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LIFE BEEF CARBON: A common framework for quantifying Western European beef farms carbon footprints

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**Supplementary material**

Supplementary Table S1 Inventory analysis of studies carried out in Ireland, France, Spain and Italy modelling greenhouse gas (GHG) emissions from beef farming systems

| Nations | Project type | Model type and study goal(s) | Farm description and carbon (C) footprint1 | GHG Emission factors | Other impacts |
| --- | --- | --- | --- | --- | --- |
| Ireland | National research project | Casey and Holden (2006) developed a cradle to gate life cycle assessment (LCA) model for suckler beef systems – The studies main aim was to estimate GHG emissions from a typical beef farm. The study also tested mitigation strategies using scenario analysis. | National average farm gross C footprint  11.3 kg CO2e/kg LW. | IPCC (1996) and literatures sources | No |
| Ireland | National research project | Foley et al. (2011) developed BEEFGEM a whole farm GHG model for suckler beef – The goals of this study were to assess the GHG emissions and profitability of alternative suckler beef systems. | National average farm gross C footprint  23.1 kg CO2e/kg CW.  Research farms gross C footprints scenario range  18.9-22.0 kg CO2e/kg CW. | Ireland national GHG inventory method, IPCC (2006) and literatures sources | No |
| Ireland | National research project | Clarke et al. (2013) developed a cradle to farm-gate LCA model for suckler beef – The study examined GHG emissions from grass-based beef farms differing in stocking rate and type of male i.e. bull or steer. | Research farm gross C footprints scenario range  20.1-23.1 kg CO2e/kg CW. | Ireland national GHG inventory method, IPCC (2006) and literatures sources | No |
| Ireland | National research project | Crosson et al. (2013) developed Carbon Audit, which is a certified whole farm GHG model constructed from BEEFGEM – This studies goal was to quantify GHG emissions from commercial suckler and dairy calf to beef farms with the Irish beef industry. | 200 commercial farms part of the beef quality assurance scheme – 32 000 farms are part of this scheme and are audited every 18 months.  2Gross C footprints range 9.0-14.6 kg CO2e/kg LW. | Ireland national GHG inventory method, IPCC (2006) and literatures sources | No |
| Ireland | National research project | Murphy et al. (2017) applied BEEFGEM a whole farm GHG model for dairy calf to beef systems – The goal of this research was to quantify the effect of diet and slaughter age on GHG emissions and farm profitability. | Research farm gross C footprints range  8.9-14.9 kg CO2e/kg CW. | Ireland national GHG inventory method and literature sources | No |
| France | National research project | Dollé et al. (2011) used GES’TIM a cradle to farm-gate LCA model for French livestock production that is part of the certified tool CAP’2ER – The aim of this review study was to estimate carbon footprints for French beef and sheep meat. | 5 farms representative of national beef farm systems.  Gross C footprints range 11.3-14.0 kg CO2e/kg LW.  3Net C footprints range  6.5-8.5 kg CO2e/kg LW. | French national GHG inventory, IPCC (2006) and literature sources | Yes – Non-renewable energy use |
| France | National research project | Doreau et al. (2011) developed a gate to gate LCA model for beef finishing systems – Goal of this research was to estimate the effect different diets have on GHG emissions from bull beef finishing systems. | Research farm. Gross C footprints range  3.7-5.2 kg CO2e/kg LWG.  Net C footprints range  3.7-4.6 kg CO2e/kg LWG. | Methane emission from cattle was measured and manure emissions were based on IPCC (2006). Literature was used for other sources | No |
| France | National research project | Veysset et al. (2014) used GES’TIM a cradle to farm-gate LCA model for livestock production that is now part of CAP’2ER – Aim was to assess GHG emissions and non-renewable energy use from real-world French farm businesses. | 59 commercial farms. Gross C footprints range 11.0-14.7 kg CO2e/kg LW.  Net footprint ranged from  8.0-12.1 kg CO2e/kg LW. | French national GHG inventory, IPCC (2006) and literature sources | Yes – Non-renewable energy use |
| Italy | European research project; LIFE+ Climate changE-R | Emilia Romagna Agriculture and Fishing (2018) developed a cradle to farm-gate LCA model for beef systems – The aim of this research was to quantify the environmental performance of beef cattle from the Emilia-Romagna region. | 8 commercial Italian farms in Emilia-Romagna. Gross C footprints range  8.8-13.5 kg CO2e/kg LW. | Italian national GHG inventory, IPCC (2006) and literature sources | No |
| Italy | National research project | Boselli (2015) applied CAP’2ER cradle to farm gate LCA model for Italian beef systems – The main goal of this research was to estimate the environmental impact of breeding and finishing beef production systems in Northern Italy. | 30 commercial farms in northern Italy. Gross C footprints range  15.2-37.7 kg CO2e/kg LW finished. | French national GHG inventory, IPCC (2006) and literature sources | Yes – Acidification, Eutrophication, Energy demand, biodiversity, water footprint |
| Spain | National research project | Batalla et al. (2014) developed a cradle to farm gate LCA model for Spanish livestock systems – The goal of this study was to estimate a group of Spanish beef farms GHG emissions. | 5 commercial beef farms in Andalusia. Gross C footprints range  15.3-48.1 kg CO2e/kg CW. | IPCC (2006) and literature sources | No |
| Spain | European research project; Regen farming | del Hierro et al. (2017) developed NAIA a cradle to farm gate LCA model for Spanish livestock systems – The goal of this research was to describe a model to estimate the GHG emissions from meat produced by ruminant livestock in the Basque country. | Model farm in the Basque region. Beef C footprint was not estimated. | Spanish national GHG inventory, IPCC (2006) and literature sources | No |
| All | European research project; Animal Change | Hutchings et al. (2013) developed a farm model to simulate GHG emissions from livestock systems – The aim of this research was to develop a model to simulate GHG emissions from ruminant production systems in Europe, Africa and South America. | National or regional representative livestock farms. Beef C footprint was not estimated. | IPCC (2006) and literature sources | No |

