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The effect of lameness on the environmental performance of milk production by rotational grazing

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Abstract

Dairy production leads to significant environmental impacts and increased production will only be feasible if the environmental performance at farm level permits a sustainable milk supply. Lameness is believed to become more prevalent and severe as herd sizes increase, and can significantly reduce milk output per cow while not influencing other attributes of the production system. The objective of this work was to quantify the effect of lameness on the environmental performance of a typical grazed grass dairy farm and evaluate the theoretical value of sensor-based real-time lameness management. Life cycle assessment was used to compare a typical baseline farm with scenarios assuming increased lameness severity and prevalence. It was found that lameness could increase the farm level global warming potential, acidification potential, eutrophication potential and fossil fuel depletion by 7-9%. As increased herd sizes will increase cow: handler ratio, this result was interpreted to suggest that the use of sensors and information and communication technology for lameness detection could improve management on dairy farms to reduce the adverse impact on environmental performance that is associated with lameness.

Key words: Life cycle assessment, Dairy farm, Environmental impacts, Feed usage efficiency, Real time lameness detection

1. Introduction

Globally, livestock production is believed to have adverse environmental consequences, impacting air, water, soil and ecology (IDF, 2009). Ireland is an example of a country that generates significant GDP (gross domestic product) (1.5%) from cattle (Teagasc, 2012), at the cost of agriculture being the single largest contributor (>20%) to greenhouse gas (GHG) emissions (Duffy et al., 2014; Hynes et al., 2009). With the abolishment of the EU milk quota (Kempen et al., 2011), the output of the Irish dairy industry is expected to increase by 50% by 2020 (Department of agriculture, 2010). The Irish Environmental Protection Agency (EPA) estimated that the GHG emissions from the Irish dairy sector will increase by 12% as a consequence (EPA, 2012). Similar trends may apply in other countries and regions because of the increasing global demand for dairy products (Mekonnen and Hoekstra, 2012). Reducing the environmental impact of dairy farms striving for increased productivity is a significant issue for all stakeholders in the dairy supply chain (Hristov et al., 2013).

There have been many studies of the environmental impact of milk production (Fantin et al., 2012; Thomassen et al., 2008; Yan et al., 2013a), with a tendency to focus on GHG emissions (Casey and Holden, 2005; Dalgaard et al., 2014). Life cycle

assessment (LCA) has been widely used for such assessments (O'Brien et al., 2012; Thomassen et al., 2008; Yan et al., 2013b), and (Meul et al., 2014) demonstrated that LCA can support environmental decision making at the commercial dairy farm level. These LCA models can help farmers to identify environmental hotspots to focus improved management and (Yan et al., 2013b) showed that LCA could be used to evaluate the contribution of specific management tactics on the impact of milk production.

Lameness in dairy cattle refers to any abnormality which causes an altered gait, and is a major health and welfare issue for dairy farms (Cha et al., 2010). It is generally believed to influence the milk yield of affected cows and is related to a number of key management tactics (Barnes et al., 2011; Gomez and Cook, 2010). Some authors (Tranter and Morris, 1991; Warnick et al., 2001; Whitaker et al., 1983) found lameness decreased milk yield until treated, (Lucey et al., 1986) found a decrease that continued after treatment and (Cobo-Abreu et al., 1979) observed no change in yield. Recent studies have found that lameness causes reductions in milk yield and profit at the farm level (Borderas et al., 2008; Bruijnijis et al., 2010; Ettema and Østergaard, 2006), while (Green et al., 2002) found that over 70% of cows became lame at least once in a year with a total mean reduction in milk yield per 305-day lactation of approximately 360 kg. The decrease in milk yield from lame cows is mainly because of a reduction in standing time for feeding and a lack of willingness to move for feeding and milking (Bach et al., 2007; Miguel-Pacheco et al., 2014). This can reduce feed use efficiency (Bareille et al., 2003; Palmer et al., 2012) potentially exacerbating

the environmental impacts associated with milk production process. There is scope to develop information driven operational management specific to lameness that could allow farm managers to improve the feed usage efficiency and optimise treatment to reduce the environmental impacts at the farm level. While the economic cost of lameness management is reasonably well understood (Bruijnis et al., 2010; Cha et al., 2010), baseline environmental impacts of lameness are not known.

