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GLOBAL AGRICULTURAL GREENHOUSE GAS EMISSIONS:

Enteric Methane

FOOD, AGRICULTURE, RESEARCH & POLICY.

THE SIMPSON CENTRE.
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THE SIMPSON CENTRE. THOUGHT FOR FOOD.

Abstract

Efforts to reduce emissions across sectors are implemented globally, as increasing environmental, social, and economic pressures accumulate. The Global Methane Pledge, an agreement between over 100 different countries including the USA and EU, commits to limiting average global temperature increase to ≤ 1.5 degrees. Parties committed to the pledge are required to disclose national methane emissions following IPCC guidelines. High variability in emission estimates and calculation methodology for enteric methane produced by cattle in the agricultural sector confound comparability between countries and previous reports. Depending on use of Tier 1, 2, 3 approaches and default emission factors covering different animal, ration, management, and environmental dimensions, emission factors uncertainty values ranged from ±6 to ±50 percent. As the specificity and resolution of data increases as countries move from Tier 1 to Tier 2 and Tier 3 approaches, the resulting emission factors should increase in accuracy, accordingly, reflecting regional and country-specific operations. Relative to the other Annex I Parties to the United Nation Framework Convention on Climate Change, average methane emission per head of dairy cattle in Canada is high, linked to increased animal weight and milk productivity. Conversely, average non-dairy cattle emission per head in Canada is low, and is ranked the lowest among major global producers.

Keywords: *Enteric Fermentation, Methane, National Inventory Report Greenhouse Gas Emissions, Agriculture*

Global Agricultural GHG Emissions:

Enteric Methane

The Global Methane Pledge was first announced by President Biden and President von der Leyen in September 2021, officially joined by Canada at the COP 26 Climate Summit a 2 months later (Environment and Climate Change Canada, 2021c). The pledges' primary objective is to reduce global methane emissions by at least 30 percent from 2020 levels by 2030 (European Commission & United States of America, 2021). Methane, a short-lived and potent greenhouse gas relative to carbon dioxide, is especially prevalent to the pledges' commitment of limiting average global temperature increase to ≤ 1.5 degrees. The Canadian agricultural sector accounts for 30 percent of national methane emissions, of which 93 percent can be directly attributed to cattle production (Canada, 2021). Despite lack of official Federal methane reduction targets for the agricultural sector, the sector's sizeable emission output may be targeted approaching 2030.

While not as attention-grabbing as the methane mitigation potential 3-nitrooxypropanol or Asparagopsis (Black et al., 2021), the methodology in place to estimate emissions is a crucial, although often overlooked, pillar in emission reduction calculations and potential. Inclusion and exclusion determinants in emission accounting requires further standardization and research at a foundational level. Application of current methodology in Canada for determination of emission targets, several of the most promising mitigation strategies would be disregarded, limiting producer's capacity to meet proposed national targets.

The objectives presented are twofold; first, it seeks to gain a better understanding of how Canada and the world measures enteric fermentation from cattle, the single largest source of agriculturally based methane emissions in Canada. Second, the report looks to place Canadian emissions into a global context by comparing measurements, production characteristics, and emissions across all Annex I Parties to the United Nation Framework Convention on Climate Change (UNFCCC).

DATA AND SOURCES

Complete descriptions of the International Panel on Climate Change (IPCC) Tier 1, Tier 1a (2019 Refinement), and Tier 2 methodologies described within this paper can be found in Volume 4 Chapter 10.1 through 10.4 and Annex 10A.1 and 10A.2 of the 2006 Guidelines and 2019 Refinement. Methodology and emission data reported by Annex I Parties was collected through 2021 National Inventory Submissions (NIS), publicly available on the UNFCCC website[1] . The 2021 NIS comprised the National Inventory Report (NIR) and Common Reporting Format (CRF) tables, encompassing 1990 to 2019 (UNFCCC, 2019). The NIR and supplementary materials within the NIR described the technique in the methodological review. Data was collected from the CRF tables (Table 3.As1, 3.As2) for each country included in the review. Annex I Parties to the UNFCCC comprises the United States of America, Canada, all 27 European Union (EU) member states, the United Kingdom, Iceland, Norway, Switzerland, Russia, Belarus, Ukraine, Turkey, Kazakhstan, Japan, Australia, and New Zealand (UNFCCC, 2019). Monaco and the EU are also parties to the conference but were excluded. Monaco does not report any agricultural emissions (Direction de l'Environnement, 2021), and the EU provides a summary of member states (European Environment Agency, 2021). For a complete list of the countries included and specific information regarding sources reference Table 1.

MEASUREMENTS

The guidelines for estimating national GHG emissions, including the methodology for estimating agricultural emissions, was developed by the IPCC (Intergovernmental Panel on Climate Change, 2021). The methodology was first introduced in 1994 and updated in 1996 with the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, and further expanded with supplemental material in 2000 (Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories and Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types) and 2003 (Good Practice Guidance for Land Use, Land-Use Change and Forestry). In 2006, the 1996 guidelines were replaced with the 2006 IPCC Guideline for Nation Greenhouse Gas Inventories. Additional supplements were published in 2013 (2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol and 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands). The most recent update to the methodology occurred in 2019 with the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Fundamentally, emission level estimates are a product of an emission factor, measuring emission per unit of activity (e.g., head of cattle) and a measure of activity (e.g., size of cattle herd) (Dong et al., 2006, sec. 10.3.2). The IPCC provides default emission factors specific to major geographical regions (North America, Eastern Europe, Oceania, etc.), and level

[1] The 2021 National Inventory Submission can be found at: https://unfccc.int/ghg-inventories-annex-i-parties/2021

of productivity (low productivity, high productivity) (Dong et al., 2006; Gavrilova et al., 2019, p. 10.39). Default values facilitate countries with limited data or relatively insignificant emission sources, estimated with only activity data. This method is referred to as a Tier 1 approach within the IPCC methodology, with the inclusion of a productivity factor introduced in the 2019 Refinement referred to a Tier 1a approach (Gavrilova et al., 2019, sec. 10.2.2).

The IPCC generally recommends using a Tier 2 or 3 approach for dairy and beef cattle (Gavrilova et al., 2019, sec. 10.3.2). A Tier 2 approach builds on the Tier 1 methodology, and requires disaggregated activity data (e.g., calves, cows, bulls) as a baseline. For example, in Canada, a cattle production stage model is used to disaggregate the national cattle herd by subcategory (i.e., beef cows, or background steers), production environment (i.e., confined, pasture, feedlot), period of year (months), and province (Environment and Climate Change Canada, 2021, sec. A3.4.1). Second, emission factors are estimated, depending on the country, through country or regional-specific production and animal characteristic data (Gavrilova et al., 2019, sec. 10.3.2). The IPCC provides the methodology for estimating the emission factor. However, it can be modified to reflect better country-specific practices, referred to as a Tier 2 country-specific model, with the inclusion of additional feed data. A Tier 3 model goes beyond Tier 2 country-specific models by utilizing higher resolution and more detailed cattle production data, theoretically improving the accuracy of emission estimates.

ENTERIC FERMENTATION

Methane from enteric fermentation is the single largest source of agricultural-based greenhouse gas emissions in Canada (Environment and Climate Change Canada, 2021b). Cattle production is responsible for the largest share of enteric emissions, contributing approximately 96 percent of total enteric emissions in 2019 (Canada, 2021). Cattle and other ruminants produce methane as a by-product of digestion when plant derivatives, such as fiber, cellulose, or sugar, are broken down by microbial fermentation within the animal's rumen and emitted through eructation (Black et al., 2018). Methane production quantities depend on several factors, such as feed nutrient profile, quality, quantity, cattle genetics, and rumen characteristics. A combination of feed and cattle characteristic data is used to develop general models to estimate methane emission quantities.

