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A Review of Livestock Methane Emission Factors

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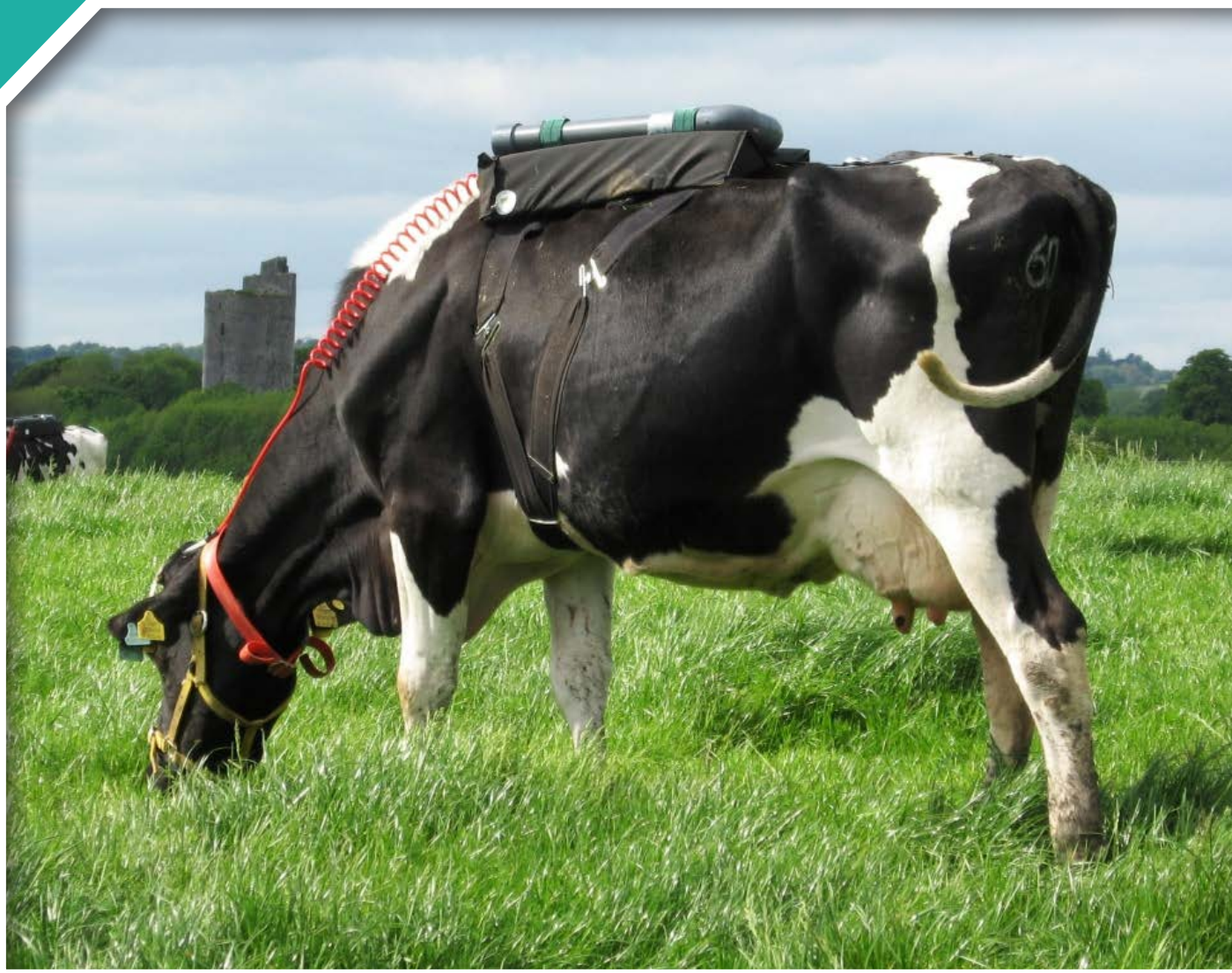

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Government of Ireland

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- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

A Review of Livestock Methane Emission Factors

(2016-CCRP-DS.11)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Teagasc

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DISCLAIMER

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Contents

List of Figures

List of Tables

Executive Summary

Teagasc and University College Dublin, with support from the Environmental Protection Agency (EPA) inventory team, reviewed the livestock methane emission factors used in the national greenhouse gas inventory approach for the agriculture sector and assessed potential reduction strategies. Livestock methane emission factors are annual estimates of methane emissions per head. They are used in conjunction with livestock statistics to estimate annual livestock methane emissions. Methane emission factors are computed using country-specific methods or methods provided by the Intergovernmental Panel on Climate Change (IPCC). Currently, Ireland uses tier 2 (country-specific data and emission factors) methods for cattle and tier 1 (default data and emission factors) IPCC methods for the remaining livestock species. The latter are less accurate than the former. The objectives of this desktop study were twofold: first, to evaluate the activity data of Ireland's national greenhouse gas inventory's livestock methane emission factors and, second, to update/recommend new, more advanced methods/emission factors for computing Ireland's tier 1 and 2 livestock methane emissions.

The assessment of methane emission factor activity data showed that several important input variables for livestock methane are based on 2003 activity data or expert opinion, for example milk composition, cow live weight and turnout dates. The possibility of reviewing and updating these activity data was determined by assessing the data collected by current inventory data sources – the Department of Agriculture, Food and the Marine and the Central Statistics Office – and other potential sources. The potential inventory data sources assessed were the Teagasc National Farm Survey (NFS), Bord Bia quality assurance scheme sustainability survey and Irish Cattle Breeding Federation (ICBF). Data collection and verification methods were assessed for these potential inventory data sources.

The outcomes of the evaluations showed that activity data are available to regularly review and, if required, update several additional input variables for Irish livestock methane emission factors. These activity data are verified for current data sources and the Teagasc NFS using farm records, livestock passports and inspections. For other potential data sources (Bord Bia and ICBF), farm diary estimates are sometimes used, for example length of the grazing season. Based on an assessment of these data sources and the development of updated prototype models, it is likely that the inventory's dairy cow methane emission factors will increase by 4% for enteric fermentation and 12% for manure management, with a combined increase of 4.4%.

New and simplified prototype national inventory models should be implemented for the beef and dairy emission estimates. These new models will facilitate a process that will allow the inventories to be updated on a more regular and more comprehensive basis with accurate information from the sources identified above. The new prototype sheep model developed by Teagasc and provided to the EPA should be implemented within the national inventories to generate tier 2 emission factors for sheep production.

New methods for computing Irish livestock methane emission factors were identified by evaluating methodologies reported in the IPCC 2006 guidelines, national studies and other countries' greenhouse gas inventory submissions to the United Nations Framework Convention on Climate Change (UNFCCC). For the inventory submissions, the 2017 emission computation methods of the submissions to the UNFCCC of all Annex 1 (developed) countries were evaluated, as well as those of five non-Annex 1 nations (Brazil, China, India, South Africa and Uruguay). The results of the literature review highlighted that national and international methods to develop advanced livestock methane emission factors, for example tier 2 or tier 3, were often similar to or followed the IPCC tier 2 methods for cattle or sheep. The main differences found were in the equations used to calculate livestock feed requirements and manure excretion and in the parameters used to estimate enteric or manure methane conversion rates.

Tier 2 methods were used by the majority of Annex 1 countries to estimate methane emissions from key livestock categories, for example cattle and sheep. Several Annex 1 parties used tier 2 methods for other

livestock species, for example Switzerland applies this method for horses and mules. This implies that, for the most prevalent Irish livestock species (cattle and sheep), methane emission factors should be computed using IPCC tier 2 methods. For sheep, the tier 2 method should be applied with feed equations and parameters from national studies on the Irish sheep flock. The tier 2 methods for cattle can be improved using recent Irish emission studies on enteric methane instead of estimates from other nations. However, the categorisation of cattle needs to be simplified to utilise more data from new or current data sources.

1 Introduction

1.1 Contextual Background

Methane is emitted directly by livestock and from their manure. Livestock naturally emit methane from their mouth and rectum following the internal (enteric) fermentation of ingested forages and feedstuffs. Ruminants such as cattle exhale or eruct the largest volumes of methane, because the large rumen section of their stomach digests ingested food via enteric fermentation. On average, the stomach accounts for 90% of the methane generated by enteric fermentation in ruminants (Johnson *et al*., 2000). The remaining methane emission from this process occurs in the lower digestive tract, for example the large intestine. Enteric fermentation also occurs in non-ruminants, but rarely in the stomach; thus, the volume of methane they directly emit is quite small. Manure is usually more important as a source of methane for non-ruminants. Methane is emitted from manure when it decomposes anaerobically. Generally, the national volume of methane emitted from the manure of livestock tends to be smaller than the volume of methane emitted from enteric fermentation.

At the national scale, livestock methane emissions are estimated according to Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas (GHG) inventories. The IPCC guidelines for national inventories were published in 1997 and 2006 (IPCC, 1997, 2006), following international literature reviews of scientific measurements of anthropogenic GHG emission sources. The two editions of the IPCC guidelines outline a three-tiered approach to estimate methane and GHG emissions from agriculture. Tiers 2 and 3 require country-specific data and are more complex, but improve the accuracy of national emission estimates. The simplest IPCC approach, tier 1, is considered acceptable to use when a GHG emission source (e.g. enteric methane from deer) is not a key category or when there is a paucity of national data for non-Annex I countries (i.e. developing nations). A key category is defined by the IPCC as one that has a significant influence on a nation's total inventory of GHG emissions in terms of absolute levels of emissions and removals, the trend in emissions and removals or uncertainty in emissions or removals. The IPCC recommends that developed nations (Annex I countries) should use country-specific emission factors (tier 2) when livestock are key categories of national GHG emissions.

Currently, the Irish national GHG inventory uses a combination of tier 1 and 2 IPCC approaches to estimate livestock enteric and manure methane emissions. In 2006, tier 2 methods to estimate cattle enteric and manure methane emissions were adopted in Ireland's national GHG inventory for the first time and submitted to the United Nations Framework Convention on Climate Change (UNFCCC). The tier 2 methods developed by O'Mara (2006) significantly improved the accuracy of Irish livestock methane emission estimates for cattle, but did increase national inventory data requirements. The extra activity data in the tier 2 methods are used to estimate or describe:

- regional cow populations;
- cattle and in-calf heifer populations;
- birth and mortality rates;
- parturition dates;
- farm feeding practices:
    - grazing season length and housing periods;
    - concentrate (e.g. barley) and fodder feeding;
- milk and meat production;
- cattle size and slaughter age;
- farm facilities:
    - manure storage systems.

2 Activity Data

2.1 Current Inventory Data Sources and Flows

Activity data to estimate livestock methane emissions are updated annually. For the tier 1 approach, only livestock numbers are updated, whereas for tier 2 a number of input variables are updated, reflecting activity data needs. The Central Statistics Office (CSO) is the official source of most livestock population statistics for inventory purposes. Synthetic fertiliser use and poultry population statistics are provided by the Department of Agriculture, Food and the Marine (DAFM). For the tier 2 methods, the DAFM also provides cattle population data from its annual Animal Identification and Movement (AIM) reports (e.g. DAFM, 2016). The AIM reports provide detailed county information for calf populations and national population data on stillborn calves, dairy and beef cattle deaths, slaughtering, disposals, imports and exports. Furthermore, the reports classify calf and cattle populations into multiple categories using various criteria, including dam type, sire type, breed, gender and age.

The AIM calf populations are attributed annually to 12 dairy cow systems and 18 beef (suckler) cow systems developed by O'Mara (2006) and the AIM cattle populations are allocated to 24 female and 29 male non-breeding cattle systems, also described by O'Mara (2006). The dairy and suckler cow systems are summarised in Table 2.1. These systems were subdivided according to region and calving date. The regions used coincided with those used for the implementation of the European Union (EU) Nitrates Directive (EU, 1991) and national regulations on good agricultural practices for the protection of water [e.g. Statutory Instrument (S.I.) 134 of 2014; Government of Ireland, 2014]. The average dairy cow milk yield is updated annually using domestic milk volume deliveries compiled by the CSO. Data on milk fed to calves sourced from the Teagasc National Farm Survey (NFS) are also included in the dairy cow milk yield calculation.

Male and female non-breeding cattle systems are not split by region, but are further divided according to sire type, dam type (dairy or suckler) and maturity (early or late) (Table 2.2). Livestock methane emission factors are calculated annually for the O'Mara (2006) dairy cow, suckler cow and non-breeding cattle systems. These emission factors are subsequently weighted using the CSO principal animal classification system (Table 2.3) and pertinent AIM population data to derive national country-specific emission factors.

The CSO carries out national surveys of animal populations in June and December each year. The June survey is used to estimate animal numbers for non-breeding cattle categories on the basis that it takes account of the movement of animals into the different age categories (0–1 years to 1–2 years and >2 years). For dairy cows and suckler cows, an average of the population in June and December is used. No AIM population data are available for breeding bulls and dairy and beef in-calf heifers; therefore, for these groups, national methane emissions are estimated using the most appropriate system from the 53 female and male cattle production systems in O'Mara (2006) and the CSO animal census surveys.

Activity or input data for tier 2 livestock methane emissions are not currently updated for several key input variables, for example animal turnout and housing dates, calving dates, dairy cow milk fat

Table 2.1. Description and breakdown of the 30 cow categories developed by O'Mara (2006)

Dam type	Calving season	Calving dates	Empty or stillbirth (missed calvings)	Nitrate regions	Cow categories
Dairy	Spring	3	0	3	3×3=9
Dairy	Autumn	1	0	3	1×3=3
Suckler	Spring	3	2	3	5×3=15
Suckler	Autumn	1	0	3	1×3=3

Table 2.2. Description and breakdown of the 53 non-breeding cattle categories developed by O'Mara (2006)

Cattle categories		Male		Female	
		Dairy	Suckler	Dairy	Suckler
Early-maturing beef bull	Slaughtered	2	2	2	2
	Exports	0	0	0	0
	On-farm deaths	2	2	2	2
Late-maturing beef bull	Slaughtered	4	4	3	3
	Exports	3	2	3	3
	On-farm deaths	2	2	2	2
Friesian bull	Slaughtered	2	–	–	–
	Exports	2	–	–	–
	On-farm deaths	0	–	–	–
Total		17	12	12	12

Table 2.3. CSO animal classification for cattle populations

Cattle type	Classification
Breeding cattle	Dairy cows, suckler beef cows
Beef cattle	Male < 1 year, male 1–2 years, male > 2 years
	Female < 1 year, female 1–2 years, female > 2 years
Other cattle	Breeding bulls, dairy in-calf heifers, suckler (beef) in-calf heifers

and protein production, meat production, cow live weight farm feeding practices and farm facilities. Information is taken from historical national statistics when reporting of the variable(s) of interest ceases. For example, the national GHG inventory currently uses calving dates from the 2003 Cattle Movement Monitoring System (CMMS) report published by the DAFM in 2004 (DAFM, 2016), because calving dates have not been published by the DAFM for subsequent years. When historical national statistics are not available or are older than 2003, activity data are obtained from the reports of O'Mara (2006) and Hyde *et al*. (2008). The report of O'Mara (2006) provides activity data from 2003 on animal turnout and housing dates, milk composition and farm feeding practices. Input data on farm facilities, for example manure storage systems and over-wintering periods, are taken from a farm survey, largely conducted by Hyde *et al*. (2008) for the period April 2003 to October 2003.

Since the survey of Hyde *et al*. (2008), there have been important changes in Irish agricultural policy (i.e. milk quota removal) along with further developments in farm technologies and management practices (DAFM, 2010). This is likely to have significantly changed the activity data of some key static tier 2 input variables used to estimate Irish livestock methane emissions. New activity data are available from the reports of existing data providers to frequently review or update some of these variables, for example milk composition. It may also be possible to regularly check or renew additional data for static livestock methane input variables by utilising activity data from new sources. Beyond cows and beef cattle, additional data from new or existing sources may be useful for developing tier 2 or 3 methods to estimate methane emissions from other important livestock categories (e.g. sheep).

2.2 Potential Inventory Data Sources

The Teagasc NFS, Bord Bia sustainability survey and Irish Cattle Breeding Federation (ICBF) database were identified as potential sources of activity data that could be used in the derivation of emission factors for the cattle herd. These potential data sources were thoroughly assessed and are described in the following sections.

2.2.1 Teagasc National Farm Survey

The Teagasc NFS was established in 1972. It is part of the EU's Farm Accountancy Data Network (FADN). The NFS fulfills Ireland's statutory obligation to provide data on farm outputs, costs, indebtedness and income to the European Commission. Overall, 900–1100 farms are typically included in the NFS annually, depending on the size of the annual farm population. Since 2012, a standard output of €8000 was set as the minimum threshold for inclusion of a farm in the NFS sample (Hennessy and Moran, 2016). The NFS usually represents over 90% of the agricultural sector's standard gross output. Many farmers stay in the NFS sample for several years, but after a certain period farms exit the survey and new farms are introduced to keep the sample representative. The farms included in the survey are weighted according to their utilisable agricultural area (size) using annual aggregation factors from the national census (CSO). This is to ensure that the NFS is nationally representative for different farm sizes. The NFS categorises farms into six different production systems or types, namely dairy, tillage, sheep, cattle rearing, cattle other and mixed livestock. The dominant farm enterprise, in terms of standard output, is used to determine farm type. Farms are not included in the survey when the main enterprise is a pig or poultry system, because of the inability to obtain a nationally representative sample of these systems.

Trained NFS recorders carry out interviews with farmers on-site. All recorders are provided with survey instructions to ensure that a standardised approach is used for data collection. The current survey is normally completed after a number of on-farm visits. Recorders visit farms two or three times a year to fill in the survey and collect data and the survey is normally completed after a couple of visits. For new farms, a further one or two visits may be needed. A wealth of financial, demographic and resource data are collected from each farm. These data are verified, where possible, using receipts and farm accounts. In 2007, the NFS was gradually expanded to gather more resource or technical information. Some examples of technical variables added to the survey include animal turnout and housing dates, concentrate feeding rates and weaning rates. This information is used to generate technical performance indicators (e.g. number of days grazing), which are reported annually in NFS enterprise factsheets. Supplementary farm surveys are sometimes carried out with the NFS sample; for example, Läpple *et al*. (2014) and Hennessy *et al*. (2011) surveyed grassland management, manure application and storage practices in 2009. These extra farm surveys collect specific technical, demographic or economic data in more detail than in the primary survey.