1 Carbon footprint was estimated in kg of CO2 equivalent (CO2e) and related to live weight (LW), live weight gain (LWG) or carcass weight (CW).

2 Gross carbon footprint excludes the removal of carbon by soil (carbon sequestration).

3 Net carbon footprint includes the removal of carbon by soil (carbon sequestration).

Supplementary Table S2 Key nitrogen and greenhouse gas emission factor computations of selected beef farm modelling tools – Carbon Audit, CAP’2ER and Bovid-CO2.

| Emission factor (EF) | Carbon Audit | CAP’2ER | Bovid-CO2 |
| --- | --- | --- | --- |
| N excretion | N excretion (kg/d) = N excreted dung + N excreted urine N excreted dung = (N intake × 0.262) + 0.0091 (Yan et al. 2007). N excreted urine = (N intake × 0.467) - 0.0008 (Yan et al. 2007).  N intake (kg/d) = Feed intake × N concentration of the diet | Default values per animal category adjusted based on the time housing or grazing (Nitrates Directive; European Council, 1991) | Default value per animal category. This was the same for each farm (MAPAMA, 2017) |
| N leaching | N leaching (kg/yr) = (N from fertilizer spreading + N from manure excreted by cattle on pasture + N available from stored manure) × 0.1  (Duffy et al., 2014) | N leaching = N inputs - N outputs + symbiotic fixation + atmospheric deposition - N storage - N volatilization  N inputs = Mineral fertilizers + Concentrate feeds N outputs = live weight | Not taken into account |
| Methane (CH4) from enteric fermentation | CH4 estimated in MJ/d for categories  Grazing = 6.5% of gross energy intake (GEI1; Tier 22; IPCC, 2006)  Indoors = DEI3 × [0.096 + 0.035 SDMI/TDMI4] - 2.298 (FL5 - 1)  (Tier 2; Yan et al., 2000)  Concentrate >90% of DM6 diet = 3% of GEI (Tier 2; IPCC, 2006) | g CH4/kg digestible organic matter = 45.2 – 6.66 × NI + 0.75 × NI2 + 19.65 × PCO – 35 × PCO - 2.69 × NI × PCO where NI = feeding level expressed as a % of BW. PCO = proportion of concentrate feeds in the DM diet.  (Tier 3; Sauvant et al., 2016) | EF dependant on GEI and digestibility. EF adapted from IPCC (Tier 2; MAPAMA, 2017) |
| CH4 from solid manure | kg CH4/animal category per yr = Manure VS excreted7 × 0.67 × B07× ((MCF1 × MS1) + (MCF2 × MS2)) where B0 = 0.24, MCF8 for solid manure system (FYM) is 0.02 and 0.17 for slurry, and MS is proportion of manure handled in storage system (Tier 2 IPCC, 2006; Met Eireann 2013) | Emissions factors for animal categories calculated with IPCC (2006) Tier 2 equation (Non-digestible organic matter× 0.67× B0 × MCF). | Emissions factors by animal category depending on the temperature (Tier 1; IPCC, 2006) |
| CH4 from manure spreading | CH4 emission from manure spreading negligible (Chadwick et al., 2000). | Not taken into account | Not taken into account |