The objective of this work was to quantify the effect of lameness on the environmental performance of a typical grazed grass dairy farm and evaluate the theoretical value of sensor-based real-time lameness management. LCA was used to model a typical Irish low-cost, grass-based, rotational grazing dairy farm (Fitzgerald et al., 2005), which was then compared with scenarios combining ranges of prevalence and severity of lameness in the herd.

2. Materials and methods

LCA was used to evaluate the environmental impact using four stages: (1) goal and scope, (2) life cycle inventory analysis, (3) life cycle impact assessment and (4) interpretation (ISO, 2006a, 2006b) using Gabi 6.0 (PE-International, 2012).

The goal of the study was to evaluate the impact of lameness on the environmental performance of milk production. This was undertaken to establish a baseline for evaluating the value of sensor and ICT derived information for real-time lameness management.

The system was low-cost (use less purchased feed than confinement system), grass-based rotational grazing milk production (Fitzgerald et al., 2005) operating over one year. The system boundary was from cradle to farm gate, including land preparation, cultivation process and nutrient management for grass production, production and transportation of synthetic fertilizers, silage and concentrated feed, production and use of electricity and diesel on farm (Figure 1). Infrastructure (except the manure storage tank), farm and milking machinery, refrigerant for milk cooling, pesticides, udder disinfectants and disposal of silage plastic was not included due to data unavailability, but these were not thought to be influenced by the lameness scenarios. All manure was assumed to be spread on the grazing and grass silage areas of the farm. GHG associated with manure spreading and CO₂ from farming machinery were included. Soil carbon sequestration was not included because the model farm was assumed to be mature and in equilibrium (IPCC, 2006). The functional unit was “1 kg of energy corrected milk (ECM) delivered at the farm gate” (Sjaunja et al., 1990) with ECM calculated as:

$$ECM = \text{milk delivered} \times (0.25 + 0.12 \times \text{Fat} \% + 0.07 \times \text{protein}) \quad (1)$$

In order to differentiate the dairy from non-dairy activities (e.g. producing heifers for sale) allocation was by the method of (Yan et al., 2013b). All animal numbers were expressed as livestock unit (LU) equivalents based on the ratio of nitrogen excretion compared with a typical dairy cow with the allocation factor as the proportion of all

dairy LU to total LU. The allocation between milk and co-product meat from dairy cows was based on the energy and protein requirement of herd (O'Brien et al., 2012). The proportion of the total energy and protein requirements of the herd for meat production in an Irish pasture based system was taken as 12% (Shalloo et al., 2004).

The activity data (Table 1) were taken from (Yan et al., 2013b), who reported data from a farm survey that represented a typical Irish commercial farm focused on milk production. Specific data for feed ingredients and their proportion were taken from (O'Brien et al., 2012) (Table 2), with background data taken from the 'Thinkstep™ Food and Feed database' (Thinkstep, 2014). The environmental impacts of concentrate feed co-products was allocated by economic methods based on relative market value using factors in the same database. As most of the concentrate feed used in Irish dairy farms is imported from the EU, the origins of crop production were assumed to be EU in proportion to market share.

The methods and emission factors (EF) used are shown in (Table. 3). Methane (CH₄) emissions from enteric fermentation were dependent on feed intake and calculated following IPCC Tier 2 methods (IPCC, 2006). The net energy (NE) from pasture is estimated as the difference between total NE requirement (NE_L, NE_M and NE_P) and gross NE provided by silage and concentrate feed. The estimated milk output for NE_L included the milk consumed (301 kg/cow) by the calf and 6.5% of gross energy intake lost as CH₄ was taken as the emission factor because grazed grass was assumed to be the major dietary component for the dairy cow (O'Mara, 2006). CH₄ emissions from

stored manure were estimated using national average EF (Duffy et al., 2014) following IPCC Tier 2 methods (IPCC, 2006). The CH₄ emission from manure deposited by animals on pasture was not included because the quantity is negligible (IPCC, 2006). The seasonal CH₄ emission factors used for manure application were the average of 12 g CH₄/m³ for spring, 0.07 g CH₄/m³ for summer and 6.8 g CH₄/m³ for autumn (Chadwick et al., 2000) (Table 3) because specific time of manure application was not known.