In 2012, the NFS dataset measured farm-level sustainability for the first time. Sustainability is a broad concept covering diverse economic, social and environmental issues. As a result, the NFS uses key metrics or indicators to assess each of these components of farm-level sustainability, as well as further metrics to evaluate a fourth component termed innovation. The key farm-level environmental sustainability indicators measured by the NFS are nitrogen use and GHG emissions. GHG emissions are calculated according to the IPCC (2006) guidelines and methodologies for all NFS farm types. The IPCC method considers GHG emissions from day-to-day farming activities or on-farm emissions only. The national GHG inventory emission algorithms (Duffy *et al*., 2015) are used to estimate a farm's annual IPCC GHG emissions in CO_2 equivalents (CO_2eq). The annual farm IPCC GHG emissions are related to physical farm outputs and the profitability of the enterprise. Annual CO_2 emissions from on-farm fuel and electricity use are reported separately to be consistent with the national inventory reporting conventions/structure.

The NFS dairy dataset is also sufficiently detailed to calculate annual GHG emissions using a life-cycle assessment (LCA) approach. This method is widely used to report the carbon footprint of a system, goods or a service (kgCO_2eq/unit of output) and has become an important market measure of sustainability. The most widely used LCA method to quantify emissions from farming systems is referred to as a cradle-to-farm-gate approach. This method is deployed by the NFS. It attempts to estimate all GHG emissions from a production system until the primary product is sold from the farm. This LCA approach does not account for emissions post farm, that is, those relating to processing, distribution, retail, consumption and waste. The NFS cradle-to-farm-gate LCA model calculates on-farm emissions and off-farm emissions associated with the production of imported farm inputs (e.g. artificial fertiliser and feed). For on-farm emissions, the LCA model uses the same algorithms as the national

GHG inventory report, but for off-farm emissions equations from other reports are used. O'Brien *et al*. (2015) previously reported all of the calculations of a dairy LCA model and carbon footprint analysis for NFS dairy farms. The NFS dairy farm carbon footprints are updated annually using the same model. For beef cattle and sheep systems, similar LCA models are available (Crosson *et al*., 2013; O'Brien *et al*., 2016), but the NFS dataset is currently not detailed enough to apply them. It is envisaged that the data collection process will be expanded to facilitate such an analysis in the future.

2.2.2 Bord Bia sustainability survey

Origin Green is a national sustainability programme operated by Bord Bia that unites government, private food companies and farmers. The primary goal of Origin Green is to provide assurance to customers that Irish food is produced to the highest quality and sustainability standards. To fulfill this ambition, private food companies complete a sustainability charter and farmers participate in quality assurance and sustainability schemes. The Origin Green initiative started in 2012, with 137,000 farm assessments completed in its first 4 years. Most farm assessments (n = 117,000) for this period were conducted as part of the Beef Quality Assurance Scheme (BQAS; Bord Bia, 2017a,b). The remainder were completed for the Sustainable Dairy Assurance Scheme (SDAS; Bord Bia, 2013). Farm assessments have yet to be completed for other production systems, but it is expected that information on sheep production will be available shortly following the development of the Sustainable Beef and Lamb Assurance Scheme (SBLAS) in 2017. There are also plans to further develop schemes for pigs, poultry and grain farmers to enable similar sustainability assessments to be conducted.

The current quality assurance and sustainability schemes were developed by a technical advisory committee representing Bord Bia, Teagasc, the Food Safety Authority of Ireland (FSAI), the DAFM, industry (producers and processors) and other technical experts. This group designed an assessment procedure to record and evaluate data in a systematic way at the individual farm level. The individual farm-level assessment is conducted with the farmer on-site by an independent auditor every 18 months.

To reduce the time needed to collect data on-site and avoid data collection duplication, permission can be given to the auditor to obtain information from sources that the farmer already provides data to. The existing data sources that can provide useful data for farm assessments are the DAFM, ICBF and food processors. The following information can be provided:

- DAFM – a full livestock profile for a farm's herd(s) can be obtained from the AIM database. This includes the numbers of animals in different categories, births, deaths and movements in and out of the herd over the course of the previous year.
- ICBF – number and breeds of cows, number of calves registered, calving rate, average calving interval, replacement rates, average Economic Breeding Index (EBI) of cows and progeny, average milk yields and lactation lengths, sales and purchase weights.
- Food processors – milk volume sales per month, milk fat and protein content, milk lactose content, meat quality, herd health certificate details, animal cleanliness and milking equipment servicing details.

During a farm visit, the auditor determines whether the farmer or herd complies with the regulations set out in the scheme's standards and completes a farm sustainability survey. This broad and comprehensive survey was originally introduced by Bord Bia in 2011 and allows a carbon footprint to be generated for each participating farm. It can also be used with the Teagasc/Bord Bia carbon navigator. In total, the sustainability survey has 13 parts:

1. housing and turnout;
2. manure management;
3. feeding;
4. silage;
5. sheep data;
6. water use;
7. fertiliser (beef and dairy);
8. soil and fertilisation;
9. pesticides and herbicides;
10. biodiversity;

11. economic sustainability;
12. social sustainability;
13. energy.

For dairy farms, the survey has a supplementary section with questions on dairy breeding, milk exports, water heating and milking equipment. The sustainability survey is conducted for the past calendar year. After the farm visit, a comprehensive report is produced on the performance of the farm under the scheme's sustainability and quality assurance criteria.

2.2.3 ICBF database

The ICBF was established in 1997 by the beef industry and started its operations in 1998, with its current structure finalised in 2000. The ICBF is a non-profit organisation charged with providing cattle breeding information services to the Irish dairy and beef industry. The overall goal of the ICBF is to benefit farmers, the agri-food industry and wider communities through genetic gain. Livestock genetic improvement comes about when the parents of the next generation are genetically superior to their colleagues. The ICBF enhances natural livestock genetic gain by actively identifying and selecting livestock with superior genes. This complex process requires:

- identification of and ancestry and quantitative data on those traits of importance for large numbers of animals in each generation;
- a genetic evaluation system to identify superior animals in each generation;
- a breeding scheme design which ensures that the required data are available and that farmers use genetically superior animals in each generation;
- farmers and industry partners who provide accurate data from their own herds and utilise information services provided by the ICBF in their cattle breeding decisions.

All of the information collected from this activity is used to maintain and grow the national cattle breeding database, which was created when the ICBF was formed. Prior to the national cattle breeding database, there were several separate computer systems supporting different aspects of cattle breeding in Ireland. Additionally, each had its own data collection system. For example, there were 18 pedigree cattle breeding data-collecting systems (Herd Book), eight milk-recording organisations with their own system and the DAFM system.

The ICBF established the national cattle breeding database using a software system from a Dutch cattle breeding organisation. Creating the database involved an enormous effort in terms of negotiating agreements for the sharing of data, establishing shared data collection systems and consolidating existing computer files into a single shared database. Once data-sharing agreements were reached, the ICBF team of information technology developers adapted the Dutch software system to meet the needs of the Irish breeding industry. The adaptation of the database has now reached the point where no support is required from the suppliers of the initial Dutch system.

In all, 90% of Irish dairy and beef cattle are recorded in the ICBF database (Wickham *et al*., 2012). The services that the ICBF provides to farmers, pedigree cattle breeders, milk-recording organisations and artificial insemination organisations are also shown. For example, farmers can access their own data and assess their livestock's performance through the service known as HerdPlus. The services that the ICBF created were developed using a range of new information technologies. These services, along with the national database, are also playing a fundamental role in facilitating research into genomic selection in Irish cattle breeding.

In 2008, the ICBF expanded its operation, with support from AbacusBio Ltd, to establish Sheep Ireland. The Sheep Ireland programme has four pillars: the Sheep Ireland database, ram producer pedigree breeders, central progeny test farms and maternal lamb producer farms. Performance data recorded for these farms and breeders are contained in the Sheep Ireland centralised database. This database also captures ancestry recording in liaison with breed society flock books. The Sheep Ireland database is used for national genetic evaluations, storing breeding values and providing flock reports to participating farmers.

2.3 Data Sources Assessment

Current and potential inventory data sources were evaluated according to the following criteria: set-up year, national representation, frequency of data collection, method(s) of data collection and verification of data (Table 2.4). This analysis showed that, except

Table 2.4. Assessment criteria for current and potential inventory data sources

Criteria	DAFM	CSO	Teagasc NFS	Bord Bia[a]	ICBF
Set-up year	1919	1847	1972, 2012[b]	2012	1998
Livestock categories	All	All	Cattle, sheep, horses	Cattle, sheep	Cattle, sheep
Farms sampled	All	All	900–1100	45,000	23,000
National representation	Full	Full	Full	Partial	Partial
Collection frequency	Monthly, annually	Monthly, annually, occasionally[c]	2–3 times per year	18 months	Monthly, annually
Collection methods	Post, internet, farm visit	Compiled from other data sources, post, internet	Farm visit	Farm visit	Internet
Data verification	Inspections, livestock passports	Data verified by other sources, e.g. the DAFM	Farm accounts, diaries	Farmer diary estimates	Farmer diary estimates and milk recording

[a]**Quality assurance schemes sustainability survey.**

[b]**The sustainability survey of the NFS was set up in 2012.**

[c]**Census of agriculture is carried out every 10 years; farm structures survey is carried out periodically. The CSO also occasionally conducts supplementary farm surveys.**

for the ICBF and the Bord Bia sustainability survey, the data sources provided annual information dating back to the start of the GHG inventory reporting period (i.e. 1990). All data sources collected or compiled information for dairy, beef and sheep, but nationally representative population data were gathered for these livestock categories only by the Teagasc NFS, DAFM and CSO. The DAFM and CSO also compiled national population information for other livestock categories (e.g. pigs and poultry).

The Teagasc NFS and Bord Bia survey collect data via the farm visit approach described previously. Farm data are not generally directly collected by the ICBF except for some commercial farm live weight data. The ICBF gathers data from other sources (e.g. the DAFM) or captures farm information from the online services that it provides (e.g. HerdPlus). The DAFM obtains farm data through inspections and from its livestock traceability system. This system gathers livestock inventories from all farms. Farmers can supply this information online or by post. It is a legal requirement for farmers to supply this information to the DAFM. Livestock populations are verified by the DAFM through animal tagging and passport identification. This DAFM data source is shared with other sources to verify livestock populations. The CSO also uses validated data from industry and local authorities. The Teagasc NFS generally uses farm accounts to validate farm data. However, for some activity data this is not possible (e.g. cattle housing dates). When this occurs, farm diaries or estimates are used. The Bord Bia sustainability survey uses only farmer diaries or estimates to verify the data collected. Additional surveys conducted by the CSO (e.g. survey of agricultural production methods) also follow this approach.

2.4 Static Activity Data Update Options

Information gathered by the DAFM, CSO, Teagasc NFS, Bord Bia and ICBF was compared with the static input activity data. This analysis indicated that there is information available from new and existing data sources that can be used to update some important static input variables in the estimation of emission factors (Table 2.5).

2.4.1 Cattle and in-calf heifer populations

The national inventory calculates methane emissions from the cattle and in-calf heifer categories that O'Mara (2006) created using population data from the DAFM annual AIM report and the CSO. Non-breeding cattle populations are assigned to these categories according to gender, age at slaughter, export and death. Excluding heifers exported before 6 weeks, O'Mara (2006) allocated 69% of all non-breeding heifer category populations to suckler dams and the remainder to dairy. This apportioning was based on DAFM 2003 national

Table 2.5. New livestock activity data for the national GHG inventory

Animal category	Parameter	National average 2015	Reference
Dairy cow	Milk fat content	4.03%	CSO (2018)
Dairy cow	Milk protein content	3.50%	CSO (2018)
Dairy cow	Mean calving date	3/3/2015	ICBF (2017)
Dairy cow	Grazing season	239 days	Teagasc (2017a) and Bord Bia (2016, 2017b)
Dairy cow	Concentrate fed per year	905 kg/cow	Teagasc (2017a) and Bord Bia (2016, 2017b)
Dairy cow	Average live weight	538	ICBF (2017)
Dairy cow	Manure storage systems	–	Teagasc (2017a) and Bord Bia (2016, 2017b)
Suckler cow	Grazing season	217	Teagasc (2017b) and Bord Bia (2016, 2017b)
Suckler cow[a]	Concentrate fed per year	444 kg/cow	Teagasc (2017b)
Suckler cow	Average live weight	600	ICBF (2017)
Suckler cow	Manure storage systems	–	Teagasc (2017a) and Bord Bia (2016, 2017b)
Finishing cattle	Grazing season	145	Teagasc (2017c) and Bord Bia (2016, 2017b)
Finishing cattle	Concentrate fed per year	763 kg/LU[b]	Teagasc (2017c)
Finishing cattle	Manure storage systems	–	Teagasc (2017a) and Bord Bia (2016, 2017b)
Lowland lamb	Mortality	7%	Teagasc (2017d)
Lowland ewe	Lambs per ewe	1.34	Teagasc (2017d)

[a]**Includes concentrate fed to weanling.**

[b]**Livestock unit (LU) is one dairy cow's annual organic nitrogen excretion or 85 kg of organic nitrogen/year.**

estimates for the total number of suckler and dairy female calves born less Friesian female calves. O'Mara (2006) further divided some non-breeding suckler and dairy heifer categories (e.g. heifers slaughtered at 21–26 months) into early- and late-maturing breeds. These heifer category populations were split 0.5:0.5 or 0.33:0.67 between early- and late-maturing breeds, respectively. O'Mara (2006) verified this approach by comparing his population ratio estimates for non-breeding heifers of varying maturity with national statistics.

The current approach updates the proportions of non-breeding heifers allocated to dairy and suckler dams using the DAFM annual AIM report. However, these proportions are still estimated on a national basis by dividing the total number of suckler or dairy beef female calves born by all female calves born less Friesians. It is unlikely that these proportions are the same for some non-breeding heifer categories, for example female heifers slaughtered before 15 months and after 24 months. We suggest that data contained in the AIM database could be used to review this apportioning method. The current inventory uses proportions from O'Mara (2006) to allocate pertinent non-breeding heifer category populations to early- and late-maturing breeds. The DAFM AIM database could be used as an option to update the non-breeding heifer populations by maturity.

The same procedures described for non-breeding females are used with DAFM AIM male cattle populations to apportion males, first, to suckler and dairy dams and, second, to early- and late-maturing breeds. However, O'Mara (2006) adapted these procedures for some male cattle categories to account for pure dairy Friesian males. For instance, 30% of male cattle slaughtered at 24–30 months were assumed to be pure Friesian males, with the remainder being late-maturing breeds, split 69:31 between suckler dams and dairy dams. Similar assumptions were made for male cattle exported between 12 and 30 months and for male cattle slaughtered at 21–26 months. O'Mara (2006) verified his pure dairy Friesian population estimates by comparing the inventory's estimate with the DAFM AIM report. The current national inventory uses the same population apportioning assumptions as O'Mara (2006) for pure Friesian males and early- and late-maturing breeds. This should be reviewed using the same data source option identified for non-breeding heifers.

The CSO population statistics are used to estimate methane emissions from in-calf heifers in their first and second year. The AIM database is also able to provide this information. The DAFM does not provide statistics on in-calf heifer categories in its AIM report, but it is possible to estimate the population of dairy

replacement female calves born. The population of dairy in-calf heifers estimated from the CSO is generally less than the number of dairy heifer calves born 2 years previously. Unlike in-calf dairy heifers, replacement beef heifers are further split into late- and early-maturing breeds in the national methane inventory. For this division, 30,000 replacement beef heifers are assumed to be early-maturing breeds. This assumption was taken from O'Mara (2006). The DAFM AIM database could be used to review this population assumption.

2.4.2 Parturition dates

For most livestock categories, the inventory does not require data on parturition dates to estimate methane emissions. However, for cow and cattle systems, calving date information is required for the tier 2 method developed, because most dairy and beef farms operate spring calving pasture-based systems. The DAFM and ICBF regularly collect calving dates from farms, but the DAFM does not regularly report calving statistics. The ICBF database, which represents most cattle farms, does report calving statistics for dairy and beef cows (ICBF, 2017) and provides an option to review the calving dates that the national inventory currently uses. The DAFM AIM database could be used to obtain data for the cattle farms that the ICBF excludes.

Similar to cattle farms, sheep farms typically operate seasonal grass-based systems for mid-season lamb production. Ewes generally lamb in mid to late spring (i.e. March to April). However, unlike cattle systems, lambing date statistics are not reported by the ICBF and DAFM. The Sheep Ireland database and Teagasc Profit Monitor reports were identified as the main options for obtaining this information. However, neither source is nationally representative. For other livestock categories, parturition dates are generally not required to estimate national methane emissions. Therefore, expert opinion was considered sufficient if required.

2.4.3 Farm feeding practices

Grazing season and housing period

Housing and turnout dates from O'Mara (2006) and Hyde *et al*. (2008) are used to estimate the length of the grazing season for most livestock categories in the national inventory. O'Mara (2006) used the farm facilities survey (B. Hyde, EPA, 9 January 2019, personal communication), manure storage guidelines and data from Hyde *et al*. (2008) to estimate turnout and housing dates. Hyde *et al*. (2008) surveyed the facilities of 402 farms. The livestock species included in this survey were cows, cattle, sheep, horses and deer.

The Teagasc NFS and Bord Bia sustainability survey are carried out for a calendar year and collect livestock housing dates and turnout dates to pasture. The NFS gathers the dates that dairy cows are turned out by day to pasture, turned out full-time to pasture, housed by day and housed full-time. Additionally, the NFS collects grazing rotation start and end dates for dairy cows and the number of days that cows are re-housed during the grazing season. For cattle, the NFS collects average turnout and housing dates. The Bord Bia sustainability survey collects average full-time turnout and housing dates for dairy cows, suckler cows, finishing cattle and other cattle (e.g. weanlings). This survey also gathers data on the number of days that cattle and cows are re-housed during the grazing season. The CSO survey of agricultural production methods is another source of data for the length of the grazing season. This periodical survey estimates the number of months that livestock spend at pasture.

