration) were assumed to be in equilibrium.

The LCA method allocates GHG emissions between multifunctional processes (O'Brien *et al.*, 2011), including the production of concentrate co-products, such as barley grain and barley straw, and the production of milk and meat on-farm. The procedures used to allocate GHG emissions between co-products were updated using recently published LCA guidelines (IDF, 2010). For concentrate co-products, GHG emissions were allocated based on their relative economic values using data from Nemecek and Kägi (2007), Central Statistics Office (CSO, 2010) and Ecoinvent (2010). Table 5 shows the composition, economic allocation and origin of concentrates used by the farming systems. For milk and meat, GHG emissions were allocated on the basis of the physiological feed requirements of the cow to produce milk and meat. The following equation from the IDF (2010) was used to calculate the allocation factor for milk and meat:

$$AF = 1 - 5.7717 \times (M_{\text{meat}} / M_{\text{milk}}) \qquad (1)$$

where AF is the allocation factor for milk, M_{meat} the sum of BW of all animals including bull calves and culled mature animals and M_{milk} the sum of mass of milk sold, corrected to 4% fat and 3.3% protein.

GHG emissions calculated using LCA were estimated in terms of their 100-year global warming potentials (CO_2 equivalents; CO_2-eq), which on a weight basis relative to CO_2 was set to a factor of 25 for 1 kg of CH_4 and to a factor of 298 for 1 kg of N_2O (Forster *et al.*, 2007). The temporal coverage of the LCA method in the GHG model was a period of 1 year. Thus, the approach generated a static account of dairy systems' annual on-farm, off-farm and total (on-farm plus off-farm) GHG emissions. Dairy systems produce food and provide environmental services (e.g. landscape conservation). Consequently, LCA estimates of annual GHG emissions were expressed per unit of farm area (t CO_2-eq/on-farm ha) and per unit of product (kg CO_2-eq/kg FP (fat and protein)). Furthermore, LCA estimates of annual GHG emissions per unit area and per unit of product were updated also to estimate emissions per total ha (on-farm and off-farm hectares required to produce purchased forage and concentrate) and per kg of fat and protein corrected milk (FPCM).

IPCC methodology. The sources of GHG considered using the IPCC method are enteric fermentation, manure management and agricultural soils (emissions of N_2O from synthetic and organic fertiliser use, manure excreted by grazing cattle and N_2O emissions from ammonia (NH_3) re-deposition and nitrate (NO_3) leaching). These are the sources the IPCC consider relevant for dairy farming (Schils *et al.*, 2005). The IPCC approach in the GHG model excludes GHG removals from farm sinks, because GHG sinks are not reported in the agricultural sector. The IPCC method was applied to quantify GHG emissions from dairy cows and replacement heifers (0 to 2 years).

The IPCC method was implemented in the GHG model using IPCC emission factors from the agriculture section of the Irish GHG national inventory (Duffy *et al.*, 2011b; Table 6) and the parameters generated by the MDSM. The IPCC emission factors are categorised into three different tiers, with each successive tier having an increased level of detail and accuracy. Presently, the Irish GHG inventory uses IPCC emission factors from different tiers to calculate emissions from dairy production. Thus, the IPCC method in the GHG model uses tier-1 emission factors to calculate N_2O emissions from agricultural soils and tier-2 emission factors to estimate CH_4 emissions from enteric fermentation and manure management (Duffy *et al.*, 2011b). GHG emissions quantified using the IPCC method were estimated in terms of their 100-year global warming potential using the same procedure as described for the LCA method.

The IPCC method in the GHG model produces a static account of annual GHG emissions from dairy production. Annual GHG emissions quantified using the IPCC method were expressed per unit of product to test the effect of methodology and per on-farm ha, because national inventories of GHG emissions are assessed in isolation from food production, for example, annual GHG emissions per nation state (Casey and Holden, 2005; Crosson *et al.*, 2011). GHG emissions per unit of product were allocated between milk and meat using the IDF (2010) approach previously described for the LCA method.

Scenario analysis

Farm-management changes to reduce calculated GHG emissions, using IPCC and LCA methodologies, were simulated

Table 3 *Emission factors used in the life cycle assessment[a] approach for quantification of on-farm greenhouse gas emissions*

Gas and source	Emission factor	Unit	References
CH_4			
Enteric fermentation			
Dairy cows and replacements (conserved feed)[b]	DEI × (0.096 + 0.035 × (S_{DMI}/T_{DMI})) − (2.298 × (FL − 1))	MJ/day per animal	Duffy *et al.* (2011b)
Dairy cows and replacements (grass; >50% DMI)	0.065 × GEI	MJ/day per animal	Duffy *et al.* (2011b)
Manure storage	Total manure OM stored × 0.24 × 0.67 × ((prop. in slurry type system × 0.39) + (prop. in solid manure[c] system × 0.01))	kg/year	Duffy *et al.* (2011b)
Grazing returns[d]	Total manure OM excreted during grazing × 0.24 × 0.67 × 0.01	kg/year	Duffy *et al.* (2011b)
N_2O-N			
Grazing returns	0.02 × (N in manure − NH_3 loss)	kg/kg N	Duffy *et al.* (2011b)
Synthetic N fertiliser application	0.0125 × (N in fertiliser − NH_3 loss)	kg/kg N	Duffy *et al.* (2011b)
Manure application	0.0125 × (N in manure − NH_3 loss)	kg/kg N	Duffy *et al.* (2011b)
Slurry storage	0.001 × (N stored)	kg/kg N	Duffy *et al.* (2011b)
Solid manure storage	0.02 × (N stored)	kg/kg N	Duffy *et al.* (2011b)
NO_3 leaching	0.025 × (N applied/ha × 0.1)	kg/kg NO_3^-	Duffy *et al.* (2011b)
NH_3 re-deposition	0.01 × (sum of NH_3 sources)	kg/kg NH_3	Duffy *et al.* (2011b)
CO_2			
Diesel combustion	2.62 × diesel use	kg/l	Nemecek and Kägi (2007)
Lime	0.44 × lime application	kg/kg lime	IPCC (2006)
Urea	0.73 × urea application	kg/kg urea	IPCC (2006)

CH_4 = methane; DEI = digestible energy intake; S_{DMI} = silage DMI; T_{DMI} = total DMI; FL = feeding levels above maintenance energy; DMI = dry matter intake; GEI = gross energy intake; OM = organic matter; prop. = proportion; N_2O-N = nitrous oxide – nitrogen; N = nitrogen; NO_3 = nitrate; NH_3 = ammonia; CO_2 = carbon dioxide.
[a]All emissions associated with the dairy production system up to the point milk is sold from the farm.
[b]Replacements are dairy heifers aged 0 to 2 years.
[c]Dry matter content >20%.
[d]Manure excreted during grazing.

with the GHG model for both dairy systems using scenario modelling. The following scenarios were simulated:

- increasing forage quality to achieve a higher net energy content (+0.05 unit feed lactation (UFL)/kg DM; Jarrige, 1989);
- increasing milk production without compromising fertility and other important traits via genetic improvement (+500 kg milk produced per cow);
- reducing on-farm synthetic N fertiliser application to decrease the farm N surplus (−25 kg N/ha);
- reducing the replacement rate (−3%) to reduce the proportion of non-milk producing animals in the herd;
- covering the manure store and flaring of CH_4.