| CH4 from manure deposited by grazing cattle | kg CH4/animal category per yr = Manure VS excreted × 0.67 × B0 × MCF  where MCF = 0.01 and B0 = 0.24  (Tier 2; IPCC, 2006; Met Eireann, 2013) | Emissions factors for animal categories calculated with IPCC (2006) Tier 2 equation (Non-digestible organic matter \* 0.67 × B0 × MCF). | Not taken into account |
| Nitrous oxide (N2O) from stored manure  \* EF dependant on the manure storage system and nitrogen excretion | Solid storage: 0.02 kg of N2O -N/kg of N excreted. Slurry with natural crust cover: 0.005 kg of N2O-N/kg of N excreted (Tier 2; IPCC, 2006). | N2O-N emission calculated as function of manure N stored.  Solid storage: 0.5% of N excreted. Slurry with natural crust cover: 0.5% of N excreted. Pit storage below animal confinements: 0.2% of N excreted Deep bedding with no mixing: 1% of N (Tier 2; IPCC, 2006) | N2O-N emission calculated as function of manure N stored.  Solid storage: 0.5% of N excreted.  Slurry with natural crust cover: 0.5% of N excreted.  Pit storage below animal confinements: 0.2% of N excreted. Deep bedding with no mixing: 1% of N excreted  (Tier 2; IPCC, 2006) |
| N2O from manure spreading | 1% of manure N spread in solid and slurry form emitted as N2O–N  (Tier 1; IPCC, 2006). | 1% of N spread whatever the manure type (solid manure or slurry) emitted as N2O. (Tier 1; IPCC, 2006) | 1% of N spread whatever the manure type (solid manure or slurry) emitted as N2O.  (Tier 1; IPCC, 2006) |
| N2O from mineral fertilizer spreading | Regardless of the fertilizer type 1% of mineral N spread emitted as N2O-N  (Tier 1; IPCC, 2006). | 1% of N mineral spread whatever the fertilizer type emitted as N2O-N  (Tier 1; IPCC, 2006) | 1% of N mineral spread whatever the fertilizer type emitted as N2O -N (Tier 1; IPCC, 2006) |
| N2O from manure deposited by grazing cattle | EF urine = 0.02 kg N2O-N /kg N EF faeces = 0.02 kg N2O-N /kg N (EF urine × N urine + EF faeces × N faeces) × 1.5 (Tier 1; IPCC, 2006). | EF urine = 0.015 kg N2O-N /kg N EF faeces = 0.004 kg N2O-N /kg N  (EF urine × N urine + EF faeces × N faeces) × 1.5 (Oenema et al., 1997). | 1% of the total N excreted by animals grazing pasture emitted as N2O -N. (Tier 1; IPCC, 2006) |
| N2O crop residues | 1% of N input from crop residues (Tier 1; IPCC, 2006). Not included for permanent grassland. | Not considered | 1% of N input from crop residues (Urbano, 2010; Dominguez, 1997; IPCC, 2006) |
| N2O temporary grassland ploughing | Not considered for temporary grassland. Assumed stable | N released calculated according to sequestration/releasing of C: C/N = 10 1% of N released (Tier 1; IPCC, 2006). | Not considered |
| N2O from N that is re-deposited after leaching | 0.75% of N leached from N inputs emitted as N2O-N (Tier 1; IPCC, 2006). | 0.75% of N leached from N inputs emitted as N2O -N. (Tier 1; IPCC, 2006) | 0.75% of N leached from N inputs emitted as N2O -N.  (Tier 1; IPCC, 2006) |