O'Mara (2006) used partial and full-time turnout and housing dates to estimate housing and grazing periods for dairy cows. However, for cattle, O'Mara (2006) used only full-time turnout and housing dates. Therefore, the Teagasc NFS was selected as the best option available to regularly review and, if required, update dairy cow housing and turnout periods. The NFS collects similar data for cattle and should be used. The Bord Bia sustainability survey could also be used periodically to help validate the NFS data.

Concentrate and fodder feeding

The national inventory uses country-specific data to quantify the amount of concentrate fed to cows and cattle. O'Mara (2006) described in detail the approach and data sources that the inventory uses to estimate concentrate supplementation for cows and cattle, that is the Teagasc 2003 NFS questionnaire on farm feeding practices, the DAFM, and Fallon *et al*. (2001). In short, O'Mara (2006) used feeding data gathered by the NFS and measured by Fallon *et al*. (2001) to

estimate daily livestock concentrate feeding rate(s) on a monthly or seasonal basis for the cow and cattle categories that he created. These daily concentrate feeding rates were used to estimate annual cow and cattle concentrate intakes for all categories and were weighted using population data from the AIM database and the CSO to estimate national concentrate totals fed to dairy cows, suckler cows and non-breeding cattle. National concentrate totals for these livestock categories were compared with the DAFM records for compound concentrate sales in 2003 and adjusted where necessary.

Currently, the national inventory estimates annual concentrate intakes per animal, as well as national totals, using the same daily livestock concentrate feeding rates for cows and cattle as reported by O'Mara (2006). This information needs to be reviewed. The main data source options available to revise cow and cattle daily feeding rates are the Teagasc NFS and Bord Bia sustainability survey. The NFS collects daily concentrate feeding rates for dairy cows on a monthly and annual basis. These data are collected annually or seasonally for suckler cows and other cattle categories. Bord Bia collects daily cow and cattle concentrate feeding rates for the indoor and outdoor periods. Furthermore, both surveys collect data on the types of fodder (conserved forages) that are typically fed to cows and cattle indoors, for example grass silage, maize silage and hay. This information may be useful in reviewing the assumption in the national inventory that grass silage is typically the only winter fodder fed to cows and cattle. Currently, the national inventory bases the type of conserved forage fed to cows and cattle on the 2003 NFS questionnaire on farm feeding practices.

In contrast to the cow and cattle concentrate intake per animal, the inventory's national estimates of the total quantity of concentrate fed to these animals does vary from year to year because of fluctuations in the populations in the different livestock categories. However, to our knowledge, the inventory's national totals for the quantity of concentrate fed to cows and cattle are not regularly compared with relevant data sources. The CSO and DAFM frequently report the national quantities of compound concentrate feeds purchased for livestock and are the most suitable sources available for reviewing this information for cows and cattle. If such a review indicates that the inventory's national totals for concentrate fed to livestock should be revised, then daily feeding rates for cows and cattle could be adjusted using the same approach as that described by O'Mara (2006).

Similar to cows and cattle, it is not clear how often the national inventory reviews the gross energy intake (GEI) of different pig categories. The DAFM and CSO report the national quantity of pig feed purchased by farmers. These feed data could be used to periodically review the emission estimates for pigs in consultation with industry experts. Besides cows, cattle and pigs, national information is collected on the types of forage fed to sheep through the Bord Bia sustainability survey. This survey also gathers data on concentrate feeding practices, but does not collect any estimates on daily concentrate feeding rates for sheep. The Teagasc NFS records sheep feed purchases and can be used to estimate concentrate supplementation rates. These data could be used in conjunction with national estimates from the DAFM and CSO to estimate typical concentrate feeding rates for sheep. For the other livestock categories, currently the best options are to review or update concentrate and fodder feeding estimates periodically using expert opinion .

2.4.4 Milk and meat production

Regarding milk production, tier 2 methane emission estimates for dairy and suckler cows assume that the annual composition of milk is constant. National information is not regularly available on the typical composition of suckler cow milk, but the CSO compiles a detailed dataset on dairy cow milk deliveries. Milk fat and protein contents for national milk deliveries are reported on a monthly and annual basis by the CSO. The CSO annual milk composition data were identified as the best option available to update the milk component of the livestock methane section of the national inventory.

The national inventory tier 2 methane estimates assume that milk deliveries per cow are the same across regions and for spring and autumn calving systems. From the data published it is not clear if the data can be disaggregated by region or dairy production system. The Teagasc NFS dataset contains milk yield and milk fat and protein information that can be broken down by region. The dataset is large enough to be representative of spring calving dairy systems. It could therefore be used in conjunction with the CSO national milk delivery data to estimate

regional milk deliveries. The NFS contains limited data for autumn calving systems, but the ICBF database does collect autumn calving information and could provide an option to update the national inventory. National milk deliveries exclude milk fed to dairy calves and milk used for other purposes, for example home use. This volume of milk is updated in the national inventory using data from the Teagasc NFS; however, this is not reported separately in the national inventory but is included in the estimation of average milk yield per cow.

The CSO compiles data on meat production using national livestock slaughtering data and average carcass weights. The DAFM forwards to the CSO the number of slaughterings in meat processing establishments that it approves. This typically covers 95% of all livestock kills. Data for the remaining 5% is obtained from local authorities. Average slaughter weights of sheep are derived from data provided by the DAFM and average pig slaughter weights are obtained directly from pork and bacon export factories. Average carcass weights of cattle are obtained from the DAFM's beef carcass classification scheme.

For estimating methane emissions, O'Mara (2006) calculated weighted average final slaughter weights for male and female non-breeding cattle categories and compared these estimates against average final weights reported by the DAFM in 2003. The weighted average final slaughter weights of 342 kg for male cattle and 278.5 kg for female cattle from O'Mara (2006) were within 10 kg of the average female and male values reported by the DAFM. The DAFM frequently updates statistics on male and female cattle final slaughter weights.

Further options are available for updating the national inventory's cattle weight information, that is, the ICBF database and Teagasc NFS. The ICBF database captures weight information from farm weighing events, cattle movements, purchases, sales and slaughterings. This information is reported back to farmers as part of its services, for example HerdPlus. In 2016, the HerdPlus service had over 23,000 dairy and beef herd members. The Teagasc NFS captures economic information on cattle purchases and sales and calculates cattle weights. The planned expansion of the NFS to carry out carbon assessments of beef cattle farms may provide additional cattle weight and age information. The NFS data, along with information on commercial cattle herds provided to the ICBF, could be useful in verifying or updating the national inventory's default live weights for suckler and dairy cows, and non-breeding cattle growth rates.

The ICBF also collects similar data for sheep as part of its Sheep Ireland database. However, most of these data are from pedigree herds that may not be representative. In addition, the membership level for this new ICBF service is currently low. The Teagasc NFS uses the same approach as described for cattle to collect sheep and lamb weights. Bord Bia farm sustainability auditors generally do not collect animal production data, except for sheep. The Bord Bia auditors collect the estimated weight of lambs sold to meat plants and the age at sale. This information, along with NFS data, may be useful in estimating average lamb growth rates and could be used to update the inventory's adapted tier 1 approach for calculating sheep enteric methane emissions.

Representative animal production data for pigs and poultry are available only from the CSO and DAFM. For pigs, country-specific weight information is used to estimate GEI sand manure methane emissions. Currently, pig weights are not updated. The CSO and DAFM were identified as the best options for regularly reviewing pig weights. For poultry, it is currently not necessary to review or update bird weights or egg production as the national inventory uses a tier 1 approach to estimate methane from these animals.

2.4.5 Manure storage systems

Hyde *et al*. (2008) conducted a survey of farm facilities that was nationally representative and covered each of the regions included in the Nitrates Directive Action Programme. This survey gathered data on farmland fragmentation, the type of livestock accommodation, forage storage facilities, soiled water storage and manure management practices. For manure management practices, data were collected on outwintering of livestock (i.e. at pasture all year round) and the methods that farms use to apply and store livestock manure. The survey recorded three different types of manure storage systems: slurry, dungstead and farmyard manure. Slurry storage systems were split into eight subcategories (e.g. tank in roof slatted area or shed and lined lagoon) and dungstead was divided into two categories based on the typical dry matter content of the manure.

The results from Hyde *et al*. (2008) were used in the national inventory to apportion manure from housed cows, cattle, pigs and sheep to the IPCC manure storage systems: slurry pit storage and deep bedding. For the remaining animal categories, other or additional IPCC manure storage systems were used, for example liquid (slurry) storage and litter management systems. The allocation of manure to IPCC storage systems facilitated the development of a tier 2 method to estimate national methane emissions from cattle manure. The national inventory still uses data from Hyde *et al*. (2008) to allocate manure to storage systems. However, the results of this survey may not be representative of current farm practices. Therefore, it is recommended that the national inventory livestock manure storage systems are reassessed. The Teagasc NFS, Bord Bia sustainability survey, CSO and DAFM were identified as potential options for reviewing the inventory's livestock manure storage systems. The Teagasc NFS assesses the type of housing used on farms, that is, bedded or slatted, the systems of slurry storage, the method of manure spreading (e.g. splash plate or trailing shoe) and the timing of manure application. The NFS collects estimates of the proportion of livestock housed in bedded and slatted systems and gathers data on the proportion of livestock's slurry managed in different storage systems. The survey uses the same slurry storage system options as Hyde *et al*. (2008) apart from the "other" category. The Bord Bia survey collects fewer data than the NFS on farm manure storage systems and uses a different approach. For instance, the Bord Bia survey does not gather data on the number of livestock housed in bedded or slatted systems. The survey estimates the proportion of slurry that is spread from a tank and lagoon throughout the year and the percentage of solid manure emptied from a dungstead. It also gathers information on manure spreading and slurry agitation practices.

The Teagasc NFS and Bord Bia surveys are limited to collecting information on manure storage for cows and cattle. For other livestock categories, namely pigs, poultry and sheep, manure storage and spreading information is available from the CSO and DAFM. The CSO survey of agricultural production methods gathers information on the type of manure stored on farms (slurry or solid manure), the method of slurry storage (tank or lagoon) and whether slurry storage systems are covered or uncovered. However, this survey does not estimate the proportion or volume of manure stored on farms. The DAFM regularly visits farms and assesses the type(s) and size(s) of manure storage systems used for livestock. This assessment is usually carried out as part of a cross-compliance inspection for the Single Farm Payment Scheme. Farms are not cross-compliant when their manure storage system(s) for livestock do not meet the minimum storage requirements outlined in the regulations for the protection of water (S.I. No. 134 of 2014; Government of Ireland, 2014). The DAFM does not report the status of a farm's manure storage system(s), but this inspection information or any other data that the DAFM holds on this (e.g. records on farm waste management schemes) may be useful for supplementing other data sources. It may also be useful for reviewing manure storage systems for other livestock categories for which expert opinion is largely the only option.

2.5 Data Sources and Emission Factor Development

The assessment of data sources indicates that Ireland can develop higher tier methane emission factors for additional key livestock categories. This is particularly needed for the sheep category, as the inventory still uses the generic tier 1 approach to estimate methane emissions from sheep. The inventory can move to a tier 2 approach for sheep as information is available from additional sources on sheep populations, finishing ages, concentrate usage, housing periods and manure storage systems. The potential to increase the accuracy of sheep methane emission factors beyond tier 2 is limited by the data available, but there is the potential to go to a tier 3 approach for cattle depending on activity data availability.

As outlined, detailed cattle population data are gathered by the DAFM and held in the AIM database. Further information is available from this source on concentrate feed purchases, cattle production and calving. The DAFM may also have data on manure storage systems. Taking the wealth of data collected by the DAFM and further data gathered by the CSO, Teagasc NFS, Bord Bia sustainability surveys and animal feed industry, it should be possible to develop more accurate type of cattle methane emission factors. Ideally, the data from these sources should be pooled into a single database to potentially operate a tier 3

method for cattle (Figure 2.1). This approach would simplify data operations and increase the potential to automate the process.

2.6 Activity Data Conclusions

The evaluation of current and potential inventory data sources shows that activity data are available to regularly review and, if required, update several of the presently static input variables required in the estimation of livestock emission factors in the national emission inventory. These activity data are verified for current data sources and the Teagasc NFS using farm records, livestock passports and inspections. For other potential data sources (Bord Bia and ICBF), farm diaries or estimates are sometimes used, for example length of the grazing season. However, this is consistent with the approach currently used in the inventory for such variables. Revising the activity data used for static inventory variables using the data sources identified will improve the accuracy of Ireland's national GHG emission estimate. The evaluation of inventory data sources also indicates that Ireland can move to tier 2 methane emission factors for sheep and potentially a tier 3 approach for cattle. The realisation of these emission factor developments will further improve the estimation of the sector's GHG mitigation efforts and the overall accuracy of the national GHG inventory.

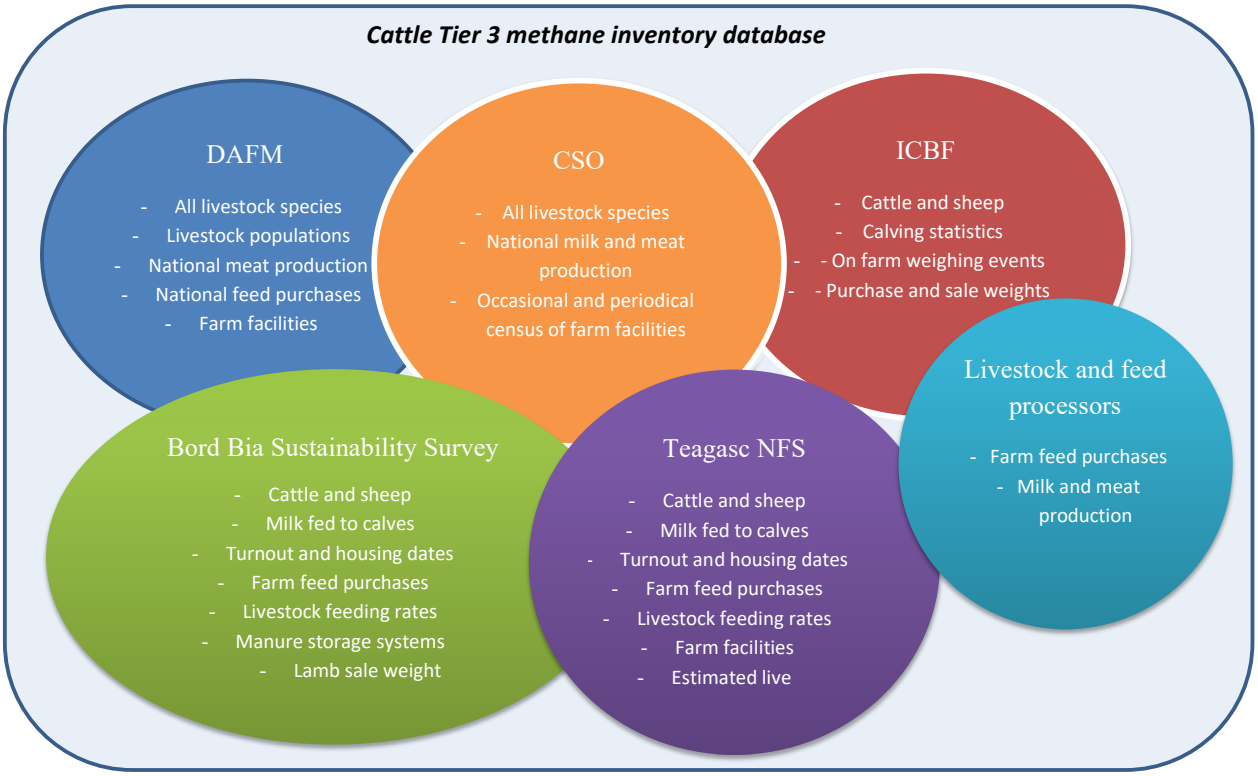

Figure 2.1. Cattle conceptual tier 3 methane emission factor input database.

3 Methodological Review

Initially, Ireland, like most countries, used default tier 1 methane emission factors for all livestock species to estimate national emissions. Over this initial period (1990–2000), the annual national GHG emission inventories consistently showed that methane from Ireland's livestock, particularly dairy cows and cattle, was a key source of national GHG emissions (typically > 15%). In 2000, the EPA commissioned research that aimed to enhance the understanding of GHG emissions from key livestock categories and to develop strategies to mitigate their emissions. This research was partly carried out in response to the IPCC (1997) general recommendation that countries with relatively large cattle populations should use tier 2 or higher methods to estimate livestock GHG emissions. This recommendation was given directly, during the early stage of Irish research on livestock emissions, by a UNFCCC expert review team. The expert review team evaluated Ireland's annual GHG emission reporting in 2001 and 2003 and recommended that country-specific emission factors should be developed to estimate GHG emissions from key national emission categories, for example cattle.

In 2006, Ireland's national GHG submission to the UNFCCC included tier 2 methane emission factors for key livestock categories for the first time, following the completion of research on GHG emissions by O'Mara (2006) and Hyde *et al*. (2008). The country-specific tier 2 cattle methane emission factors developed by O'Mara (2006) were generally greater than the tier 1 factors previously used for dairy cows and other cattle. For example, O'Mara (2006) reported that the tier 2 methane emission factor for enteric fermentation in dairy cows was 9% greater in 2003 than the original tier 1 annual estimate (100 kg of enteric methane per cow per year). Thus, when the tier 2 methane emission factors were first adopted for the year 2003, Ireland's national emissions from livestock increased by 37 kilotonnes (kt) of methane. However, when the tier 2 approach was applied for the base year the increase was greater (49 kt). Consequently, the reduction in livestock methane emissions was 12 kt more than that estimated using the tier 1 method.

