The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms

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ABSTRACT

The purpose of this study was to model the effect of 3 divergent strains of Holstein-Friesian cows in 3 pasture-based feed systems on greenhouse gas (GHG) emissions. The 3 strains of Holstein-Friesian compared were high-production North American (HP), high-durability North American (HD), and New Zealand (NZ). The 3 feed systems were a high grass allowance system (MP, control); high stocking rate system (HS); and high concentrate supplementation system (HC). The MP system had an overall stocking rate of 2.47 cows/ha and received 325 kg of dry matter concentrate per cow in early lactation. The HS system had a similar concentrate input to the MP system, but had an overall stocking rate of 2.74 cows/ha. The HC system had a similar overall stocking rate to the MP system, but 1,445 kg of dry matter concentrate was offered per cow. A newly developed integrated economic-GHG farm model was used to evaluate the 9 milk production systems. The GHG model estimates on-farm (emissions arising within the farm's physical boundaries) and production system (incorporating all emissions associated with the production system up to the point milk leaves the farm gate) GHG emissions. Production system GHG emissions were always greater than on-farm emissions, and the ranking of the 9 systems was usually consistent under both methods. The exception was the NZ strain that achieved their lowest GHG emission per unit of product in the HC system when indirect emissions were excluded, but their lowest emission was in the HS system when indirect emissions were included. Generally, the results showed that as cow strain changed from lower (HD and NZ) to higher genetic potential (HP) for milk production, the GHG emission per kilogram of milk solids increased. This was because of a decline in cow fertility in the HP strain that resulted in a higher number of nonproductive animals, leading to a lower total farm milk solids production and an increase in

emissions from nonproductive animals. The GHG emission per hectare increased for all strains moving from MP to HS to HC feed systems and this was associated with increases in herd total feed intake. The most profitable combination was the NZ strain in the HS system and this combination resulted in a 12% reduction in production system GHG emission per hectare compared with the NZ strain in the HC system, which produced the highest emissions. This demonstrates that grass-based systems can achieve high profitability and decreased GHG emissions simultaneously.

Key words: Holstein-Friesian strain, pastoral-based system, greenhouse gas, profitability

INTRODUCTION

In February 2005, the accession of Russia meant that the Kyoto protocol was no longer a statement of intent but a legally binding document to reduce greenhouse gas (GHG) emissions (Buchner and Carraro, 2006). Ireland ratified the treaty as a member state of the European Union and, by European law, cannot allow national emissions to increase by more than 13% above 1990 levels between 2008 and 2012; otherwise, there will be financial penalties. Currently, Ireland is unlikely to meet this limit. Ireland's agricultural sector is one of the largest sources contributing 26% of GHG emissions nationally (Ireland EPA, 2009). Within this sector, pastoral dairy farming is estimated to be the source of 38% of emissions (Lovett et al., 2008). Therefore, to meet the targets of the Kyoto Protocol and the future target of the European Union to reduce 2020 GHG emissions by 20% below 1990 levels (Whalley and Walsh, 2009), there will be pressure to decrease emissions from all aspects of agriculture.

The main GHG emitted from pastoral dairy farms are methane (CH₄) from enteric fermentation and manure management, nitrous oxide (N₂O) from soils and manures, and carbon dioxide (CO₂) from energy use and carbon loss from soil. Based on previous studies of European grassland systems (Olesen et al., 2006; Lovett et al., 2008), the carbon balance of soils was assumed to be in equilibrium. Thus, CO₂ emissions were

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limited to energy use. Many strategies have been suggested to reduce emissions from pastoral dairy farms including supplementation of livestock diets with oil or fat (Jordan et al., 2006), improved grassland and nitrogen fertilizer management (Velthof et al., 1998), and anaerobic digestion of stored manure (Amon et al., 2006). However, the reliance of pastoral dairy production systems on grazed grass as the main source of feed provides little opportunity to introduce many of the proposed mitigation strategies; that is, reducing emissions by manipulating the diet of livestock or by controlling emissions from farm waste treatment facilities. In addition to difficulties of introducing mitigation strategies to dairy production systems, the uncertainty in estimating GHG emissions, particularly N_2O , is large, which makes it difficult to identify and implement mitigation strategies for agriculture (Velthof et al., 1998).

It is also desirable that mitigation strategies are not detrimental to farm profitability and that they can be readily implemented to obtain widespread adoption. Within the context of grass-based systems of milk production, the key variables affecting output and profitability are the type of cow, stocking rate, and the quantity of purchased feed supplements. Farm system modeling can be a useful tool to quantify the effects of these variables on GHG emissions and to combine them with the economic effect of management decisions. When individual GHG mitigation strategies are assessed in isolation, their implementation may affect GHG emissions elsewhere within the farming system, thereby altering the overall net benefit of the mitigation strategy. A modeling approach is the only useful method of capturing all of the sinks and sources of GHG from milk production systems.

The objective of this study was to describe a whole-farm model and use it to investigate the effect of cow genotype (strain of Holstein-Friesian) and feed system (variation in stocking rate and level of concentrate fed) on GHG emissions and profitability. The input data were sourced from a 5-yr study carried out at Teagasc Dairy Research Centre in Ireland that examined the effect of strain of Holstein-Friesian and feed system (Horan et al., 2005; McCarthy et al., 2007). The novel aspect of this study was the estimation of GHG emissions from different cow genotypes in various grass-based feed systems.

MATERIALS AND METHODS

Defining the Dairy Production System

Most dairy production systems in Ireland are based on spring-calving cows and grazed grass (Dillon et al.,

1995). The objective of the dairy system is to transform resources (i.e., grass and external inputs) into commodities such as milk and meat (Powell et al., 2008). A conceptual model of a typical spring-calving, grass-based dairy production system and associated GHG emissions is illustrated in Figure 1. This flowchart is divided into 2 distinct sections: “upstream” and “dairy farm.” The upstream section represents the main external inputs required to maintain the productivity of the modern spring-calving milk production system. The dairy farm section displays the key components within the physical boundaries of a spring-calving, grass-based production system: 1) soil, 2) feed, 3) ruminant animals (cows, heifers, and calves), and 4) manure, and their interactions.