Tier 1

Of the 42 countries included in this review, only Cyprus used a Tier 1 approach to estimate enteric fermentation emissions, and only in the case of non-dairy cattle (Ministry of Agriculture Rural Development and Environment, 2021, sec. 5.2). As of 2021, this approach was otherwise not used by Annex I parties to estimate dairy cattle emissions (See Table 3). Methodology utilized is attributed to the 2006 Guidelines, where total enteric fermentation emissions

($CH_{4,EF}$), for cattle type t, is a function of the regional default emission factor ($EF_{t,r}$) and the herd size (N_t), see Equation 1 (Gavrilova et al., 2019, e. 10.19).

$$CH_{4,ef,t} = EF_{t,r} * \left(\frac{N_t}{10^6}\right) \tag{1}$$

Cyprus utilizes Western Europe's default emission factor (Ministry of Agriculture Rural Development and Environment, 2021, p. 5.2), one of eight fixed regions and factors presented within the 2006 guidelines, including North America, Eastern Europe, Western Europe, Oceania, Latin America, Asia, Africa and the Middle East, and the Indian Subcontinent (Dong et al., 2006). A comparison of default values can be found in Table 1.

The 2019 Refinement provides several improvements to the 2006 Guidelines. First, default emission factors are estimated using more recent data (Gavrilova et al., 2019, sec. 10B.1), replacing the original estimates based on data from the 1990s and early 2000s (Dong et al., 2006, sec. 10B.1). Second, default emission factors are expanded to cover nine discrete regions by dividing Africa and Middle East into North Africa and Middle East, and Sub-Saharan Africa (Gavrilova et al., 2019). Lastly, the 2019 Refinement introduces the Tier 1a approach, differentiating livestock populations by productivity. The Tier 1a model closely resembles the original Tier 1 and can be found in Equation 2, where both $EF_{t,r}$ and N_t are dependent on productivity level (p) (Gavrilova et al., 2019).

$$CH_{4,ef,t} = \sum_p EF_{t,r,p} * \left(\frac{N_{t,p}}{10^6}\right) \tag{2}$$

The 2019 Refinement identifies two productivity systems (high and low). Low productivity describes local subsistence agriculture generally characterized by multi-use cattle such as cows used for milk production, meat, and draft power (Gavrilova et al., 2019, sec. 10.2.2). High productivity systems are production systems aimed to sell into national and international markets. Within high productivity systems, cattle production is more specialized; for example, bulls are primarily used for breeding, and beef cows are used to produce offspring for meat (Gavrilova et al., 2019, sec. 10.3.2). A Tier 1a approach is appropriate in countries and regions where dual agricultural systems are present. Tier 1a default values are provided for Latin America, Asia, Sub-Saharan Africa, North Africa and the Middle East, and the Indian Subcontinent (Gavrilova et al., 2019, sec. 10.3.2). As seen in Figures 1 through 6, high productivity systems are increasingly comparable to North America, Europe, and Oceania.

Tier 2

The Tier 2 approach is the most used method for estimating enteric fermentation emissions from cattle. Of the 42 countries considered in this review, 39 use a Tier 2 approach to estimate emissions from non-dairy cattle and 37 for dairy cattle (See Table 3). The approach requires disaggregated activity data, with subcategories typically based on age, type of production, and sex, in addition to a feed intake or energy requirement estimate for each subcategory (Gavrilova et al., 2019, sec. 10.2.2). Within the 2006 Guidelines and 2019 Refinement, two general approaches for estimating feed intake and the corresponding emission factors are presented. Several countries have also developed their own methodology for estimating feed intake and emission factors, with 12 countries using a country-specific approach for dairy cattle and 15 for non-dairy, indicated in Table 3.

Simplified Tier 2 Approach

The Simplified Tier 2 approach presented in the 2006 Guidelines estimates daily dry matter intake (DMI) as a function of animal weight (LW) and the digestibility of the rations consumed (DE) or estimated dietary net energy concentration ($\mathrm{NE_{ma}}$) (Dong et al., 2006, p. 10.22). Each cattle subcategory, Growing and Finishing Cattle (Equation 3), Mature Beef Cattle (Equation 4), and Mature Dairy Cattle (Equation 5), use separate equations to estimate daily dry matter intake.

$$\mathrm{DMI_{GFC,2006}} = \mathrm{LW}^{0.75} * \left[\frac{(0.2444*\mathrm{NE_{ma}} - 0.0111*\mathrm{NE_{ma}^2} - 0.472)}{\mathrm{NE_{ma}}}\right] \tag{3}$$

$$\mathrm{DMI_{MBC,2006}} = \mathrm{LW}^{0.75} * \left[\frac{(0.0119*\mathrm{NE_{ma}^2} + 0.1938)}{\mathrm{NE_{ma}}}\right] \tag{4}$$

$$\mathrm{DMI_{MDC,2006}} = \left[\frac{\left(\frac{(5.4*\mathrm{LW})}{500}\right)}{\left(\frac{(100-\mathrm{DE})}{100}\right)}\right] \tag{5}$$

The guidelines provide default values for the $\mathrm{NE_{ma}}$ based on diet type (Dong et al., 2006, sec. 10.2.2). Four diet categories are presented based on forage quality of the forages (low, medium, or high) or if cattle receive a high grain diet. The value can range from 3.5 on a low-quality diet to 8.5 on a high grain diet. The value of $\mathrm{NE_{ma}}$ can also be estimated as a function of DE, and the ratio of net energy in diet for maintenance (REM, see Equation 22) where a $\mathrm{NE_{ma}}$ values of 3.5 and 8.5 would correspond to DE values of approximately 46 percent and 83 percent respectively, see Equation 6 (Dong et al., 2006, p. 10.23).

$$\mathrm{NE_{ma}} = \frac{\mathrm{REM}*18.45*\mathrm{DE\%}}{100} \tag{6}$$

The 2019 Refinement provided several updates to the Simplified Tier 2 approach. First, Growing Cattle is divided into 4 categories, Calves (Equation 7), Growing Cattle (Equation 8), Steers on Feedlots (Equation 9), and Heifers on Feedlots (Equation 10), each with a separate DMI equations (Gavrilova et al., 2019, p. 10.30).

$$\mathrm{DMI_{Calves}} = \mathrm{LW}^{0.75} * \left[\frac{(0.0582*\mathrm{NE_{ma}} - 0.00266*\mathrm{NE_{ma}^2} - 0.1128)}{0.239*\mathrm{NE_{ma}}}\right] \tag{7}$$

$$\mathrm{DMI}_{\mathrm{Growing}} = \mathrm{LW}^{0.75} * \left[\frac{(0.0582*\mathrm{NE}_{\mathrm{ma}}-0.00266*\mathrm{NE}_{\mathrm{ma}}^{2}-0.0869)}{0.239*\mathrm{NE}_{\mathrm{ma}}}\right] \tag{8}$$

$$\mathrm{DMI}_{\mathrm{Feedlot\ Steer,Bulls}} = 3.83 + (0.0143 * \mathrm{LW} * 0.96) \tag{9}$$

$$\mathrm{DMI}_{\mathrm{Feedlot\ Heifer}} = 3.184 + (0.01536 * \mathrm{LW} * 0.96) \tag{10}$$

Second, the equation used for estimating DMI for mature non-dairy cattle has been removed (Gavrilova et al., 2019, p. 10.31). Instead DMI values are estimated as a percentage of weight and dependent on the digestibility of feed and stage of production (See Table 4).

