Supplementary material S1

Feed ration

The average studied ration for the dairy cow were an aggregated ration of daily rations optimised for replacement heifers (divided into four growth stages), first calvers (10400 kg ECM/lactation period) and older cows (11500 kg ECM/lactation period) with a 334-day lactation period (divided into four phases) and 74-day dry period (divided into two phases). Different rations were optimised for indoor and grazing periods and combined to an annual ration accounting for the length of the grazing period (Supplementary Table S1).

Manure

Nutrients in manure were based on NorFor calculations for each ration with the addition of nutrients in straw for bedding (daily addition of straw with 1 kg dry matter (DM) for cows, 0.85 and 1.6 kg DM for older and younger heifers, respectively in indoor periods). To estimate N in applied manure, ammonia (NH3) and nitrous oxide (N2O) emissions from manure in animal house and storage were deducted with 56 g NH3-N/kg N excreted from animal house, 31 g NH3-N/kg N excreted and 5 g N2O-N/kg N excreted from storage of slurry and 135 g NH3-N/kg N excreted from heifer deep bedding system (house and storage), according to Karlsson and Rodhe (2002) and Ngwabie (2009). The NH3 emission factor used when estimating indirect N2O-emissions (20% NH3-Nof applied N as manure) was the average from a detailed calculation with the official software program SiM (Jordbruksverket, 2012; Linder 2001) for three realistic scenarios with some variations in spreading date, crop species and spreading techniques (e.g. band spreading and incorporation time of slurry) resulting in 17-22% NH3-Nof applied N as manure. Data on emitted NH3 and N2O from excreta deposited on pasture were according to Naturvårdsverket (2009) (NH3) and IPCC (2006) (N2O). Crop-available N (i.e. utilisation rate) used in the present study follow recommendations in Jordbruksverket (2009), which are lower than the calculated estimates but are used in practice as there is large variation in NH3 emissions caused by actual weather conditions, soil structure, etc.

Crop production at farm

Regional yields of annual crops were based on official statistics for a six year period (2005-2010) (Jordbruksverket, 2011). Yields data for highly productive grass/clover and forage maize were obtained from regional extension services, as there is a lack of good quality statistics for these crops. However, national statistics (1989-1992) were used to correlate yields of temporary grassland between the regions. Yields and share of DMI from pasture were estimated according to Frankow-Lindberg (1988) and not differentiated between regions.

The average amount of applied manure (25 tonne/ha and occasion) equalled about 100 kg total N before application losses of NH3 and was assumed for all crops except forage maize, for which it was almost doubled to simulate actual practice. Manure applications to temporary grassland were set to five occasions during a three-year period (four occasions for normal quality silage in West and North regions). Annual crops received one application per season. The general crop-specific N rates were reduced due to N release from pre-cropped grassland by 18 kg N/ha (grass-dominated) and 40 kg N/ha (grass with 20% clover content) for spring crops and due to N release from long-term use of manure by 20 kg N/ha (South, S West and S East region) and 15 kg N/ha (West and North) based on stocking rate, in accordance with the national recommendations published annually (Jordbruksverket, 2009). Final N rates were supplied first as crop-available N in manure and the remaining part as synthetic fertiliser (ammonium nitrate), and thus spring barley in all regions only received N from manure, except in South region. Phosphorus and potassium were supplied with manure and fertilisers to meet crop needs (Jordbruksverket, 2009). NH3 emissions from application of ammonium nitrate fertilisers considered for the indirect N2O emissions were according to Hutchings *et al.* (2001).

GHG emissions from production of ammonium nitrate were set to 5.27 kg CO2e/kg N as used by Wallman *et al.* (2011), which is based on the assumption that 60% is produced in fertiliser plants (e.g. Yara) with best available technique (BAT) to refine N2O and that 40% is from European average fertiliser plants.