The management changes were simulated one by one and in combination to determine the cumulative efficacy of the selected farm-management changes, which were not all directly additive. The present IPCC guidelines were used to predict GHG emissions from enclosed manure stores where gas is captured (IPCC, 2006). Scenario modelling also was used to test the effects of C sequestration by grassland soils on dairy system GHG emissions. Carbon sequestration by grassland soils is caused predominately by farm-management changes, for instance the conversion of arable land to grassland (Soussana *et al.*, 2010). Thus, the scenario analysis assumed that the grassland area of both dairy systems was newly established (<2 years) and had previously been used for growing arable crops. The simulated rate of sequestration of C by grassland soils was estimated as 2.5 t C/ha per year based on the review of Soussana *et al.* (2010). The ratio of molecular weights of CO_2 and C were used to quantify CO_2 sequestration (3.67 kg CO_2/kg C).

Results

GHG emissions of grass and confinement dairy systems

The GHG emissions of the Grass system and the Confinement system, calculated using LCA, are shown in Tables 7 and 8, respectively. GHG emissions quantified using the IPCC method for both systems are shown in Table 9. The LCA results show that the Confinement system decreased on-farm GHG emissions (kg CO_2-eq) per tonne of product (FPCM and FP) on average by 9% relative to the Grass system (Tables 7 and 8). However, when off-farm GHG emissions were included, the Confinement system increased total GHG emissions per unit of product by 16% compared with the Grass system. The IPCC results (Table 9) per tonne

Table 4 *Emission factors used in the life cycle assessment[a] approach for quantification of NH_3-N emissions and off-farm greenhouse gas emissions*

Gas and source	Emission factor	Unit	References
NH_3-N			
Housing	11 to 38[b]	g/luuk per day	Duffy *et al.* (2011a)
Slurry storage	(2 to 4)[c] × area slurry store	g/m^2 per day	Duffy *et al.* (2011a)
Solid manure[d] storage	94 × area solid manure store	g/m^2 per year	Duffy *et al.* (2011a)
Yard[e]	7	g/cow per day	Duffy *et al.* (2011a)
Slurry application	(0.15 to 0.59)[f] × TAN in slurry spread	kg/kg TAN	Duffy *et al.* (2011a)
Solid manure application	0.81 × TAN in solid manure spread	kg/kg TAN	Duffy *et al.* (2011a)
Grazing cattle	−0.51 + (0.0742 × synthetic N rate/ha[g])	g/luuk per day	Duffy *et al.* (2011a)
Synthetic N fertiliser use[h]	(0.08–0.23)[i] × N fertiliser for crops	kg/kg N	Duffy *et al.* (2011a)
CO_2-eq			
Diesel	0.354 × diesel use	kg/l	Nemecek and Kägi (2007)
Electricity	0.582 × electricity us	kg/kWh	Howley *et al.* (2009)
Lime	0.82 × lime application	kg/kg lime	Duffy *et al.* (2011b)
Ammonium-based N fertiliser	6.7 × ammonium-based N fertiliser	kg/kg N	Kramer *et al.* (1999)
Urea	3.2 × urea use	kg/kg N	Snyder *et al.* (2009)
Triple super phosphate	1.67 × P_2O_5 fertiliser use	kg/kg P_2O_5	Pré Consultants (2008); Ecoinvent (2010)
Concentrate grass[j]	0.78 × concentrate use	kg/kg concentrate	Pré Consultants (2008); Ecoinvent (2010)
Concentrate confinement[k]	0.83 × concentrate use	kg/kg concentrate	Pré Consultants (2008); Ecoinvent (2010)

NH_3-N = ammonia − nitrogen; N = nitrogen; luuk = UK livestock unit, equivalent to 500 kg BW; TAN = total ammoniacal nitrogen; CO_2-eq = carbon dioxide equivalent; P_2O_5 = phosphorus pentoxide; DM = dry matter.
[a]All emissions associated with the dairy production system up to the point milk is sold from the farm.
[b]Dependent on age of animal.
[c]Dependent on slurry storage facility.
[d]DM content >20%.
[e]Yard = NH_3-N from collecting yard prior to milking.
[f]Dependent on DM content of slurry and season of application.
[g]Synthetic N fertiliser applied to grazing area.
[h]Synthetic N fertiliser applied to silage, hay and cereal crops.
[i]Dependent on fertiliser compound and site of application (grassland or arable land).
[j]Concentrate blend used in the seasonal grass-based system.
[k]Concentrate blend used in the confinement system.

Table 5 *Concentrate ingredients for a seasonal grass-based dairy system (Grass) and a confinement dairy system (Confinement)*

Dairy system and concentrate ingredients	Proportion in concentrate blend (g/kg DM)	Economic allocation (%)[a]	Origin
Grass			
Beet pulp[b]	280	4	Germany
Palm kernel oil	10	17	Malaysia
Maize grain	100	100	USA
Maize gluten	20	8	USA
Molasses	30	5	Germany
Palm kernel meal	160	1	Malaysia
Rape meal	80	26	Germany
Soya bean meal	120	59	Brazil
Rolled wheat	200	93	Ireland
Confinement			
Rolled barley	290	90	Ireland
Beet pulp	190	4	Germany
Maize gluten	160	8	USA
Soya bean meal	325	59	Brazil
Palm kernel oil	25	17	Malaysia

[a]The economic allocation represents the percentage of emissions of the base product, for example, rapeseed allocated to the concentrate ingredient (e.g. rape meal).
[b]Citrus pulp substituted with beet pulp because of insufficient data.

of product show that GHG emissions were, on average, 8% lower for the Confinement system than the Grass system.

The LCA approach found that on-farm GHG emissions per on-farm ha were higher for the Confinement system than the Grass system (Tables 7 and 8). However, per total (on and off-farm area) ha, total GHG emissions were 11% greater for the Grass system than the Confinement system. Per on-farm ha, the IPCC results show that GHG emissions were lower for the Grass system than the Confinement system (Table 9).