Third, the methodology to estimate DMI for lactating dairy cows was updated to include milk production (Gavrilova et al., 2019, p. 10.31). The DMI estimate is now a function of live weight (LW) and fat corrected milk (FMC); see Equation 11, expanding on the 2006 guidelines which only including variables for weight and digestibility (Equation 5). The FMC variable is itself a function of daily milk production, measured in kilograms of milk (Milk), and milk fat content, also measured in kilograms ($\mathrm{Fat}_{\mathrm{kg}}$), see Equation 12.

$$\mathrm{DMI}_{\mathrm{LDC}} = 0.0185 * \mathrm{LW} + 0.305 * \mathrm{FCM} \tag{11}$$

$$\mathrm{FCM} = (0.4324 * \mathrm{Milk}) + (16.216 * \mathrm{Fat}_{\mathrm{kg}}) \tag{12}$$

The 2006 Guidelines do not directly connect DMI and the emission factor. However, DMI can be converted into gross energy (GE) by multiplying DMI by the energy density of feed; a default value of 18.45 MJ kg^{-1} DMI is included within the guidelines (Dong et al., 2006, sec. 10.3.2). GE can subsequently estimate the emission factor following a gross energy approach, described in the following section. Within the 2019 refinement, a direct link between the emission factor ($\mathrm{EF}_{\mathrm{DMI}}$) and DMI is demonstrated, where $\mathrm{EF}_{\mathrm{DMI}}$ is a function of DMI, measured in kg DMI day^{-1}, and a methane yield variable (MY) measure the emissions, in grams, per kilogram of DMI consumed, see Equation 13 (Gavrilova et al., 2019, p. 10.46).

$$\mathrm{EF} = \mathrm{DMI} * \left(\frac{\mathrm{MY}}{1000}\right) * 365 \tag{13}$$

The value used for the methane yield variable can be found in Table 5. For dairy cattle, the value is dependent on DE and the percent of neutral detergent fibre in the feed (NDF) (Gavrilova et al., 2019, p. 10.46). As seen in the table, higher DE and lower NDF result in lower methane yields per kilogram of DMI. For non-dairy cattle, the value is solely based on DE. Low digestibility is associated with high forage diets and high methane yield values; as the share of forage in diets decreases, digestibility increases, and the methane yield decreases.

Of the 42 National Inventory Reports reviewed, only Australia reported using a Simplified Tier 2 approach, and only in the case of estimating DMI for feedlot cattle (Australian Government Department of Industry Science Energy and Resources et al., 2021). Although the Simplified Tier 2 approach is not generally applied by Annex I parties, it provides the framework for several country-specific methodologies, including Australia (Australian Government Department of Industry Science Energy and Resources et al., 2021), Japan (Ministry of the Environment & National Institute for Environmental Studies, 2021), and New Zealand (Pickering et al., 2021).

Gross Energy Approach

The Gross Energy Approach is the preferred Tier 2 method presented in the 2006 Guidelines and 2019 Refinement and the most used methodology to estimate enteric methane emissions (Dong et al., 2006, sec. 10.3.2; Gavrilova et al., 2019, sec. 10.3.2). A total of 24 countries explicitly use this approach to estimate the emission factor for dairy cattle and 22 countries in the case of non-dairy cattle, see Table 3. The emission factor is estimated as a function of gross energy intake (GE), measured in megajoules head^{-1} day^{-1}, a methane conversion factor ($\mathrm{Y_m}$), and time in production, see Equation 14 (Gavrilova et al., 2019, p. 10.46). The conversion rate of megajoules to kilograms is 55.65.

$$\mathrm{EF_{GE}} = \frac{\mathrm{GE} * \left(\frac{\mathrm{Y_m}}{100}\right) * 365}{55.65} \tag{14}$$

The values used for GE and $\mathrm{Y_m}$ can vary throughout the year or through different stages of production. As a result, Equation 14 can be modified by taking a weighted average of the annual emission using time in each stage of production as the weights (Environment and Climate Change Canada, 2021; Gavrilova et al., 2019).

Daily gross energy intake is estimated using Equation 15 and is a function of a series of net energy requirements (NE), the ratios of energy available for maintenance and growth (REM and REG, respectively), and feed digestibility (DE) (Gavrilova et al., 2019, p. 10.29).

$$\mathrm{GE} = \left[\frac{\left(\frac{\mathrm{NE_m} + \mathrm{NE_a} + \mathrm{NE_l} + \mathrm{NE_{work}} + \mathrm{NE_p}}{\mathrm{REM}}\right) + \left(\frac{\mathrm{NE_g}}{\mathrm{REG}}\right)}{\mathrm{DE}}\right] \tag{15}$$

Each net energy and ratio variable are estimated within the model and found in Equations 16 through 23. The net energy requirement for maintenance ($\mathrm{NE_m}$) is a measure of the daily net energy to keep the animal in a homeostatic state (Gavrilova et al., 2019, p. 10.24). The model $\mathrm{NE_m}$ is dependent on animal weight (LW) and a coefficient indicating sex and stage or production ($\mathrm{Cf_i}$), see Equation 16.

$$\mathrm{NE_m} = \mathrm{Cf_i} * \mathrm{LW}^{0.75} \tag{16}$$

Three $\mathrm{Cf_i}$ coefficient default values in the 2019 Refinement are consistent with earlier versions. Non-lactating cows, steers, heifers, and calves have a$\mathrm{Cf_i}$ value of 0.322. Increased by 20 percent, lactating cows $\mathrm{Cf_i}$ value of 0.386 reflects increased lactation requirements, and for bulls $\mathrm{Cf_i}$ is increased by 15 percent ($\mathrm{Cf_i} = 0.370$) (Gavrilova et al., 2019, p. 10.24). The $\mathrm{Cf_i}$ parameter can be adjusted to reflect increased energy requirements in cold temperatures for cattle for cattle kept outdoors. The cold adjusted $\mathrm{Cf_i}$ ($\mathrm{Cf_{i,(Cold)}}$) can be found in Equation 17 and is a function of $\mathrm{Cf_i}$ and mean daily winter temperature (°C) (Gavrilova et al., 2019, p. 10.19).

$$\mathrm{Cf_{i,(Cold)}} = \mathrm{Cf_i} + 0.0048 * (20 - {}^\circ\mathrm{C}) \qquad (17)$$

The $\mathrm{Cf_{i,(Cold)}}$ parameter is used in Canada between October and April and is estimated at a provincial level (Environment and Climate Change Canada, 2021, p. 80). The cold adjusted value is applied cattle wintering outdoors. Across Canada, adjusted values range from 0.43 in Manitoba to 0.37 in Ontario, compared with 0.35, the average national $\mathrm{Cf_i}$ value.

Equation 18 estimates net energy for activity ($\mathrm{NE_a}$) and is a function of net energy requirement for maintenance and an activity coefficient ($\mathrm{C_a}$) (Gavrilova et al., 2019, p. 10.23). The activity coefficient measures the additional energy required to feed given production schemes. Three default values are provided; stall, pasture, and large grazing areas and are assigned values of 0.00, 0.17, and 0.36, respectively (Gavrilova et al., 2019, p. 10.24). A weighted average of the activity coefficients can be estimated if production employs multiple feeding situations. Within Canada, the Cattle Production Stage Model used does differentiate by production environments (i.e., confined or on pasture), and may not require average $\mathrm{C_a}$ value estimates (Environment and Climate Change Canada, 2021, p. 80).

$$\mathrm{NE_a} = \mathrm{C_a} * \mathrm{NE_m} \qquad (18)$$

Net energy for lactation ($\mathrm{NE_l}$) is a function of daily milk production, Milk, measured in kg of milk produced per day, and the milk fat content, Fat, expressed as a percentage of production (Gavrilova et al., 2019, p. 10.25). The equation to estimate $\mathrm{NE_l}$ can be found in Equation 19.

$$\mathrm{NE_l} = \mathrm{Milk} * (1.47 + 0.40 * \mathrm{Fat}) \qquad (19)$$

The net energy requirements for work ($\mathrm{NE_{work}}$) is a measure of additional energy for draft cattle (Gavrilova et al., 2019, p. 10.26), an uncommon application by Annex I countries. Of the 41 countries considered, only two reported a $\mathrm{NE_{work}}$ value in the submitted CRF tables (Portugal, 2021; Slovakia, 2021). However, for completeness, Equation 20, used to estimate $\mathrm{NE_{work}}$ as a function of $\mathrm{NE_m}$ and daily hours worked (Hours) (Gavrilova et al., 2019, p. 10.26).

$$\mathrm{NE_{work}} = 0.10 * \mathrm{NE_m} * \mathrm{Hours} \tag{20}$$

The net energy requirement for pregnancy, $\mathrm{NE_p}$, is a measure of the total energy requirements for pregnancy averaged across a year. Estimates for $\mathrm{NE_p}$ is equal to 10% of $\mathrm{NE_m}$ (Gavrilova et al., 2019, p. 10.27).