LCA data for pesticide use were obtained from Flysjö *et al.* (2008) and Wallman *et al.* (2011). Seed were calculated as a net flow, i.e. subtracted from the total yield. Data on diesel use for various field operations in annual crop production were estimated per hectare for each species, irrespective of region (Wallman *et al.*, 2011) except for harvest and transport, where diesel use was correlated to crop yield. Lubricant oil use was assumed to be 0.0024 kg/MJ diesel (Flysjö *et al.*, 2008). An extra 10% of diesel used on the farm in connection with crop cultivation (e.g. crop inspection) was added per crop. No regional variation in amount of seeds for each crop species was assumed, due to the low impact. Cropland requirements for feed production at farm level were within national legislation limits for stocking rates (i.e. maximum 22 kg P/ha, which approximately corresponds to 1 cow including replacement) and thus realistic to use.

Silage production

Grass/clover leys are normally cut three times per year and three cuts were thus assumed for all regions except North, where two cuts reflected the regional standard. One additional cut was assumed for production of the higher nutrient quality silage except in West region, where the higher quality silage were produced solely by better optimisation of harvest time and management, according to advisors in the regional extension service. In S East a fourth cut was assumed only every third year due to occasional droughts. Normal harvest practice for temporary grassland in Sweden is that the sward is mown and conditioned and left drying for one or two days (depending on the weather) in a swathe. When the DM content is around 30% the crop lifted and chopped with a forage harvester.

Assumed losses of silage DM in a bunker silo (mainly as respiration) were based on Honig (1980) and Seibt (1991) for grass/clover silage (13%) and according to Svensson ( 2010) for maize silage (5%). DM losses as discarded feed after opening of silo, spill from feeding and silage left by animals were based on Seibt (1991) and Lindstrøm *et al.* (2009). Data on the use of silage additives and plastics were taken from Strid and Flysjö (2007).

Diesel use in silage production was estimated to be 48-68 l/ha and year. This included field operations to establish the ley in a nurse crop (6.5 l/ha, which equalled 50% of diesel used in the nurse crop divided over three years), spreading of fertiliser 2-4 times per year (1.5 l/ha), spreading of manure (0.7 l/Mg manure) and use of the mower conditioner (7 l/ha per cut) (Edström *et al.*, 2005; Gunnarsson *et al.*, 2007; Arvidsson *et al.*, 2010; Wallman *et al.*, 2011). Diesel use for the forage harvester, transport from field to storage and packing of the bunker silo added up to a total of 3.2 l/Mg DM (forage harvester 1.7 l diesel/Mg DM, transport 1.0 l diesel/Mg DM, packing of bunker silo 0.5 l diesel/Mg DM (Jonsson, 1986; Wiersma and Holmes, 2000; Edström *et al.*, 2005; Gunnarsson *et al.*, 2007; Buckmaster, 2009 ; Hörndahl, 2012)). Diesel use for feed out-take from the silo and loading was set to a total of 12.3 l/Mg DM stored silage (5.6 l diesel/Mg DM is for outtake and loading and 6.7 l diesel/Mg DM for mixing and feeding) (Hörndahl, 2007; Hörndahl, 2012).

Purchased concentrate products

CF and land requirements for the major ingredients in the concentrate products are shown in Table 1S. For feed ingredients not included in the LCA feed database (e.g. triticale), CF was estimated as for farm grown crops but without manure. All grain included in concentrate products was assumed to have been cultivated in the immediate vicinity of each feed industry. The CF of the concentrate products included in the present study varied between 0.47-0.83 kg CO2e/kg product and land use between1.6-2.1 m2/kg and year.

References

Arvidsson J, Hillerström O, Keller T, Magnusson M and Eriksson D 2010. Dragkraftsbehov och maskinkostnad för olika redskap och bearbetningssystem (Tractive power and costs for various machinery and cultivation systems. Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala, Sweden.

Buckmaster DR 2009 Equipment matching for silage harvest. American Society of Agricultural and Biological Engineers 25, 31-36.

Edström M, Pettersson O, Nilsson LG and Hörndahl T 2005. Jordbrukssektorns energianvändning (Energy use in agriculture). Swedish Institute of Agricultural and Environmental Engineering, Uppsala, Sweden.