GHG emissions components

LCA. Methane accounted for 51% of total GHG emissions (total of CO_2-eq on-farm and off-farm) in the Grass system and for 57% in the Confinement system, N_2O accounted for 36% in the Grass system and for 15% in the Confinement system and CO_2 accounted for 13% in the Grass system and for 27% in the Confinement system (Tables 7 and 8). The main contributors to total GHG emissions in the Grass system were CH_4 emissions from enteric fermentation (44%), N_2O emissions from excreta deposited during grazing (13%); GHG emissions associated with the production of fertiliser (10%), and N_2O emissions from synthetic fertiliser application (9%; Table 7). Enteric fermentation was the greatest contributor to on-farm GHG emissions (54%) in the

Table 6 *IPCC[a] emission factors for quantification of dairy farm GHG emissions*

Gas and source	Emission factor	Unit
CH_4		
Enteric fermentation		
Dairy cows and replacements[b] (conserved feed)	DEI × (0.096 + 0.035 × (S_{DMI}/T_{DMI})) − (2.298 × (FL − 1))	MJ/day per animal
Dairy cows and replacements (grass; >50% DMI)	0.065 × GEI	MJ/day per animal
Manure storage	Total manure OM stored × 0.24 × 0.67 × ((prop. in slurry type system × 0.39) + (prop. in solid manure[c] system × 0.01))	kg/year
Grazing returns[d]	Total manure OM excreted during grazing × 0.24 × 0.67 × 0.01	kg/year
N_2O-N		
Slurry storage	0.001 × (N stored)	kg/kg N
Solid manure storage	0.02 × (N stored)	kg/kg N
Manure application	0.0125 × (N in manure − NH_3 loss)	kg/kg N
Synthetic N fertiliser application	0.0125 × (N in fertiliser − NH_3 loss)	kg/kg N
Grazing returns	0.02 × (N in manure − NH_3 loss)	kg/kg N
NH_3 re-deposition	0.01 × (sum of NH_3 sources)	kg/kg NH_3-N
NO_3 leaching	0.025 × (N applied/ha × 0.1)	kg/kg NO_3-N

IPCC = Intergovernmental Panel on Climate Change; GHG = greenhouse gas; CH_4 = methane; DEI = digestible energy intake; S_{DMI} = silage DMI; T_{DMI} = total DMI; FL = feeding levels above maintenance energy; DMI = dry matter intake; GEI = gross energy intake; OM = organic matter; prop. = proportion; N_2O = nitrous oxide; N = nitrogen; NH_3 = ammonia; NO_2 = nitrate.
[a]IPCC emission factors as applied in Ireland for quantification of GHG emissions (Duffy *et al.*, 2011b).
[b]Replacements are dairy heifers aged 0 to 2 years.
[c]DM content >20%.
[d]Manure excreted during grazing.

Grass system followed by N_2O from excreta deposited during grazing (16%), N_2O from fertiliser application (11%) and CH_4 emissions from slurry storage (9%). Enteric CH_4 emissions per unit of intake for dairy cows in the Grass system were 23.1 g/kg DMI. Off-farm GHG emissions consisted mainly of GHG emissions from the production of fertiliser (57%) and concentrate feed (26%; Table 7).

The main contributors to total GHG emissions in the Confinement system were CH_4 emissions from enteric fermentation (36%), GHG emissions from the production of concentrate (25%) and CH_4 emissions from manure storage (20%; Table 8). On-farm GHG emissions in the Confinement system were mainly due to enteric CH_4 (57%), but CH_4 losses per unit of intake for dairy cows were 4% lower for the Confinement system (22.3 g/kg DMI) than the Grass system. Methane from manure storage was the next largest source of on-farm GHG emissions (31%). The production of concentrate feed was the main source of off-farm GHG emissions (69%) followed by CO_2 emissions from electricity, fuel and lime production (15%; Table 8). The main sources of GHG emissions from concentrate production were CO_2 emissions from the conversion of rainforest to agricultural land (35%), GHG emissions from energy and fertiliser production (17%), CO_2 emissions from agricultural field operations and transport of feed (15%) and N_2O emissions from fertiliser application (12%).

IPCC method. Methane accounted for 64% of GHG emissions (in CO_2-eq) in the Grass system and for 90% in the Confinement system, N_2O accounted for 36% in the Grass system and for 10% in the Confinement system (Table 9). The main sources of GHG emissions in the Grass system were CH_4 emissions from enteric fermentation (55%) and manure storage (9%), N_2O emissions from manure excreted by grazing cattle (16%), N_2O from synthetic fertiliser application (11%) and N_2O from NO_3^- leaching and NH_3 re-deposition (6%; Table 9). Methane from enteric fermentation (58%) and N_2O and CH_4 from manure storage (33%) were the main contributors to GHG emissions in the Confinement system (Table 9).

Scenario analysis

LCA. The predicted effects of selected farm-management changes and C sequestration on GHG emissions from the Grass and Confinement systems calculated using the LCA method are shown in Tables 7 and 8.

Improving forage quality reduced on-farm and total GHG emissions per unit of product and area by 4% to 5% for the Grass system (Table 7) and by 3% for the Confinement system (Table 8). The strategy reduced CH_4 emissions from enteric fermentation and manure storage, N_2O emissions from fertiliser use and manure excreted by grazing animals and off-farm emissions from concentrate and fertiliser production (Tables 7 and 8).

Increasing milk production through genetic improvement increased GHG emissions per livestock unit (LU; equivalent to one dairy cow) of both dairy systems (3%). However, the increase in milk production (6% to 8%) was greater than the increase in dairy systems' GHG emissions. Therefore, GHG emissions per unit of product decreased (3% to 4%).

Table 7 *Effect of selected farm-management changes and C sequestration on the annual GHG emissions of a seasonal grass-based dairy system (Grass) calculated using life cycle assessment with a GHG model (O'Brien* et al.*, 2011)*