The equation to estimate net energy requirements for growth, $\mathrm{NE_g}$, can be found in Equation 21. $\mathrm{NE_g}$ is a function of average live body weight BW, mature bodyweight or target weight for disaggregated data, MW, and daily weight gain, WG (Gavrilova et al., 2019, p. 10.24). The coefficient, C, equals 0.8 for female cattle, 1.0 for steers, and 1.2 for bulls.

$$\mathrm{NE_g} = 22.02 * \left(\frac{\mathrm{BW}}{\mathrm{C*MW}}\right)^{0.75} * \mathrm{WG}^{1.097} \tag{21}$$

The remaining variables included within Equation 15 are functions of feed digestibility. The ratio of net energy available for maintenance in a diet to digestible energy consumed, REM, can be estimated using Equation 22 (Gavrilova et al., 2019, pp. 10.28-10.29). The ratio of net energy available for growth in a diet to digestible energy consumed, REG, can be estimated using Equation 23.

$$\mathrm{REM} = \left[1.123 - (4.092 * 10^{-3} * \mathrm{DE}) + (1.26 * 10^{-5} * \mathrm{DE}^2) - \left(\frac{25.4}{\mathrm{DE}}\right)\right] \tag{22}$$

$$\mathrm{REG} = \left[1.164 - (516 * 10^{-3} * \mathrm{DE}) + (1.308 * 10^{-5} * \mathrm{DE}^2) - \left(\frac{37.4}{\mathrm{DE}}\right)\right] \tag{23}$$

Country-Specific Tier 2 and Tier 3 Approaches

This section provides an overview of the variables and approaches taken to estimate the emission factors for enteric methane production. Country-specific methodologies were developed in Australia, Austria, Denmark, Germany, Ireland, Japan, Liechtenstein, Netherlands, New Zealand, Norway, Romania, Sweden, Switzerland, United Kingdom, France, and Russia. Of those countries, Germany (Dairy only), Netherlands (Dairy only), Switzerland (Dairy only), United Kingdom, and France have developed Tier 3 methods for estimating emissions. The methodologies complexity in emission estimation approaches and variables differ between countries but share several similarities.

Australia

Australia developed models for estimating emissions from beef cattle throughout the production cycle (grazing pasture, feedlot) and dairy cows (Australian Government Department of Industry Science Energy and Resources et al., 2021, sec. 5.3.2). All three approaches estimate DMI and resemble the Simplified Tier 2 approaches provided by the IPCC. The addition of daily weight gain and additional metabolic considerations for lactation and pregnancy differentiates dairy cows and beef cattle on pasture from the standard Simplified Tier 2 methodology (Australian Government Department of Industry Science Energy and Resources et al., 2021, p. 5.3.2). In feedlot beef cattle, Australia uses Equation 3[2] for estimating total DMI. DMI estimation is then broken-down by feed components (soluble residue, hemicellulose, and cellulose), multiplying intake of each feed component by the corresponding methane yield (Australian Government Department of Industry Science Energy and Resources et al., 2021, sec. 5.3.2.3). The estimated uncertainty for the enteric fermentation emission factor is ±22 percent, slightly less accurate than the IPCC Tier 2 approaches (Australian Government Department of Industry Science Energy and Resources et al., 2021, sec. 5.3.6).

Austria

Austria methodology closely resembles the gross energy approach described in Equation 14, and reports using a 2006 IPCC default methane conversion factor (Austria, 2021, sec. 5.2.2). The estimate of the GE variable differentiates the model from the standard GE approach. The GE value is based on the energy content of the feed consumed rather than net energy requirements. While GE value is estimated outside the model, it accounts for cattle diet composition and the forage and feed concentrates DMI fractions. Austria's NIR reports an uncertainty equivalent to the IPCC Tier 2 approach of ±20 percent (Austria, 2021, sec. 5.2.4).

Denmark

Like Austria, Denmark's Tier 2 methodology utilizes a combination of gross energy and a feed intake (Nielsen et al., 2021, sec. 5.3.2). The methodology accounts for seasonal variation by taking the weighted average estimated summer and winter emission factors. The gross energy estimate is based on the DMI energy content (dairy) or energy content of the feeding unit[3] (non-dairy) and the intake quantity. The energy conversion rates for dairy emissions are based on outside estimates; however, for non-dairy, estimates are based on feed composition and focused on the and energy

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[2] Within Australia's 2021 NIR the methodology used for estimating DMI for beef cattle on feedlots is attributed to the 2019 Refinement however the equation shown belongs to the 2006 guidelines for growing cattle.

[3] One Feeding Unit is equivalent to the energy content of 1 kg barley (85 per cent dry matter).

content and fraction of protein, fat, and carbohydrates within each feeding unit. The estimated uncertainty for the emission factor of ±20 percent is comparable to the IPCC tier 2 approach (Nielsen et al., 2021) .

Ireland

Ireland's Tier 2 approach developed by Yan et al. (2000) and presented in O'Mara (2006) and takes a gross energy approach for estimating emissions. The approach estimates daily methane emissions as a function of digestible energy intake, the ratio of silage in total DMI, and feeding level. Cattle feeding levels were determined by a series of net energy estimates, similar to the IPCC methodology, but included additional factors such as stage of pregnancy and milk protein content. The methodology improves on the uncertainty of the emission factor estimate with a value of ±15 percent (Duffy et al., 2021, sec. 5.2.1).

Japan

Japan’s methodology does not incorporate additional feed data or directly account for feed digestibility, differing considerably from other Country Specific Tier 2 approaches (Ministry of the Environment & National Institute for Environmental Studies, 2021, sec. 5.2.1). The approach models DMI as a function of weight, daily weight gain, and milk production, dependent on breed, age, sex, stage of production, and use, involving the development of thirteen equations (Ministry of the Environment & National Institute for Environmental Studies, 2021, pp. 5–6). Lack of feed data within the model may be associated with the emission factor’s high uncertainty values, which range from -26 percent to 32 percent for dairy cattle and -40 percent to 49 percent for non-dairy cattle compared with the IPCC Tier 2 approach (Ministry of the Environment & National Institute for Environmental Studies, 2021, pp. 5–8).

New Zealand

New Zealand utilizes a DMI approach for estimating enteric emissions. DMI is estimated as a function of the energy content of the feed and total metabolizable energy requirements (Pickering et al., 2021, sec. 4). metabolizable energy requirements are based on estimates of the energy requirements for maintenance, additional energy requirements for production, and additional requirements for grazing. New Zealand's approach for estimating net energy requirements goes beyond IPCC Tier 2 model. For example, Energy requirements for grazing are based on multiple factors, including an estimate of DMI, the digestibility of feed, the energy content of the feed, other energy requirements, terrain, the availability of green forage, and animal metabolic characteristics (Pickering et al., 2021, sec. 4.3.5). New Zealand's methodology is on the high end of complexity for country-specific Tier 2 approaches and could compare to countries using Tier 3 approach given the estimated uncertainty on the emission factor of ± 15.5 percent (Ministry for the Environment, 2021b, sec. A3).