Within the dairy farm section (Figure 1), 2 subsystems exist: grazing feed period (a) and housing feed period (b). In the grazing feed subsystem, livestock graze the crop (grass) in situ and return feces and urine directly to the soil. The grazing feed subsystem is a unique feature of ruminant livestock systems (Schils et al., 2007) and is the prominent component of grass-based milk production systems. The critical role of the grazing component arises because grazed grass, when properly managed, is the cheapest source of high quality feed (O’Kiely, 1994; Peyraud and Delaby, 2001; Shalloo et al., 2004). Thus, dairy farmers aim to maximize the utilization of grazed grass in the diets of dairy cows to optimize profitability. In Ireland, grass fails to meet the nutritional requirements of dairy cows for part of the year, generally from late November to late February, because of poor grass growth and wet soil conditions. As a result, a second feed subsystem, the housing feed subsystem, is used. Within the housing feed subsystem, cattle are kept indoors and primarily consume conserved grass silage. The manure produced by cattle within the housing feed subsystem and other waste is stored and mechanically returned to soil when field conditions are appropriate in the spring and early summer.

The GHG emissions from each section are shown in Figure 1. Greenhouse gas emissions from the dairy farming system can be distinguished between those arising within the dairy farm’s physical boundaries (on-farm GHG emissions) and those arising upstream of the dairy farm section (indirect GHG emissions). The main sources of on-farm GHG emissions are managed soils, enteric fermentation, manure management, and energy use. Managed soils are a major source of N_2O . Nitrous oxide is predominantly emitted from soils following the application of nitrogen fertilizers (Bouwman, 1996). Energy is required to apply nitrogen fertilizer to soils. Consequently, CO_2 is indirectly emitted. Additional energy and nitrogen fertilizer are required to conserve grass as silage, which is needed for the housing feed

Figure 1. A flowchart of a pastoral dairy farming system and associated greenhouse gas emissions, nitrous oxide (N₂O), carbon dioxide (CO₂), and methane (CH₄); (a) and (b) represent the grazing and housing feed subsystems, respectively. In the grazing feed subsystem, ruminants graze grass and return manure directly to soil. In the housing feed subsystem, ruminants are kept indoors and primarily fed grass silage.

period. The production and harvesting of grass silage releases further N₂O from soil and CO₂ emissions from energy use.

Enteric fermentation is the digestive process of ruminants. During this process, feed is broken down by microorganisms into simple molecules for absorption into the bloodstream, and CH₄ is produced as a by-product

(Koch et al., 2000). Methane is then emitted by the ruminant predominantly via eructation. The production rate of CH₄ from enteric fermentation largely depends on feed intake and digestibility.

The type of feed system used determines the GHG emissions from manure management. In the grazing feed subsystem, N₂O is the chief GHG emitted from

manure with the primary source being urine deposition. This is due to rapid hydrolysis of urea in urine (de Klein and Eckard, 2008). Methane is also released from manure when animals are grazing, but the emissions are low because conditions are usually unsuitable for methanogenesis (IPCC, 2006). In the housing feed subsystem, CH₄ is the principal GHG released. During the housing feed period, manure is stored under anaerobic conditions, which allows methanogenic bacteria to decompose organic components of ruminant manure and release CH₄ (Husted, 1994; Sneath et al., 2006). In some circumstances, oxygen may be present within manure storage facilities. As a result, small quantities of N₂O are emitted. Further emissions of CH₄ and N₂O occur from the housing feed system, when stored manure is removed and applied to land. The removal and spreading of manure also requires energy (fossil fuels); thus, CO₂ is emitted through the combustion of fuel. Generally, GHG emissions are higher from manure in the housing feed subsystem compared with the grazing feed subsystem (Schils et al., 2005).

The predominant sources of indirect GHG emissions are the production and transportation of purchased inputs (fertilizer, concentrate, and energy), nitrogen loss from the dairy farm, and dairy processing. The main GHG released following the manufacture and transport of external inputs to the dairy system are N₂O and CO₂. The GHG emissions from the production of some external inputs (medicines and machinery) were excluded because of their small impact (Cederberg and Mattsson, 2000). Nitrogen loss from the dairy production system occurs via leaching or volatilization and may leave the physical farm boundary and be redeposited elsewhere. Depending on conditions, the redeposited nitrogen may then be lost as N₂O (Nevison, 2000). Similar to previous studies (Schils et al., 2005; Olesen et al., 2006), indirect GHG emissions were only assessed up to the farm gate. That is, GHG emissions from dairy processing and further stages were omitted.

Modeling GHG Emissions

A GHG model was developed to quantify the GHG emissions of the grass-based dairy production systems defined previously. The GHG model calculates emissions in combination with the Moorepark Dairy System Model (MDSM; Shalloo et al., 2004). The MDSM, a whole-farm simulation model of grassland-based dairy systems, was used to define the parameters required by the GHG model and to calculate profitability of dairy farms. Parameters defined by the MDSM included farm size, animal inventory, milk production, feed intakes, herbage quality (chemical composition), grazing season length, slurry, fertilizer, and application of lime. The

Table 1. Default parameters of the modeled farm

Item	Amount
Farm size, ha	38.8
Gross milk price, c/kg	27.0
Price ratio of protein to fat	2.6
Replacement heifer price, €	1,540
Culled cow price, €	270
Labor costs, €/month	1,905
Concentrate costs, €/t	200

default parameters of the MDSM (Table 1) were obtained from the results of experiments conducted in Moorepark over recent years (Dillon et al., 1995; Horan et al., 2005; McCarthy et al., 2007). Within the MDSM, it was assumed that the area of land was fixed at 38.8 ha (O'Donnell et al., 2008). Therefore, when 38.8 ha were fully utilized, any further expansion was through purchased feed. The MDSM was also defined to assume that all male calves were sold and replacement heifers were reared on farm from birth. Feed energy requirements are calculated in the MDSM based on the net energy required for milk production, maintenance, and BW change (Jarrige, 1989). Variable costs (fertilizer, contractor charges, medical and veterinarian fees, artificial insemination, silage, and reseedling), fixed costs (machinery maintenance and operating costs, farm maintenance, car, telephone, electricity, and insurance), and market prices (calf, cull cow, and milk) in the MDSM were based on current prices (Teagasc, 2008). The MDSM also includes full labor expenses, where one labor unit costs €22,855 per yr (1,848 h).