Emission and source	Location	Grass system	Improved forage quality	Improved genetics[a]	N surplus[b]	Replacement rate[c]	Covered manure store[d]	Predicted combined mitigation[e]	Grassland carbon sink[f]
			+0.05 UFL/kg DM[g]	+500 kg milk/cow	−25 kg N/ha	15%			
CH_4 (kg CO_2-eq[h]/LU)									
Enteric fermentation	On-farm	2967.4	2843.3	3074.1	2967.4	2985.7	2967.4	2959.7	2967.4
Manure storage	On-farm	481.3	460.0	490.3	481.3	477.3	145.5	141.3	481.3
Fertiliser production	Off-farm	5.7	5.4	5.9	5.2	5.7	5.7	5.2	5.7
Concentrate production	Off-farm	9.6	9.6	9.6	9.6	9.4	9.6	9.4	9.6
Other inputs[i]	Off-farm	1.7	1.7	1.8	1.7	1.8	1.7	1.7	1.7
N_2O (kg CO_2-eq/LU)									
Fertiliser spreading	On-farm	591.8	565.5	616.8	533.9	596.9	591.8	535.8	591.8
Manure storage	On-farm	16.4	15.8	16.6	16.4	16.1	3.0	2.9	16.4
Manure spreading	On-farm	87.1	83.2	88.3	87.1	85.6	87.4	82.9	87.1
Grazing returns[j]	On-farm	871.7	826.7	902.2	871.7	878.0	871.7	860.6	871.7
NO_3 leaching	On-farm	246.3	234.6	255.4	234.6	247.8	246.4	232.8	246.3
NH_3 re-deposition	On-farm	88.5	84.4	90.2	87.9	87.5	88.5	84.3	88.5
Fertiliser production	Off-farm	409.4	391.2	426.7	369.4	412.9	409.4	370.7	409.4
Concentrate production	Off-farm	110.0	110.0	110.0	110.0	108.4	110.0	108.4	110.0
CO_2 (kg CO_2-eq/LU)									
Manure storage	On-farm	0.0	0.0	0.0	0.0	0.0	20.7	20.4	0.0
Fuel combustion	On-farm	126.4	121.4	130.5	126.4	127.7	126.4	126.6	126.4
Lime application	On-farm	51.7	49.4	53.9	51.7	52.2	51.7	51.9	51.7
Soil carbon	On-farm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−3605.5
Fertiliser production	Off-farm	295.9	282.7	308.1	269.3	298.3	295.9	269.7	295.9
Concentrate production	Off-farm	202.3	202.3	202.3	202.3	199.4	202.3	199.4	202.3
Other inputs	Off-farm	211.7	206.7	216.2	211.7	215.6	211.7	214.9	211.7
On-farm kg CO_2-eq/LU	On-farm	5529	5284	5718	5459	5555	5200	5099	1923
Total[k] kg CO_2-eq/LU	Total	6775	6494	6999	6638	6806	6447	6279	3169
Allocated to milk (%)	–	88	88	89	88	90	88	90	88
On-farm kg CO_2-eq/t FP	On-farm	12 178	11 575	11 715	12 024	12 149	11 455	10 318	4236
On-farm kg CO_2-eq/t FPCM[l]	On-farm	908	863	874	897	906	854	770	316
Total kg CO_2-eq/t FP	Total	14 924	14 224	14 339	14 621	14 886	14 200	12 704	6981
Total kg CO_2-eq/t FPCM	Total	1113	1061	1069	1091	1110	1059	948	521
On-farm kg CO_2-eq/on-farm ha	On-farm	14 056	13 435	13 960	13 878	13 737	13 222	12 927	4889
Total kg CO_2-eq/total ha	Total	15 292	14 658	15 237	14 982	14 943	14 551	14 159	7154

C sequestration = carbon sequestration; GHG = greenhouse gas; N = nitrogen; CH_4 = methane; N_2O = nitrous oxide; NO_3 = nitrate; NH_3 = ammonia; CO_2 = carbon dioxide; UFL = unit feed lactation; DM = dry matter; LU = livestock unit equivalent to one dairy cow; FP = Kg of milk fat plus protein; FPCM = fat and protein corrected milk.

[a]Milk production per cow of Grass system increased while maintaining fertility performance.

[b]N surplus per ha of Grass system reduced by 25 kg N/ha via reduction in synthetic N use.

[c]Replacement rate of Grass system reduced from 18% to 15%.

[d]Manure stores of Grass system covered and CH_4 flared.

[e]Predicted cumulative efficacy of selected farm-management changes.

[f]Permanent grassland C sequestration increased from 0 to 2.5 t C/ha per year.

[g]1 UFL is 7.11 MJ of net energy.

[h]CO_2-eq = CO_2 equivalent where CO_2 = 1; CH_4 = 25; NO_2 = 298.

[i]Production of fuel, electricity and lime.

[j]Manure excreted on pasture by grazing cattle.

[k]Total = on-farm GHG emissions or ha and off-farm GHG emissions or ha.

[l]FPCM = (0.337 + 0.116 × %fat + 0.06 × %protein) × kg milk (Thomassen and de Boer, 2005).

Table 8 *Effect of selected farm-management changes and C sequestration on the annual GHG emissions of a confinement dairy system (Confinement) calculated using life cycle assessment with a GHG model (O'Brien* et al.*, 2011)*

Emission and source	Location	Confinement system	Improved forage quality	Improved genetics[a]	N surplus[b]	Replacement rate[c]	Covered manure store[d]	Predicted combined mitigation[e]	Grassland carbon sink[f]
			+0.05 UFL/kg DM[g]	+500 kg milk/cow	−25 kg N/ha	15%			
CH_4 (kg CO_2-eq[h]/LU)									
Enteric fermentation	On-farm	3385.1	3286.9	3482.7	3385.1	3415.1	3385.1	3411.1	3385.1
Manure storage	On-farm	1843.4	1797.8	1906.4	1843.4	1878.5	474.6	487.5	1843.4
Fertiliser production	Off-farm	1.8	1.8	1.9	1.6	1.8	1.8	1.6	1.8
Concentrate production	Off-farm	90.0	87.8	93.2	90.0	92.0	90.0	92.8	90.0
Purchased fodder	Off-farm	2.9	2.8	3.0	2.9	3.0	2.9	3.0	2.9
Other inputs[i]	Off-farm	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
N_2O (kg CO_2-eq/LU)									
Fertiliser spreading	On-farm	120.6	117.8	124.4	92.1	121.3	120.6	93.4	120.6
Manure storage	On-farm	54.5	52.9	55.8	54.5	55.3	2.9	2.8	54.5
Manure spreading	On-farm	147.9	143.2	151.7	147.9	150.4	148.5	149.7	147.9
Grazing returns[j]	On-farm	96.6	96.6	96.6	96.6	81.2	96.6	81.2	96.6
NO_3 leaching	On-farm	66.1	64.6	67.6	60.3	64.8	66.2	59.0	66.1
NH_3 re-deposition	On-farm	115.0	111.4	117.9	114.7	116.6	115.0	115.3	115.0
Fertiliser production	Off-farm	83.6	81.6	86.2	63.9	84.0	83.6	64.8	83.6
Concentrate production	Off-farm	535.5	522.1	554.1	535.5	547.3	535.5	552.2	535.5
Purchased fodder	Off-farm	220.8	214.2	227.0	220.8	225.0	221.1	224.8	220.8
CO_2 (kg CO_2-eq/LU)									
Manure storage	On-farm	0.0	0.0	0.0	0.0	0.0	94.8	97.7	0.0
Fuel combustion	On-farm	93.4	91.7	95.8	93.4	94.0	93.4	94.6	93.4
Lime application	On-farm	25.9	25.4	26.6	25.9	25.5	25.9	25.7	25.9
Soil carbon	On-farm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1804.6
Fertiliser production	Off-farm	72.1	70.5	74.4	59.0	72.4	72.1	59.7	72.1
Concentrate production	Off-farm	1713.3	1670.3	1772.9	1713.3	1751.1	1713.3	1766.6	1713.3
Purchased fodder	Off-farm	156.3	152.3	161.9	156.3	160.5	156.3	161.9	156.3
Other inputs	Off-farm	495.8	494.6	497.4	495.8	508.1	495.8	508.6	495.8
On-farm kg CO_2-eq/LU	On-farm	5949	5788	6126	5914	6003	4624	4618	4144
Total[k] kg CO_2-eq/LU	Total	9322	9087	9599	9255	9449	7998	8055	7517
Allocated to milk (%)	–	90	90	90	90	92	90	92	90
On-farm kg CO_2-eq/t FP	On-farm	11 128	10 800	10 803	11 064	11 115	8650	8040	7752
On-farm kg CO_2-eq/t FPCM[l]	On-farm	820	796	796	816	819	638	593	571
Total kg CO_2-eq/t FP	Total	17 440	16 956	16 929	17 313	17 497	14 962	14 024	14 064
Total kg CO_2-eq/t FPCM	Total	1285	1250	1248	1276	1290	1103	1034	1037
On-farm kg CO_2-eq/on-farm ha	On-farm	30 216	29 401	30 268	30 040	29 657	23 486	23 612	21 049
Total kg CO_2-eq/total ha	Total	13 774	13 427	13 730	13 674	13 580	11 816	11 658	11 107