Flysjö A, Cederberg C and Strid I 2008. LCA-foderdatabas för konventionella fodermedel (LCA-feed data base of conventional feeds). Gothenburg, Sweden.

Frankow-Lindberg BE 1988. Betesvallens avkastning och tillväxtmönster vid olika intensivt utnyttjande (Pasture growth and growth pattern when cut at different frequencies). Swedish University of Agricultural Sciences, Dep of Plant Husbandary, Uppsala, Sweden.

Gunnarsson C, Spörndly R, Rosenqvist H, Sundberg M and Hansson P-A 2007. Optimeriing av maskinsystem för skörd av ensilage med hög kvalitet (Optimisation of machinery systems for high quality forage harvest). Swedish University of Agricultural Sciences, Dep. of Biometry and engineering, Uppsala, Sweden.

Honig H 1980. Mechanical and respiration losses during pre-wilting of grass. Proceedings from the Occasional Symposium No.11 Forage conservation in the 80's, 201-204.

Hutchings NJ, Sommer SG, Andersen JM and Asman WAH 2001. A detailed ammonia emission inventory for Denmark. Atmospheric Environment 35, 1959-1968.

Hörndahl T 2007. Energiförbrukning i jordbrukets driftsbyggnader (Energy use in farm buildings). Swedish University of Agricultural Sciences, Department of Agricultural Biosystems and Technology, Alnarp, Sweden.

Hörndahl T 2012. Projekt Energieffektivisera gården (utfodring och blandning av fullfoder). Swedish University of Agricultural Sciences, Dep of Biosystems and Technologies, Alnarp, Sweden.

IPCC 2006. N2O Emissions from managed soils, and CO2 emissions from lime and urea application. In IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 Agriculture, Forestry and Other land use. (ed. HS Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe),. National Greenhouse Gas Inventories Program IGES, Japan, 11.15-11.24.

Jonsson B 1986. Avverkning och Arbetsbehov vid ensilering (Harvest and labour requirement at ensiling). Swedish Institute of Agricultural and Environmental Engineering (JTI), Uppsala, Sweden.

Jordbruksverket 2009. Riktlinjer för gödsling och kalkning (Guidelines for fertilisation and limeing). Jordbruksverket (Swedish Board of Agriculture), Jönköping, Sweden.

Jordbruksverket 2011. Jordbruksverkets statistikdatabas (Statistics Database from the Swedish Board of Agriculture). Retrieved on 18 June 2013 from <http://www.sjv.se/etjanster/etjanster/statistikdatabas>

Jordbruksverket 2012. Dataprogrammet STANK in MIND (Software tool for agriculture nutrient balancec etc.). Retrieved on 18 June 2013 from <http://www.jordbruksverket.se/amnesomraden/odling/vaxtnaring/cofotenstankinmind/omstankinmind.4.6beab0f111fb74e78a78000102.html>.

Karlsson S and Rodhe L 2002. Översyn av Statistiska Centralbyråns beräkning av ammoniakavgången i jordbruket - emissionsfaktorer för ammoniak vid lagring och spridning av stallgödsel *(Emmission factors used for ammonia volatiled in the management of manure, used in calculations by the Statistics Sweden)*. Swedish Institute of Agricultural and Environmental Engineering, Uppsala, Sweden.

Linder J 2001. STANK - the official model for input/output accounting on farm level in Sweden, Proceedings of the Food 21 workshop on Element balances as a sustainable tool workshop, 16-17 March 2001, Uppsala, Sweden, p. 35.

Lindstrøm J, Green O and Johnsen J 2009. Tab ved håndtering af ensilage på bedriften (Handling losses of silage at farm). Dansk Landbrugsrådgivning, Århus, Denmark.

Naturvårdsverket 2009. National Inventory Report 2009 Sweden - submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Naturvårdsverket (Swedish Environmental Protection Agency), Stockholm, Sweden.

Ngwabie NM 2009. Multi-location measurements of GHG and emissonrates of methane and ammonia from a naturally - ventilated barn for dairy cows. Biosystems Engineering 103, 68-77.