The GHG model integrates the parameters defined by the MDSM with specific GHG emission factors (**EF**; Tables 2 and 3) in Excel (Microsoft Corp., Redmond, WA) to quantify emissions. The GHG model is a sub-model of the MDSM and creates a static account of annual GHG emissions. The GHG model is designed to calculate emissions from day-to-day farming activities [e.g., from the pastoral spreading of slurry (on-farm GHG emissions)] and to estimate indirect emissions (e.g., GHG emissions arising from the manufacture of concentrate feeds). The model calculates emissions of CO₂, CH₄, and N₂O in terms of their 100-yr global warming potentials [CO₂ equivalents (**CO₂-eq**)], which, on a weight basis relative to CO₂, were set to a factor of 23 for 1 kg of CH₄ and 296 for 1 kg of N₂O (IPCC, 2001). The main outputs of the GHG model were an estimate of annual on-farm, indirect, and production system (on-farm plus indirect) GHG emissions. The model expresses emissions on a farm per unit area (CO₂-eq, t/ha) and per unit of product [CO₂-eq, kg/kg of milk and CO₂-eq, kg/kg of milk solids (**MS**)] basis.

An allocation was applied to GHG emission per unit of product because milk production produces the co-

Table 2. Emission factors for quantification of on-farm greenhouse gas emissions

Gas and source	Emission factor	Unit	Reference
Methane (CH ₄)			
Enteric fermentation			
Dairy cows (conserved feed only)	$[1.06 + 10.27 \times (\text{dietary forage proportion}) + (0.87 \times \text{DMI})]$	MJ/d per cow	Mills et al. (2003)
Dairy cows (grass only)	$0.065 \times \text{GEI}^1$	MJ/d per cow	Ireland EPA (2009)
1–2 yr old heifers	$0.065 \times \text{GEI}$	MJ/d per animal	IPCC (2006)
Calves	$0.065 \times \text{GEI}$	MJ/d per animal	IPCC (2006)
Slurry application	$(0.00007 \text{ to } 0.0123)^2 \times \text{slurry application rate}$	kg/m ³	Chadwick et al. (2000)
FYM ³ spreading	$0.0027 \times \text{FYM applied}$	g/kg	Chadwick et al. (2000)
FYM storage	$0.000017 \times \text{FYM stored}$	kg/m ³ per d	Sneath et al. (2006)
Slurry and dirty water storage	$0.0112 \times \text{diluted slurry stored}$	kg/m ³ per d	Sneath et al. (2006)
Silage effluent	$0.165 \times (\text{silage effluent BOD}^4)$	kg/1,000,000 BOD	US EPA (1990)
Nitrous oxide (N ₂ O)			
Pastorally deposited dung	$0.0019 \times \text{N in pasture dung}$	kg/kg of N	Yamulki et al. (1998)
Pastorally deposited urine	$0.0056 \times \text{N in pasture urine}$	kg/kg of N	Yamulki et al. (1998)
N fertilizer application	$0.01 \times \text{N in fertilizer}$	kg/kg of N	Brown et al. (2002)
Slurry spreading	$(0.0012 \text{ to } 0.0097)^2 \times \text{slurry application rate}$	kg/m ³	Chadwick et al. (2000)
FYM spreading	$0.2 \times (\text{N of FYM applied})$	kg/kg of N	Chadwick et al. (2000)
FYM storage	$0.0004 \times \text{FYM stored}$	kg/m ³	Sneath et al. (2006)
Slurry storage	$0.00001 \times \text{slurry stored}$	kg/m ³ per d	Sneath et al. (2006)
Carbon dioxide (CO ₂)			
Diesel combustion	$2.88 \times \text{diesel use}$	kg/L	Reinhardt (1993)
Lime	$0.12 \times \text{lime application}$	kg/kg	Ireland EPA (2009)

¹GEI = gross energy intake.²Depending on the month of application.³FYM = farmyard manure (DM content >20%).⁴BOD = biological oxygen demand.

products milk and meat (Williams et al., 2006; Thomassen et al., 2008). Similar to previous life cycle analysis studies (Cederberg and Mattsson, 2000; Basset-Mens et al., 2009), emissions were allocated between co-products according to biological causality. However, instead of

allocating emissions to milk and meat based on feed, GHG emissions were allocated to co-products based on emissions produced. Thus, emissions produced by cows from birth to first calving were allocated to meat, and emissions produced by cows when lactating were al-

Table 3. Emission factors for quantification of on-farm ammonia emissions and indirect greenhouse gas emissions

Gas and source	Emission factor	Unit	Reference
Ammonia (NH ₃)			
Housing	$(0.012 \text{ to } 0.034)^1 \times \text{lu}^2$	kg/lu per d	Hyde et al. (2003)
Manure storage	$0.0008 \times \text{excretion stored}$	kg/m ² per d	Hyde et al. (2003)
Grazing excreta	$2.27 + (0.0683 \times \text{annual N rate/ha} \times \text{lu})$	g/lu per d	Misselbrook et al. (2000)
Slurry application	$0.6 \times \text{TAN}^3 \text{ slurry spread}$	kg/m ³	Hyde et al. (2003)
FYM ⁴ application	$0.76 \times \text{TAN FYM spread}$	kg/m ³	Hyde et al. (2003)
FYM storage	$0.0025 \times \text{FYM stored}$	kg/m ² per d	Misselbrook et al. (2000)
Dirty water and silage effluent	$0.0004 \times \text{dirty water and effluent stored}$	kg/m ² per d	Misselbrook et al. (2000)
Yard ⁵	$0.008 \times \text{no. of cows}$	kg/cow per d	Hyde et al. (2003)
Carbon dioxide equivalent (CO ₂ -eq)			
Diesel	$1.0062 \times \text{diesel use}$	kg/L	Kramer et al. (1999)
Electricity	$0.685 \times \text{electricity use}$	kg/kWh	McGettigan (personal communication)
Lime	$0.03573 \times \text{lime application}$	kg/kg of lime	West and Marland (2002)
N fertilizer	$6.487 \times \text{N fertilizer use}$	kg/kg of N	Kramer et al. (1999)
Concentrate	$0.502 \times \text{concentrate use}$	kg/kg	Pre Consultants (2008)
Nitrous oxide (N ₂ O)			
Nitrate leaching	$0.025 \times (\text{N applied per ha} \times 0.1)$	kg/kg of NO ₃ ⁻	IPCC (2006)
Ammonia deposition	$0.01 \times (\text{sum of NH}_3 \text{ sources})$	kg/kg of NH ₃	Mosier et al. (1998)

¹Dependent on age of animal.²lu = livestock units expressed in units of 500 kg of BW.³TAN = total ammoniacal nitrogen content.⁴FYM = farmyard manure (DM content >20%).⁵Yard = ammonia from collecting yard before milking.