C sequestration = carbon sequestration; GHG = greenhouse gas; N = nitrogen; CH_4 = methane; N_2O = nitrous oxide; NO_3 = nitrate; NH_3 = ammonia; CO_2 = carbon dioxide; UFL = unit feed lactation; DM = dry matter; LU = livestock unit equivalent to one dairy cow; FP = Kg of milk fat plus protein; FPCM = fat and protein corrected milk.

[a]Milk production per cow of Confinement system increased while maintaining fertility performance.

[b]N surplus per ha of Confinement system reduced by 25 kg N/ha via reduction in synthetic N use.

[c]Replacement rate of Confinement system reduced from 18% to 15%.

[d]Manure stores of Confinement system covered and CH_4 flared.

[e]Predicted cumulative efficacy of selected farm-management changes.

[f]Permanent grassland C sequestration increased from 0 to 2.5 t C/ha per year.

[g]1 UFL is 7.11 MJ of net energy.

[h]CO_2-eq = CO_2 equivalent where $CO_2 = 1$; $CH_4 = 25$; $NO_2 = 298$.

[i]Production of fuel, electricity and lime.

[j]Manure excreted on pasture by grazing cattle.

[k]Total = on-farm GHG emissions or ha and off-farm GHG emissions or ha.

[l]FPCM = (0.337 + 0.116 × %fat + 0.06 × %protein) × kg milk (Thomassen and de Boer, 2005).

Increasing milk production had little effect (<0.7%) on GHG emissions per unit area, because the on- and off-farm area of both dairy systems increased (3% to 4%) to supply the extra feed required for the increased milk production.

Reducing the farm N surplus reduced the on-farm and total GHG emissions per unit of product and area for both systems (1% to 2%; Tables 7 and 8). The strategy reduced N_2O emissions from on-farm fertiliser use, N_2O from NO_3^- leaching and NH_3 re-deposition and off-farm emissions from fertiliser production.

For both dairy systems, the LCA method found that reducing the replacement rate increased GHG emissions per LU (Tables 7 and 8), because the ratio of dairy cows to replacement animals increased. However, GHG emissions per unit area decreased (1% to 2%), because the number of replacement animals and the stocking rate declined. Reducing the replacement rate had little effect on GHG emissions per unit of product (Tables 7 and 8), because reducing the replacement rate decreased GHG emissions per unit area but increased the percentage of GHG emissions allocated to milk rather than to beef (Tables 7 and 8).

Covering the manure store and flaring CH_4 reduced on-farm and total GHG emissions per unit of product and area from the Grass system by 6% and 5%, respectively (Table 7). On-farm and total GHG emissions per unit of product and area decreased by 22% and 14%, respectively, when CH_4 from manure storage was flared in the Confinement system (Table 8). The management change eliminated N_2O emissions from slurry storage and significantly reduced CH_4 emissions from slurry storage.

Combining farm-management changes reduced on-farm GHG emissions per unit of product by 15% for the Grass system and by 28% for the Confinement system (Tables 7 and 8). Per on-farm ha, combining management changes reduced on-farm GHG emissions by 8% for the Grass system and by 22% for the Confinement system. When off-farm emissions were included, combining management changes reduced total GHG emissions per unit of product by 15% for the Grass system and 20% for the Confinement system. Per total ha, combining management changes reduced total GHG emissions by 7% for the Grass system and by 15% for the Confinement system (Tables 7 and 8).

Assuming that the grassland area of both dairy systems was newly established (<2 years) and had previously been used for growing arable crops reduced on-farm GHG emissions per unit of product and area by 30% for the Confinement system and by 65% for the Grass system. Similarly, the assumption reduced total GHG emissions per unit of product and area by 19% for the Confinement system and by 53% for the Grass system. The reductions were caused by grassland C sequestration (Tables 7 and 8).

IPCC method. The predicted effect of selected farm-management changes on GHG emissions from the Grass and Confinement systems calculated using the IPCC method are shown in Table 9. The IPCC method results show that in the Grass and Confinement systems' GHG emissions per unit of product and area were reduced by improving forage quality (3% to 5%), reducing the farm N surplus (1%) and capturing CH_4 from manure stores (6% to 24%). Increasing milk production per cow reduced baseline dairy systems' GHG emissions per unit of product (3% to 4%), but had a minor effect on GHG emissions per unit area (<0.7%). Reducing the replacement rate decreased baseline dairy systems' GHG emissions per unit area (2%), because the stocking rate declined. However, the strategy had little effect on GHG emissions per unit of product, because reducing the replacement rate increased the proportion of GHG emissions allocated to milk compared with beef (Table 9). The IPCC approach found that combining management changes reduced GHG emissions per unit of product by 16% for the Grass system and by 30% for the Confinement system (Table 9). Per unit area, combining management changes reduced GHG emissions by 9% for the Grass system and by 24% for the Confinement system (Table 9).