Nitrogen emissions were mainly generated from animal excreta, with data taken from national inventory reporting (Duffy et al., 2014). Accordingly 36.2% of N in stored manure was assumed to contribute to indirect N₂O emission as NH₃, and the EF for liquid manure and solid manure was 0.01. Other N in stored manure was assumed to contribute to direct N₂O emission and the EF for liquid and solid manure was 0.01 and 0.02, respectively. Manure on pasture accounts for indirect N₂O emission as NH₃ (5.6%) and NO₃ (10%), with EFs of 0.01 and 0.025, respectively. The remaining manure was assumed to contribute to direct N₂O emission and EF was 0.02. According to previous ammonia report on Irish grass land (Hyde et al., 2003), 1.6% of inorganic N fertilizers spread on field was volatilized as NH₃. The indirect N₂O emissions as NH₃ from manure and soiled water spreading were also included Table 3.

In order to calculate the potential leaching of N and P, a farm gate balance approach was used assuming an average P surplus taken from (Buckley et al., 2013). The P

surplus for specialist dairy farms in Ireland is between 1 and 10 kg, the P surplus lost to waterways was estimated using 0.5 kg P/ha per year (Schulte et al., 2011). According to IPCC (IPCC, 2006), 30% of the N from fertilizer, manure storage and excretion is lost through leaching in the form of nitrate (NO₃).

Greenhouse Gas emissions related to on-farm energy consumption (diesel consumption for field activities and electricity use for heating, milking and cooling processes) were estimated from the amount of diesel (litres) and electricity (kWh) used and EFs from Eco-invent 3.0 (Ecoinvent, 2014) and specific LCIA methods as deployed in Gabi 6.0. Fertilizer was assumed to be produced outside Ireland, primarily from Germany (lime, nitric acid, phosphate fertilizer) with some production data (Potassium Chloride) from the EU-27. The compound fertilizer (N-P-K) was assumed to be mixed from calcium ammonium, nitrate, urea, diammonium phosphate, and potassium chloride. The transportation of feed and fertilizer was assumed to be by diesel trucks with 22 t payload and European emission standard 3. These background data were taken from the Gabi professional database (Thinkstep, 2014).

Four impacts were calculated from the LCI data: Global Warming Potential (GWP) with a time horizon of 100 years (kg CO₂-eq), Eutrophication Potential (EP) (kg PO₄³⁻-eq), Acidification Potential (AP) (kg SO₂-eq) and Fossil Fuel Depletion (FFD) (kg oil-eq). The method was CML2001 for GWP, EP and AP and ReCiPe for FFD. Interpretation focused on sensitivity analysis and lameness scenarios.

2.1 Lameness scenarios

Data from recent 7 lameness studies (Table 4) considering confinement, pasture based system and mixed system of dairy production were analyzed to develop the scenarios. As the main breed in dairy cows, Holstein cows were used as research breed in most of lameness studies, thus the values we used below is for Holstein. Due to the geographical proximity, large sample size and small variance in milk reduction, the maximum value (1.8 kg (milk) d⁻¹) for total milk loss was taken from Green et al. (2002), and the minimum value (0.52 kg (milk) d⁻¹) was taken from Bach et al. (2007). Lameness can also cause the animal to lose weight, however this is typically <20 kg, which accounts for less than 5% of original body weight (Ettema and Østergaard, 2006; Norring et al., 2014). Ettema et al. (2006) found weight changes over 14 to 56 days. The reduced energy demand due to weight change was calculated using (Shalloo et al., 2004):

$$\text{Energy for maintenance} = \text{activity allowance} \times (1.4 + 0.6 \times \text{body weight} / 100) \times 365 \quad (2)$$

Lameness prevalence in dairy farms ranges from 20%-80% and the prevalence tends to increase with increased herd size (Barker et al., 2010; Barnes et al., 2011; Sarjokari et al., 2013). The mean prevalence of lameness in UK dairy farms is 37% (Barker et al., 2010). These values were used to define scenario limits. According to Juarez et al (2003) the effect of lameness on fat and protein content is negligible. The energy provided by feed is mainly used to support the net energy (NE) requirement for

lactation (NE_L), maintenance (NE_M) and pregnancy (NE_P) (O'Mara, 2006). The energy required for pregnancy is not affected by lameness. The modified feed demand was calculated based on reduced milk output, weight change and total energy balance. Change in CH_4 emissions from enteric fermentation for the herd was calculated as the difference between dry matter intake (DMI) of the average herd and that calculated for a reduced DMI accounting for milk yield and weight loss of lame cows. The CH_4 emission associated with reduced feed intake by lame cows was subtracted from the total emission of the manure storage system. The nitrogen emission associated with the decreased manure from lame animals was subtracted from total nitrogen emission of the dairy farm.