Table 4. Milk production, BW, and reproductive performance for 3 strains of Holstein-Friesian cows [high production (HP); high durability (HD); and New Zealand (NZ)] within the Moirepark (MP), high concentrate (HC), and high stocking rate (HS) feed systems¹

Item	MP			HS			HC		
	NZ	HD	HP	NZ	HD	HP	NZ	HD	HP
Lactation records, n	65	65	65	65	65	65	65	65	65
Milk production									
Milk, kg/cow	6,335	6,656	6,748	6,255	6,527	6,531	6,597	7,588	7,724
Fat, g/kg	43.9	40.9	40.6	45.6	41.1	41	44.5	40.1	40
Protein, g/kg	36.5	35.6	34.5	36.1	35.5	34.8	37.2	35.8	35.4
Lactose, g/kg	46.7	46.6	46.3	46.6	46.7	46.6	47.5	47.1	47.7
Average BW, kg	552	590	558	542	580	551	541	594	564
Reproduction ²									
Gestation length, d	278	284	284	278	284	284	278	284	284
42-d in-calf rate, %	74	65	54	74	65	54	74	65	54
Overall pregnancy rate, %	93	86	74	93	86	74	93	86	74
Total services per cow	1.61	1.79	2.07	1.61	1.79	2.07	1.61	1.79	2.07

¹McCarthy et al. (2007).²Breeding was initiated at, on average, 60 DIM.

located to milk. Emissions produced during pregnancy were allocated to meat when cows were not lactating.

The models were used in combination to simulate and calculate the GHG emissions from the dairy production systems studied by Horan et al. (2004, 2005) (Table 4). In short, 9 dairy farming systems differing in strain of Holstein-Friesian and type of pasture-based feed system were compared. Three strains of Holstein-Friesian cows, high-producing North American (**HP**), high-durability North American (**HD**), and New Zealand (**NZ**), were compared. The HP strain represented animals selected solely for milk production. In contrast, the HD strain represented a breeding program in which selection was based on improving several traits simultaneously; these included milk production, fertility, and muscularity. The NZ strain represented the highest possible genetic merit expressed in the NZ genetic evaluation system (Breeding Worth). The anticipated transmitting abilities and relative economic importance of each trait for these strains were previously reported (McCarthy et al., 2007).

Each strain was allocated to 1 of 3 pasture-based feed systems: 1) high grass allowance system typical of spring-calving herds (**MP**, control); 2) high concentrate supplementation (**HC**); and 3) a high stocking rate system (**HS**). The MP system had an overall stocking rate of 2.47 cows/ha and N fertilizer input of 290 kg of N/ha and received 325 kg of DM concentrate per cow in early lactation. The HC system had an overall stocking rate and N fertilizer input similar to that of the MP system, but 1,445 kg of DM concentrate was offered per cow per lactation, with a greater proportion fed in early spring. The HS system had concentrate and N input similar to that of the MP system, but had an overall stocking rate of 2.74 cows/ha. Both the MP and HC

systems were designed to allow each strain to express its potential within each feed system largely unaffected by limitations in feed supply. This did not apply in the HS system where the aim was to reduce the feed allowance by increasing the stocking rate, which resulted in a lower postgrazing sward surface height than either the MP or HC systems.

Emission Factors

The on-farm and indirect GHG emissions were calculated using EF from the most relevant research. Within this study, it was assumed that no sinks exist because most pastures within Ireland are semi-permanent or permanent pastures where the long-term carbon flux from the soil is in balance. The quantification of on-farm GHG emissions was determined by use of the EF in Table 2. The variable EF of Chadwick et al. (2000) were used for GHG emissions from pastorally spread slurry. The selection of EF for slurry spreading was dependent on season of spreading. The farm's slurry application profile was assumed to be 0.40, 0.40, and 0.20 in the spring, summer, and autumn, respectively, based on the survey of Carton (O. Carton, Teagasc, Wexford, Ireland; personal communication). Enteric CH₄ emissions were estimated using fixed EF (IPCC, 2006; Ireland EPA, 2009) when grazed grass was the major dietary component (>50% of DMI) for the dairy cow and for all dietary intakes for 1- to 2-yr-old heifers and calves. When grass silage and concentrate feeds were the major dietary components for the dairy cow, an equation of Mills et al. (2003) was used. The EF for lime application was based on the assumption that CO₂ is emitted at a rate of 0.12 kg per kg of lime applied (Ireland EPA, 2009).

Table 5. Inputs required for and emissions (CO₂ equivalents; CO₂-eq) from 1 t of DM concentrate ingredients

Input	Barley	Soy meal	Corn gluten	Pulp	Minerals and vitamins	Emissions (CO ₂ -eq, kg)			
						Barley	Soy meal	Corn gluten	Pulp
Farm									
Land, m ²	371.3	416.5	280.2	76.6	—	—	—	—	—
Fuel use, kg	3.5	3.5	13.2	2.2	—	16.9	4.0	11.0	3.4
Seed/drying, kg	5.0	4.6	107.3	—	—	2.7	4.9	29.7	—
Organic manure, ha	—	—	0.028	0.005	—	—	—	35.1	15.0
N fixation, kg	—	4.2	—	—	—	—	42.0	—	—
N-P-K, kg	22.1	2.7	2.8	0.4	—	112.7	2.1	73.4	1.8
Lime, kg	0.50	0.92	—	—	—	—	0.01	—	—
Protectants, ¹ kg	0.08	0.05	0.04	0.02	—	0.51	0.37	0.31	0.12
Processor									
Crop, kg	250	93.5 ²	247 ³	65 ⁴	—	132.8	44.0	142.5	3.8
Electricity, kWh	8.8	5.8	67.2	3.2	—	1.1	4.4	43.2	0.4
Heat, MJ	36.3	102.0	1,036.9	21.6	—	2.4	8.0	73.5	0.6
Miscellaneous	—	0.2	—	2.4	—	—	5.5	2.6	—
Transport, tkm ⁵	61.8	678.4	1,862.9	356.0	—	5.9	8.3	19.6	3.2
Output, kg of DM	250	110	260	350	30	142.2	70.3	281.4	8.0

¹Protectants are chemicals applied to crops to prevent or kill diseases.