Norway

Norway uses Equation 14 to estimate its emission factor but developed a separate methodology for estimating gross energy and the corresponding methane conversion factor (The Norwegian Environment Agency et al., 2020, sec. 5.4.1, 2021, sec. 5.4.1). In the case of Norwegian dairy cattle, GE estimate is based on energy corrected milk production and the proportion of feed concentrates within the diet. For growing cattle, age and weight are factors in GE and $\mathrm{Y_m}$ estimates. Compared with the IPCC Tier 2 Approaches, uncertainty associated with dairy cows was estimated to be ±28 percent, and for growing cows, ±25 percent (The Norwegian Environment Agency et al., 2020, sec. 5.4.2).

Romania

Romania is the only country included in the review that developed country-specific methodology for non-dairy cattle (Olteanu, 2021, sec. 5.2.2). Its approach uses Equation 14 for estimating the emission factor but estimates gross energy as a function of diet component proportions and energy content (gross protein, gross fat, gross pulp, and extractable non-nitrogenous substances) and total feed consumed. Dairy cattle use the standard IPCC gross energy approach for estimating emissions and the associated error term is equal to the IPCC value of ±20 percent (Olteanu, 2021, sec. 5.2.3).

Sweden

The Swedish methods use a DMI approach to estimate annual enteric emissions (Kellner & Hytteborn, 2021, sec. 5.2.2). In the case of dairy and beef cows, emissions are estimated as a function of DMI and the feed fatty acid content. The fatty acid content of the feed is determined by the proportion of silage and concentrate and the fatty acid content of each component. The DMI estimate is a combination of the metabolizable content of the diet, determined by the proportion of silage and concentrates, and an estimate of the metabolizable energy requirement, dependent on milk yield, milk components (i.e., fat and protein content), weight, and pregnancy. A similar methodology is used to estimate emissions from bulls and heifers; DMI is estimated by dividing the metabolic energy requirements by the feed energy content. The quotient is converted to gross energy by multiplying the feed energy content by a methane conversion factor. Country-specific conversion factors are based on the proportion of feed concentrates in the diet. The methodology used for estimating emissions from dairy cattle is comparable to the IPCC approach in terms of accuracy with an estimated error term of ±20 percent, and a decreased in accuracy for non-dairy cattle at ±25 percent (Swedish Environmental Protection Agency & Swedish Environmental Protection Agency, 2021, sec. 7.2.7).

Russia

Russia's country-specific methodology bases emission factor estimates using the IPCC GE model (Equation 14) and the default methane conversion factors of 6.5 percent (Romanovskaya et al., 2021, sec. 5.3.2). Like in the case of Romania, Norway, and Austria, a different methodology was developed to estimate gross energy. Gross energy intake is estimated as a function of total feed intake and the proportion and energy content of feed ingredients. The Russian methodology accounts for five feed types; feed concentrates (without compound feeds), compound feeds, roughage, succulent feed, and other, encompassing remaining feed not further classified (Romanovskaya et al., 2021, p. 172) . The reported uncertainty was lower than any other Tier 2 approach, and lower than most Tier 3 approaches, with a value of ±1.83 percent[4](Romanovskaya et al., 2021, sec. 5.3.3).

Germany

Germany developed a Tier 3 emission methodology to estimate emissions from dairy cattle and uses a Tier 2 gross energy approach to estimate emissions from non-dairy cattle (Federal Environment Agency, 2021, sec. 5.2.2). The estimated emission factor is a function of diet components and considers the quantity of fiber, n-free extracts, protein, and fat. Like the Australian method, each component has a corresponding methane yield, and the emission factor is equal to the sum of the products (feed intake multiplied by methane yield). The reported Tier 3 emission factor estimate uncertainty value of ±20 percent[5] is comparable to the IPCC tier 2 approach (Federal Environment Agency, 2021, sec. 5.2.3).

Netherlands

The Netherlands reports using a Tier 3 emission factor for dairy cattle and a Tier 2 Country Specific emission factor for non-dairy cattle (van der Zee et al., 2021). The Dutch Tier 3 approach predicts methane emission by considering the chemical composition[6] of various feed components[7], the digestibility of the feed components, level of feed intake, and rumen characteristics, in combination with a cattle digestion simulation. Detailed descriptions of the methodology can be found in section 3.2.3 of van der Zee et al (2021). The Tier 2 country specific estimates follow the IPCC gross energy approach (Equation 14) with a country-specific methodology for estimating gross energy, in which GE is a function of

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[4] An emission factor uncertainty estimate is extremely low compared with other Tier 2 Country Specific and Tier 3 methodologies the closest reported value using a similar approach is the Netherlands at 15 percent. Unless the cattle population is extremely homogeneous a value of 1.83 percent is unlikely given that the country uses a Tier 2 approach.

[5] There may have been a typo in the reporting of the uncertainty estimate as the value presented for non-dairy cattle was found to be ±11.2 percent but used the IPCC gross energy approach which has a reported value of ±20 percent.

[6] The chemical compositions of interest in the Dutch model includes soluble carbohydrates, starch, cell walls (hemi-cellulose, cellulose and lignin), crude protein, crude fat and crude ash

[7] The feed components of interest in the Dutch model include grass herbage, grass silage, maize silage, low-protein concentrates, protein-rich concentrates, and wet by-products

DMI and feed energy content (van der Zee et al., 2021, p. 47). The Tier 3 approach estimated uncertainty value of ±15 percent is more accurate compared to the IPCC Tier 2 methodology [8] (van der Zee et al., 2021, sec. 3.3).

Switzerland uses a Tier 3 methodology to estimate enteric methane emissions from dairy cattle (Federal Office for the Environment, 2021, sec. 5.2.2.1). The methodology resembles an IPCC gross energy approach but uses a country-specific gross energy estimate based on Swiss feeding recommendations and animal performance characteristics. The estimated emission factors are also used in the Liechtenstein country-specific Tier 2 approach, given production system similarities (Weber, 2021, sec. 5.2.2.1).

United Kingdom

The United Kingdom uses a DMI approach in its Tier 3 methodology (Brown et al., 2021, sec. 5.3.1). The DMI is estimated using metabolizable energy requirements based on cattle performance, productivity, and breed characteristics (Brown et al., 2021, sec. 5.3.2). Additionally, the model incorporates feed types and nutritional components such as energy and protein content. Emission estimates occur on a high temporal frequency compared to other methodologies as emissions are estimated monthly compared with seasonal or annual estimates. The reported uncertainty in the emission factor estimate is ± 0 percent. Compared to other Tier 3 methods (Brown et al., 2021, p. 733), this estimate is highly unlikely[9].

France

France recently developed a Tier 3 approach to estimate enteric methane emissions with a detailed description of the methodology presented in Eugene et al. (2019). The approach is based on estimates for DMI and digestible organic matter intake (DOMI). Within the model, DMI based on the total net energy requirements estimated from productivity and production characteristics is estimates. DOMI is estimated as a function of daily DMI, feed organic matter content, and feed digestibility. To convert DOMI to methane emissions, a methane conversion factor is estimated as a function of the feeding level (kg DMI/100 kg LW) and concentrate proportion of the diet. The estimated value of DOMI is multiplied by the methane conversion factor, and subsequently multiplied by 365 to estimate an annual emission factor. The

[8] The value presented shows combined uncertainty, which is a combination of the uncertainty associated with the activity data and emission factor uncertainty

[9] The reported activity data (herd size) uncertainty was ±13.73 percent well above other uncertainty estimates in comparable countries. It may be the case that the value was added to the wrong column in the table as ±13.73 percent would be within normal range for a Tier 3 model.

uncertainty value of ±15 percent associated with the emission factor is equivalent to other Tier 3 methods (Andre et al., 2021, sec. 5.2.3).