| N2O from N that is re-deposited after volatilization | 1% of ammonia (NH3) volatilized from N inputs (Tier 1; IPCC, 2006).  Ammonia = Housing + grazing + manure spreading + mineral fertilizer application  Housing - Slats 0.01-0.04 kg NH3/animal per day. Bedded 0.01-0.03 kg NH3/animal per day (Hyde et al., 2003).  Grazing - 20% of N excreted on pasture emitted as NH3 (Tier 1; IPCC, 2006)  Manure spreading - 26-48% of TAN9 for slurry and 81% of TAN for solid manure (Hyde et al., 2003, Duffy et al., 2015)  Fertilizer - 2% of N for ammonium-based fertilizer and 23% of Urea fertilizer N (Misselbrook et al., 2007) | 1% of ammonia (NH3) volatilized from N inputs. (Tier 1; IPCC, 2006)  N volatilized is calculated with NH3 and nitrogen oxide (NO) emissions from mineral N and manure spreading: 10% of NH3 and NO emitted from N mineral spreading are re-deposited 20% of NH3 and NO emitted from manure spreading are re-deposited | 1% of ammonia (NH3) volatilized from N inputs. (Tier 1; IPCC, 2006)  N volatilized is calculated with NH3 and NO emissions from N minerals and manure spreading: 10% of NH3 and NO emitted from N mineral spreading are re-deposited 20% of NH3 and NO emitted from manure spreading are re-deposited |
| CO2 equivalent (CO2e) fuel combustion | 3.02 kg CO2e/litre of diesel  (Carbon Trust, 2013). | 3.25 kg CO2e/ litre of fuel | 2.98 kg CO2e/litre of diesel  2.97 kg CO2e/litre of gasoline  (CNMC, 2017) |
| CO2 limestone application | 0.12 kg CO2-C/kg limestone  (Tier 1; IPCC, 2006). |  | 0.12 kg CO2-C/kg limestone |
| CO2e from electricity | 0.60 kg CO2e/kWh10  (Howley et al., 2011). | 0.055 kg CO2e/ kW | 0.15-0.36 kg CO2e/kWh  (MAPAMA, 2017) |
| CO2e from making mineral fertilizer and lime | Mineral N: 7.11 kg CO2e/kg N  P fertilizer: 1.85 kg CO2e/kg P  K fertilizer: 1.77 kg CO2e/kg K  Lime: 0.15 kg CO2e/kg  (Carbon Trust, 2013). | Mineral N is only considered: 5.36 kg CO2e/kg N | Mineral N11: 3.15-6.17 kg CO2e/kg N (Gac et al., 2011)  Lime: 0.0116 kg CO2e/kg |
| CO2e from producing compound concentrate feedstuffs | 16% crude protein (CP) without soybean meal: 0.18 kg CO2e/kg DM.  17% CP with soybean meal:  0.87 kg CO2e/kg DM.  12.5% CP without soybean meal:  0.24 kg CO2e/kg DM. (Ecoinvent 2010; Carbon Trust, 2013). | 0.76 kg CO2e/kg DM and 1.579 kg CO2e/kg DM (soy cake). Purchased forages not considered | 0.5-0.6 kg CO2e/kg DM (dependant on concentrate CP).  1.58 kg CO2e/kg DM soy cake. |
| Carbon sequestration | Not considered. Model was updated to include permanent grassland as a sink: 370 kg C/ha (Soussana et al., 2010). | Permanent grassland: 570 kg C/ha.  Hays: 125 kg C/100 ml.  Mountain pasture: 250 kg C/ha.  Temporary grassland: 80 kg C/ha Other crops not in rotation: 160 kg C/ha | Not considered. The emission factors provided by CAP2ER were adopted. |