²Soybean economic allocation, 65% meal, 35% oil.

³Corn for starch production economic allocation, corn gluten meal 10%, germ meal 8%, corn gluten feed 12%, starch 70%.

⁴Sugar beet economic allocation, 4% pulp, 92% sugar, 4% molasses.

⁵tkm = tonne per kilometer.

The quantification of indirect GHG emissions was determined by use of the EF in Table 3. Emissions from electricity production were calculated using data from the EPA (M. McGettigan, Environmental Protection Agency, Wexford, Ireland; personal communication). Ammonia (NH₃) and leached N, although not GHG in their own right, are responsible for the production of indirect GHG emissions. Therefore, it was also necessary to estimate NH₃ emissions (Hyde et al., 2003) and N leaching (Ireland EPA, 2009; Table 3). In this study, the GHG emissions from concentrate production were calculated using the software package Simapro (Pre Consultants, 2008). The ingredients of the concentrate were barley, soybean meal, corn gluten, beet pulp, and minerals and vitamins (0.25:0.11:0.26:0.35:0.03). The inputs required to produce 1 t of DM concentrate are presented in Table 5 with their associated GHG emissions. The concentrate ingredients soybean meal, corn gluten, and beet pulp are by-products of the production of vegetable oil, starch, and sugar, respectively. Thus, it was necessary to allocate GHG emissions between outputs for these ingredients. Greenhouse gas emissions were allocated based on the monetary value of these products using the data contained within Simapro (Table 5).

Based on the literature (Lovett et al., 2006), it was assumed that the EF for CH₄ from enteric fermentation and N₂O from fertilizer application and global warming potentials would have the greatest effect on GHG emissions. Sensitivity analysis was conducted on these

key input variables using data from the IPCC (2006) to test their effect on the total GHG emission from the production system.

RESULTS

Model Outputs from the Dairy Farming Systems

The total herd feed intake (kg of DM/yr) for the 3 pasture-based systems increased in the order MP to HS to HC, but there was little effect of cow strain on feed intake (Table 6). The lowest feed intake occurred when the NZ strain was in the MP feed system (474 t of DM/yr) whereas the highest occurred with the NZ strain in the HC feed system (576 t of DM/yr). The percentage of the feed intake provided from silage was highest for the HP strain in the HS feed system (23%), whereas silage intakes were highest for the HP strain in both the MP and HC feed systems. The proportion of feed intake obtained from concentrate was approximately 8% in the MP and HS feed systems with a maximum of 24% for the NZ strain in the HC feed system.

Milk yield (kg/farm per yr) for the 3 pasture-based feed systems increased in the order MP to HS to HC (Table 6). The NZ and HD strains had similar farm milk yields, but the HP strain had a lower farm milk yield. Compared with the other 2 strains, the HP strain resulted in a decline in cow numbers, an increase in the ratio of nonproductive animals to dairy cows, and a fall in farm annual milk yield in each of the 3 feed systems.

Table 6. Moorepark Dairy System Model¹ output in a fixed land area scenario (38.8 ha) for 3 strains of Holstein-Friesian cows [high production (HP); high durability (HD); and New Zealand (NZ)] within the Moorepark (MP), high concentrate (HC), and high stocking rate (HS) feed systems

Item	MP			HS			HC		
	NZ	HD	HP	NZ	HD	HP	NZ	HD	HP
Dairy cows, ² n	79.2	74.9	70.4	88.2	83.2	77.8	92.4	84.1	78.1
Calves, ² n	19.9	22.4	28.4	22.2	24.9	31.4	23.2	25.2	31.5
1–2 yr old heifers, ² n	14.9	18.1	25.1	16.6	20.1	27.8	17.4	20.3	27.9
Stocking rate, livestock units/ha	2.36	2.30	2.27	2.62	2.56	2.56	2.75	2.58	2.56
Pasture intake, kg of DM/cow per yr	4,085	4,171	4,099	4,039	4,027	3,936	3,404	3,625	3,621
Silage intake, kg of DM/cow per yr	1,018	1,092	1,176	1,005	1,067	1,157	887	981	1,039
Concentrate intake, kg of DM/cow per yr	412	439	502	412	439	502	1,388	1,419	1,487
Total intake, kg of DM/cow per yr	5,423	5,582	5,595	5,364	5,414	5,413	5,654	5,973	6,028
Herd pasture intake, t of DM/yr	345	343	333	380	366	354	342	337	330
Herd silage intake, t of DM/yr	93	99	107	102	106	116	97	99	108
Herd concentrate intake, t of DM/yr	35	36	38	39	39	42	137	125	124
Herd total feed intake, t of DM/yr	474	477	478	521	511	511	576	561	562
Milk yield, kg/cow per yr	6,385	6,764	6,796	6,262	6,502	6,473	6,585	7,413	7,647
Milk yield, kg/farm per yr	505,820	506,763	478,404	552,457	540,614	503,734	608,359	623,742	596,898
Total profit/farm, € milk price 27 c/L	56,797	50,683	36,352	64,025	53,513	35,609	61,431	57,690	49,428
Total profit/farm, € milk price 30 c/L	74,502	68,169	53,834	83,351	72,217	54,431	83,014	79,161	71,569
Total profit/farm, € milk price 20 c/L	15,424	9,673	–4,498	18,864	9,808	–7,721	10,996	7,520	–2,310

¹Shalloo et al. (2004).²Average animal numbers.