Discussion

Studies that have compared GHG emissions from seasonal calving grass-based and confinement dairy systems generally have used environmental system analysis approaches such as LCA (Arsenault *et al.*, 2009; Rotz *et al.*, 2009). The IPCC method of quantifying agricultural GHG emissions has rarely been used to assess emissions from these different systems of dairy production (Schils *et al.*, 2006; Browne *et al.*, 2011). Thus, the application of the LCA and IPCC methods in this study provides a unique opportunity to determine if these methods agree on their predictions of GHG emissions from seasonal grass-based and confinement dairy systems. However, given that our comparison of dairy systems is based on a single farm for each system, it cannot be considered to be a representative comparison of grass and confinement systems of dairy production.

Methodology comparison of grass-based and confinement dairy systems' GHG emissions: IPCC v. LCA

Effect of dairy systems on GHG emissions. Consistent with previous international studies, the LCA and IPCC methods agreed that CH_4 from enteric fermentation was the main cause of on-farm GHG emissions for seasonal grass-based and confinement dairy systems (Schils *et al.*, 2005 and 2006; Rotz *et al.*, 2009; O'Brien *et al.*, 2011). Both methods also agreed with the previous studies that the other main sources of on-farm GHG emissions for the grass-based system were N_2O emissions from manure excreted by grazing cattle and N_2O emissions from fertiliser application (Schils *et al.*, 2006; Basset-Mens *et al.*, 2009). Similarly, the IPCC and LCA methods supported previous analysis that on-farm GHG emissions in the confinement system were emitted mainly from manure storage when enteric CH_4 emissions were excluded (Arsenault *et al.*, 2009; Rotz *et al.*, 2010). Thus, apart from enteric CH_4 emissions, the main sources of on-farm GHG emissions differed between dairy systems. The contribution of on-farm sources to GHG emissions varied

Table 9 *Effect of selected farm-management changes and C sequestration on the annual GHG emissions of a seasonal grass-based dairy system (Grass) and a confinement dairy system (Confinement) calculated using the Intergovernmental Panel on Climate Change method with a GHG model (O'Brien* et al.*, 2011)*

Dairy system	Emission and source	Baseline system	Improved forage quality +0.05 UFL/kg DM[f]	Improved genetics[a] +500 kg milk/cow	N surplus[b] −25 kg N/ha	Replacement rate[c] 15%	Covered manure store[d]	Predicted combined mitigation[e]
Grass	CH_4 (kg CO_2-eq[g]/LU)							
	Enteric fermentation	2967.4	2843.3	3074.1	2967.4	2985.7	2967.4	2959.7
	Manure storage	481.3	460.0	490.3	481.3	477.3	145.5	141.3
	N_2O (kg CO_2-eq/LU)							
	Manure storage	16.4	15.8	16.6	16.4	16.1	3.0	2.9
	Fertiliser spreading	591.8	565.5	616.8	533.9	596.9	591.8	535.8
	Manure spreading	87.1	83.2	88.3	87.1	85.6	87.4	82.9
	Grazing returns[h]	871.7	826.7	902.2	871.7	878.0	871.7	860.6
	NH_3 leaching	246.3	234.6	255.4	234.6	247.8	246.4	232.8
	NH_3 re-deposition	88.5	84.4	90.2	87.9	87.5	88.5	84.3
	kg CO_2-eq/LU	5351	5114	5534	5280	5375	5002	4900
	Allocated to milk (%)	88	88	89	88	90	88	90
	kg CO_2-eq/t FP[i]	11 786	11 201	11 337	11 631	11 755	11 017	9915
	kg CO_2-eq/t FPCM[j]	879	835	846	868	877	822	740
	kg CO_2-eq/on-farm ha	13 603	13 001	13 510	13 425	13 292	12 716	12 423
Confinement	CH_4 (kg CO_2-eq/LU)							
	Enteric fermentation	3385.1	3286.9	3482.7	3385.1	3415.1	3385.1	3411.1
	Manure storage	1843.4	1797.8	1906.4	1843.4	1878.5	474.6	487.5
	N_2O (kg CO_2-eq/LU)							
	Manure storage	54.5	52.9	55.8	54.5	55.3	2.9	2.8
	Fertiliser spreading	120.6	117.8	124.4	92.1	121.3	120.6	93.4
	Manure spreading	147.9	143.2	151.7	147.9	150.4	148.5	149.7
	Grazing returns[i]	96.6	96.6	96.6	96.6	81.2	96.6	81.2
	NO_3 leaching	66.1	64.6	67.6	60.3	64.8	66.2	59.0
	NH_3 re-deposition	115.0	111.4	117.9	114.7	116.6	115.0	115.3
	kg CO_2-eq/LU	5829	5671	6003	5795	5883	4410	4400
	Allocated to milk (%)	90	90	90	90	92	90	92
	kg CO_2-eq/t FP	10 905	10 582	10 587	10 841	10 894	8249	7660
	kg CO_2-eq/t FPCM	804	780	780	799	803	608	565
	kg CO_2-eq/on-farm ha	29 610	28 806	29 664	29 435	29 066	22 399	22 497

C sequestration = carbon sequestration; GHG = greenhouse gas; N = nitrogen; CH_4 = methane; CO_2 = carbon dioxide; N_2O = nitrous oxide; NO_3 = nitrate; NH_3 = ammonia; UFL = unit feed lactation; DM = dry matter; LU = livestock unit equivalent to one dairy cow; FP = Kg of milk fat plus protein; FPCM = fat and protein corrected milk.

[a]Milk production per cow of baseline farms increased while maintaining fertility performance.

[b]N surplus per ha of baseline farms reduced by 25 kg N/ha via reduction in synthetic N use.

[c]Replacement rate of baseline farms reduced from 18% to 15%.

[d]Manure stores of baseline farms covered and CH_4 flared.

[e]Predicted cumulative efficacy of selected farm-management changes.

[f]1 UFL is 7.11 MJ of net energy.

[g]CO_2-eq = CO_2 equivalent where CO_2 = 1; CH_4 = 25; NO_2 = 298.

[h]Manure excreted on pasture by grazing cattle.

[ij]FPCM = (0.337 + 0.116 × %fat + 0.06 × %protein) × kg milk (Thomassen and de Boer, 2005).

between systems, because of differences in the housing period of dairy cows and the proportion of feed produced on-farm. Therefore, system specific strategies should be developed to achieve the largest reduction in on-farm GHG emissions from grass-based and confinement dairy systems.