The primary reason that the national reduction in cattle methane emissions was greater using tier 2 emission factors than when using tier 1 estimates was that the higher tier approach captured reductions brought about by improvements in livestock productivity, that is, dairy cow milk yield and age at slaughter. The mitigating influence of higher livestock productivity on methane emissions is well documented (e.g. Gerber *et al*., 2013). The purpose of this chapter is to assess how the methane emission factors developed by O'Mara (2006) were computed and to compare these methods with those reported in national GHG inventory reports of other countries. Additionally, we aim to evaluate the potential to further refine cattle tier 2 methane emission factors and emission factors for the remaining livestock species. This was assessed by examining the methods reported in the IPCC (2006) guidelines, national GHG inventory submissions and scientific studies.

3.1 National Methods

3.1.1 Cattle

The methane calculations for livestock in the 2015 national inventory were reviewed by assessing the Irish GHG emission common reporting format submission to the UNFCCC and key national reports, for example O'Mara (2006) and Duffy *et al*. (2017). This showed that the inventory generally applies the same computation methods and categories as the IPCC for tier 1 livestock calculations. The national inventory uses over 60 subcategories to calculate enteric and manure methane emissions from cattle. The main benefits of segregation of a livestock category into different production practices are that it typically increases accuracy and the potential to capture reductions in methane emissions as a result of a change in age structure and animal performance within the overall livestock population. The main disadvantage of splitting a livestock category into many subcategories is that it increases the number of data required to estimate emissions, which may be difficult to fully update periodically. This risks causing

a decrease in overall data quality and inventory accuracy.

The assessment of national livestock methane emissions also showed that several of the algorithms used to derive annual methane emission factors for cattle were different from those in the IPCC tier 2 method. The alternative algorithms used were based on Irish research that was considered more appropriate than the IPCC tier 2 equations. Irish equations were used to estimate cattle energy and feed requirements, whereas manure excretion rates and enteric methane emissions were based on the French net energy (NE) system adapted for Irish conditions (O'Mara, 1996). Enteric methane emissions were estimated using the relevant standard IPCC gross energy requirement conversion factor (Ym) and a prediction equation from Yan *et al*. (2000). The approach selected to estimate enteric methane emissions was based on the composition of the cattle diet. The IPCC Ym of 6.5% was used when the cattle diet was grazed grass and concentrate; otherwise, the following equation of Yan *et al*. (2000) was applied:

$$\text{Enteric methane (MJ/d)} = DEI \times (0.096 + 0.035 \times S_{DMI}/T_{DMI}) - (2.298 \times FL) - 1 \ (R^2 = 0.89) \quad (3.1)$$

where DEI = digestible energy intake (MJ/d); S_{DMI} = silage dry matter intake; T_{DMI} = total dry matter intake; and FL = feeding levels above maintenance energy. This algorithm uses digestible energy intake to predict enteric methane emissions. It was developed using experiments carried out in Northern Ireland from 1992 to 1997 that measured enteric methane emissions from steers and dairy cows offered a grass silage-based diet. The equation is considered more appropriate for Irish cattle fed grass silage.

The Irish national inventory approach to estimate cattle methane emission factors is consistent with the general steps of the IPCC tier 2 method. It has been applied by Irish researchers on several occasions since it was developed.

As discussed, there are challenges in updating some of the parameters of the cattle methane emission factors for the categories that O'Mara (2006) created. Prototype dairy and suckler cow methane models were developed as part of this study to try and overcome some of these issues. These new models use the same nutritional values for feeds as the current inventory and follow the same approach and timestep as O'Mara (2006) to quantify the nutritional requirements and methane emissions of cows. For the new models, the New Zealand Ym values provided by H. Clark (AgResearch, New Zealand, via personal communication to O'Mara, 2006) were reviewed using Irish emission studies (e.g. Wims *et al*., 2010; O'Neill *et al*., 2011). This review showed that the average Ym coefficient of these studies was inconclusive when compared with the current inventory, but it is recommended that these are further reviewed and presented to the national inventory implementation group. The calculations of the prototype models were streamlined by removing the regional division of spring or autumn cow categories. In addition, the new models use an average spring calving date instead of three different dates.

For the inventory computations, the prototype model changes mean that the six "regions" contained in the O'Mara (2006) dairy and suckler cow methane models are no longer required – they are replaced with the "All cows" worksheet and the "Parameters" worksheet. The older model's "Cow numbers" and "Housing" worksheets are replaced with the "Inputs" worksheet. The "Lactation curves" worksheet was revised for dairy to remove the necessity to manually change milk yield for each region. The revised cow model calculations were automated. This eliminated the requirement to manually change data and parameters (e.g. "Approximate Proportion concentrate") using functions such as goal seek. The effect of calculation changes on the model operations is detailed in full in the document titled "O'Brien and Shalloo Cow methane model instructions", which is available on the EPA SmartSimple system (https://epa.smartsimple.ie).

The new prototype cow models require more input data, for example calving dates, turnout and housing dates. It should be possible to obtain these data from the sources discussed previously.

The effect of updating inventory data for dairy cows was tested using the prototype models for emission factor calculation in this study. The parameters that could be updated with national data were calving date, grazing season length, milk composition and concentrate feeding rate. Calving date was revised using the ICBF (2017) statistics and milk composition was obtained from the CSO (2018). Teagasc NFS data were used to revise the length of the grazing

season and concentrate feeding rate. The quality of concentrate and forage in terms of digestibility, energy and protein were quantified using the same nutritional values that O'Mara (2006) reported. Table 3.1 summarises the change in each parameter and its effect on dairy cow methane emission factors. The change in milk composition resulted in the largest increase in the enteric methane emission factor and slightly increased the manure methane emission factor. The shorter grazing season caused the largest increase in the manure methane emission factor. In agreement with O'Mara (2006), concentrate feeding had a small effect on cattle methane emission factors. The only parameter change that decreased both emission factors was earlier calving date.

The combined effect of changing all parameters described was a 4% (4.2 kg) increase in the enteric methane emission factor and a 12% increase in the manure methane emission factor (1.2 kg) from the 2015 situation. This is a significant increase for the enteric methane emission factor, which was largely driven by greater feed intake to support a higher milk fat and protein yield. The greater yield of protein also meant that more nitrogen was retained, but further analysis showed that nitrogen excretion per cow increased. The main reasons for the excretion increase were higher feed intake and greater feeding of concentrate. The latter has a higher estimated crude protein content than forage. Thus, this feed increased the nitrogen concentration of the overall diet.

3.1.2 Sheep

Ireland should replicate a simpler tier 2 version of the New Zealand method for calculating GHG emissions from sheep using a prototype model developed in this study from national research (e.g. Bohan *et al*., 2016; O'Brien *et al*., 2016) for lowland sheep production systems (approximately 80% of sheep production; Hennessy and Moran, 2016). The central component of this model is the quantification of dry matter intake (DMI) and GEI. The approach is similar to that in the cattle model and entails computing the NE that ewes, hoggets (1–2 years) and rams require monthly for maintenance, animal growth, body condition score (BCS) change, milk production and pregnancy. Maintenance, BSC and pregnancy are calculated using equations from an adapted Irish version of the French nutrition system (O'Mara, 1996):

$$\text{Energy required for maintenance (UFL/d)} = (0.033 \times LW^{0.75}) \times AA \quad (3.2)$$

where UFL = 1 kg of air-dried standard barley or 7.11 MJ/kg of dry matter (DM), LW = live weight in kg and AA = activity allowance, which is increased by 10% when sheep are at pasture. A ewe's body condition is assumed to change across the production year depending on the level of production and pregnancy requirements. The ewe is assumed to lose 0.2 of a BCS unit in month 3 of pregnancy and 0.15 of a BCS unit in months 4 and 5 of pregnancy. The ewe is lactating for 4 months and loses 0.4, 0.3, 0.2 and 0.1 of a BCS unit in each subsequent month. During the dry period, after weaning, the ewe regains her BCS again over 4 months at a rate of 0.4 of a BCS unit in the first month, 0.5 of a BCS unit in the second and third months and 0.1 of a BSC unit in the fourth month:

$$\text{Energy required for BCS gain (UFL/d)} = LW \times 0.13 \times 5.6 \times \text{BCS gain} \quad (3.3)$$

$$\text{Energy received from BCS loss (UFL/d)} = LW \times 0.13 \times 4.36 \times \text{BCS gain} \quad (3.4)$$

NE is quantified for the last 2 months of pregnancy for ewes and was estimated as 0.3 UFL/d. The NE required for milk production was estimated using an

Table 3.1. Influence of updating parameters on 2015 methane emission factors for Irish dairy cows

Parameter	Change	Enteric fermentation (kg methane/year)	Manure (kg methane/year)
Baseline (2015)	No change	113.0	10.0
Calving date	–9 days	112.7 (–0.3%)	9.9 (–0.9%)
Grazing season length	–10 days	114.0 (1.0%)	11.0 (10.1%)
Milk composition	+0.37 fat%, +0.19 protein%	116.2 (2.8%)	10.1 (1.4%)
Concentrate feeding rate	+146 kg	113.2 (0.1%)	10.0 (–0.2%)
All listed	As above	117.2 (3.7%)	11.2 (12.1%)

equation from the 2007 French ruminant nutrition system (INRA, 2007):

$$\text{Energy required for milk production (UFL/d)} = MY \times ((0.0071 \times PC) + (0.0043 \times FC) + 0.2224) \quad (3.5)$$

where MY = milk yield (kg/d); PC = protein content (%) and FC = fat content (%). The NE requirements for the growth of sheep other than ewes were based on the work of Rattray *et al*. (1973). The NE requirements for lamb and hogget growth varied by month and are summarised in Table 3.2.

Sheep category weights, growth rates, activity, milk production and composition data were obtained from the NFS, McDonald *et al*. (2011) and O'Mara (1996). The nutritional quality of forage and concentrate in terms of digestibility, energy and protein was also obtained from O'Mara (1996). The quantity of forage fed was estimated by subtracting the NE provided by concentrate from a sheep category's total NE requirement and then dividing the NE required from forage by its NE concentration. The DMI of feed was converted to GEI using gross energy concentration values reported by O'Mara (1996). Enteric methane loss for ewes, hoggets and rams was estimated as 6.5% of GEI. For lambs, no enteric methane emissions were estimated for the first month post lambing, because milk was largely sufficient to sustain lamb growth. From week 5, enteric methane emissions were estimated as 4.5% of GEI. It may be possible to develop more advanced tier 2 sheep Ym coefficients by using recent research from Northern Ireland (Zhao *et al*., 2016).

The prototype sheep model also used DMI and diet digestibility to compute manure excretion rates. The quantity of manure requiring storage was computed by multiplying excretion rates by the typical number of days that Bohan *et al*. (2016) reported that sheep are housed. The fraction of manure managed in different storage systems was based on the study by Hyde *et al*. (2008). Methane emissions from manure were computed using the same approach as that described by O'Mara (2006).

The effect of using a tier 2 method for sheep is highlighted in Figure 3.1. The development of advanced tier 2 manure emission factors is unlikely, because Irish measured methane conversion factors for manure are rare. This emission source, however, is typically a small component of the agriculture sector's methane emissions, regardless of the calculation method used. Thus, the IPCC conversion factors should be sufficient to estimate methane emissions from sheep manure.

3.1.3 Improvement assessment

Irish researchers have developed non-emission inventory methods to estimate methane emissions from cattle and sheep (e.g. Lovett *et al*., 2006; O'Brien *et al*., 2016). For cattle, most of these methods were developed prior to the 2006 Irish inventory methodology update and therefore they were not assessed. However, for sheep, one recently developed method (O'Brien *et al*., 2016) was evaluated.

The approach described by O'Brien *et al*. (2016) and discussed earlier follows the steps of the IPCC tier 2 method, but uses country-specific information on nutritional requirements. It can be used to replace the inventory's tier 1 methane emission factors for sheep enteric fermentation and improve the current tier 2 methane emission factors for sheep manure. Figure 3.1 shows that the tier 2 methane emission factor for enteric fermentation in 2015 was 31% higher than the tier 1 emission factor for ewes and 23% higher than the default factor for other sheep aged > 1 year. For lambs, the tier 2 methane emission factor for enteric fermentation was 35% lower than the current method and for the ram category it was 13% higher than the

Table 3.2. The NE requirements of lambs and hoggets for growth

Sheep life stage	NE requirement (UFL/d)
Lamb – 1 month	1.40
Lamb – 2 months	2.12
Lamb – 3 months	2.71
Lamb – 4 months	3.42
Hogget	2.6

Source: Rattray *et al*. (1973).

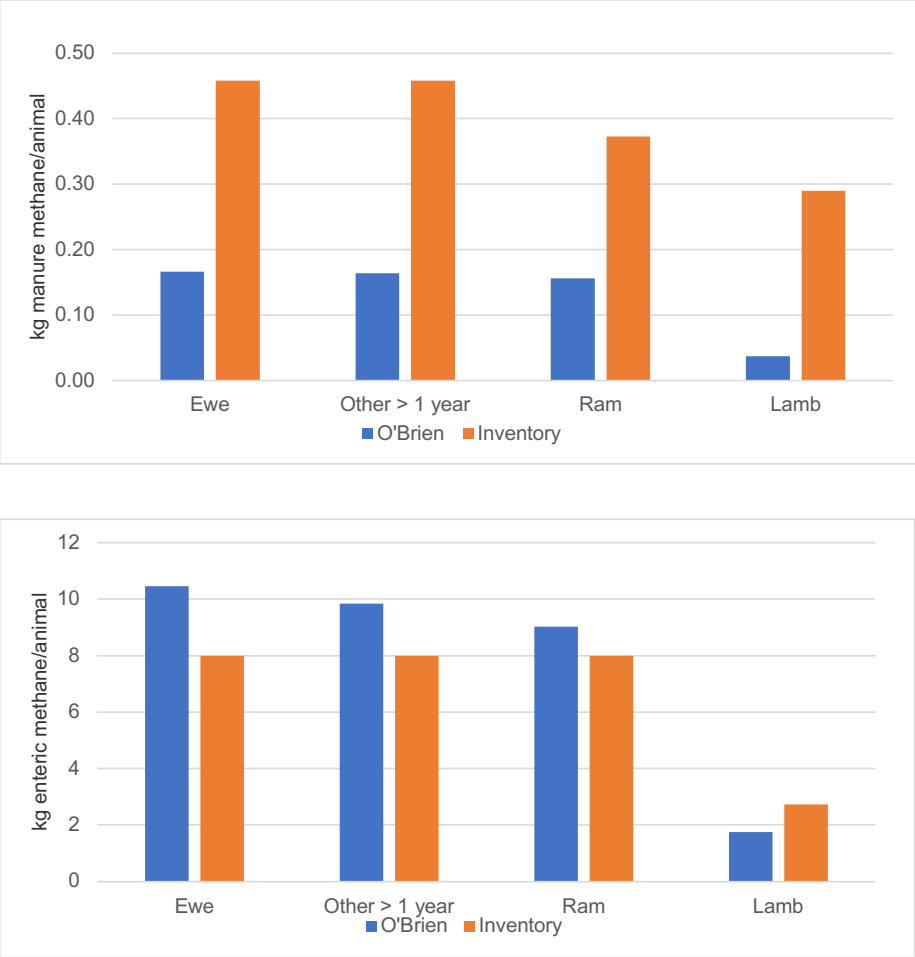

Figure 3.1. Comparison of data from O'Brien *et al*. (2016) and Irish 2015 GHG inventory annual estimates of methane emissions from lowland sheep.

tier 1 default factor. The new emission factors for methane emissions from manure were lower than the current inventory emission factors for ewes and other sheep aged > 1 year by 0.3 kg of methane/animal in 2015. They were also lower for lambs by 0.25 kg of methane/animal and for rams by 0.2 kg of methane/animal. The net effect of the new sheep tier 2 methane emission factors was an increase in emissions for all categories except lambs.

There is the potential to improve the approach of O'Brien *et al*. (2016) for estimating methane emissions by using new prediction equations for sheep enteric methane emissions from research conducted in Northern Ireland. These equations were developed by Zhao *et al*. (2016) using nutritional and methane emission data from several recent experiments. The experiments measured enteric methane emissions from Irish or UK sheep using open-circuit respiration chambers. These experiments compared a range of diets, but Zhao *et al*. (2016) collected data only from sheep offered fresh perennial ryegrass as their sole diet, that is, no concentrate supplementation. In total, Zhao *et al*. (2016) used data from 82 sheep and found that equations created using DMI or energy intake (gross or digestible) were the best predictors of sheep enteric methane emissions. These equations are similar to those for calculating the IPCC tier 2 methane conversion factors. The goodness of fit (R^2) or accuracy of enteric methane predictive equations recommended by Zhao *et al*. (2016) was high when regressed against measurements (R^2 = 0.87–0.93). This level of accuracy is similar to the enteric methane equation that the national inventory currently uses from Yan *et al*. (2000) for cattle fed silage. Thus, this suggests that the following sheep equations developed by Zhao *et al*. (2016) are suitable for carrying out tier 2 national inventory computations:

$$\text{Sheep enteric methane (g/d)} = 16.7 \times \text{DMI} + 3.1 \quad (R^2 = 0.87) \quad (3.6)$$

$$\text{Sheep enteric methane (g/d)} = 18.8 \times \text{DMI} + 5.0 \times \text{DE} - 4.9 \times \text{ME} - 9.9 \quad (R^2 = 0.93) \quad (3.7)$$

where DMI = dry matter intake (kg/d), DE = digestible energy concentration (MJ/kg DM) and ME = metabolisable energy concentration (MJ/kg DM).

Beyond tier 2, there are few, if any, national algorithms available to increase the accuracy of sheep methane emission factors to the highest IPCC level, tier 3. This is also the case for other Irish livestock species except for cattle. There is the potential to go to a tier 3 approach for this species, because recent Irish and international studies have developed better enteric methane emission factor algorithms for cattle than the IPCC tier 2 equations and equations from Yan *et al*. (2000). The improved Irish cattle methane equations were developed by various researchers, for example Jiao *et al*. (2014) and Yan *et al*. (2009). In some cases, these equations are slightly more accurate in terms of the goodness-of-fit values (R^2) found by Yan *et al*. (2000) in their study of dairy and beef emission factors. This can be partly explained by these new Irish studies focusing on methane emissions from specific cattle subcategories; for example, Jiao *et al*. (2014) developed enteric methane algorithms for growing Irish dairy cattle. The cattle methane equations from recent Irish studies usually require more data than previous algorithms. Thus, they are likely to be more difficult to apply nationally. Nevertheless, it should be possible to develop tier 3 Irish cattle enteric methane emission factors. The potential to apply tier 3 emission factors was assessed by completing an international review of current livestock methane inventories. The review also assessed livestock manure methane emission factors, because there is a paucity of national research on this source of emissions.