To model the impact of lameness the supply chain was assumed to be inelastic and that in a given year, once a farmer had made a strategic or tactical decision (e.g. grass production management), that this would be followed regardless of individual animal lameness status, thus regardless of lameness occurring or not, it was assumed that a farmer would purchase the same amount of fertiliser, concentrate feed and purchased silage as the previous year. This is tenable because the farmer cannot know in advance what the incidence of lameness will be, but has to make these decisions. This means the LCA model could capture the effect of a small change in output (milk) on the environmental burden of the production system. Any surplus feed in the lameness scenarios was allocated in two ways. Assuming it is sold off farm, calculated by combining the GHG emission per ha land in Ireland (Murphy et al., 2011) with estimated silage yield per ha land (Yan et al., 2013b) to be 0.07 kg CO_2 -eq. per kg

excess silage. Or it was assumed to be degraded and become unsuitable for feed on the farm and the GHG emission for this process was taken as 5% of GHG emission of silage production (Barber et al., 2011).

Six lameness scenarios were modelled (Table 5) to compare with the typical dairy farm (S_0) with an assumed lameness rate of 15% (Boyle, 2008). Previous studies place the range of lameness prevalence between 20% and 80% (Barker et al., 2010; Barnes et al., 2011; Sarjokari et al., 2013). The scenarios in this study range from 28% through 49% to 70% prevalence, modelled by adding more lame animals to the herd (adding 20, 40, 60 lame dairy cows, respectively). At the farm level, the effect of lameness was modeled to increase from scenario S_1 to scenario S_6 , with an assumed reduction in milk yield due to lameness.

3. Results

3.1. Baseline environmental impacts (S_0)

The GWP of energy corrected milk for S_0 was 1.18 kg CO₂-eq. /kg ECM, which was similar to the findings of Yan et al. (2013), whose data the model was built on. The dominant contributor was methane from enteric fermentation (43%), followed by animal excretion (12%), manure storage (11%), fertilizer production (10%), and fertilizer spreading (10%). The contribution of GHG emission from major process units to total GHG is close to results reported by O'Brien et al. (2012). The GHG emission for silage production was 0.07 kg CO₂-eq. per kg silage. This value was derived from the GHG emission profile of silage production in Ireland (Murphy et al.,

2011) and it is similar to values in Feedprint (Vellinga et al., 2013). Compared to (Yan et al., 2013b) a smaller emission factor (0.3 kg CO₂-eq./ kg) was used for concentrate feed and the contribution of concentrate feed to overall CF was around 4%. The manure application on farm and electricity used for animal operations accounted for 4% and 3% of total GHG emission, respectively. The diesel consumed for transportation of fertilizer and feed and farming machinery for on farm activities contributed around 2% of total GWP.

The AP for S₀ was 8.04 g SO₂-eq. /kg ECM, and was dominated by the generation of NH₃, mainly influenced by volatilization during on-farm activities like manure storage and application process (64%), excretion (19%) and fertilizer spreading (7.6%). The off farm activities including production of concentrate feed and inorganic fertilizer only accounted for 6.3% of AP. The total AP is within the range of AP value presented by (Guerci et al., 2013) and the proportion of the main contributors were similar to (O'Brien et al., 2012).

EP was dominated by on-farm activities, with the total for S₀ being 8.0 g PO₄³⁻-eq. /kg ECM. The value obtained was greater than reported by (O'Brien et al., 2012), but similar to values reported by (Guerci et al., 2013). The main reason for the difference was due to the value used for estimating the proportion of nitrate leaching to groundwater. In this study, the default IPCC value (0.3) was used (IPCC, 2006) but (O'Brien et al., 2012) used an estimated value of 10% from a national monitoring program. The most significant EP contribution was from Nitrate leaching from

fertilizer application (30%), manure application (24%) and excretion on the field (16%). If the value used by (O'Brien et al., 2012) was used then a similar result could be obtained. The ammonia from manure storage and application also accounted for a large proportion (13%) of total EP.