Seibt J 1991. Ensileringsförlusternas beroende av grödans torrsubstans i olika silotyper (The relationship between silage losses and herbage dry matter in different types of silos). Swedish UNiveresity of Agricultural Sciences, Dep of Animal Nutrition and Management, Uppsala, Sweden.

Strid I and Flysjö A 2007. Livscykelanalys (LCA) av ensilage - en jämförelse av tornsilo, plansilo och rundbal (LCA of silage - comparison of tower silo, bunker silo and round bales). Swedish University of Agricultural Sciences, Uppsala, Sweden.

Svensson E 2010. Effekt av skördetidpunkt och tillsatsmedel på kvalitet och lagringsstabilitet hos majsensilage lagrat under olika tidsperioder (Effects of harvest time and additive on chemical composition and aerobic stability of maize silage stored during different time periods). Swedish University of Agricultural Sciences, Skara, Sweden.

Wallman M, Berglund M and Cederberg C 2011. LCA-data för fodermedel (LCA-data for feedstuffs). Retrieved on 18 June 2013 from http://www.sikfoder.se/Sv/Sidor/default.aspx

Wiersma DW and Holmes BJ 2000. Estimating the Weight of Forage in a Forage Wagon. In Focus on Forage, pp. 1-2. University of Winsconsin-Madison, Madison, WI, USA.

Supplementary Table S1 Characteristics of regional feed rations

|  |  |
| --- | --- |
| Region | Feed ration |
| North  | Grass/clover silage (temporary grassland with 20% clover)Purchased concentrate mix with grain from central Sweden, i.e. longer transport1 from feed industry.Grazing of temporary grassland constitutes 50% of cow forage DMI2 during summer3 Heifer average grazing period: young4 35 days, older5 120 days |
|  |  |
| West  | Grass/clover silage (temporary grassland with 20% clover)Locally produced horse bean (Vicia faba var. equina) (3 kg/cow\*day) to replace other protein concentrate. Grain locally produced. Grazing of temporary grassland constitutes 25% of cow forage DMI during summerHeifer average grazing period: young 0 days, older 145 days  |
|  |  |
| S West  | Grass-dominated silage (temporary grassland with 5% clover)Grain locally produced, purchased protein concentrateMinor DMI from pasture6 Heifer average grazing period: young 35 days, older 135 days |
|  |  |
| S East  | Grass/clover silage (temporary grassland with 20% clover)Maize silage, 19-28 % of total forage DMMinor DMI from pasture Heifers average grazing period: young 90 days, older 150 days |
|  |  |
| South | Grass-dominated silage (temporary grassland with 5% clover)Pressed sugar beet pulp silage, grain locally produced, purchased protein concentrateMinor DMI from pastureHeifers average grazing period: young 90 days, older 150 days |

1) 3 times longer than in other regions, i.e. 300 km

2) Dry matter intake

3) 8 h/day for 3 months

4) <12 months

5) >12 months

6) Outdoor mainly for exercise 6 h/day for 4 months

 Supplementary Table S2 GHG emissions and land requirement per kg product in the feed industry for major ingredients in purchased concentrate products.

|  |  |  |  |
| --- | --- | --- | --- |
|   | GHG emissions | Land requirement | In product |
| Feedstuff | g CO2e | m2/year | % |
| Barley, oats1 | 365-4323 | 2.1-2.6 | <5-35 |
| Winter wheat, triticale1,2 | 379-3933 | 1.7-2 | <5-40 |
| Grain bran and middlings1 | 114-1284 | 0.4 | <5-15 |
| Dried beet pulp1 | 650 | 0.7 | <5-30 |
| Rape seed whole1 | 979 | 3.3 | <5-20 |
| Rape seed meal1 | 619-6555 | 1.7 | 10-45 |
| Distiller´s dried grain1,6 | 231-251 | 1 | 5-15 |
| Soy meal (Brazil) 1,7 | 578 | 3.3 | <5-40 |
| Fatty acids1 | 793 | 0 | ≤5 |
| Palm kernel expeller1 | 849 | 0.6 | <5-20 |
| Horse bean *(Vicia faba)*2 | 308 | 4.7 | - |