3.2 International Livestock Methane Emission Factors

Livestock methane emission factors reported in national GHG inventory submissions to the UNFCCC were reviewed for Annex 1 (developed) countries and five non-Annex 1 countries (i.e. Brazil, China, India, South Africa and Uruguay). The review was carried out on 2017 Annex 1 national inventory submissions, which estimated GHG emissions for the period 1990–2015 (UNFCCC, 2017a). Unlike Annex 1 countries, non-Annex 1 nations do not report emissions annually. The latest reports available for these nations were 2–3 years older and estimated GHG emissions generated prior to 2013 (UNFCCC, 2017b). The appraisal of Annex 1 and non-Annex 1 GHG inventories considered the methods that nations used to estimate livestock enteric and manure methane emission factors. The findings of this international methodological evaluation were summarised for livestock categories using the IPCC tier(s) (e.g. tier 2 or 3) that each nation used in the emission calculations. The categories of livestock evaluated were dairy and non-dairy cattle, sheep, pigs, poultry and other livestock (e.g. rabbits, horses, mules). The results of the review for each category were compared with pertinent Irish livestock methane emission factors.

3.2.1 Cattle

Ireland's tier 2 methane emission factors for cattle were within the range of results reported by Annex 1 parties. The prototype models methane emission factors for Irish dairy cows were generally lower than those of nations with heavier and higher yielding cows, for example the USA, and higher than those of nations with lighter and lower yielding cows (Table 3.3). The differences in dairy cow methane emission factors were related to the calculations and reporting methodology used, as well as cow productivity.

Most countries used tier 2 enteric methane emission factors for dairy and non-dairy cattle (Table A1.1). Tier 1 emission factors were not applied to compute enteric methane emissions from dairy cows and were only used by Cyprus and the UK for mature beef cattle and younger stock (together known as non-dairy). Tier 3 emission factors were used by Ukraine and France to quantify enteric methane emissions from dairy cows and non-dairy cattle. This tier was used by a further three countries or five in total to estimate dairy cow enteric methane emissions. Tier 3 emission factors were not used for estimating methane emissions from dairy cow manure and were rarely used for this source of emissions for non-dairy cattle.

Generally, nations that reported a higher tier method than Ireland to estimate cattle enteric methane emissions used more data-intensive and detailed

Table 3.3. Dairy cow production and tier 2 methane emission factors from Annex 1 parties 2015 national GHG inventories using the common reporting format (CRF)

Parameter	Ireland	UK	USA	New Zealand
Average live weight (kg)	535	608	680	448
Milk yield (kg/cow per year)	5458	7705	10,268	4362[a]
Gross energy (MJ/d)	261	300	IE[b]	IE
Methane from enteric fermentation (kg/year)	117.2	130.0	146.0	84.3[c]
Methane from manure (kg/year)	11.2	17.4	74.0	5.8[c]

[a]Obtained from Dairy NZ (2016).

[b]Not reported.

[c]Includes dairy heifers.

IE, included elsewhere.

emission algorithms. Tier 3 equations were normally derived from published national research projects that measured and/or modelled methane, for example the Mondferent project (Eugene *et al*., 2012, cited in CITEPA, 2017). This French project derived tier 2 and 3 methane emission factors for several categories of dairy cows and other cattle, considered as representative of the nation's breeding situations. Each category was associated with a breed, an average mass and a milk yield if necessary, as well as energy needs.

In the Swiss approach, cow feed and gross energy requirements were estimated using recommended national feeding standards that are widely used by Swiss farmers, as they form the basis for their direct support payment. The Swiss Ym was 6.9%. This is higher than the IPCC standard and mainly comes from national projects that measured methane from dairy cows in open and closed calorimeter chambers.

The Swiss and French methods to estimate dairy cow enteric methane emission factors aligned better with the current Irish inventory than the complex tier 3 approaches applied by the Netherlands and Germany. Briefly, the Netherlands used the mechanistic, dynamic model of Bannink *et al*. (2011) of the rumen fermentation process to estimate methane emissions from enteric fermentation in dairy cows. The inputs required to operate the Dutch model were feed intakes, chemical composition of feed and degradation characteristic of the constituents of feed (e.g. crude protein). Cow feed intakes were estimated according to national feeding standards and nutritional data were provided by a widely used Dutch agricultural laboratory. Detailed nutrition data were also used in the German approach to estimate dairy cow enteric methane emissions. The German method, described by Rösemann *et al*. (2017), accounted for the effects of feed composition and feed properties using a German model developed by Kirchgessner *et al*. (1994). This model, like the Dutch model, was data intensive and required information that is unlikely to be feasible to collect in the short term at a national level in Ireland.

Cattle feed intakes were required to estimate methane emissions from manure in most national inventories reviewed. The tier 3 method was used to estimate methane emissions only from the manure of Australian beef cattle fed on feedlots. The calculation was similar to that used in the current Irish approach and IPCC tier 2 method, but used measured methane conversion factors from Redding *et al*. (2015) for Australian manure storage systems. Australia was not the only nation that used country-specific methane conversion factors for manure management; other countries that used country-specific factors included New Zealand, Denmark and Austria. A few national inventories, such as that of the UK, reported the proportion of cattle slurry systems that form a natural crust cover.

Several countries recognise that methane emissions from cattle and livestock manure are linked to other GHG emissions from this source, for example nitrous oxide. For consistency, some countries used a comprehensive model that simultaneously quantified GHG and ammonia emissions from livestock. This approach was recommended in the 2017 EU

submission to the UNFCCC for its Member States (EEA, 2017), but is applied only by a few nations, for example in the German gas emission model (GAS-EM) or Denmark's integrated database model for agriculture emissions (IDA) model and in Ireland.

3.2.2 Sheep

Methane emissions from sheep were generally estimated in national inventories using tier 2 or tier 1 emission factors (Table A1.2). The tier 2 method was used more often than the tier 1 approach. Generally, countries that applied the tier 2 method used the IPCC (2006) equations to estimate sheep feed requirements, manure excretion and methane emissions. France used a more advanced method to calculate enteric methane emission factors for sheep and New Zealand reported applying a country-specific tier 2 method. The French method for estimating methane emissions from sheep was similar to the approach described earlier for French cattle, whereas the calculation of methane emissions from enteric fermentation was more complex as it considered digestive interactions in greater detail.

The New Zealand approach to calculate emissions from enteric fermentation and manure management in sheep was similar to that used for cattle. The tier 2 emission factors for both species were developed by Clark *et al*. (2003) and are regularly improved using new research. The New Zealand computations for sheep enteric methane emissions are carried out on a monthly basis and use country-specific data for sheep populations, pasture quality and productivity (e.g. milk yield and live weight). These data are generally available for sheep and beef cattle only at a national scale whereas, for dairy cattle, productivity data are available regionally.

3.2.3 Pigs

The IPCC tier 1 pig enteric methane emission factors were used by 30 of the 47 nations reviewed (Table A1.2). The remaining countries used a tier 2 method for this source of emissions, except for France, which used a tier 3 method. Tier 2 emission factors from the IPCC (2006) were primarily used to estimate methane emissions from pig manure. Only 10 nations used a tier 1 method for this source. Ireland uses a tier 2 method to estimate methane emissions from pig manure. The Irish method is consistent with that of most nations that use tier 2 emission factors. It entails computing the GEI of pigs to meet feed requirements and estimating manure excretion from feed intakes using diet digestibility data. Methane emissions from manure are computed using survey data on manure storage systems and relevant IPCC conversion factors. This tier 2 method is slightly more advanced than that of some nations (e.g. the UK and Slovenia), because manure excretion is based on national data instead of default excretion estimates provided by the IPCC.

The tier 2 and 3 methods that nations used to estimate enteric methane emissions from pigs did not differ from those described for cattle and sheep. This implies that the GEIs described to estimate methane emissions from Irish pig manure could also be used to develop tier 2 enteric methane emission factors. The Ym for pigs could be easily derived from the references of the IPCC (2006) guidelines. This was the approach used by many nations that reported a tier 2 method for this source. Country-specific Ym values were also developed by a few nations, for example Germany, but these estimates were similar to the IPCC estimate, differing by < 0.1%.

3.2.4 Poultry

Nations are not required to estimate enteric methane emissions from poultry. This category is considered by the IPCC to emit negligible emissions. Thus, there are currently no tier 1 emission factors for this source. Nevertheless, 12 nations estimated enteric methane emissions from poultry and three reported using tier 2 emission factors (Table A1.3), because the method was developed from national research. The emission factors from such research, for example the study by Wang and Huang (2005), could be applied to estimate enteric methane emissions from Irish poultry. A slightly higher number of nations estimated methane emissions from poultry manure using tier 2 emission factors instead of tier 1 factors. Australia was the only nation that reported a tier 3 method. The IPCC tier 2 equations and coefficients were generally used to estimate methane emissions from poultry. The quantity of manure excreted by poultry was estimated using national

data or IPCC default values. The tier 1 method is currently used in Ireland for this source.

3.2.5 Other livestock

Enteric methane emissions from the other livestock category were usually calculated by nations using tier 1 emission factors (Table A1.3). Nations seldom applied the tier 2 method to estimate enteric methane emissions from all species in this livestock category. Instead, most nations used tier 2 emission factors to estimate methane emissions from a few economically important production species, for example goats and deer. In general, the tier 2 approach to computing enteric methane emissions from other livestock species was very similar to the IPCC method used for cattle and sheep, apart from the Ym parameter, which was not necessarily species specific. For example, the South African Ym parameter for goats was based on sheep measurements. This approach to estimate Ym is generally acceptable as long as species have similar digestive systems. This approximation method is also recommended by the IPCC for other livestock species not listed in their guidelines and can be applied based on live weight for tier 1 emission factors.

Almost half of the nations reviewed used a tier 2 method to estimate methane emissions from the manure of a species contained within the other livestock category. Of these nations, 13 used tier 2 manure methane emission factors for all species within this category. The IPCC tier 2 equations and default manure excretion rates were generally used to estimate methane emissions from manure in this category.

Ireland used the simpler tier 1 approach for enteric and manure methane emissions in this category. Further development of these emission factors may be possible using the IPCC (2006) guidelines and Irish regulations on good agricultural practices for the protection of water (EU, 2006). The latter used Irish empirical and non-empirical data to estimate livestock organic nitrogen excretion rates, which may be suitable for computing emissions from this small source.

3.3 Methodology Conclusions

Our review demonstrates that Irish livestock methane emission factors can be computed more accurately using a tier 2 method than a default tier 1 approach for the majority of species. The tier 2 method is widely used by Annex 1 nations to estimate methane emissions from key livestock categories, for example cattle, pigs and sheep. In addition, several Annex 1 nations use this method for all species and integrate it with other methods to estimate air pollutants, for example ammonia. The tier 2 methods that nations applied were generally similar to the IPCC approach, but the equations and parameters that nations used to calculate important inputs required to derive methane emissions, such as feed intakes and manure excretion, were often based on national research. These country-specific equations are usually more accurate than the IPCC alternatives and should be used in the Irish inventory where possible, for example for sheep. There is also the potential to develop more advanced methane emission factors for Irish cattle and sheep by using national measurements of enteric methane emissions from these species. This method is considered a tier 3 approach.

4 Methane Mitigation

Methane from livestock is a key source of Irish GHG emissions. This source is typically responsible for 20% of national GHG emissions. Irish livestock methane emissions were 12% higher in 2016 than in 2010. The upward trend in livestock emissions is expected to continue and may partly result in Ireland failing to meet its GHG emission reduction commitments within the EU (2009).

The growth in Ireland's livestock methane emissions from 2010 to 2016 can primarily be explained by the 11% increase in the national cattle population to 7.3 million cattle (CSO, 2018). The majority of this population increase was a result of the dairy herd expanding by 307,000 cows and 95,000 heifers (CSO, 2018). The dairy herd expansion was primarily a reaction to the removal of the EU milk quota levy system in 2015 and the subsequent favourable, albeit volatile, economic conditions. The growth in dairy cow numbers accounted for approximately 90% of the livestock methane emission increase and was also an important driver of the rise in methane emissions from other cattle populations. This increase was counterbalanced by a reduction in the other or suckler cow population during this period. Thus, other cattle and cows accounted for only 6% of the rise in methane emissions. The remainder of the increase in methane emissions was largely due to the national flock growing by 0.5 million sheep and the poultry population increasing by 1%.

4.1 Mitigating Methane Emission Intensity

The pressure to cut national livestock populations, particularly ruminant numbers, to mitigate methane emissions is increasing globally and nationally. Reducing livestock numbers, however, is not currently a solution to the methane and GHG problem, because the world population is growing rapidly and is projected to require 58% more milk and 73% more meat by 2050 compared with 2010 consumption levels (FAO, 2011). Mitigating methane emissions and supplying this much food from livestock will be very challenging but may be possible, as several strategies are reported to mitigate methane emissions per unit of milk or meat, that is, methane emission intensity. However, it is possible to reduce methane emission intensity on a farm/ nationally while increasing total emissions through expansion, similar to what has happened in the Irish dairy industry under Food Wise. The most frequently reported methane mitigation strategies for livestock are:

- better farm management;
- farm system transformation;
- diet manipulation;
- use of biotechnologies;
- animal waste treatment.

The following sections will assess the suitability of these methane mitigation strategies for Ireland's livestock and the feasibility of including their mitigation potential in the national GHG inventory.

4.1.1 Better farm management

A variety of management practices are recommended to improve farm productivity and reduce the methane emission intensity of livestock, as well as total emissions, if not coupled with expansion. The practices proposed vary between livestock species and are generally dependent on climate, region and farming system. Consequently, several farm practices reported to reduce methane emissions are not considered to be applicable to Irish livestock systems, for example sowing drought-tolerant forages like *Leucaena* (Harrison *et al*., 2015). The management practices identified as being suitable for mitigating Irish livestock methane emissions are:

- extending the length of the grazing season for cattle;
- increasing dairy cow genetic merit via the EBI;
- optimising age at first calving;
- increasing the daily live weight gain of beef cattle and lambs;
- optimising the calving and lambing rate, that is, the numbers of calves born per cow and lambs born per ewe;
- improving grazed grass and silage quality;
- improving animal health.

Teagasc, in association with national university partners, has measured or modelled the mitigation effects of these practices for Irish cattle and previously detailed how each practice affects methane and other GHG emissions (Schulte *et al*., 2012). For example, Teagasc reported that the first practice, extending the length of the grazing season, mitigates methane emitted from internal feed digestion (enteric fermentation). The reduction can be explained by higher quality grazed grass replacing grass silage in the typical cattle diet. This change improves livestock performance and reduces the proportion of ingested forage energy lost as methane. Additionally, a longer grazing season reduces methane emissions from manure as the quantity of manure stored as slurry under anaerobic conditions is reduced (Lovett *et al*., 2008). However, to a certain extent, this reduction is offset from a GHG emission perspective by an increase in nitrous oxide emissions from manure deposited by grazing cattle. Therefore, this implies strategies to mitigate methane emissions should consider changes in non-target GHG emissions and air pollutants to avoid implementing practices that may increase overall GHG emission intensity.

Fortunately, the cattle measures that Teagasc reports mitigate methane emission intensity also reduce GHG emission intensity. The practice of increasing daily live weight gain reduces the finishing age of beef cattle and methane and GHG emissions for the same or higher levels of meat production. Calving cows for the first time at the optimum age of 23–24 months generally reduces emissions associated with rearing replacement heifers and increases production over the lifetime of the cow, which further reduces methane and GHG emissions. Increasing the calving rate has a greater positive effect on production than emissions and thus mitigates emission intensity. Improving genetic merit via the EBI does not influence beef cattle GHG emissions, but has significant potential to reduce dairy cattle emissions. This practice simultaneously improves cow performance, fertility and health, which reduces the requirement for replacement heifers and thus emissions. This strategy is applied on most dairy farms, using top EBI sires and the artificial insemination technique. A similar sire selection system is available for beef farms, the Euro-Star Index, but the GHG mitigation effect of this beef breeding index is not currently known. Further reductions are possible in beef and dairy cattle methane or GHG emission intensity by increasing the quality of grass silage and pasture (Wims *et al*., 2010). These improvements can typically be achieved by adopting rotational grazing systems on beef farms and regularly measuring grass covers on dairy farms.

The combined methane and GHG reduction potential of the better farm practices described is significant. Teagasc has illustrated this mitigation potential at a national level using a marginal abatement cost curve (MACC) and estimated, using the inventory method, that these cattle farm practices can reduce GHG emissions by 1.0 Mt of CO_2e (Schulte *et al*., 2012). This potential reduction is equivalent to approximately 5% of Irish agricultural emissions in 2015. In addition, the same MACC indicated that better livestock and arable farm practices improve economic performance. Therefore, this methane mitigation strategy is likely to be adopted by farmers, but it is unlikely to be appropriately implemented nationally without knowledge transfer support (Schulte *et al*., 2012). Teagasc, in conjunction with Bord Bia, provides this support to farmers through its extension service and online decision support tools, that is, the beef and dairy carbon navigators.

4.1.2 Farm system transformation

The primary farm system changes reported to reduce livestock methane and GHG emission intensity are:

- switching from a suckler beef system to a dairy beef system;
- adopting a bull beef finishing system instead of a steer system;
- changing from an organic or extensive ruminant system to an intensive system.