The ratio of nonproductive animals to dairy cows increased because of an increase in the replacement rate from 18 to 24 to 35% for the NZ, HD, and HP strains, respectively.

At a milk price of 27 euro-cents (c)/L or greater, on average across the 3 genotypes, the HC feed system achieved the greatest profitability followed by the HS feed system and the MP feed system (Table 6). The NZ strain achieved the greatest profitability followed by the HD strain and then the HP strain. The greatest profit associated with the HP strain was achieved in the HC feed system and the lowest profit in the MP and HS feed systems. For the NZ strain, the greatest profit was achieved in the HS feed system and the lowest in the MP feed system. The HD strain achieved the greatest profit in the HC feed system and lowest profit in the MP feed system.

At a milk price of 20 c/L, on average across the 3 genotypes, the HS feed system achieved the greatest profitability followed by the MP feed system and the HC feed system (Table 6). The NZ strain achieved the greatest profitability followed by the HD strain, with the HP strain having an economic loss. The greatest loss occurred with the HP strain in the HS feed system, and the HP strain achieved the lowest loss in the HC feed system. The NZ strain achieved the greatest profitability in the HS feed system and the lowest profit in the HC feed system. For the HD strain, the greatest profit was achieved in the HS feed system with the least in the HC feed system.

Dairy Systems GHG Emissions

The GHG emissions of 9 dairy farming systems, calculated by the GHG model, are shown in Table 7. Greenhouse gas emissions for each dairy farming system are calculated with and without indirect emissions (on-farm and production system GHG emissions). They are expressed per unit of product (kg of CO₂-eq/kg of milk and kg of CO₂-eq/kg of MS) and per unit area (t of CO₂-eq/ha). Greenhouse gas emission per unit of product was assessed with and without allocation (Table 7).

Production system GHG emissions per unit of product and per unit area were always higher than on-farm emissions. Indirect GHG emissions accounted for 25% of production system emissions in the MP and HS feed systems and 30% of production system emissions in the HC feed system. Strain had little effect on the proportion of production system GHG emissions from indirect sources. The inclusion of indirect GHG emissions affected the optimum feed system for the NZ strain when measured in terms of GHG emissions per unit of product.

The GHG emission per kilogram of milk on average across the 3 genotypes was similar for the MP and HS feed systems, but the HC feed system had lower emissions (Table 7). The NZ and HP strains had similar emissions per kilogram of milk, whereas the HD strain had the lowest emissions. For the HP strain, the lowest emission was produced per kilogram of milk in the HC

Table 7. On-farm and production system greenhouse gas (GHG) emissions (CO₂ equivalents; CO₂-eq) calculated using a GHG model in a fixed land scenario (38.8 ha) for 3 strains of Holstein-Friesian cows [high production (HP); high durability (HD); and New Zealand (NZ)] within the Moorepark (MP), high concentrate (HC), and high stocking rate (HS) feed systems

GHG measure	Source ¹	Allocation ²	MP			HS			HC		
			NZ	HD	HP	NZ	HD	HP	NZ	HD	HP
CO ₂ -eq, kg/kg of milk	On-farm	None	0.777	0.780	0.832	0.773	0.777	0.840	0.744	0.707	0.743
	Production system	None	1.040	1.045	1.116	1.024	1.033	1.117	1.059	1.003	1.052
	On-farm	Biological	0.709	0.697	0.709	0.706	0.694	0.716	0.679	0.632	0.633
	Production system	Biological	0.950	0.934	0.951	0.935	0.923	0.952	0.967	0.896	0.897
CO ₂ -eq, kg/kg of MS ³	On-farm	None	9.79	10.32	11.05	9.63	10.32	11.22	9.16	9.51	9.97
	Production system	None	13.12	13.82	14.81	12.76	13.72	14.93	13.03	13.49	14.10
	On-farm	Biological	8.94	9.22	9.42	8.79	9.22	9.57	8.36	8.50	8.50
	Production system	Biological	11.98	12.35	12.63	11.65	12.26	12.73	11.90	12.05	12.02
CO ₂ -eq, t/ha	On-farm	None	9.97	10.02	10.07	10.83	10.65	10.69	11.50	11.20	11.25
	Production system	None	13.36	13.43	13.50	14.36	14.16	14.22	16.36	15.89	15.91

¹Source: on-farm = GHG emission from day-to-day farming activities; production system = GHG emission from all activities associated with the dairy farm (i.e., manufacture of N fertilizer).

²Allocation: none = all GHG emission attributed to milk; biological = GHG emission allocated to meat based on emission produced by calves, 1–2 yr old heifers, and cows while pregnant and not lactating and GHG emission allocated to milk based on emission from cows while milking.

³MS = kg of milk fat plus protein.

feed system, and the highest in the HS feed system. For the HD strain, the lowest emission per kilogram of milk was in the HC feed system, and the highest in the MP feed system. The NZ strain achieved their lowest emission per kilogram of milk in the HS feed system and highest emission in the HC feed system.

The GHG emission per kilogram of MS on average across the 3 genotypes was similar for the MP and HS feed systems; however, the HC feed system had lower emissions (Table 7). The NZ strain produced the lowest emission per kilogram of MS followed by the HD strain and the HP strain. The HP strain produced their lowest emission per kilogram of MS in the HC feed system and the highest in the HS feed system. For the HD strain, the lowest emission per kilogram of MS was produced in the HC feed system with the highest in the MP feed system. The NZ strain produced their lowest emission per kilogram of MS in the HS feed system and highest emission in the MP feed system.

The GHG emission per unit of farm area (t of CO₂-eq/ha) for the 3 pasture-based feed systems increased in the order MP to HS to HC, but strain had only a modest effect on GHG emission per hectare (Table 7). The lowest GHG emissions per unit area occurred when the NZ strain was in the MP feed system (9.97 t of CO₂-eq/ha and 13.36 t of CO₂-eq/ha for on-farm and production system GHG emission, respectively), whereas the highest occurred with the NZ strain in the HC feed system (11.50 t of CO₂-eq/ha and 16.36 t of CO₂-eq/ha for on-farm and production system GHG emissions, respectively).