Several studies have reported that feed intake is the principal determinant of enteric CH_4 emissions from cattle (Mills *et al.*, 2003; Hegarty *et al.*, 2007; O'Neill *et al.*, 2011). In addition, feed intake is also a key variable required to quantify CH_4 and N_2O emissions from manure (Basset-Mens *et al.*, 2009). Therefore, both methods showed, similar to previous results, that on-farm GHG emissions per LU was greater (8% to 9%) for the confinement system than the grass-based system, because grass-fed cows produced 18% less milk per LU and thus consumed 16% less feed (Capper *et al.*, 2009; Rotz *et al.*, 2009). Feed intake per unit area, which is predominately controlled by the stocking rate of the dairy system, is also a major determinant of GHG emissions per unit area. Thus, decreasing the on-farm stocking rate generally reduces GHG emissions per on-farm ha (Casey and Holden, 2005).

Our results, irrespective of method, supported this relationship and showed that the dairy system with the higher on-farm stocking rate, the confinement system (5 LU/on-farm ha), emitted twice as much GHG emissions per on-farm ha than the lower stocked grass-based system (2.5 LU/on-farm ha). However, per unit of product, both methods observed that on-farm GHG emissions were greater for the grass-based system than for the confinement system. This was because TMR-fed Holstein–Friesian cows in the confinement system produced ~2.4 times more milk per on-farm ha and 21% more milk per LU than forage-fed cows (Kolver and Muller, 1998; Bargo *et al.*, 2002). In addition, TMR-fed cows emitted less enteric CH_4 as a proportion of total DMI (Johnson and Johnson, 1995; Bell *et al.*, 2010).

The LCA method also quantifies off-farm GHG emissions related to dairy systems. Similar to previous dairy LCA studies, CO_2 and N_2O emissions from the cultivation and transport of imported feed and GHG emissions from the manufacture of synthetic N fertiliser were the main contributors to off-farm GHG emissions (Thomassen *et al.*, 2008b; Van der Werf *et al.*, 2009). Off-farm GHG emissions from the grass-based system were less than half of those from the confinement system, because the confinement system consumed more imported feedstuffs than the grass-based system. As a result of the large difference between dairy systems' off-farm GHG emissions, the LCA approach found that the increase in milk yield per LU moving from the grass-based system to the confinement system (21%) was less than the increase in total GHG emission per LU (38%).

Thus, similar to previous studies, total GHG emissions per unit of product and LU were higher for the confinement system than the grass-based system (Rotz *et al.*, 2009; Flysjö *et al.*, 2011). However, per total (on-farm and off-farm) ha, total GHG emissions were lower for the confinement system than the grass-based system, because the stocking rate per total ha of the confinement system was lower than the grass-based system. The stocking rate per total ha of the confinement system was lower than the grass system due to the large area required for the off-farm production of key components of TMR such as soya bean meal (3.2 m^2/kg DM). Therefore, this finding also supports the results of Casey and Holden (2005) that reducing stocking rate decreases GHG emissions per ha.

Effect of boundary on dairy systems' GHG emissions. The IPCC method, unlike the LCA approach, does not attribute GHG emissions from the production of farm imports to primary dairy production, because these emissions are outside national boundaries or ascribed to another sector, such as energy (Schils *et al.*, 2005). Furthermore, the approach does not attribute the off-farm area required to produce farm imports to dairy systems. Omitting off-farm GHG sources and the off-farm area associated with dairy production would not matter if farming systems always ranked the same whether the IPCC or LCA methods were used. For example, our results show that excluding off-farm GHG sources had no effect on the ranking of dairy systems' GHG emissions per LU. However, when GHG emissions were expressed per unit of product, the IPCC method indicated that the grass system had higher emissions, but the LCA approach showed that the grass system had lower emissions. The different ranking of dairy systems' GHG emissions per unit of product using the IPCC and LCA method agrees with previous work and can be explained by the exclusion of emissions associated with upstream production chains (e.g. concentrate production) using the IPCC method (O'Brien *et al.*, 2011).

Per unit area, the exclusion of off-farm area required for farm imports also affected the rankings of dairy systems' GHG emissions. The IPCC method showed that per on-farm ha the grass-based system emitted lower GHG emissions, because the stocking rate was 50% lower than the confinement system. However, per total ha, the stocking rate of the confinement system was lower than the grass-based system, because the confinement system was more reliant on imported feed and thus required a greater off-farm area (Table 1). Consequently, the LCA method found that dairy systems had the opposite effect on GHG emissions per total ha. Therefore, the methods disagreed, because including the off-farm area required for farm imports affected the stocking rate of dairy systems, which is a key driver of GHG emissions per unit area (Casey and Holden, 2005).

The disagreement between the IPCC and LCA methods per unit of product and area highlights that it is incorrect to only consider on-farm components of the dairy system relevant for policy reporting (Schils *et al.*, 2006; O'Brien *et al.*, 2010 and 2011). Instead, holistic approaches such as LCA give a more realistic assessment of GHG emissions from differing dairy production systems. Holistic approaches increase emissions attributed to dairy systems relative to approaches that consider only part of the production system, but are more likely to ensure that GHG emissions are reduced and not transferred to another location (e.g. 'carbon leakage') or part of the production system. The inadequacy of the IPCC method for assessing GHG emissions from different dairy systems does not mean the approach should no longer be used to report national GHG emissions (Schils *et al.*, 2006; Crosson *et al.*, 2011). However, to achieve a reduction in GHG emissions, reform of the IPCC method is needed given the problems identified in our study and previous studies (Andrew and Forgie, 2008; Peters, 2008; Peters and Hertwich, 2008).

Consequently, it has been suggested that countries should quantify GHG emissions associated with national consumption (production and imports minus exports) in addition to estimating GHG emissions produced within a nation (Peters, 2008; Peters and Hertwich, 2008). This approach would overcome some of the problems with the present IPCC method, such as carbon leakage and credit dairy practices that reduce emissions in other sectors or nations. However, consumption-based national GHG accounting would require political decisions to extend outside national boundaries, which is a significant barrier to the implementation of the approach (Peters, 2008). Furthermore, consumption-based national GHG inventories require more complex calculations and hence assumptions, thereby increasing uncertainty and reducing the accuracy of GHG national inventories (Peters, 2008).