FFD was mainly driven by off-farm activities and was estimated for S_0 to be 57.5 g oil-eq. /kg ECM. Fertilizer production accounted for 51% of non-renewable energy use, electricity generation and concentrate feed production both contribute to 18% of FFD and diesel consumed by farm machinery and transportation was nearly 10.5%.

3.2.Lameness scenarios

The difference in the environmental impact between baseline and the lameness scenarios (Table 6) showed that severity (modelled by milk decrease and weight loss) was more important than prevalence for all impact categories. The maximum increased GWP due to lameness was estimated to be 7.76% greater than S_0 in S_6 . AP, EP and FFD were estimated to increase by around 9%. Lameness can reduce feed consumption; the unit of feed use efficiency is expressed as kg ECM per kg feed (Table 7), which is an effective indicator to measure the required feed to produce certain amount of milk with the same quality, with the reduced feed use efficiency becoming more significant as lameness increased. Allocation is applied in order to deal with the excess feed (mainly silage). When considered at the whole farm level, allocation of excess feed had a negligible effect on all of the environmental impact indicators, however, as expected the reduced feed use efficiency was lower to half

comparing to scenarios without excess feed allocation. Feed usage efficiency (kg ECM/kg feed) in scenario without excess feed allocation was estimated to increase by just over 8.6% in the maximum lameness scenario. In all cases the rank order of increase in impact per unit ECM was $S_0 < S_1 < S_3 < S_5 < S_2 < S_4 < S_6$.

4. Discussion

The activity data for S_0 were from the farm survey, but there was no information about lameness recorded so it was assumed that S_0 represented a farm with typical lameness of 15%. This is less than the UK average, but is reasonable given the herd size and the fact that (Haskell et al., 2006) found confinement systems tend to have a greater lameness prevalence (40%) than grazing system (15%), also supported by (Fabian et al., 2014). As the environmental performance of S_0 was consistent with results of other studies (Casey and Holden, 2005; Guerri et al., 2013; Yan et al., 2013b) this suggests that it is a representative baseline from which to assess the relative impact of increased lameness. The effect of lameness on milk reduction in grazing system is reported to be greater than for confinement systems (Table 4) (Hernandez-Mendo et al., 2007), perhaps because of the need for greater animal mobility during grazing and to access milking facilities. As herd sizes increase due to removal of milk quota (Kempen et al. 2011) and in the case of Ireland due to government policy (Department of agriculture, 2010), it can be expected that $S_2 - S_4$ represent the lameness that might be expected in the near future because as

commercial dairy farms increase herd size they tend to suffer more severe lameness (Barker et al., 2010; Barnes et al., 2011).

The increased global warming potential, acidification potential and eutrophication potential in S_1 , S_3 and S_5 are less than 3% of the original level in S_0 , and the difference between the scenario pairs by severity at a given prevalence (Table 6) suggests that preventing severe lameness offers real potential for minimizing the environmental impacts of a dairy farm. However the differences between S_1 - S_2 , S_3 - S_4 and S_5 - S_6 indicated that controlling prevalence is also important for minimizing lameness related environmental impacts. The proportional differences between severity scenarios (S_1 - S_2 , S_3 - S_4 and S_5 - S_6) were reduced to less than 3 fold as prevalence increase, which indicates the benefit of real time lameness management reduce as the lameness prevalence increase. In order to prevent cows developing serious lameness, early detection and subsequent treatment of lameness is necessary (Pastell and Kujala, 2007).

In the case of grazing systems, all members of the herd are observed usually twice per day during milking, but with the increase in automation, this level of observation is going to be reduced. Early detection can be achieved by providing information about cow health before clinical symptoms can be observed (Hogeveen et al., 2010). For lameness detection, continuous monitoring of hoof status, which is impossible to do manually, can be achieved using farm-based Information and communication technology (ICT) systems (Nikkilä et al., 2010; Raghuprasad et al., 2013) with

integrated motion sensors. Such technology has been demonstrated for monitoring lameness and to facilitate management decision for minimum economic loss (Alsaad et al., 2012; Flower and Weary, 2006; Gibbons et al., 2014; Pastell and Kujala, 2007). Comparing the two high lameness prevalence scenarios S_5 and S_6 in Table. 6, the theoretical consequences of early detection of lameness related environmental impacts could be greater than 5% for GWP and 6% for feed use efficiency, 7% for AP, EP and FFD. The mitigation capacity from real time management offers environmental benefits for dairy farms with serious lameness issues. In general, the increased impacts for AP, EP, FFD and feed usage efficiency in severe lame scenarios are around 4 times the impacts in less severe scenarios.