POLICY IMPLICATION OF MEASUREMENTS

The recent 2021 review “Methane Emissions from Ruminants in Australia: Mitigation Potential and Applicability of Mitigation Strategies”, Black et al. (2021) identifies and discuses different mitigation technologies and applications within the Australian livestock industry. The introduction of the Emissions Reduction Fund in 2016 aims to incentivize primary producers to reduce greenhouse gas emissions through payments, concurrently increasing animal production efficiency and productivity. Mitigation strategies outlined in the National Livestock Methane Program (NMLP) are critically compared and contrasted to determine potential and feasibility to reduce ruminant methane emissions into to the future, underpinning the Australian red meat industry's goal of reaching carbon neutrality by 2030.

The different strategies were categorized based on targeted function and evaluated across different implementation and feasibility dimensions, exploring benefits, risks and costs to different stakeholders within the sector. The categories examined were as follows: i) the role of genetic selection; ii) the use of various feel supplements; iii) the potential role of anti-methanogenic forages; iv) potential for methane reductions from a detailed understanding of rumen function; and v) best pasture management practices. The potential of vaccinations against rumen Archaea, and feed additives 3-NOP and Biochar were included.

Strategies were then ranked, based on potential for financial benefit to the Australian ruminant industries. Overall, the use of processed red marine alga, *Asparagopsis taxiformis*, and 3-NOP as feed additives were identified as the first and second most viable interventions, followed by microbial manipulation of the ruminant microbiome. The introduction of processed red marine alga and the use of 3-NOP as feed additives has prompt effects on methane emissions, demonstrating variables ranges in reduction potential. The authors suggest that the inclusion of one or both feed additives, once commercially available, should be coupled with efforts to maintain the manipulated rumen population within herds to support future generations. Other strategies, currently in place in Australia, demonstrated less potential to mitigate emissions, such as the use of various forages and the inclusion of by-products in the diet.

As environmental, social, and economic pressures build to reduce and mitigate carbon emissions, technologies such as the strategies presented by Black et al. (2021) and others are being explored by different countries and regions, based on different agricultural production operations and climate scenarios. The current IPCC methodology is not inclusive of current and prospective reduction technologies. Failure to account for various reduction technologies may deter implementation of strategies to reduce methane, as emission reduction in cattle herds would not be reflected. This increasingly prevalent reporting gap impedes future reliability and accuracy of methane reporting and disclosures and should be addressed in future methodology updates to ensure systematic calculations and improved emission estimates.

EMISSION COMPARISON

This section provides an exploratory analysis of enteric methane emissions, emission factors, and cattle characteristics reported in the CRF tables across all 42 Annex I parties included within the review. Data was collected from each country CRF Table number 3. As1 and 3. As2 and covered a period from 1990 to 2019.

DAIRY CATTLE

From Table 6, it can be observed that Canada follows many of the same trends as the larger Annex I group. From 1990 to 2019 the dairy cattle population and total enteric emissions estimate decreased considerably. In both cases, increases in per head productivity offset the smaller overall population, with both groups experiencing growth in total milk production.

Production characteristics differ between Canada and the group average. This difference is most notably in milk productivity, where Canada reports a value of daily milk production 80% higher than the group average (32.58 kg day^{-1} compared with 18.1 kg day^{-1}). Compared with other countries making up the Annex I group, Canada has the highest daily milk production for dairy cattle, see Figure 7, and is well above the regional default values, Figure 3.

As demonstrated in the methodology section, high milk productivity increases energy requirements, which in turn increases enteric emissions. As such, high productivity partially explains Canada's high emission factor. In 2019 the reported emission factor was 25 percent higher than the Annex I group average, 142 kg CH_4 $head^{-1}$ $year^{-1}$ compared with 114.3 kg CH_4 $head^{-1}$ $year^{-1}$. As seen in Figure 8, Canada is consistently above the median reported value, and in 2019 was within the highest quartile. Directly compared to other countries in 2019, see Figure 9, Canada had the 9th highest emission factor, comparable to larger producers like the United States 147 kg CH_4 (United States of America, 2021) and Germany 139 kg CH_4 (Germany, 2021). To facilitate comparison between countries with differing production systems, an emission intensity measure was estimated. The intensity measure is a ratio of daily enteric emissions to daily milk production. From an emission intensity basis, Canada produces milk at a lower rate of enteric fermentation emissions than the Annex I group average. However, the difference between Canada and group I has decreased since 1990, as other countries increase in efficiency. Compared to other countries, see Figures 10 and 11, Canada has the second lowest intensity measure and is below other large dairy producers such as the United States and New Zealand.

NON-DAIRY CATTLE

A comparison between Canada and the Annex I group averages for non-dairy cattle can be found in Table 7. The table covers several important measures including population, total emissions, and total production weight for select years between 1990 and 2019. Level of aggregation varied considerably between countries; Canada for example provided a single average estimate for non-dairy cattle while the United States provided disaggregated average values for eleven different non-dairy cattle groups. For countries that did not provide a single estimate, an average weighted value based on share of the national non-cattle herd was estimated. Sections with missing data were filled using default regional values collected from the 2019 Refinement.

Across all Annex I countries total animal population and total emission decreased by approximately 20 and 12 percent respectively. Canada did not follow this trend, as the total non-dairy cattle population grew by 4 percent, and resulted in an increase in total emissions. Total production (the product of live weight and population) increased by 21 percent compared with an 11 percent decrease for the Annex I group.

Non-dairy cattle production characteristics differ from the Annex I group averages. Notably, average weight in Canada was approximately 59 percent higher in 2019 than the group average. High average weights partially explain Canada's above average emission factors found in Canada. Low average feed digestibility values could also partially explain higher emission factors; 63.7 percent is below the Annex I average value of 66.4, and indicates average feed likely consists of low quality, or the low end of average quality forage. Interestingly, Canada has a below average methane conversion factor, 5.7, suggesting higher feed digestibility, reference Table 5.

Comparing Canadian production to other countries within the review, Canada's reported emission intensity measure for non-dairy cattle is significantly higher than other major beef producing Annex I countries, see Figure 12 and 13. This may be partially attributed to Canada's climate and outdoor wintering practices potentially increasing gross energy requirements and subsequent enteric emissions, see equations 16 and 17Canada's reported average weight is an outlier compared with the total group of countries and well above other major Annex I non-dairy cattle producers, contributing to higher emission factors.

For non-dairy cattle, emission intensities were measured in kilograms of methane emitted per tonne of live weight. This intensity measure was selected as weight correlates with beef as the system's productive output. On an intensity basis Canada has a relatively low intensity measure, as seen in Figure 15. Canada consistently ranks in the lowest quartile, suggesting lower per unit emissions. In 2019 Canada had the 7th lowest intensity measure at 108.1 kg CH_4 t live weight^{-1}, between Switzerland 107.4 kg (Switzerland, 2021) and New Zealand 108.2 kg (New Zealand, 2021). Canada also had the lowest emissions compared to major non-dairy producing countries, followed by France 120.4 kg (France, 2021) and thn United States 140.0 kg (United States of America, 2021). Compared with IPCC default regions and high productivity systems from the 2019 Refinement, Canada is once again highly competitive, with an emission intensity value below any default region; for example, Canada's emission intensity is 34 percent lower than high productivity systems in Latin America.

CONCLUSION

The IPCC developed four approaches to estimate cattle enteric methane emissions. As a baseline, the Tier 1 approach described in Equation 1 and the Tier 1a approach described in Equation 2 requires information on activity data within the country to estimate emissions. However, there are significant limitations to developing policy using the approach and equations, namely emission changes exclusively dependent on changes to the national herd size. Individual producer decisions are not accounted for unless ad hoc factors are applied. Additionally, without country specific production data, the estimated uncertainty of the emission factor is extremely high (± 50 percent), further reducing practicality and applicability.