The largest source of GHG emissions for all dairy farming systems was enteric CH₄, irrespective of strain or feed system (Table 8). The HC feed system decreased

the proportion of GHG emissions per unit of product and per unit area derived from enteric fermentation when indirect emissions were included, but the opposite occurred when indirect emissions were excluded. The HC feed system reduced the proportion of GHG emissions associated with fertilizer use and production regardless of the inclusion of indirect emission. For the HC feed system, GHG emissions associated with concentrate production increased. Greenhouse gas emissions from concentrate production accounted for 3% of production system emissions in the MP and HS feed systems and 10% in the HC feed system. Strain had limited influence on the relative contributions of each of the sources of GHG emissions.

Sensitivity analysis of CH₄ from enteric fermentation ($\pm 15\%$) resulted in a 4.9% increase/decrease in production system GHG emission per unit of product and resulted in an increase/decrease of 5.1% per unit area. Production system GHG emission per unit of product increased and decreased by 6% using the uncertainty range of the IPCC (2006) for N₂O. The production system GHG emission per unit of product and per unit area decreased by 4.3% when the original IPCC global warming potentials were used (CH₄ = 21 and N₂O = 310) and increased by 5.2% using current global warming potentials (CH₄ = 25 and N₂O = 298).

DISCUSSION

The combination of 3 cow strains and 3 feed systems, on a fixed land area, generated an 80% difference in profitability, a 22% difference in production system GHG emissions per ha, and a 17% difference in GHG emissions per kg of MS. The most profitable combina-

Table 8. On-farm and indirect greenhouse gas (GHG) sources calculated using a GHG model for 3 strains of Holstein-Friesian cows [high production (HP); high durability (HD); and New Zealand (NZ)] within the Moorepark (MP), high concentrate (HC), and high stocking rate (HS) feed systems

Source	Unit	MP			HS			HC		
		NZ	HD	HP	NZ	HD	HP	NZ	HD	HP
CH ₄ from enteric fermentation	kg of CO ₂ -eq ¹ /kg of MS ²	6.60	6.92	7.35	6.57	6.98	7.52	6.38	6.57	6.84
	t of CO ₂ -eq/ha	6.72	6.72	6.70	7.39	7.21	7.16	8.01	7.74	7.72
CH ₄ manure management	kg of CO ₂ -eq/kg of MS	1.26	1.36	1.52	1.25	1.37	1.57	1.13	1.20	1.31
	t of CO ₂ -eq/ha	1.28	1.32	1.39	1.41	1.42	1.49	1.42	1.41	1.47
Farm N ₂ O emissions	kg of CO ₂ -eq/kg of MS	1.58	1.67	1.79	1.48	1.60	1.75	1.35	1.42	1.49
	t of CO ₂ -eq/ha	1.61	1.62	1.63	1.67	1.65	1.67	1.69	1.68	1.69
Other farm sources ³	kg of CO ₂ -eq/kg of MS	0.35	0.37	0.39	0.33	0.36	0.38	0.30	0.32	0.33
	t of CO ₂ -eq/ha	0.36	0.36	0.36	0.37	0.37	0.37	0.38	0.37	0.37
Concentrate feed	kg of CO ₂ -eq/kg of MS	0.45	0.48	0.54	0.45	0.49	0.57	1.41	1.37	1.42
	t of CO ₂ -eq/ha	0.46	0.46	0.50	0.50	0.51	0.54	1.77	1.62	1.60
Fertilizer production	kg of CO ₂ -eq/kg of MS	1.67	1.76	1.88	1.52	1.66	1.80	1.36	1.45	1.52
	t of CO ₂ -eq/ha	1.71	1.71	1.71	1.71	1.71	1.72	1.71	1.71	1.71
Other indirect sources ⁴	kg of CO ₂ -eq/kg of MS	1.20	1.27	1.34	1.16	1.26	1.34	1.10	1.16	1.19
	t CO ₂ -eq/ha	1.23	1.23	1.22	1.31	1.30	1.28	1.38	1.36	1.35

¹CO₂-eq = carbon dioxide equivalent.

²MS = kilograms of milk fat plus protein.

³Other farm sources = carbon dioxide from fossil fuel use and lime application.

⁴Other indirect sources = nitrous oxide from nitrate leaching and atmospheric deposition and CO₂ from lime, electricity, and diesel production.

tion was the NZ cow strain in a HS system. This system also reduced production system GHG emission per ha by 12% compared with the highest emission produced by the NZ strain in the HC system. Furthermore, the findings of the current study are consistent with those of Basset-Mens et al. (2009) and demonstrate that grass-based systems are capable of emission-efficient milk production while the objectives of profitability and reduced GHG emissions are not mutually exclusive.

On-Farm and Production System GHG Emissions

As expected, production system GHG emissions were higher than on-farm GHG emissions, regardless of the method of expression of GHG emissions. These findings are similar to the results of Lovett et al. (2006) who estimated absolute GHG emissions and GHG emission per kg of milk with and without indirect emissions. Production system GHG emissions were greater than on-farm GHG emissions because of the extension of the dairy farm system boundary to include emissions associated with purchased inputs (e.g., concentrate and N fertilizer).

On-farm GHG emissions were the main component of production system GHG emissions for all dairy systems (69–75%). The main source of on-farm GHG emissions for each dairy farm system was enteric CH₄ (68%), similar to the results of other studies (Cederberg and Mattsson, 2000; Schils et al., 2005; Gibbons et al., 2006). Thus, the identification of strategies that reduce CH₄ from enteric fermentation without increas-

ing other GHG could result in large reductions in GHG emissions from dairy systems. The remaining on-farm GHG emissions are primarily N₂O from nitrogen fertilizer application (12–14%). Several strategies have been suggested to reduce N₂O from nitrogen fertilizer including improved timing of application, nitrification inhibitors, and the use of legumes as an alternative to N fertilizer (de Klein and Eckard, 2008). Any strategies that reduce the use of N fertilizer will also reduce GHG emissions associated with fertilizer manufacture, one of the largest sources of indirect emissions (35–50% of indirect emissions).