1 GEI = Gross energy intake 2 Tier 2 or higher emission factors are country specific. Tier 1 or default emission factors are IPCC (2006) global or continental averages 3 DEI = Digestible energy intake 4 SDMI/TDMI = Silage dry matter intake/total dry matter intake 5 FL = Feeding level above maintenance energy requirement 6 DM = Dry matter 7 Bo = Manure volatile solids maximum methane potential 8 MCF = Methane conversion factor 9 TAN = Total ammoniacal nitrogen 10 kWh = kilowatt hour 11 Emission factor dependant on type of fertilizer e.g., urea or ammonium fertilizer

Supplementary Table S3 Options selected by nations to mitigate beef farming systems net carbon footprint i.e. greenhouse gas emission/unit of live weight gain (LWG).

| Mitigation strategies | Ireland | France | Spain | Italy |
| --- | --- | --- | --- | --- |
| Animal performance |  |  |  |  |
| Increase average daily weight grain | ✓ | ✓ | ✓ | ✓ |
| Reduce slaughtering age | ✓ | ✓ | ✓ | ✓ |
| Improve animal health | ✓ | ✓ | ✓ | ✓ |
| Optimize age at 1st calving e.g., 24 months | ✓ | ✓ | ✓ | ✓ |
| Optimize calving rate e.g., 0.95 to 1 calf/cow per year | ✓ | ✓ | ✓ | ✓ |
| Improve genetic merit | ✓ | ✓ | ✓ | ✓ |
|  |  |  |  |  |
| Diet |  |  |  |  |
| Improve grassland management e.g., rotational grazing | ✓ | ✓ | ✓ | × |
| Increase silage or hay quality | ✓ | ✓ | ✓ | ✓ |
| Increase fraction of concentrate in the diet | × | × | ✓ | ✓ |
| Optimize concentrate crude protein content | ✓ | ✓ | ✓ | ✓ |
| Replace soy cake or meal with low emission alternatives e.g., rape cake or field beans | × | ✓ | ✓ | × |
| Feed agro-alimentary by-products | × | × | × | ✓ |
| Feed additives e.g., lipids, yeast, nitrate, amino acids etc… | × | × | ✓ | ✓ |
|  |  |  |  |  |
| Soil fertility and N fertilizer |  |  |  |  |
| Improve soil pH via liming | ✓ | ✓ | ✓ | × |
| Optimize soil N, P and K levels | ✓ | ✓ | ✓ | ✓ |
| Optimize mineral N fertilizer application via precision technologies e.g., GPS1 | × | ✓ | × | ✓ |
| Incorporate legumes into the sward (clover) | ✓ | ✓ | ✓ | × |
| Replace mineral fertilizer with organic | × | ✓ | × | ✓ |
| Change from CAN2 to Urea fertilizer | ✓ | ✓ | ✓ | ✓ |
|  |  |  |  |  |
| Management of stored manure |  |  |  |  |
| Extend length of grazing season | ✓ | ✓ | ✓ | × |
| Cover manure store e.g., UV-stabilised plastic covers, peat, straw or wood chips | ✓ | ✓ | ✓ | ✓ |
| Store solid manure on solid impermeable floor equipped with a drainage system | ✓ | ✓ | ✓ | ✓ |
| Anaerobic digestion/biogas | × | ✓ | ✓ | ✓ |
| Aeration | × | × | × | ✓ |
| Composting | × | × | ✓ | × |
| Partial/total replacement of deep litter with fully slatted floor | × | × | ✓ | ✓ |
| Install fans to reduce straw bedding | × | × | × | ✓ |
| Air cleaning systems (e.g., scrubbers) | × | × | ✓ | × |
|  |  |  |  |  |
| Manure treatment |  |  |  |  |
| Nitrification inhibitor | × | ✓ | × | ✓ |
| Urease inhibitor | ✓ | × | × | ✓ |
| Acidification | × | × | × | × |
| Solids separation | × | × | × | × |
| Low emission slurry spreader | ✓ | ✓ | ✓ | ✓ |
| Manure injection (Rapid soil incorporation) | × | ✓ | ✓ | ✓ |
|  |  |  |  |  |
| Energy |  |  |  |  |
| Increase renewable energy use e.g., solar | ✓ | ✓ | ✓ | ✓ |
| Low energy lighting | ✓ | ✓ | ✓ | ✓ |
| Minimize electricity consumption by using metering devices | ✓ | ✓ | ✓ | ✓ |
| Match tractor power to field work task | ✓ | ✓ | ✓ | ✓ |
|  |  |  |  |  |
| Carbon sequestration |  |  |  |  |
| Preserve or increase permanent grasslands | ✓ | ✓ | ✓ | ✓ |
| Maintain or plant hedgerows/trees | ✓ | ✓ | ✓ | ✓ |
| Minimum or no till | ✓ | × | × | ✓ |

1 Global positioning system.

2 Calcium ammonium nitrate.

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