The national inventory can partly capture the influence of these farm system changes on methane emissions. The conversion of a suckler beef system to a dairy beef system changes the dam breed of cattle to dairy and alters the calf-rearing method to a non-suckling method. The latter change eliminates the need to keep suckler cows, which reduces costs and methane emissions. The removal of sucklers from the herd and the change in cattle dam breed has little impact on production. Therefore, the methane and GHG emission intensity of the dairy beef system is significantly lower than that of the suckler beef system. The results of Irish beef studies by Clarke *et al*. (2013)

and Murphy *et al*. (2017) confirm that this is the case and show that dairy beef systems emit up to 40% less GHG emissions per unit of carcass weight than suckler systems. Similar beef modelling studies conducted in Europe and New Zealand, for example that by Flysjö *et al*. (2011), have reported the same or greater GHG reductions for dairy beef systems.

The large national increase in surplus calves from the dairy herd and slow or static growth in beef demand should make this suckler displacement strategy feasible. The suitability of a small, but nevertheless important, fraction of surplus dairy calves for beef production may be an issue for purchasers. This issue may be possible to overcome through cross-breeding, the use of biotechnologies, for example sexed semen (Schulte *et al*., 2013), or changing finishing systems.

Methane emissions from dairy and suckler beef systems can be reduced significantly by changing from steer to bull finishing. Bulls grow quicker than castrated males and are thus usually finished 6–8 months earlier than steers. Earlier finishing reduces dairy beef or suckler beef GHG emission intensity by 10–20% (Clarke *et al*., 2013; Murphy *et al*., 2017). This system conversion strategy, however, is generally associated with a large increase in concentrate feed costs in the finishing phase. The greater feed cost of bull beef systems in Ireland significantly increases the risk of economic loss. This strategy is unlikely to be adopted nationally without direct support.

Beef farms can mitigate methane emission intensity without financial support by increasing the stocking rate. Higher stocked or more intensive ruminant farms that are well managed usually produce more digestible forages and feeds than extensive systems, thus offering better-quality diets. This tends to improve productivity and economic performance and reduce methane emission intensity. Many studies have shown the benefits of farm intensification, for example Rotz *et al*. (2010), Capper *et al*. (2008) and Thomassen *et al*. (2008). However, Thomassen *et al*. (2008) reported that intensification increases GHG emissions from feed production, which can lead to very intensive systems, that is, > 3.0 livestock units per hectare, having the opposite effect on GHG emission intensity. Thus, the potential of farm intensification to reduce GHG emission intensity is limited. Nevertheless, intensification has substantial capacity to reduce the GHG emission intensity of Irish beef and sheep farms given their low stocking rates, that is, typically < 1.6 livestock units per hectare. This strategy also has the potential to reduce the emission intensity of modestly stocked dairy farms and should be considered for this significant group of Irish milk producers.

4.1.3 Diet manipulation and use of biotechnologies

A detailed review of 900 publications on livestock methane emission sources was conducted by the Food and Agriculture Organization (FAO) in 2013. This exhaustive review evaluated the mitigation potential, safety and effectiveness of a plethora of diet modifications and biotechnologies targeting livestock methane emissions. Hristov *et al*. (2013) and Montes *et al*. (2013) summarised the findings of the FAO's analysis and provided mitigation strategy recommendations (Tables 4.1 and 4.2). The results for enteric methane showed that biotechnologies that inhibit methane emissions can be very effective, but the persistency of the reduction was unclear (see Table 4.1). A recent dairy cow experiment by Hristov *et al*. (2015), however, showed that long-term enteric methane emission mitigation is possible by regularly mixing the inhibitor 3-nitro-oxypropanol (3-NOP) into the feed ration. This finding has been supported by subsequent studies, for example Vyas *et al*. (2016), showing that 3-NOP improves productivity. The inhibitor is expected to be effective for ruminants housed full-time, but it is not clear if it will be as effective for grazing ruminants if fed in pulses at each milking. Further research is required to determine if 3-NOP can consistently mitigate methane emissions from typical Irish production systems or if other inhibitors could be safely used, for example seaweed algae (Machado *et al*., 2014).

Manipulation of methane-producing microbes in the rumen (archaea) by vaccination was recommended by Hristov *et al*. (2013). However, there are no reports in the literature of vaccination being able to reduce emissions in either the long term or the short term. Thus, the potential mitigating effect of vaccines is unknown, like that of many biotechnologies and several diet modifications. Hristov *et al*. (2013) also noted that the short-term effects of some diet modifications were unreliable, that is, they could increase or decrease enteric methane emissions. The only modifications to the diet reported to have

Table 4.1. Diet modifications and biotechnologies targeting enteric methane emission mitigation

Category	Potential methane-mitigating effect[a]	Long-term effect known	Effective[b]	Safe for environment and animal[c]	Recommended[d]
Diet modification					
Lipids	Medium	No?[e]	Yes	Yes	Yes?[f]
Plant extracts					
Tannins[g]	Low	No?	Yes	Yes	Yes?
Saponins	Low?	No	?	Yes	No?
Essential oils	Low?	No	?	Yes	No
Electron receptors					
Fumaric and malic acids	No effect to high	?	?	Yes	No?
Nitroethane	Low	No	Yes?	No	No
Nitrate	High	No?	Yes	?	Yes?[h]
Ionophores[i]	Low	No?	Yes?	Yes?	Yes?
Improve forage quality	Low to medium	Yes	Yes	Yes	Yes
Include concentrate	Low to medium	Yes	Yes	Yes	Yes?[j]
Biotechnologies					
Exogenous enzymes	No effect to low	No	No?	Yes?	No?
Defaunation	Low	No	?	Yes	No
Manipulation of rumen archea	Low?	No	?	Yes?	Yes?[k]
Inhibitors					
BCM and BES[l]	High	?	Yes	No	No
Chloroform	High	No?	Yes	No	No
Cyclodextrin	Low	No	Yes	No	No
3-NOP	Medium	?	Yes	?	?

Source: Hristov *et al.* (2013).

[a]High >30% mitigating effect; medium 10–30% mitigating effect; low <10% mitigating effect. Mitigating effect refers to the percentage change over a standard practice (i.e. study control) and is based on a combination of study data and the judgment of Hristov *et al.* (2013).

[b]Effectiveness is determined on the basis of methane mitigation potential, effect on feed intake (no negative effect is beneficial) and/or effect on animal productivity (no negative effect or improvement is beneficial).

[c]Based on available data and expert opinion of Hristov *et al.* (2013).

[d]Based on available research or lack of sufficient research.

[e]? = uncertainty because of limited research or lack of data, inconsistent or variable results or lack of (or too few) data on persistency of the effect.

[f]Lipids are recommended when their use is economically feasible, e.g. high oil by-products of the biofuel industry. Maximum recommended rate in ruminant diets is 6–7% (total fat) of dietary dry matter. Their potential negative effects on animal productivity must be considered. The economic feasibility of supplementing diets with edible lipids is questionable.

[g]Detrimental effects when dietary crude protein is marginal or inadequate or when condensed tannins are astringent and in high concentrations, but with adequate dietary crude protein some condensed tannins can have wide-ranging benefits.

[h]Practicality of use is unknown. Caution must be exercised when feeding nitrate. Animals should be properly adapted and readapted if nitrate supplementation is discontinued for a period of time. Unwise to use nitrate when diets have high nitrogen concentrations.

[i]Most data are for monensin. The overall conclusion is that ionophores may have a mitigating effect of up to 5%, but ionophores are proscribed by the EU.

[j]High levels can have negative effects on fibre degradability and milk composition in dairy cows.

[k]This promising technology is not developed or commercially available.

[l]Both inhibitors are unsafe as they deplete ozone.

BCM, bromochloromethane; BES, 2-bromoethane sulfonate.

Table 4.2. Diet modifications and animal waste management options to mitigate methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) emissions from livestock manure

Category	Species[a]	Potential methane-mitigating effect[b]	Potential N_2O mitigating effect[b]	Potential NH_3 mitigating effect[b]	Effective[c]	Recommended[d]
Diet modification						
Reduced dietary protein	AS	?[e,f]	Medium	High	Yes (N_2O and NH_3)	Yes (N_2O and NH_3)
High-fibre diets	SW	Low	High	?	Yes (N_2O)	Yes (N_2O)
Grazing intensity[g]	AR	?	High?	?	Yes (N_2O)	Yes (N_2O)
Housing						
Biofiltration	AS	Low?	?	High	Yes (NH_3 and CH_4?)	Yes (NH_3 and CH_4?)
Manure system[h]	DC, BC and SW	High	?	High	Yes (CH_4 and NH_3)	Yes (CH_4 and NH_3)
Manure treatment						
Anaerobic digestion	DC, BC and SW	High	High[i]	Increase[j]	Yes (CH_4 and N_2O)	Yes (CH_4 and N_2O)
Solids separation	DC and BC	High	Low?[i]	?[k]	Yes (CH_4)	Yes (CH_4)
Aeration	DC and BC	High	Increase?[l]	?[l]	Yes (CH_4)	Yes (CH_4)
Manure acidification	DC, BC and SW	High	?[m]	High[m]	Yes (CH_4 and NH_3)	Yes (CH_4 and NH_3)
Manure storage						
Decreased storage time	DC, BC and SW	High	High	High	Yes (all)	Yes (all)
Storage cover with straw	DC, BC and SW	High	Increase?[n]	High	Yes (CH_4 and NH_3)	Yes (CH_4)
Natural or induced crust	DC and BC	High	Increase?[n]	High	Yes (CH_4 and NH_3)	Yes (CH_4)
Aeration during slurry storage	DC, BC and SW	Medium to high	Increase?[l]	?[l]	Yes (CH_4)	Yes (CH_4)
Composting	DC, BC and SW	High	?[l]	Increase[l]	Yes (CH_4)	Yes (CH_4)
Litter stacking	PO	Medium	NA	?	Yes (CH_4)	Yes (CH_4)
Decreased storage temperature	DC and BC	High	?	High	Yes (CH_4 and NH_3)	Yes (CH_4 and NH_3)
Sealed storage with flare	DC, BC and SW	High	High	?[o]	Yes (CH_4 and N_2O)	Yes (CH_4 and N_2O)

Source: Montes *et al.* (2013).

[a]AS, all species; AR, all ruminants; BC, beef cattle; DC, dairy cattle; PO, poultry; SW, swine/pigs.

[b]High >30% mitigating effect; medium 10–30% mitigating effect; low <10% mitigating effect. Mitigating effect refers to the percentage change over a standard practice (i.e. study control) and is based on a combination of study data and the judgment of Montes *et al.* (2013).

[c]Effectiveness is determined on the basis of GHG or NH_3 mitigation potential; in some cases, effects on feed intake and/or animal productivity are also considered.

[d]Based on available research or lack of sufficient research.

[e]? = uncertainty because of limited research or lack of data, inconsistent or variable results or lack (or too few) data on persistency of the effect.

[f]Insufficient research. Modelling suggests that enteric methane emissions may increase. If rumen function is impaired, manure methane emissions may increase.

[g]Reducing grazing intensity lowers urinary nitrogen input to the soil but can also increase N_2O emissions by increasing residual organic matter during freeze–thaw cycles. NH_3 emissions may also increase.

[h]Manure system that reduces the time between manure excretion and moving manure from animal house decreases NH_3 and CH_4 emissions from the building, but the effect on N_2O is unclear.

Table 4.2. Footnotes continued

[i]Anaerobic digestion and solids separation reduce the source of degradable carbon in the manure applied to soil and thus reduce potential N_2O emissions.

[j]Ammonia emissions will increase as more organic nitrogen is decomposed to NH_3; magnitude is unclear.

[k]Reducing the solids content of manure facilities infiltration and prevents NH_3 losses from land application.

[l]In some cases, aeration of manure may stimulate the transformation of NH_3-N into NO_3-N, which decreases the potential for N_2O emissions and NH_3 emissions. In most cases, composting increases NH_3 losses.

[m]Manure acidification decreases the fraction of volatile NH_3 in manure, but may increase N_2O emissions after land application.

[n]Covering the manure with a permeable porous cover promotes nitrification and N_2O emissions.

[o]Covering the manure store with an impermeable cover prevent NH_3 volatilisation during storage and increases the content of NH_3 in manure, which generally results in greater NH_3 emissions after land application.

NA, not applicable.

a consistent long-term mitigating effect on enteric methane emissions were increasing forage quality or including concentrate in the diet. Both options have a low or medium potential to reduce enteric methane emissions. Hristov *et al*. (2013), however, warned that high concentrate inclusion levels can depress fibre degradability, which could decrease production and increase methane emissions from stored manure. The latter can offset reductions in enteric methane emissions and cause overall methane emissions to rise.

Improving forage quality tends to reduce methane emissions from manure storage, in addition to enteric fermentation (Montes *et al*., 2013). This diet modification has a positive effect on ruminant performance and mitigates methane emission intensity. Furthermore, unlike most diet modifications and biotechnologies, increasing forage quality tends to improve financial performance.

4.1.4 Animal waste management

Most methane from livestock manure is produced during anaerobic storage. There are many waste management options available to control methane emissions from this source (Table 4.2). Montes *et al*. (2013) reviewed these options and recommended several manure treatments for cattle and pigs. The manure treatments recommended were anaerobic digestion, acidification, solids separation and aeration. Anaerobic digestion has substantial potential to reduce manure methane emissions, but is only economical at a large scale and may require co-digestion with food by-products. This option is cost-prohibitive for grazing Irish ruminants, but may be viable for large pig producers (Schulte *et al*., 2012). The waste treatment also reduces nitrous oxide emissions, but Montes *et al*. (2013) noted that it can increase ammonia emissions. This increase can be partly avoided by using low ammonia emission manure-spreading technologies, for example trailing shoe slurry spreaders.

Manure acidification has high potential to reduce methane emissions and mitigates ammonia emissions. The treatment, however, requires strong hazardous acids that may not be suitable for on-farm use. Additionally, the long-term effects of acidified manure on soil fertility may be negative unless lime is regularly applied. On the other hand, soil fertility is not likely to be an issue for solids separation and aeration. Both have substantial capacity to mitigate manure methane emissions, but it is uncertain what effect these options have on ammonia and nitrous oxide emissions. Montes *et al*. (2013) indicated that aeration is likely to increase nitrous oxide emissions and found that solids separation can have an adverse effect on ammonia losses.

Negative trade-offs were also a problem for most of the manure storage options that Montes *et al*. (2013) recommended to reduce methane emissions, for example natural or artificial storage covers tend to increase nitrous oxide emissions. The storage options that did not tend to increase undesired emissions and mitigated methane emissions were reducing the storage temperature or using sealed stores with flares. However, the effect of these options on some emissions is uncertain. The only manure storage option identified that clearly reduced all GHG and ammonia emissions was decreasing storage time. This option is already recommended for Irish cattle producers and may be possible for piggeries.

4.2 Mitigation Conclusions

The methane and GHG emission intensity of Irish livestock can be reduced at little or no cost by improving farm practices and changing beef farm systems; if not accompanied by further expansion this will result in reductions in total emissions. Teagasc has quantified the impact that both strategies have on GHG emission intensity and continues to provide mitigation advice, in conjunction with Bord Bia, to dairy and beef producers via the carbon navigator. This decision support tool is helping to improve farm performance, but the national GHG inventory parameters and assumptions need to be updated to reflect these improvements in emissions and livestock productivity. The national inventory partly captures the reduction in methane emissions when producers change from a suckler beef system to a dairy beef system. This system change has significant potential to reduce methane emission intensity, but may have a negative effect on meat quality if producers cannot source suitable surplus dairy calves. There are additional strategies that can reduce methane emissions from livestock, that is, diet modifications, biotechnologies and animal waste management, but their persistency or effects on other emissions are often uncertain. In addition, many are cost-prohibitive for Irish producers. Thus, more research is required, particularly for alternative strategies with high mitigation potential, for example the inhibitors 3-NOP and seaweed algae.

5 Whole-farm Livestock Greenhouse Gas Models

A widely used approach for quantifying GHG emissions from livestock production systems is whole-farm modelling. In contrast to the IPCC method, whole-farm modelling does not specify the estimation of GHG emissions by sector, but by the definition of system boundaries (Schils *et al*., 2005). This allows a holistic analysis of methane and GHG emissions that is not possible within the framework of the IPCC method, because on-farm GHG emissions emanating from livestock farming systems are reported in three different sectors (Soussana *et al*., 2010): agriculture, land-use change and forestry, and energy. Furthermore, the IPCC method considers only national GHG emissions; thus, even if GHG emissions from national sectors are combined to generate a "whole-farm" balance, any emissions generated outside the national boundaries are not included (Cerri *et al*., 2009). For example, a large proportion of concentrate feeds used within Irish cattle systems are produced in other nations, with the associated GHG emissions from cultivation and harvesting largely included in the inventories of the nation(s) that produce the concentrate feeds.

As well as the production-focused IPCC approach, a consumption-based method could be used to quantify national GHG emissions. Peters and Hertwich (2008) have outlined the methodology for this. Estonia has quantified GHG emissions associated with national consumption (Gavrilova and Vilu, 2012). Quantifying national GHG emissions based on production and consumption identifies any major transfers of GHG emissions from one nation to another (carbon leakage). This is an issue as some nations are not obliged to reduce GHG emissions. The consumption approach requires the development of farm models capable of quantifying GHG emissions associated with the life cycle of goods and services, that is, the carbon footprint and methane emission intensity (Peters, 2008). Farm GHG models report using systems analysis or LCA to quantify emissions. Both of these modelling methods use a systems approach to quantify GHG emissions. The system boundary and functional unit included when modelling GHG emissions have a direct impact on the conclusions from the systems approach used (O' Brien *et al*., 2012). When these modelling approaches are applied using the same set of assumptions (e.g. boundaries, unit of expression, methane emission factors), the results should be the same. The steps of both farm modelling approaches are briefly described in the following sections.

5.1 Systems Analysis

Systems analysis has been widely used by researchers to quantify GHG emissions from ruminant systems and assess methane mitigation strategies (Beukes *et al*., 2010; O'Brien *et al*., 2011; Clarke *et al*., 2013). The main stages of system analysis according to Grant *et al*. (1997) are conceptual framework definition, quantitative model development, model application and results interpretation.