Effect of unit of expression on GHG emissions. The IPCC and LCA methods use different approaches to report GHG emissions. The IPCC guidelines report annual GHG emissions per nation state (Crosson *et al.*, 2011). Thus, dairy farm GHG emissions are frequently assessed in isolation from dairy production for instance, per unit area or per LU (Casey and Holden, 2005; Capper *et al.*, 2009). In contrast, the LCA approach is typically applied to quantify GHG emissions per unit of product for dairy production systems, for example, Arsenault *et al.* (2009) and Flysjö *et al.* (2011). Previous studies have shown that expressing GHG emissions per unit area, per LU or per unit of product can change the ranking of dairy systems' GHG emissions (Casey and Holden, 2005; Capper *et al.*, 2009; O'Brien *et al.*, 2011). Our results agreed with these findings; for instance, the IPCC approach found that the confinement system had lower emissions per unit of product and higher emissions per on-farm ha and per LU than the grass-based system. Similarly, the LCA method showed that the confinement system emitted lower total emissions per total ha than the grass-based system, but per unit of product the dairy systems had the opposite effect.

Thus, these findings show that reducing emissions on a livestock or area basis will not lead to the highest reduction in GHG emissions possible for a given level of product. The FAO (2006) predict that between 2000 and 2050 demand for dairy products will double due to a growing affluent human population. Therefore, if dairy production is to decrease emissions and supply sufficient milk to satisfy future demand, GHG emissions should be quantified per unit of product (Capper *et al.*, 2009; del Prado *et al.*, 2010). Expressing GHG emissions on a product basis would incentivise producers to adopt practices to increase the efficiency of production, which reduces GHG emissions for a given level of production (Beukes *et al.*, 2010). Furthermore, it would encourage the production of milk production within specific regions where it can be produced with the least impact on GHG emissions. In contrast, mitigation strategies that reduce emissions per LU or per unit area may not reduce emissions per unit of product, because assessing emissions on a livestock or area basis does not assess the effect mitigation strategies can have on milk production.

Effect of selected farm-management changes on dairy systems' GHG emissions

The IPCC and LCA methods were also used in this study to determine, via scenario analysis, if farm-management changes could be introduced to reduce GHG emissions from grass-based and confinement dairy systems. The results indicated, similar to previous studies, that single management changes to improve animal performance, increase N-use efficiency or improve forage quality can reduce GHG emissions by improving productive efficiency (Schils *et al.*, 2005; Lovett *et al.*, 2008; Beukes *et al.*, 2010). Similarly, our findings agreed with previous studies that individual strategies to control emissions from manure storage, in particular flaring CH_4 emissions, substantially reduce on-farm (22% to 24%) and total (14%) GHG emissions from confinement systems (Weiske *et al.*, 2006; Rotz *et al.*, 2010). However, for grass-based dairy producers, the results of this study suggest that reducing emissions from manure storage does not have a large effect on GHG emissions (5% to 7%), because most manure is voided during grazing. As expected, the ability of strategies to reduce GHG emissions was affected by changes in off-farm GHG emissions. However, the effect of management changes on off-farm emissions could only be considered when using the LCA approach. Thus, our study demonstrated, similar to Schils *et al.* (2005) that the IPCC method is not suitable for analysis of mitigation strategies, because it does not assess the effect that farm-management changes have on off-farm GHG emissions.

Although individual management changes generally had a small effect on GHG emissions ($<5\%$), when several management strategies were combined the on-farm (15% to 30%) and total (15% to 20%) GHG emission intensity of dairy systems was reduced significantly. Thus, these results suggest that dairy producers can play a major role in addressing climate change if the benefits associated with the mitigation strategy can be credited to the producer. However, GHG mitigation strategies will be successfully adopted by farmers only if they are also shown to be profitable. Assessing the cost-effectiveness of farm-management changes was outside the scope of this study, but previous reports indicate that most management changes tested in this study increase the profitability of dairy production (Lovett *et al.*, 2008; Beukes *et al.*, 2010). Indeed, the only strategy evaluated in this study that previous reports indicate is not economically viable was the flaring of CH_4 from manure storage (Weiske *et al.*, 2006). However, considering the rapid increase in energy prices in recent years and potential market subsidies, capturing and flaring CH_4 from manure stores for electricity generation or heating may prove to be a viable option in the future.

The analysis of the effect of management changes on dairy systems' GHG emissions also revealed that the procedure used to allocate emissions between co-products can influence LCA results. For instance, the results of this study demonstrate that when all GHG emissions were attributed to milk, reducing the annual cow replacement rate reduces emissions from non-milk producing animals and therefore GHG emissions per unit of product. This finding is consistent with previous studies that used this allocation technique (Beukes *et al.*, 2010; Vellinga *et al.*, 2011). However, when emissions were allocated between milk and meat based on the physiological feed requirements of the animal to produce these products, the management strategy had no effect. The strategy of reducing replacement rate had no effect using the allocation technique used in this study, because the proportion of emissions allocated to milk increased, which offset the reduction in GHG emissions from non-milk producing animals. The large influence that different allocation procedures have on LCA results supports the most recent international standards recommendation that LCA studies should avoid allocation by expanding the boundaries of the production system to include the avoided product (e.g. meat; ISO, 2006a). This approach increases the complexity of LCA studies and requires more data but overcomes the allocation problem identified in this and previous studies (Cederberg and Stadig, 2003; Thomassen *et al.*, 2008a).

Carbon Sequestration

Another important issue in the evaluation of GHG emissions from dairy systems is C sequestration by grassland soils. However, studies often do not consider or mention C sequestration (e.g. Casey and Holden, 2005). Studies that have considered C sequestration by grassland soils have reported that the process makes a substantial (37% to 77%), albeit short-lived contribution (20 to 50 years) to reducing GHG emissions from dairy systems (Schils *et al.*, 2005; Rotz *et al.*, 2009). Our scenario analysis findings for the LCA method agree that C sequestration following the conversion of arable land to grassland can substantially reduce GHG emissions, but the results of the IPCC approach did not support these findings. This was because the IPCC method does not report C sequestration by grassland soils in the agricultural sector (Schils *et al.*, 2005). Thus, until the IPCC method is reformed, farm-management practices that improve C sequestration will not reduce reported GHG emissions from the agricultural sector.

Conclusion

The results of the IPCC and LCA methods show that reducing dairy systems' GHG emissions on a per unit area basis is not necessarily the most effective approach to reduce GHG emissions for a given level of product. Therefore, given the growing demand for dairy products, mitigation efforts should focus on reducing GHG emissions per unit of product. The IPCC and LCA methods did not rank grass-based and confinement dairy systems' emissions per unit of product in the same order, because the IPCC method excludes GHG emissions from farm supply chains (e.g. concentrate production). Thus, a complete assessment of GHG emissions per unit of product for differing dairy systems can be made only using holistic approaches such as LCA. Scenario analysis showed that GHG emissions per unit of product of both dairy systems could be reduced significantly when several farm-management practice changes were combined. In addition, the analysis showed that the LCA method should be used to assess changes in GHG emissions per unit of product. However, further standardisation of the LCA methodology is needed given the sensitivity of the approach to milk and meat allocation decisions.

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