1) Flysjö et al. 2008 and Wallman et al. 2011

2) Calculations based on Wallman et al. 2011 and yield statistics

3) Variation depending on yield, species, variety and region

4) Variation depending on distance from closest mill to feed factory

5) Variation depending on processing data and distance to feed industry

6) Agrodrank™ 90, variation depending on distance to feed industry

7) Assumed 50% from South and 50% from Center-West regions

Supplementary Table S3 Greenhouse gas emissions from the life cycle of feed rations (cradle to feed consumed) optimised for cows with an annual milk yield of 9900 kg ECM including replacement heifers and feed losses (land use and land use change not included).

|  |  |  |
| --- | --- | --- |
|   |   |  kg CO2e/kg ECM incl heifers1 (% of total)  |
|   | Regions | North | West | S West | S East | South |
| Normal nutrient quality silage7 | **Roughages** | **0.292** | **63%** | **0.298** | **69%** | **0.332** | **63%** | **0.310** | **70%** | **0.295** | **71%** |
| Grass/clover silage | 0.247 | 53% | 0.265 | 62% | 0.301 | 57% | 0.224 | 51% | 0.227 | 55% |
| Pasture2 | 0.045 | 10% | 0.033 | 8% | 0.031 | 6% | 0.035 | 8% | 0.036 | 9% |
| Straw |   |  | 0.000 | 0% | 0.000 | 0% | 0.000 | 0% | 0.000 | 0% |
| Maize silage |   |   |   |   |   |   | 0.052 | 12% |   |   |
| Beet pulp silage3 |   |   |   |   |   |   |   | 0.032 | 8% |
| **Concentrate** | **0.172** | **37%** | **0.131** | **31%** | **0.199** | **37%** | **0.132** | **30%** | **0.121** | **29%** |
| Grain | 0.056 | 12% | 0.061 | 14% | 0.041 | 8% | 0.039 | 9% | 0.052 | 13% |
| Protein concentrate4 | 0.114 | 25% | 0.036 | 8% | 0.157 | 30% | 0.093 | 21% | 0.066 | 16% |
| Horse bean5 |   |   | 0.031 | 7% |   |   |   |   |   |   |
| Mineral and lime6 | 0.002 | 0.4% | 0.002 | 0.4% | 0.001 | 0.2% | 0.000 | 0.0% | 0.003 | 0.8% |
| **Total** | **0.463** |  | **0.429** |  | **0.531** |  | **0.442** |  | **0.417** |   |
| Higher nutrient quality silage8 | **Roughages** | **0.305** | **64%** | **0.311** | **75%** | **0.374** | **68%** | **0.334** | **75%** | **0.334** | **76%** |
| Grass/clover silage | 0.261 | 55% | 0.279 | 67% | 0.343 | 62% | 0.247 | 56% | 0.272 | 62% |
| Pasture | 0.044 | 9% | 0.033 | 8% | 0.031 | 6% | 0.035 | 8% | 0.035 | 8% |
| Straw |   |  | 0.000 | 0% | 0.000 | 0% | 0.000 | 0% | 0.000 | 0% |
| Maize silage |   |   |   |   |   |   | 0.053 | 12% |   |   |
| Beet pulp silage |   |   |   |   |   |   |   | 0.026 | 6% |
| **Concentrate** | **0.168** | **36%** | **0.104** | **25%** | **0.178** | **32%** | **0.109** | **25%** | **0.104** | **24%** |
| Grain | 0.055 | 12% | 0.058 | 14% | 0.037 | 7% | 0.032 | 7% | 0.040 | 9% |
| Protein concentrate | 0.110 | 23% | 0.025 | 6% | 0.139 | 26% | 0.076 | 17% | 0.060 | 14% |
| Horse bean |   | 0.019 | 4% |   |   |   |   |   |   |
| Mineral and lime | 0.002 | 0.5% | 0.002 | 0.6% | 0.001 | 0.3% | 0.000 | 0.0% | 0.003 | 0.7% |
| **Total** | **0.473** |  | **0.415** |  | **0.552** |  | **0.443** |  | **0.437** |  |

1) 1 cow includes 0.98 replacement heifer.