5.1.1 Conceptual framework

In general, the first step of systems analysis is to formulate a conceptual model of the farming system of interest. The delimitation of the system boundaries of conceptual models is determined by the objective of the study. Generally, whole-farm models that have quantified GHG emissions from ruminant production systems estimate emissions from on- and off-farms sources related to the livestock product(s) up to the point that they are exported from the farm (Olesen *et al*., 2006). Off-farm emissions from the production of external farm inputs such as concentrate feed and fertilisers include methane and other GHG emissions

5.1.2 Model development

The second step of systems analysis entails creating a mathematical model of the production system defined in the opening stage. During this stage a series of algorithms is applied to mathematically model the farming system. In most cases, these equations are based on empirical relationships from representative field studies (Shalloo *et al*., 2004). Occasionally, data from the farming system under study are used to estimate livestock methane and other GHG emissions (Schils *et al*., 2005; Del Prado

et al., 2013). The equations used to estimate GHG emissions in livestock simulation models are referred to as emission factors. Sometimes these emission factors are obtained from the IPCC guidelines (IPCC, 2006) to estimate on-farm emissions. However, the IPCC emission factors are designed to enumerate national-level emissions and thus they often lack the refinement to quantify the effect that changes to production systems have on GHG emissions on individual farms (Schils *et al*., 2006). As a result, direct methane emission measurements that have been recently published in the scientific literature are sometimes used to assess on-farm emissions. In the case of off-farm emissions, almost all emission factors are obtained from literature sources or databases, for example Ecoinvent (2010).

Normally, data collected on-farm or representative farm information such as regional statistics are used as input data to operate whole-farm GHG models. The emissions output from previous livestock GHG models have been expressed per farm, per hectare of farmland and per unit of product, for example per kg of fat- and protein-corrected milk or per kg of carcass weight (Thomassen *et al*., 2008; Clarke *et al*., 2013).

5.2 Life-cycle Assessment

Life-cycle assessment considers the environmental effects of a product or service system (ISO, 2006a). The method also adopts a systems approach but, in contrast to systems analysis, the LCA methodology is internationally standardised (ISO, 2006a,b). The International Organization for Standardization (ISO) originally developed standards for LCA in 1997, which were subsequently revised in 2006 (ISO 14040–14044). The main phases of LCA are goal and scope definition, life-cycle inventory analysis, life cycle impact assessment and life-cycle interpretation.

5.2.1 Goal and scope definition

This stage requires clearly stating the aims and objectives of an LCA project and the intended audience (ISO, 2006a). The scope of an LCA study requires clearly describing the system under study and defining the boundaries of the studied system (ISO, 2006a). Typically, the system boundaries of livestock LCA studies are defined to assess GHG emissions from all processes up until the point that the primary product is sold from the farm (Beauchemin *et al*., 2011). This is commonly referred to as a "cradle-to-farm-gate" LCA. Some studies have also analysed further production stages, for instance the processing stage and distribution to the retailer (Berlin, 2002; Hessle *et al*., 2017). The main environmental effects evaluated in previous LCA studies of livestock have been GHG emissions, acidification potential, eutrophication potential, land use and energy use.

5.2.2 Life-cycle inventory analysis

The second phase of LCA involves the compilation of inputs, outputs and emissions for a given product system throughout its life cycle (ISO, 2006b). The aim of this stage of LCA modelling is to develop a model that quantifies the different resources used and the amount of waste and emissions generated per functional unit (Rebitzer *et al*., 2004). Resources used on-farm are normally collected directly or computed using relevant data sources. Emissions from on-farm processes are mainly estimated by applying emission factors from the literature or the IPCC (IPCC, 1997, 2006). For most LCA studies of livestock systems, international databases, for example Ecoinvent (2010), or literature sources are used to estimate the resources used and emissions generated from processes that are indirectly related to the production system of interest, for example data on fuel and fertiliser production.

5.2.3 Life-cycle impact assessment

The inventory analysis phase lists the various substances used and pollutants emitted from a livestock production system (Thomassen *et al*., 2008). These results are generally difficult to interpret and thus a further stage known as life-cycle impact assessment is needed to complete the LCA results (ISO, 2006a,b). This phase aggregates resources and emissions from the inventory analysis phase and computes (characterisation) various potential environmental effects (Guinee *et al*., 2002). Environmental impacts are computed by converting the results of the inventory analysis stage using relevant characterisation or equivalency factors. For instance, the global warming potential metric in CO_2eq is applied during this stage to assess the impact of methane and other GHG emissions on climate change (Basset-Mens *et al*., 2009). The life-cycle

impact assessment stage allows the environmental effects of a livestock system to be assessed in a more meaningful way.

5.3 Modelling Applications

Recent LCA and whole-farm GHG models from cool or temperate livestock regions were assessed. Table 5.1 provides a description of the modelling methods and emission factors used by 11 dairy studies, nine beef studies, three sheep studies and two pig studies. In general, models calculated methane emissions according to the approaches reported in national GHG inventories and the IPCC guidelines. A few studies used alternative equations for these sources, such as Capper *et al*. (2009), or measured methane directly as part of an on-farm research trial, for example Doreau *et al*. (2011). Whole-farm or LCA models were used for the following purposes:

- to quantify the environmental effects of farm systems and mitigation strategies;
- to estimate the environmental sustainability of commercial farmers, e.g. Bord Bia quality assurance schemes;
- to investigate the effect that modelling decisions have on GHG emissions.

5.3.1 Farm systems

Cattle studies compared GHG emissions from organic and conventional production systems, extensive and intensive systems and confinement and grazing systems. These comparisons were generally representative of farms for a particular region. Many modelling studies that compared contrasting production systems aimed to assess the effect that intensification, defined as an increased use of inputs per ha (e.g. fertiliser), has on methane and GHG emissions. The results of these studies highlight that the effect of intensification on GHG emissions varies depending on the unit of expression. For instance, when dairy farm GHG emissions are quantified per ha of land, whole-farm models usually show that reducing the intensity of dairy systems reduces GHG emissions (Beukes *et al*., 2010; O'Brien *et al*., 2011). However, when GHG emissions are assessed on a per unit of product basis (GHG emission intensity), extensification usually increases methane and GHG emissions (Capper *et al*., 2009; O'Brien *et al*. 2011). Given the rising demand for livestock products such as milk, this implies that GHG emissions should not be assessed in isolation from production.

According to Capper *et al*. (2009) and Capper (2011), increasing the intensity of cattle systems reduces methane and GHG emission intensity through improved productive efficiency, defined as "units of milk or meat produced per unit resource inputs". Improving productive efficiency facilitates the dilution of maintenance effect, whereby the total resource cost per unit of product is reduced (Bauman *et al*., 1985). This effect and reproductive changes are partly captured by the current national GHG inventory. The inventory could better reflect the influence that cattle efficiency has on methane emission intensity by updating important nutritional parameters, for example concentrate feeding rates.

Intensification can have undesirable effects such as reducing reproductive efficiency and decreasing soil carbon levels (Zehetmeier *et al*., 2012; Van Middelaar *et al*., 2013). For instance, Van Middelaar *et al*. (2013) reported that converting grassland to arable land to support higher stocking rates improved dairy farm production levels, but also dramatically increased soil carbon losses. Consequently, intensification nearly doubled GHG emissions per unit of product. Similarly, O'Brien *et al*. (2016) reported that including carbon sequestration by grassland resulted in extensive hill sheep farms having lower GHG emissions per kg of live weight than intensive lowland farms. These inconsistent findings regarding intensification demonstrate that, to determine methane and GHG emission intensity, all sources and sinks of GHG emissions should be assessed.

Beef modelling studies report that methane and GHG emission intensity can be mitigated by rearing beef from the dairy herd instead of the suckler herd. This system change removes methane from suckler cows and dramatically reduces the methane emission intensity of the live weight or carcass weight, as most of a dairy cow's emissions are allocated to milk (Zehetmeier *et al*., 2012). The reduction is lower in terms of live weight because the terminal traits of surplus dairy cattle are inferior to those of suckler cattle. Irish dairy farmers generally select easier calving and shorter gestation sires, which has a negative influence on carcass weight production. It may be possible to change this by using new

Table 5.1. Summary of studies modelling GHG emissions from livestock systems since 2009

Livestock species	Study	Farm description	Methodology and study goal(s)	Methane emission factors
Beef	Beauchemin *et al*. (2011)	Average farm in western Canada	LCA – multi-year model that assessed strategies to mitigate GHG emission intensity from suckler beef	IPCC (2006)
Beef	Capper (2011)	Average US farm	Whole-farm model – compared 1977 beef system GHG emissions with modern conventional systems	IPCC (2006) and literature sources
Beef	Clarke *et al*. (2013)	Irish research farm	LCA – combined LCA model with a suckler beef bio-economic model and examined emissions from farms differing in stocking rate and finishing system	Ireland national GHG inventory method
Beef	Doreau *et al*. (2011)	French research farm	LCA – completed an LCA of finishing or feedlot beef bull systems and estimated the effect that different diets have on GHG emissions	Enteric methane emissions were measured. IPCC (2006) used for manure emissions
Beef	Hessle *et al*. (2017)	Average Swedish farm in the Västra Götaland region	LCA – assessed the effect that four environmental improvement scenarios have on GHG emissions, nutrient loss and energy use from beef and milk	Swedish national GHG inventory method and IPCC (2006)
Beef	Murphy *et al*. (2017)	Irish research farm	Whole-farm model – coupled a beef GHG model with a dairy beef bio-economic model to quantify the effect of diet and slaughter age on GHG emissions	Ireland national GHG inventory method and literature sources
Beef	Ridoutt *et al*. (2013)	Commercial Australian farms	LCA – assessed carbon, water and land-use footprints of contrasting cow–calf beef systems	Australian national GHG inventory method
Beef	Stackhouse *et al*. (2012)	Industry-simulated Californian farm	LCA – quantified effect that a growth promoter has on GHG emissions from suckler beef	IPCC (2006) and US literature sources
Beef	Veysset *et al*. (2014)	Commercial French farms	LCA – conducted a technical-economic survey of 53 suckler beef farms and quantified GHG emissions and fossil fuel use	French literature sources
Dairy	Bell *et al*. (2011)	UK research farm	LCA – a Markov chain was used with LCA to compare GHG emissions from cows offered different levels of forage	IPCC (1997, 2006)
Dairy	Beukes *et al*. (2010)	Average New Zealand farm in the Waikato region	Whole-farm model – integrated three models to investigate the effect that different management scenarios have on dairy farming system GHG emissions	New Zealand national GHG inventory method
Dairy	Capper *et al*. (2009)	Average US farm	Whole-farm model – compared GHG emissions from a mid-1940s dairy system and a modern conventional system	IPCC (2006) and literature sources
Dairy	Chobtang *et al*. (2016)	Commercial New Zealand farms in the Waikato region	LCA – evaluated the cradle-to-farm-gate environmental performance of 53 commercial farms using the Dairy base dataset	New Zealand national GHG inventory method
Dairy	Del Prado *et al*. (2013)	Commercial farms in northern Spain	LCA – coupled LCA and nutrient cycling models to estimate GHG emissions and nutrient use efficiency for 17 dairy farms	IPCC (2006) and literature sources
Dairy	Dolle *et al*. (2009)	Average farms in four French regions	LCA – evaluated the effect that different allocation methods have on dairy farms' GHG emission intensity	Literature sources
Dairy	Mc Geough *et al*. (2012)	Average farm in Eastern Canada	LCA – multi-year model that assessed the effect that different allocation methods have on the GHG emission intensity of raw milk	IPCC (2006)
Dairy	O'Brien *et al*. (2011)	Irish research farm	Whole-farm model – combined a bio-economic dairy model with a GHG model to examine the effects that genetic potential and grazing system have on dairy GHG emissions	Ireland national GHG inventory method

Table 5.1. Continued

Livestock species	Study	Farm description	Methodology and study goal(s)	Methane emission factors
Dairy	O'Brien *et al*. (2015)	Commercial Irish farms	LCA – related the GHG emission intensity of 221 dairy farms to economic performance using the Teagasc NFS	Ireland national GHG inventory method
Dairy	Van Middelaar *et al*. (2013)	Average Dutch farm	LCA – coupled LCA with an economic model to assess the effect that different feed strategies have on GHG emissions	Dutch national GHG inventory method
Dairy	Zehetmeier *et al*. (2012)	Average German farm	Whole-farm model – assessed the effect that increasing dairy cow milk yield has on GHG emissions from the dairy and beef industries	German national GHG inventory method
Pig	McAuliffe *et al*. (2017)	Commercial Irish farms	LCA – compared GHG emissions and environmental metrics of average- and top-performing pig farms	Ireland national GHG inventory method
Pig	Reckmann *et al*. (2013)	Average farm in northern Germany	LCA – quantified GHG emissions and environmental metrics for a typical pig farm	IPCC (2006) and literature sources
Sheep	Jones *et al*. (2014)	Commercial sheep farms	Whole-farm model- analysed GHG emissions from 64 sheep farms and identified areas for improvement	IPCC (2006) and literature sources
Sheep	O'Brien *et al*. (2016)	Average Irish sheep farm and commercial farms[a]	LCA – evaluated the effect of intensification on GHG emissions and resource use of sheep farms	IPCC (2006) and literature sources
Sheep	Wiedemann *et al*. (2015)	Average Australian, UK and New Zealand sheep farms	LCA – evaluated the effect that allocation methods have on GHG emissions from typical sheep farms	Literature sources

[a]**Statistical average for a representative sample of regional or national farms.**

animal breeding technologies, for example genomic selection.

5.3.2 Mitigation strategies

Whole-farm GHG models have assessed the effect of several farm practices on emissions. Examples include selecting higher yielding livestock, improving fecundity, reducing replacement rates, varying the grazing period, the treatment of managed manure and improving nutrient management. The effect of breeding higher yielding livestock on GHG emissions varies between studies. Murphy *et al*. (2017) showed that a 13% increase in beef cattle live weight gain per day reduced GHG emissions per unit of carcass weight by 19%. Similar results were reported by Bell *et al*. (2011) for milk production. In both studies, the reduction was explained by a decrease in methane emissions as a result of improvements in feed conversion efficiency (kg of milk or meat/kg of feed) and decreasing maintenance costs. In contrast, O'Brien *et al*. (2011) reported that Holstein Friesian cows with higher milk yields had increased emissions per unit of product relative to lower yielding cows. This was because higher yielding Holstein Friesian cows had a lower herd fertility rate and a shorter lifespan, which resulted in increased methane emissions from replacement heifers (O'Brien *et al*., 2011). Thus, this study indicates that it is important to consider a combination of genetic traits in attempting to reduce methane emission intensity.

Beukes *et al*. (2010) modelled the effect of reducing herd replacement rates on GHG emissions of dairy systems. The analysis showed that a 10% reduction in the replacement rate reduced GHG emissions per unit of product by 14% on average. This decrease in GHG emissions occurred because of a decline in the number of non-productive animals. It is possible to improve cattle fertility through genetic selection and better reproductive management, for example through the use of cow heat detection aids (Vellinga *et al*., 2011). Improving reproductive management can also reduce emissions from sheep farms. For instance, Ledgard *et al*. (2011) reported that a higher

lambing percentage was partly responsible for a 22% reduction in GHG emissions from New Zealand sheep production. Increased farm profitability was the main driver of this change. It was also a driver of improvements in animal yields.

The influence of the length of the grazing period on GHG emissions was evaluated by Schils *et al*. (2005) and O'Brien *et al*. (2015). Schils *et al*. (2005) investigated the effect of reducing the grazing period and reported that the strategy decreased nitrous oxide emissions from animal excreta deposited on pasture, but increased methane and nitrous oxide emissions from manure storage to a similar extent. Thus, the strategy had no effect on GHG emissions. Furthermore, Schils *et al*. (2005) reported that the strategy had undesirable effects on other types of pollution, for example ammonia. Thus, this demonstrates that models should also consider the undesirable secondary effects (pollution swapping) of GHG mitigation strategies (Del Prado *et al*., 2013). The effect of extending the grazing period was examined by O'Brien *et al*. (2015). This study showed that the strategy caused a greater reduction in methane and nitrous oxide emissions from manure storage than the increase in nitrous oxide emissions from animal excreta deposited on pasture. In addition, the strategy reduced the GHG emission intensity of dairy systems by 0.17% per day and improved economic performance.

The potential of feed additives and growth promoters to mitigate methane emissions was assessed by Beauchemin *et al*. (2011) and Stackhouse *et al*. (2012). Beauchemin *et al*. (2011) reported that dietary oils mitigated the GHG emission intensity of western Canadian beef systems by 2–8%. However, Hristov *et al*. (2013) reported that this strategy was economically risky and highlighted that the long-term mitigation efficacy of oils and fats was uncertain. It may also be difficult to record this mitigation potential in national GHG emission inventories. Stackhouse *et al*. (2012) showed that antibiotic growth promoters reduced GHG emission intensity by 5–9% for California beef cattle; however, these growth implants are proscribed in the EU. Few models directly assess strategies to mitigate methane from manure storage. McAuliffe *et al*. (2017) highlighted anaerobic digestion as a promising technology to mitigate the environmental impact of pig manure. This strategy can also capture bioenergy and produce electricity, but requires more favourable tariffs.

5.3.3 Commercial farms

The environmental sustainability of commercial livestock farms is regularly estimated in developed nations using whole-farm or LCA models. O'Brien *et al*. (2015) estimated the milk carbon footprints of 221 Irish dairy farms using a life-cycle approach and evaluated economic performance. The research showed a wide range in the carbon footprint of Irish dairy farms (0.50–1.97 kg of CO_2eq/kg of fat- and protein-corrected milk). Generally, dairy farms with a lower milk carbon footprint were more profitable. For example, the milk carbon footprint of the top third of farms in terms of net margin per ha was 15% less than that of the bottom third. Partial least-squares regression indicated that farm practices that increase milk solid yield per ha and grazed grass utilisation mitigated methane emission intensity and improved economic performance. The average methane emission factor for dairy cows (110 kg of methane/cow) was within the range of recent Irish inventory estimates.