Comparing the impact indicators (Table. 6), lameness has a similar effect by increasing all environmental impacts of dairy farm. However, the regional impacts (AP and EP) are relatively more sensitive to lameness than the global impact (global warming). Dairy farming is dependent on local ecosystem services (Ogilvy, 2015). Acidification and eutrophication can cause a significant negative effect by decreasing services such as water quality, provisioning (grass) and nutrient cycling. (MEA, 2005). Reducing ecosystems service will increase the financial cost of production (Nguyen et al., 2012) and jeopardise the sustainability of dairy farms. Real time lameness management can offer a mitigation option for local ecosystem management.

Lameness also has a significant effect on FFD. The theoretical mitigation capacity by

real time lameness management could reduce lameness associated FFD by 9%. As national grid mixes transition to greater proportions of renewable energy (Finn and Fitzpatrick, 2014) the importance of FFD will decrease, but until this happens, investment in minimising lameness will offer a continuous improvement option for farmers that will have both economic and environmental benefits.

Similar to impact indicators, when lameness prevalence was not greatly increased above normal incidence, there was little impact on feed use efficiency (0.8%). In herds with greater lameness prevalence, the feed usage efficiency could decrease by 8%, which is less than the proportional change in AP, EP and FFD. Early detection of lameness can prevent decrease in feed usage efficiency, but as the storage time for surplus silage on a farm can be up to 5 years (Kaiser et al., 2004), from an economic point of view retaining or selling surplus silage could reduce the decrease of lameness related feed usage efficiency by almost 50% (Table 7). The simplified approach to this component of the model might be perhaps misleading because the consequence is not detected in the impact indicators, so there is little need to focus on this issue from an environmental point of view.

According to emission reduction targets for 2020 in Ireland, specified in the Climate Change Response Bill (Schulte et al., 2011), agriculture has to contribute a 30% reduction. Suitable mitigation options for the dairy sector with the have been estimated to achieve up to 15% emission reduction (Schulte et al., 2011).

Implementation of real time lameness management has the potential to make a meaningful contribution to these environmental reduction targets that have so far not been factored into assessments. Such real time management should mean that current herd sizes have emissions similar or smaller than S_0 and larger herds should be controlled to emissions similar to S_1 by early detection and proper treatment. Furthermore, lameness as a significant factor for animal welfare, which has been related to economic impacts (Bruijn et al., 2010), so real time management could not only improve the environmental performance of milk production, but also increases the welfare of dairy cows and offer economic returns (Cha et al., 2010; Ettema and Østergaard, 2006). Future work will look at life cycle costing to quantify whether a win (environment) – win (welfare) – win (economic) outcome is possible with real time lameness management. It also should be noted that this study only focused on Holstein cows, due to the limited information of lameness effect on dairy cows. In future study, it is worth to explore whether other breed cows have the same lameness rate and effect as Holstein cows, which may demand farm survey with big sample size.

5. Conclusions

The study identified the negative environmental impacts of increased lameness in dairy herds that might be expected as herd sizes increase. This means there will be benefits from early detection of lameness and its management that could be achieved by using sensors and ICT systems for farm management. Environmental impact

increases of more than 7-9% for global warming, acidification, eutrophication and fossil fuel depletion depended on lameness prevalence and severity. The maximum feed usage efficiency reduction ranged from 4.8%-8.6%, which was greatly influenced by feed management. Given that increased herd size means a greater cow: handler ratio, a sensor and ICT system is probably the best way to achieve lameness detection in real time so that severity does not escalate and prevalence can be controlled.

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Figure:

Fig. 1 “Cradle to farm-gate” system diagram of modelled dairy farm

Fig. 2 Change of flows by lameness in dairy farm

Table:

Table 1. Characteristics of modelled dairy farm

Item	unit	dairy farm in S₀
Total land occupation	ha	53
Dairy cow	Number	68
Total LU	LU	97
Total milk Output	L	372580
Concentrate feed	t	75
Silage ^a	t	120
Grass	t	192
Stocking rate	LU/ha	1.8
Fertiliser (CAN)	t	18
Compound fertiliser N-P-K (24-2.2-4.5)	t	4
Compound fertiliser N-P-K (24-2.5-5)	t	6
Compound fertiliser N-P-K (24-2.5-10)	t	6
Electricity	kWh	27048
Diesel ^b	L	2639

a: It is assumed that 25% of harvested DM is reduced for silage yield

b: on-farm diesel use is 2602 L

Table 2. Ingredients and proportion of concentrate feed

Ingredients	Proportion (g/kg DM)	Origin
Beet pulp	280	EU (Germany, France, Poland and others)
Palm kernel oil	10	Malaysia
Maize	100	EU (France, Italy, Romania Germany and others)
Maize gluten	20	EU (France, Italy, Romania Germany and others)
Molasses	30	EU (Germany, France, Poland and others)
Palm kernel meal	160	Malaysia
Rape meal	80	Germany
Soybean meal	120	Italy
Wheat	200	EU (Germany, France, UK, Poland and others)

Table 3. Methods and emission factors applied in LCA model

Pollutants	Source	Amount	Emission Factor	Reference
Kg CH₄	Enteric	CH ₄ =kg DMI/herd *18.45 * Ym % /55.65	Ym =6.5%	(IPCC, 2006)
	Storage	CH ₄ =Σ LU _i * EF _i	Animal specified EF	(Duffy et al., 2014)
	Pasture	CH ₄ = (12+0.07+6.8)/3 * V _{slurry}	Season dependent EF	(Chadwick et al., 2000)
Kg CO₂-eq.	Diesel use	CO ₂ -eq.= l diesel * EF	Provided by Gabi	(PE-International, 2012)
	Electricity use	CO ₂ -eq.= kWh * EF	Provided by Gabi	(PE-International, 2012)
Kg N₂O direct	Storage	N ₂ O = (M _{N in liquid} * N _{direct} % * 0.001+ M _{N in solid} * N _{direct} % * 0.02) * 44/28	EF _{liquid} N ₂ O = 0.001 EF _{solid} N ₂ O = 0.02	(Duffy et al., 2014)
	Pasture	N ₂ O = M _{N in pasture} * N _{direct} % * 0.02 * 44/28	EF _{pasture} N ₂ O = 0.02	(Duffy et al., 2014)
Kg N₂O indirect	Fertilizer	N ₂ O = M _{N in fertilizer} * N _{direct} % * 0.01 * 44/28	EF _{fertilizer} N ₂ O = 0.01	(Duffy et al., 2014)
	Spreading	N ₂ O = M _{N in manure} * 0.01 * 44/28	EF _{spreading} N ₂ O= 0.01	(IPCC, 2006)
	Storage	N ₂ O = (M _{N in liquid} + M _{N in solid}) * 0.362 * 0.01 * 44/28	EF _{liquid} NH ₃ = 0.01 EF _{Solid} NH ₃ = 0.01	(Duffy et al., 2014)
	Pasture	N ₂ O = M _{N in pasture} * 0.056* 0.01 * 44/28	EF _{pasture} NH ₃ = 0.01	(Duffy et al., 2014)
	Pasture	N ₂ O = M _{N in pasture} * 0.1 * 0.025 * 44/28	EF _{pasture} NO ₃ = 0.025	(Duffy et al., 2014)
	Fertilizer	N ₂ O = M _{N in fertilizer} * 0.016* 0.01 * 44/28	EF _{fertilizer} NH ₃ = 0.01	(Duffy et al., 2014; Hyde et al., 2003)
	Fertilizer	N ₂ O = M _{N in fertilizer} * 0.1 * 0.025 * 44/28	EF _{fertilizer} NO ₃ = 0.025	(Duffy et al., 2014; Hyde et al., 2003)