The development of Tier 2 approaches improves upon the Tier 1 methods by decreasing the uncertainty value of the emission factor estimates (± 20 percent) through incorporating country specific information. While differences between the Simplified and Preferred Tier 2 approaches exist, the models account for stage of production, sex, weight, feed quality (measured in digestibility), and in dairy operations, milk production. The gross energy approach also considers growth rate, climate, activity level, and pregnancy, providing a comprehensive estimate reflective of production practices and characteristics within the country. Despite the improvement in accuracy, IPCC methods are limited by the variable dependency on productivity measures, and therefore are difficult to translate into policy options without reducing or restricting production. Policies aiming to decrease cattle weight, growth rates, or milk productivity to reduce emissions would suffer from poor uptake as those measures direct tie to income. Changing farming practices, such as wintering indoors or reducing time in pasture, may be more viable policy options. However, these options may require significant initial investment and increases production costs to observe large emission reductions. Incremental improvements, such forage quality or feed supplementation, are not directly accounted for within the methodology, but likely effect emission outcomes.

Country specific methodology amends the short comings of the Tier 2 approaches. This is best reflected in methods that combined both an energy requirement and feed components; energy requirements account for production practices and cattle characteristics, while the addition of feed components accounts for impact of incremental changes in diet on emission measures. Despite these improvements, specific efforts designed to reduce emissions remain unaccounted, and to quote the Netherlands NIR, the methods fail to account for measures which could such as the inclusion of feed additive that could "demonstrably mitigate enteric CH_4 emissions" (van der Zee et al., 2021, p. 44).

Average emissions per head of cattle in Canada tend to be higher than other Annex I countries, a result above average weight and milk productivity. In the case of non-dairy cattle, digestibility is well below the international high per head emission average estimate. Canadian production is competitive on an emissions intensity basis, ranked sixth overall, with the second lowest emission intensity for dairy cattle and the lowest major producer emission factor for non-dairy cattle. Compared with regional estimates, Canadian non-dairy emission intensity estimates are well below other major producing regions, including Latin America.

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Tables

Table 1

Country List

Country	Abbreviation	National Inventory Report	Common Reporting Format Tables	Translation
Australia	AUS	(Australian Government Department of Industry Science Energy and Resources, 2021; Australian Government Department of Industry Science Energy and Resources et al., 2021)	(Australia, 2021)	
Austria	AUT	(Anderl et al., 2021)	(Austria, 2021)	
Belarus	BLR	(Narkevich I.P. et al., 2021)	(Belarus, 2021)	Russian
Belgium	BEL	(Belgian Interregional Environment Agency et al., 2021)	(Belgium, 2021)	
Bulgaria	BGR	(Executive Environment Agency at the Ministry of Environment and Water, 2021)	(Bulgaria, 2020)	
Canada	CAN	(Environment and Climate Change Canada, 2021b, 2021, 2021a)	(Canada, 2021)	
Croatia	HRV	(Marković & Glückselig, 2021)	(Croatia, 2021)	
Cyprus	CYP	(Ministry of Agriculture Rural Development and Environment, 2021)	(Cyprus, 2021)	
Czechia	CZE	(Beranova et al., 2021)	(Czechia, 2021)	
Denmark	DNK	(Nielsen et al., 2021)	(Denmark, 2021)	
Estonia	EST	(Kupri et al., 2021)	(Estonia, 2021)	
Finland	FIN	(Statistics Finland & The Natural Resources Institute Finland, 2021)	(Finland, 2021)	
France	FRA	(Andre et al., 2021)	(France, 2021)	French
Germany	DEU	(Federal Environment Agency, 2021)	(Germany, 2021)	
Greece	GRC	(Ministry of the Environment and Energy, 2021)	(Greece, 2021)	
Hungary	HUN	(Katalin, 2021)	(Hungary, 2021)	
Iceland	ISL	(Keller et al., 2021)	(Iceland, 2021)	
Ireland	IRL	(Duffy et al., 2021)	(Ireland, 2021)	
Italy	ITA	(di Cristofaro & Cordella, 2021)	(Italy, 2021)	

Country	Abbreviation	National Inventory Report	Common Reporting Format Tables	Translation
Japan	JPN	(Ministry of the Environment & National Institute for Environmental Studies, 2021)	(Japan, 2021)	
Kazakhstan	KZA	(Tokpaev, 2021)	(Kazakhstan, 2021)	Russian
Latvia	LVA	(Skrebele et al., 2021)	(Latvia, 2021)	
Liechtenstein	LIE	(Weber, 2021)	(Liechtenstein, 2021)	
Lithuania	LTU	(Juška & Žiukelytė, 2021)	(Lithuania, 2021)	
Luxembourg	LUX	(Bechet et al., 2021)	(Luxembourg, 2021)	
Malta	MLT	(The Malta Resources Authority, 2021)	(Malta, 2021)	
Netherlands	NLD	(van der Zee et al., 2021)	(Netherlands, 2021)	
New Zealand	NZL	(Ministry for the Environment, 2021a, 2021b; Pickering et al., 2021)	(New Zealand, 2021)	
Norway	NOR	(The Norwegian Environment Agency et al., 2020, 2021)	(Norway, 2021)	
Poland	POL	(Olecka et al., 2021)	(Poland, 2021)	
Portugal	PRT	(Pina & Portuguese Environment Agency, 2021)	(Portugal, 2021)	
Romania	ROU	(Olteanu, 2021)	(Romania, 2021)	
Russian Fed.	RUS	(Romanovskaya et al., 2021)		Russian
Slovakia	SVK	(Slovak Hydrometeorological Institute et al., 2021)	(Slovakia, 2021)	
Slovenia	SVN	(Verbič et al., 2021)	(Slovenia, 2021)	
Spain	ESP	(MITECO, 2021)	(Spain, 2021)	Spanish
Sweden	SWE	(Swedish Environmental Protection Agency & Swedish Environmental Protection Agency, 2021)	(Sweden, 2021)	
Switzerland	CHE	(Federal Office for the Environment, 2021)	(Switzerland, 2021)	
Turkey	TUR	(Turkish Statistical Institute, 2021)	(Turkey, 2021)	
Ukraine	UKR	(Ministry of Environmental Protection and Natural Resources of Ukraine, 2021)	(Ukraine, 2021)	
United Kingdom	GBR	(Brown et al., 2021)	(United Kingdom, 2021)	
United States	USA	(United States Environmental Protection Agency, 2021a, 2021b)	(United States of America, 2021)	

Note. UNFCCC National Inventory Submission repository can be found at the following link: https://unfccc.int/ghg-inventories-annex-i-parties/2021

Table 2

Cattle Emission Factors

Region	Cattle Type	IPCC 2006[a]	IPCC 2019[b]	Tier 1a: HP[b]	Country	IEF: 2019[c]
North America	Non-Dairy Cattle	53	64	-	CAN	71
					USA	59
Western Europe	Non-Dairy Cattle	57	58	-	AUT	59
					BEL	47
					CHE	47
					CYP	57
					DEU	46
					DNK	41
					ESP	62
					FIN	56
					FRA	53
					GRB	55
					GRC	63
					IRL	49
					ISL	38
					ITA	48
					LIE	43
					MLT	35
					NLD	35
					NOR	61
					PRT	58
					SWE	50
Eastern Europe	Non-Dairy Cattle	85	58	-	BGR	64
					BLR	51
					CZE	59
					EST	44
					HRV	60
					HUN	54
					KAZ	52
					LTU	58
					LVA	46
					POL	50
					ROU	64
					RUS	57
					SVK	61
					SVN	61
					UKR	48
Oceania	Non-Dairy Cattle	60	63	-	AUS	52
					NZL	61
Asia	Non-Dairy Cattle	47	54	43	JPN	60
Middle East	Non-Dairy Cattle	31	60	61	TUR	47
Latin America	Non-Dairy Cattle	56	56	55	-	-