Chobtang *et al*. (2016) and Del Prado *et al*. (2013) carried out similar research as O'Brien *et al*. (2015) for New Zealand and Spanish dairy farms, respectively. Del Prado *et al*. (2013) reported similar levels of variability among farms' carbon footprints as O'Brien *et al*. (2015), but Chobtang *et al*. (2016) found that most New Zealand dairy carbon footprints were close to the average value. This may be the case if farms are operating at a similar level of efficiency; however, there was significant farm performance variability. Chobtang *et al*. (2016) also assessed other environmental measures, for example acidification and health measures such as cancer effects. The variability across farms for these measures was generally much higher than that for the carbon footprint. Off-farm impacts were important for several environmental and health measures assessed and could be improved by increasing forage utilisation. Veysset *et al*. (2014) also recommended increasing forage utilisation to mitigate GHG emissions from commercial French suckler beef farms. The authors highlighted that farms that produced the best forage and heaviest cattle mitigated GHG emission intensity by 50% compared with the least productive farms. The least productive French farms were larger in area and operated mixed crop–livestock systems.

Jones *et al*. (2014) estimated lamb carbon footprints for lowland, upland and hill sheep farms in the UK and

reported that lowland farms had the smallest mean footprint. There was substantial variability across lamb carbon footprints, which was largely driven by animal and grassland productivity. The authors recommended a suite of management practices to reduce the carbon footprint of lambs, including improving lambing rates (lambs/ewe), increasing lamb growth rates and optimising mating rates and concentrate usage. These improvements are likely to be problematic for hill farms where local conditions are very challenging. Nevertheless, some improvement should be possible as Jones *et al*. (2014) reported that top-performing hill farms outperformed mean lowland farms.

5.3.4 Modelling decisions

Quantifying GHG emissions from livestock systems involves making important decisions such as the definition of system boundaries and the allocation of emissions to co-products. O'Brien *et al*. (2011) examined the influence that different system boundaries have on GHG emissions from dairy farms varying in cow genotype and concentrate supplementation. This analysis showed that high concentrate dairy systems reduced on-farm GHG emissions per kg of milk solids, but the opposite occurred for the New Zealand strain of Holstein Friesian when the system boundary was expanded to include off-farm GHG emissions. Further research by O'Brien *et al*. (2012) demonstrated similar results for grass-based and confinement dairy systems and highlighted that reducing national GHG emissions to comply with EU targets is likely to increase GHG emissions from dairy production. This research demonstrates that livestock systems' GHG emissions should be assessed using a holistic approach such as LCA to ensure that changes to dairy systems reduce GHG emissions. O'Brien *et al*. (2011) recommended integrating the LCA method into the Irish inventory framework. This may be possible using datasets such as the Teagasc NFS.

Various criteria or methods were evaluated for allocating GHG emissions to the products of sheep and dairy systems. Wiedemann *et al*. (2015) compared seven different criteria for allocating GHG emissions between sheep products, that is, live weight and greasy wool. The case study results were relatively similar when GHG emissions were expressed per kg of total products, but varied widely when emissions were split between products based on their economic value. The study recommended allocating GHG emissions between sheep products according to their protein requirements or using the mass of protein sold. Dolle *et al*. (2009) and Mc Geough *et al*. (2012) showed similar variability in dairy systems' GHG emission intensity based on allocation method. The authors identified the advantages and disadvantages of several methods. Mc Geough *et al*. (2012) recommended basing the allocation decision on the clarification needed and availability of data, which agrees with the conclusions of Rice *et al*. (2017) for Irish dairy systems. Rice *et al*. (2017) reported that simple mass allocation was the best approach, but advised using a range of allocation methods to understand the uncertainty associated with the decision.

5.4 Whole-farm Model Conclusions

This review of whole-farm models showed that most studies used a life-cycle approach to quantify GHG emissions and overall environmental performance metrics of livestock. Generally, modelling studies estimated livestock methane emissions according to the calculations provided in national inventory reports or the IPCC guidelines. These calculations vary widely from country to country depending on local conditions and livestock research capabilities, but normally show that improvements in animal productivity and switching from suckler to dairy beef systems mitigate methane emission intensity. Unlike models of most nations, Irish whole-farm models are regularly applied on a national basis to estimate GHG emissions from commercial cattle systems. Irish cattle models follow the national inventory method to estimate methane and are applied using the Teagasc NFS and Bord Bia sustainability survey. These models capture changes in important parameters, for example housing dates, and could be used instead of the current inventory approach for estimating methane emissions from dairy and suckler cows. This change is likely to increase the methane mitigation capacity of the sector.

Irish and international whole-farm models have also reported trade-offs between livestock GHG emissions, land use and other environmental measures. For example, increasing concentrate supplementation reduced cattle methane emission intensity but

increased GHG emission intensity. These trade-offs are difficult to identify using the national GHG inventory's sector-based approach. This is also an issue for Ireland's air pollutant inventory and could lead to mitigation strategies causing pollution swapping. Whole-farm models can generally identify such risks and should be used with national emission inventories.

6 Recommendations

The livestock methane emission factor improvements that we recommend are:

- Regularly review and update all key parameters of tier 2 cattle methane emission factors using DAFM, CSO and new data sources, i.e. the Teagasc NFS, Bord Bia sustainability survey and ICBF data.
- Utilise more DAFM and CSO livestock population and production data (e.g. milk composition records) to estimate methane emissions and revise O'Mara (2006) cattle breed population assumptions using current data sources. This is likely to change cattle enteric methane estimates by 3–5%.
- Deploy the updated beef and dairy model developed as part of this overall project.
- Review current methane emission factors used based on all available methane emission factors.
- Update turnout dates, housing dates, farm feeding practices and manure storage systems/ management systems using data from Teagasc, Bord Bia and any other source. Verify data on farm feeding practices and manure storage systems using information collected by the DAFM and/or CSO.
- Review and update cattle and sheep live weights and parturition dates using the ICBF or Sheep Ireland database and industry and DAFM records.
- Deploy whole-farm models developed by Teagasc to evaluate the effect that methane mitigation strategies for livestock have on other environmental metrics, for example ammonia
- Move away from using default tier 1 methane emission factors for sheep. The inventory should preferably use recent Irish research to develop country-specific tier 2 methane emission factors for sheep (O' Brien *et al*., 2016).

Strategies to reduce enteric or manure methane emissions should also consider other emission sources and GHGs to avoid a net increase in the GHG emission intensity of livestock. Several farm practice and system changes are proposed to reduce livestock methane and GHG emission intensity. The following cost-effective options are recommended:

- extend the length of the grazing season for cattle;
- increase dairy cow genetic merit via the EBI;
- optimise age at first calving;
- increase the daily live weight gain of beef cattle and lambs;
- optimise the calving and lambing rate, e.g. number of calves born per cow per annum;
- improve grazed grass and silage quality;
- switch from a suckler beef system to a dairy beef system.

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Abbreviations

3-NOP	3-Nitro-oxypropanol
AIM	Animal Identification and Movement
BCS	Body condition score
CO_2eq	CO_2 equivalent
CSO	Central Statistics Office
DAFM	Department of Agriculture, Food and the Marine
DM	Dry matter
DMI	Dry matter intake
EBI	Economic Breeding Index
EU	European Union
FAO	Food and Agriculture Organization
GEI	Gross energy intake
GHG	Greenhouse gas
ICBF	Irish Cattle Breeding Federation
IPCC	Intergovernmental Panel on Climate Change
kt	Kilotonne
LCA	Life-cycle assessment
MACC	Marginal abatement cost curve
NE	Net energy
NFS	National Farm Survey
S.I.	Statutory Instrument
UNFCCC	United Nations Framework Convention on Climate Change
Ym	Gross energy requirement methane conversion factor

Appendix 1

Table A1.1. Methods applied by Annex 1 and non-Annex 1 nations in 2017 to quantify cattle methane emission factors for the 1990–2015 period

Annex	Continent	Nation	Dairy		Non-dairy	
			Enteric	Manure	Enteric	Manure
Annex 1	America	Canada	T2	T2	T2	T2
		USA	T2	T2	T2	T2
Annex 1	Asia	Japan	T2	T2	T2	T2
		Kazakhstan	T2	T2	T2	T2
		Turkey	T2	T1	T2	T1
Annex 1	Asia/Europe	Russia	T2	T2	T2	T2
Annex 1	Europe	Austria	T2	T2	T2	T2
		Belarus	T2	T2	T2	T2
		Belgium	T2	T2	T2	T2
		Bulgaria	T2	T2	T2	T2
		Croatia	T2	T2	T2	T2
		Cyprus	T2	T2	T1	T2
		Czech Republic	T2	T2	T2	T2
		Denmark	T2	T2	T2	T2
		Estonia	T2	T2	T2	T2
		Finland	T2	T2	T2	T2
		France	T2, T3	T2	T2, T3	T2
		Germany	T3	T2	T2	T2
		Greece	T2	T2	T2	T2
		Hungary	T2	T2	T2	T2
		Iceland	T2	T2	T2	T2
		Italy	T2	T2	T2	T2
		Latvia	T2	T2	T2	T2
		Liechtenstein	T2	T2	T2	T2
		Lithuania	T2	T2	T2	T2
		Luxembourg	T2	T2	T2	T2
		Malta	T2	T2	T2	T2
		Monaco	NO	NO	NO	NO
		Netherlands	T3	T2	T2	T2
		Norway	T2	T2	T2	T2
		Poland	T2	T2	T2	T2
		Portugal	T2	T2	T2	T2
		Romania	T2	T2	T2	T2
		Slovakia	T2	T2	T2	T2
		Slovenia	T2	T2	T2	T2
		Spain	T2	T2	T2	T2
		Sweden	T2	T2	T2	T2
		Switzerland	T3	T2	T2	T2
		Ukraine	T3	T2	T3	T2
		UK	T2	T2	T1, T2	T2
Annex 1	Oceania	Australia	T2	T2	T2	T2, T3
		New Zealand	T2	T2	T2	T2
Non-Annex 1	America	Brazil	T2	T2	T2	T2
		Uruguay	T2	T2	T2	T2
	Africa	South Africa	T2	T2	T2	T2
	Asia	China	T2	T2	T2	T2
		India	T2	T1	T2	T1

NO, not occurring; T1, tier 1; T2, tier 2; T3, tier 3.

Table A1.2. Methods applied by Annex 1 and non-Annex 1 nations in 2017 to quantify sheep and pig methane emission factors for the 1990–2015 period

Annex	Continent	Nation	Sheep		Pigs	
			Enteric	Manure	Enteric	Manure
Annex 1	America	Canada	T1	T2	T1	T2
		USA	T1	T2	T1	T2
Annex 1	Asia	Japan	T1	T1	T2	T2
		Kazakhstan	T2	T1	T1	T1
		Turkey	T1	T1	T1	T1
Annex 1	Asia/Europe	Russia	T1	T1	T2	T2
Annex 1	Europe	Austria	T1	T1	T1	T2
		Belarus	T1	T1	T1	T2
		Belgium	T1	T1	T1	T2
		Bulgaria	T2	T2	T1	T2
		Croatia	T2	T2	T2	T2
		Cyprus	T1	T1	T1	T1
		Czech Republic	T1	T1	T1	T1
		Denmark	T2	T2	T2	T2
		Estonia	T1	T1	T2	T2
		Finland	T2	T2	T2	T2
		France	T2, T3	T2	T2, T3	T2
		Germany	T1	T2	T2	T2
		Greece	T2	T2	T1	T1
		Hungary	T1	T2	T1	T2
		Iceland	T2	T2	T1	T1
		Italy	T2	T1	T1	T2
		Latvia	T1	T1	T1	T2
		Liechtenstein	T2	T2	T2	T2
		Lithuania	T2	T2	T2	T2
		Luxembourg	T2	T2	T1	T2
		Malta	T2	T1	T1	T2
		Monaco	NO	NO	NO	NO
		Netherlands	T1	T1	T1	T2
		Norway	T2	T1	T1	T2
		Poland	T1	T1	T1	T1
		Portugal	T2	T2	T2	T2
		Romania	T2	T2	T2	T2
		Slovakia	T2	T2	T1	T1
		Slovenia	T1	T2	T1	T2
		Spain	T2	T1	T2	T2
		Sweden	T1	T1	T1	T2
		Switzerland	T2	T2	T2	T2
		Ukraine	T2	T2	T1	T2
		UK	T1	T2	T1	T2
Annex 1	Oceania	Australia	T2	T2	T2	T3
		New Zealand	T2	T2	T1	T2
Non-Annex 1	America	Brazil	T1	T1	T1	T2
		Uruguay	T1	T1	T1	T1
	Africa	South Africa	T2	T2	T2	T2
	Asia	China	T2	T2	T1	T2
		India	T1	T1	T1	T1

NO, not occurring; T1, tier 1; T2, tier 2; T3, tier 3.

Table A1.3. Methods applied by Annex 1 and non-Annex 1 nations in 2017 to quantify poultry and other livestock methane emission factors for the 1990–2015 period

Annex	Continent	Nation	Poultry		Other livestock[a]	
			Enteric	Manure	Enteric	Manure
Annex 1	America	Canada	NE	T2	T1	T1
		USA	NE	T2	T1	T2
Annex 1	Asia	Japan	NE	T2	T1	T1
		Kazakhstan	NE	T1	T1	T1
		Turkey	NE	T1	T1	T1
Annex 1	Asia/Europe	Russia	NE	T1	T1	T1
Annex 1	Europe	Austria	T2	T1	T1	T1
		Belarus	T1	T1	T1, T2	T1,T2
		Belgium	T1	T1	T1	T1
		Bulgaria	NA	T2	T1	T1
		Croatia	T1	T2	T1	T2
		Cyprus	NE	T1	T1	T1
		Czech Republic	NE	T1	T1	T1
		Denmark	T1	T2	T1	T2
		Estonia	NE	T1	T1	T1
		Finland	NE	T2	T1	T2
		France	NE	T2	T2	T2
		Germany	NE	T2	T1	T2
		Greece	T1	T1	T1	T1
		Hungary	T1	T2	T1	T2
		Iceland	T1	T1	T1	T1
		Italy	NE	T1	T1, T2	T1
		Latvia	NE	T1	T1	T1
		Liechtenstein	T2	T2	T2	T2
		Lithuania	NE	T1	T1	T1
		Luxembourg	NO	T2	T1	T2
		Malta	T1	T2	T1	T1
		Monaco	NO	NO	NO	NO
		Netherlands	NE	T2	T1	T1
		Norway	T1	T2	T1, T2	T1
		Poland	NE	T1	T1	T1
		Portugal	NE	T2	T1	T1, T2
		Romania	NE	T2	T2	T2
		Slovakia	NE	T1	T1	T1
		Slovenia	NE	T2	T1	T2
		Spain	NE	T2	T1, T2	T1, T2
		Sweden	NE	T1	T1	T1
		Switzerland	T2	T2	T2	T2
		Ukraine	NE	T2	T1	T1, T2
		UK	NE	T2	T1	T1, T2
Annex 1	Oceania	Australia	NE	T3	T1	T2
		New Zealand	NE	T1	T1, T2	T1, T2
Non-Annex 1	America	Brazil	NE	T1	T1	T1
		Uruguay	NE	T1	T1	T1
	Africa	South Africa	NE	T2	T1, T2	T1, T2
	Asia	China	NE	T1	T1, T2	T1, T2
		India	NE	T1	T1	T1

[a]Other livestock includes goats, horses, mules, donkeys, camels, rabbits, deer, llamas, ostriches, reindeer and alpacas. Cattle, sheep, pigs and poultry were not part of this category.

NE, not estimated; NO, not occurring; T1, tier 1; T2, tier 2; T3, tier 3.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 288

A Review of Livestock Methane Emission Factors

Authors: Donal O'Brien and Laurence Shalloo

Identify pressures

Ireland is legally obliged as an EU Member State to reduce non-Emission Trading System (ETS) greenhouse gas (GHG) emissions. The target for the sector in 2020 is a 20% reduction on 2005 levels, with annual limits set for each year over the period 2013–2020. The non-ETS reduction target for 2030 is 30%. Ireland's GHG emission projections for 2017 indicate that the nation is unlikely to achieve 2020 targets, because the dominant sectors, i.e. transport and agriculture, are expected to expand. Most of the projected growth in agricultural GHG emissions is expected to be in the form of methane emissions from livestock. Cattle and sheep are the main livestock sources of methane emissions. These methane sources represented 27% of non-ETS GHG emissions in 2016. Populations of cattle and sheep have increased since 2010 to nourish an increasing world population. Mitigating rising methane emissions from these species is difficult but possible, by improving farm practices or adopting new technologies. This mitigation, however, is only partially accounted for by current livestock methane emission factors.

Inform policy

Livestock methane emission factors are annual estimates of methane emissions per head. They are used with livestock statistics to estimate the change in national methane emissions. Methane emission factors are computed using country-specific methods or those provided by the Intergovernmental Panel on Climate Change (IPCC). Ireland uses country-specific tier 2 emission factors for cattle and default IPCC tier 1 emission factors for the remaining livestock species. Ireland's tier 2 bovine methane emission factors are a major improvement on the tier 1 approach, but our review showed that some of these emission factors are based on activity data from 2003. The possibility of updating these activity data was determined by assessing the information collected by current inventory data sources and potential sources, namely the Teagasc National Farm Survey (NFS), Bord Bia sustainability surveys (SDAS and SBLAS) and the Irish Cattle Breeding Federation (ICBF). These data sources were also used to determine the potential to move to higher tier emission factors. The IPCC 2006 guidelines, national studies and countries' GHG inventory submissions were reviewed to identify better methods to estimate emission factors.

Develop solutions

Activity data are available to regularly update most of the key input variables used to quantify Irish livestock methane emission factors. These data are verified, where possible, for current data sources and the Teagasc NFS, and can be checked with data from Bord Bia and the ICBF. There is the potential to improve tier 2 methods or models for bovines by using recent Irish research on enteric methane instead of estimates from other nations. For sheep, methane emission factors can be improved by using the tier 2 model that was developed by Teagasc and provided during the project, instead of the current default tier 1 method. The new sheep model uses a similar approach as the tier 2 bovine emission model and can be operated using the current and new inventory data sources mentioned. Adopting the new sheep and bovine emission factors in the national inventory will improve its ability to capture the effect that mitigation strategies have on livestock methane emissions.

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