V_{slurry}: Volume of slurry

M: Mass

N_{direct} %: percentage of N contributed to direct N₂O emission

Pasture: Animal excretion on the field

Table 4. Effect of lameness on production

Production system	Confinement based					Pasture based	Mixed ^a		
Country	US 1	Finland 1	Spain 1	UK 1	Canada 1		UK 2	France 1	
Time of experiment	NS	220 days	8 months	60 days	106 days		18 months	1988-1998	
Lameness type	LCS1-4	LCS 4&5	LCS 4&5	Foot lesion	Hoof Injury		NS	Foot lesion	Hock Lesion
Number of cows	193 -197	80	120	143	72		900	551	
Breed	Holstein	Ayrshire ^b	Holstein	Holstein	Holstein		Holstein	Holstein	
Period of disease (day)	NS	NS	NS	7.7 ^c	28 ^d		NS	60	131
Total feed intake loss (kg)	NS	NS	NS	NS	NS	NS	NS	27.8	48.1
Total milk yield loss (kg)	NS	NS	NS	NS	NS	NS	360	76	108.6
R _{milk/feed}	NS	1.9-4.3	1.7-3.7	NS	NS	NS	NS	1.79	2.26
DMI loss-max (kg/day)	NS	3.3	1	1.57	NS	NS	NS	NS	NS
DMI loss-min (kg/day)	NS	1.7	0.3	1.57	NS	NS	NS	NS	NS
Milk loss-max (kg/day)	5.5	2.6	3.7	NS	3.44	3.72	1.80 ^e	NS	NS
Milk loss-min (kg/day)	1.1	0.6	0.5	NS	2.16	3.08	0.52 ^e	NS	NS
Change of F% and Protein	< 2%	NS	NS	NS	NS	NS	NS	NS	NS

Reference: US 1 (Juarez et al., 2003), Finland 1 (Norrington et al., 2014), Spain 1(Bach et al., 2007), UK 1(Gonzalez et al., 2008), Canada 1(Hernandez-Mendo et al., 2007), UK 2(Green et al., 2002), France 1 (Bareille et al., 2003)

a: France 1: Access to pasture during spring and summer, mix diet based on maize silage during autumn and winter. UK 2: Cows were at pasture in the summer months and fed on grass with concentrate ration fed in the parlor. During the winter, cows were housed in cubicles and fed a concentrate ration in the parlor and conserved forage in yards. **b:** The predominant breed was Ayrshire, but the examined group also included 3 Holsteins, 2 Brown Swiss, 1 Jersey, and 1 Finncattle. **c:** 7.7 day for average time from onset to diagnosis. **d:** 4 week period on pasture. **e:** the maximum and minimum value is for milk loss during 305 day lactation period. NS=No specified

Table 5. Scenarios and parameters of lameness

Scenario	Prevalence of lameness	Severity of lameness lameness effect	Milk reduction (kg milk/day per cow)	Weight loss
S ₀	15%	N/A	N/A	N/A
S ₁	28%	minimum	0.52	0.67%
S ₂	28 %	maximum	1.80	3.50%
S ₃	49 %	minimum	0.52	0.67%
S ₄	49 %	maximum	1.80	3.50%
S ₅	70%	minimum	0.52	0.67%
S ₆	70%	maximum	1.80	3.50%

Table. 6 The change of percentage and value of environmental impacts of modelled dairy farm

Impact Categories	Unit	S0	S1	S2	S3	S4	S5	S6
Global Warming Potential	kg CO ₂ -eq. /kg ECM	1.18	1.19(0.68%)	1.21(2.43%)	1.20(1.37%)	1.24(4.81%)	1.20(2.07%)	1.42(7.76%)
Acidification Potential	g SO ₂ -eq./kg ECM	8.04	8.11(0.83%)	8.28(2.94%)	8.18(1.68%)	8.5(6.06%)	8.25(2.54%)	8.8(9.38%)
Eutrophication Potential	g PO ₄ ³⁻ -eq. /kg ECM	8.00	8.06(0.82%)	8.23(2.94%)	8.14(1.67%)	8.5(6.05%)	8.20(2.54%)	8.6(9.37%)
Fossil Depletion	g oil-eq. /kg ECM	57.5	58.0(0.76%)	58.1(2.91%)	57.3(1.68%)	61.0(5.96%)	59.0(2.45%)	62.8(9.17%)
Feed Usage	kg ECM /kg feed	1.007	0.999(0.8%)	0.979(2.9%)	0.991(1.7%)	0.949(5.7%)	0.982(2.5%)	0.920(8.6%)

Table. 7 Feed usage change with extra feed allocation and non-extra feed allocation

Feed usage(kg ECM /kg feed)	S0	S1	S2	S3	S4	S5	S6
With Feed allocation	1.007	1.003(0.4%)	0.991(1.6%)	0.999(0.8%)	0.975(3.2%)	0.995(1.2%)	0.958(4.8%)
Without feed allocation	1.007	0.999(0.8%)	0.979(2.9%)	0.991(1.7%)	0.949(5.7%)	0.982(2.5%)	0.920(8.6%)