Effective mitigation strategies need to have a net global reduction in emissions, and including all emissions (on-farm and indirect) generated by a particular strategy is the preferred method of measurement. However, often only on-farm emissions are estimated. This would not matter if mitigation strategies always ranked the same when estimated with or without indirect emissions. Lovett et al. (2006) found that GHG emission per kilogram of milk, whether it was calculated with or without indirect emissions, did not change in ranking for systems that involved different levels of concentrate supplementation. Our results agreed with their observation for the HD and HP cow strains, in that the ranking was consistent across the 3 feed systems for on-farm and production system emissions. However, when GHG emissions per unit of product were estimated without indirect emissions, the NZ strain produced their lowest emission in the HC system, but when indirect emissions were included, their lowest emission was produced

in the HS feed system. The change in ranking for the NZ strain was because of the low proportion of non-productive animals to dairy cows in the HS system, which resulted in a greater milk production increase compared with the other 2 strains in the HS system. Therefore, if mitigation strategies with a net reduction in GHG are to be developed, all emissions associated with a production system should be analyzed. The current study found that including or excluding indirect GHG emissions did not affect the ranking of production systems when GHG emissions were calculated per hectare. This occurred because estimating emissions on a per-hectare basis does not account for varying levels of milk production.

Effect of Cow Strain on GHG Emissions

The results of the current study demonstrated that within pasture-based systems, the lowest GHG emission per unit of product and maximum profitability were realized with the Holstein-Friesian cows combining high genetic potential for both production and fertility traits (HD and NZ strains), rather than those selected solely for increased milk production potential (HP strain). Higher genetic merit for fertility caused GHG emissions per unit of product to decline through a reduction in emissions from nonproductive animals and a consequent increase in total farm milk yield. Therefore, increasing fertility in conjunction with milk production performance will result in reduced GHG emission per unit of product.

The findings of this study are similar to the results of Weiske et al. (2006). Their study showed that reducing the replacement rate of dairy cows by 10% caused emissions per kilogram of milk to fall by up to 13%. This decrease in GHG emissions occurred because of a decline in the number of nonproductive animals. In our study, a similar decrease in emission per kilogram of milk (9%) occurred when the replacement rate decreased from 35% (HP strain) to 18% (NZ strain). There was a greater decline when GHG emissions were estimated per kilogram of MS (15%). Apart from that of Weiske et al. (2006), few studies have used a whole-farm modeling approach to investigate the effect that reducing the replacement rate has on all the GHG emitted on a dairy farm. Instead, several studies have modeled the effect of fertility on CH₄ emissions from dairy farms (Garnsworthy, 2004; Bell et al., 2008). These studies found that an improvement in fertility reduced the number of replacement heifers required, which caused a significant decrease in total herd CH₄ emission. Although these studies only modeled the effect of improved fertility on CH₄ emissions, the results of the current study and that of Weiske et al. (2006)

suggest that better herd fertility (reduced replacement rates) does not increase other GHG.

The GHG emission per unit of product for strains selected for high genetic potential for both production and fertility traits (NZ and HD strain) were similar when emissions were expressed per kilogram of milk. However, when emissions were expressed per kilogram of MS, the NZ strain had lower emissions than the HD strain. This occurred because the NZ strain produced the most MS per kilogram of milk. These results highlight the importance of defining the function of the milk production system. Ireland exports 85% of what it produces in the form of commodities; therefore, expressing GHG emissions of a dairy farm on an MS basis is more relevant than on a volume basis because payment is based on MS.

Strain had little effect on GHG emission per unit area because there was little difference in herd total feed intake among the 3 cow strains. Dry matter intake is the main driver of enteric CH₄ emissions (Hegarty et al., 2007), and this source is the largest contributor to GHG emissions from pasture-based dairy farms (Gibbons et al., 2006).

Effect of Feed System on GHG Emissions

The effect of feed system on GHG emission per unit of product and profitability of dairy systems differed depending on strain of Holstein-Friesian. The HC feed system reduced GHG emissions per unit of product for the HD and HP strains because those strains had a large milk production response to increased concentrate supplementation (Horan et al., 2005). The HC feed system also increased profitability when the milk price was equal to or greater than 27 c/L. The milk production response of the NZ strain to concentrate input was lower compared with HD and HP strains (Horan et al., 2005), resulting in greater GHG emission per kilogram of milk and reduced profitability.

The HS feed system reduced the GHG emission per unit of product for the NZ strain and increased profitability. Thus, the NZ HS system was the optimum system both in terms of GHG emission per kilogram of MS and profitability. The GHG emission per unit of product for the NZ strain decreased in the HS feed system because increasing the stocking rate of this strain resulted in a greater increase in total farm milk yield (9%) than GHG emission per ha (7%). The substantial increase in farm milk yield occurred because the NZ strain had a low replacement rate and thus a lower proportion of nonproductive animals. The HS feed system had a minor effect on the GHG emission per unit of product for the HD and HP strain because these strains had a higher replacement rate. This prevented a

substantial increase in farm milk yield (5%) and caused an equal or greater increase in GHG emission per unit area (5–6%).

Moving from the MP to the HS to the HC feed system caused GHG emission per hectare for all strains to increase because of a progressive increase in herd DMI. This agrees with the work of Basset-Mens et al. (2009), which found that intensification (increasing use of inputs, i.e., capital) caused GHG emissions per hectare of land to increase.

CONCLUSIONS

The influence of divergent strains of Holstein-Friesian and different feed systems on GHG emissions from pastoral dairy farms was quantified using a new GHG model. The GHG model splits GHG emissions into those arising from day-to-day farming activities (on-farm GHG emissions) and those produced off-farm but directly attributable to the production system up to the farm gate (indirect GHG emissions). This model was integrated with the MDSM, a whole-farm model, which also estimates farm profitability. The findings of the study demonstrate that mitigation strategies do not always rank the same when estimated as on-farm or as production system emissions (on-farm plus indirect GHG emission). Therefore, if effective strategies are to be developed, all emissions associated with a production system should be considered. The output of the models showed that within pasture-based feed systems, genetic selection for increased milk production (HP strain) results in greater GHG emission per unit of product and reduced profitability relative to selection on a combination of production, reproductive, and health traits (HD and NZ strains). The study also found that increasing herd total DMI increased GHG emission per hectare.

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