2) Temporary pasture, pasture only for exercise and semi-natural pasture

3) Pressed beet pulp from sugar industry. 27% DM content

4) Purchased mix incl. soy meal. rape seed meal. distillers dried grain. dried beet pulp. other by-products from cereal and fat industry. minerals and grain. All grain are withdrawn and presented in feed category "Grain".

5) *Vicia faba* var*. equina*

6) In addition to that included in purchased mix

7) Energy=10.5-10.8 MJ/kg DM. CP=136-155 g/kg DM. NDF=490-518 g/kg DM

8) Energy=11.2-11.5 MJ/kg DM. CP=150-177 g/kg DM. NDF=461-485 g/kg DM

Supplementary Table S4 Land requirement from the life cycle of feed rations with two different silage quality (cradle to intake by cattle) optimised for cows with an annual milk yield of 9900 kg ECM including replacement heifers and feed waste.

|  |  |  |
| --- | --- | --- |
|  |  | Land requirement m2/kg ECM and year incl heifers1 (% of total) |
|  | Regions | Crop land |  | Semi naturalgrassland |
|  |  | roughages | grain | Concentrate2 | TOTAL |  |
| Normal nutrientquality silage3 | North | 1.17 | 69% | 0.33 | 19% | 0.19 | 11% | 1.69 |  | 0.06 |  |
| West | 0.96 | 47% | 0.49 | 24% | 0.60 | 29% | 2.05 |  | 0.11 |  |
| S West | 0.96 | 63% | 0.26 | 18% | 0.29 | 19% | 1.51 |  | 0.07 |  |
| S East | 0.99 | 66% | 0.23 | 15% | 0.28 | 19% | 1.50 |  | 0.21 |  |
| South | 0.81 | 59% | 0.31 | 22% | 0.25 | 18% | 1.37 |  | 0.08 |  |
| Higher nutrientquality silage4 | North | 1.15 | 69% | 0.33 | 20% | 0.20 | 12% | 1.68 |  | 0.06 |  |
| West | 1.01 | 55% | 0.47 | 26% | 0.36 | 19% | 1.83 |  | 0.11 |  |
| S West | 0.97 | 66% | 0.24 | 17% | 0.25 | 17% | 1.47 |  | 0.07 |  |
| S East | 1.04 | 71% | 0.19 | 13% | 0.23 | 16% | 1.46 |  | 0.21 |  |
| South | 0.89 | 66% | 0.24 | 18% | 0.22 | 16% | 1.35 |  | 0.08 |  |

1)1 cow includes 0.98 replacement heifer

2) incl horse bean (*Vicia faba* var. *Equina*), rape seed and pressed sugarbeet pulp in West and South region

3) Energy=10.5-10.8 MJ/kg DM, CP=136-155 g/kg DM, NDF=490-518 g/kg DM

4) Energy=11.2-11.5 MJ/kg DM, CP=150-177 g/kg DM, NDF=461-485 g/kg DM

Supplementary Table S5 Increase in greenhouse gas emissions (GHG) for regional dairy rations when including GHG emissions for land use change (LUC) from Brazilian soy production. Results presented as % increase for two different LUC factors and for rations including normal (N) or higher (H) nutrient quality silage.

|  |  |  |  |
| --- | --- | --- | --- |
|  | LUC-factor1 | 2.722 | 7.383 |
|  | Silage quality | N | H | N | H |
| Regions |  |  |  |  |
| North | 9 | 9 | 27 | 27 |
| West | 12 | 5 | 39 | 15 |
| S West | 7 | 6 | 23 | 19 |
| S East | 21 | 17 | 65 | 53 |
| South | 12 | 11 | 39 | 34 |

1) kg CO2eq/kg soy meal

2) Leip et al. (2010)

3) Gerber et al. (2010)