Region	Cattle Type	IPCC 2006[a]	IPCC 2019[b]	Tier 1a: HP[b]	Country	IEF: 2019[c]
Africa	Non-Dairy Cattle	31	52	60	-	-
Indian Sub.	Non-Dairy Cattle	27	46	41	-	-
North America	Dairy Cattle	53	64	-	CAN	142
					USA	147
Western Europe	Dairy Cattle	57	58	-	AUT	137
					BEL	127
					CHE	137
					CYP	121
					DEU	139
					DNK	162
					ESP	125
					FIN	159
					FRA	124
					GRB	125
					GRC	127
					IRL	122
					ISL	110
					ITA	130
					LIE	140
					MLT	136
					NLD	135
					NOR	149
					PRT	133
					SWE	143
Eastern Europe	Dairy Cattle	85	58	-	BGR	108
					BLR	116
					CZE	156
					EST	156
					HRV	112
					HUN	125
					KAZ	102
					LTU	131
					LVA	146
					POL	119
					ROU	124
					RUS	85
					SVK	123
					SVN	126
					UKR	111
Oceania	Dairy Cattle	60	63	-	AUS	93
					NZL	90
Asia	Dairy Cattle	47	54	43	JPN	100
Middle East	Dairy Cattle	31	60	61	TUR	83
Latin America	Dairy Cattle	56	56	55	-	-
Africa	Dairy Cattle	31	52	60	-	-
Indian Sub.	Dairy Cattle	27	46	41	-	-

Note. a. (Dong et al., 2006) b. (Gavrilova et al., 2019) c. Data was Collected from the CRF Table 3.As1, see Table 1

Table 3
Methodology Review

Country	Dairy			Non-Dairy		
	Tier	C/S Methodology	C/S Conversion	Tier	C/S Methodology	C/S Conversion
AUS	2	Yes	Yes	2	Yes	Yes
AUT	2	Yes	No	2	Yes	No
BEL	2	No	Yes	2	No	Yes
BGR	2	No	No	2	No	No
BLR	2	No	No	2	No	No
CAN	2	No	Yes	2	No	No
CHE	3	Yes	Yes	2	Yes	Yes
CYP	2	No	No	1	No	No
CZE	2	No	No	2	No	No
DEU	3	Yes	Yes	2	No	Yes
DNK	2	Yes	Yes	2	Yes	No
ESP	2	No	No	2	No	No
EST	2	No	No	2	No	No
FIN	2	No	No	2	No	No
FRA	3	Yes	Yes	3	Yes	Yes
GBR	3	Yes	No	3	Yes	No
GRC	2	No	No	2	No	No
HRV	2	No	No	2	No	No
HUN	2	No	Yes	2	No	Yes
IRL	2	Yes	No	2	Yes	No
ISL	2	No	No	2	No	No
ITA	2	No	Yes	2	No	No
JPN	2	Yes	No	2	Yes	No
KAZ	2	No	No	2	No	No
LIE	2	Yes	Yes	2	Yes	No
LTU	2	No	No	2	Yes	No
LUX	2	No	No	2	No	No
LVA	2	No	Yes	2	No	Yes
MLT	2	No	No	2	No	No
NLD	3	Yes	Yes	2	Yes	No
NOR	2	Yes	No	2	Yes	No
NZL	2	Yes	Yes	2	Yes	Yes
POL	2	No	No	2	No	No
PRT	2	No	No	2	No	No
ROU	2	No	No	2	Yes	No
RUS	2	Yes	No	2	Yes	No
SVK	2	No	No	2	No	No
SVN	2	No	No	2	No	No
SWE	2	Yes	Yes	2	Yes	Yes
TUR	2	No	No	2	No	No
UKR	2	No	No	2	No	No
USA	2	No	Yes	2	No	Yes

Note. Data was Collected from the 2021 National Inventory Submissions, see Table 1

Table 4

2019 Simplified Tier 2 Approach to Estimate daily DMI for Non-Dairy Cows

Forage Type	**Digestibility (DE, %)**	**Forage DMI Capacity (kg/day), % Body Weight**	
		Non-Lactating	Lactating
Low Quality	< 52	1.8	2.2
Average Quality	52-59	2.2	2.5
High Quality	> 59	2.5	2.7

Note. Table is a reproduction of Table 10.8, found in Chapter 10.3 of the 2019 Refinement (Gavrilova et al., 2019, p. 10.31)

Table 5

Default Methane Conversion and Methane Yield Values

Cattle Type	2006 Guidelines [a]		2019 Refinement [b]				
	Description	Y_m	Description	DE, %	NDF, % DMI	Y_m	MY
Dairy Cattle	-	6.5%	High-producing cow	≥ 70	≤ 35	5.7%	19.0
			High-producing cow	≥ 70	≥ 35	6.0%	20.0
			Medium-producing cows	60 -70	> 37	6.3%	21.0
			Low-producing cows	≤ 62	> 38	6.5%	21.4
Non-Dairy	Other Cattle	6.5%	> 75% Forage	≤ 62	-	7.0%	23.3
			15 -75% Forage	62-71	-	6.3%	21.0
	Feedlot Cattle	3.0%	0-15% Forage	≥ 72	-	4.0%	13.6
			0-10% Forage [c]	≥ 75	-	3.0%	10.0

Note. a. Data from Table 10.12 of Volume 4 of the 2006 Guidelines (Dong et al., 2006, p. 10.30) b. Data from Table 10.12 of Volume 4 of the 2019 Refinement (Gavrilova et al., 2019, p. 10.45)

Table 6

Dairy Cattle Characteristics

Group	Measure	Variable	Units	1990	2000	2010	2019	Change Since 1990
Annex I	Total	Population	x1000 head	101,170	76,260	64,399	65,572	-35.2%
		Total Emissions	kt CH_4	9563.3	7690.4	7058.6	7497.9	-21.6%
		Milk Production	kt Milk Day^{-1}	1077.7	982.8	1047.5	1184.6	9.9%
	Average	Emission Factor	kg CH_4 $head^{-1}$ yr^{-1}	94.5	100.8	109.6	114.3	21.0%
		Milk Production	kg milk $head^{-1}$ day^{-1}	10.7	12.9	16.3	18.1	69.6%
		Weight	kg	548.1	555.8	559.3	563.8	2.9%
		DE	%	68.8	69.2	69.8	69.9	1.6%
		Ym	%	6.456	6.361	6.284	6.237	-3.4%
		Emission Intensity	kg CH4 kg $Milk^{-1}$	0.028	0.025	0.021	0.019	-31.1%
Canada	Total	Population	x1000 head	1370	1096	966	973	-29.0%
		Total Emissions	kt CH_4	158.1	137.4	124.2	138.3	-12.5%
		Milk Production	kt Milk Day^{-1}	29.28	29.16	27.25	31.70	8.3%
		Emission Factor	kg CH_4 $head^{-1}$ yr^{-1}	115.4	125.4	128.6	142.2	23.2%
		Milk Production	kg milk $head^{-1}$ day^{-1}	21.37	26.62	28.21	32.58	52.5%
		Weight	kg	655.4	657.3	658.0	658.6	0.5%
		DE	%	68.4	69.2	69.8	69.8	2.0%
		Ym	%	5.799	5.786	5.791	5.791	-0.1%
		Emission Intensity	kg CH4 kg $Milk^{-1}$	0.0148	0.0129	0.0125	0.0120	-19.2%

Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Table 7

Non-Dairy Cattle Characteristics

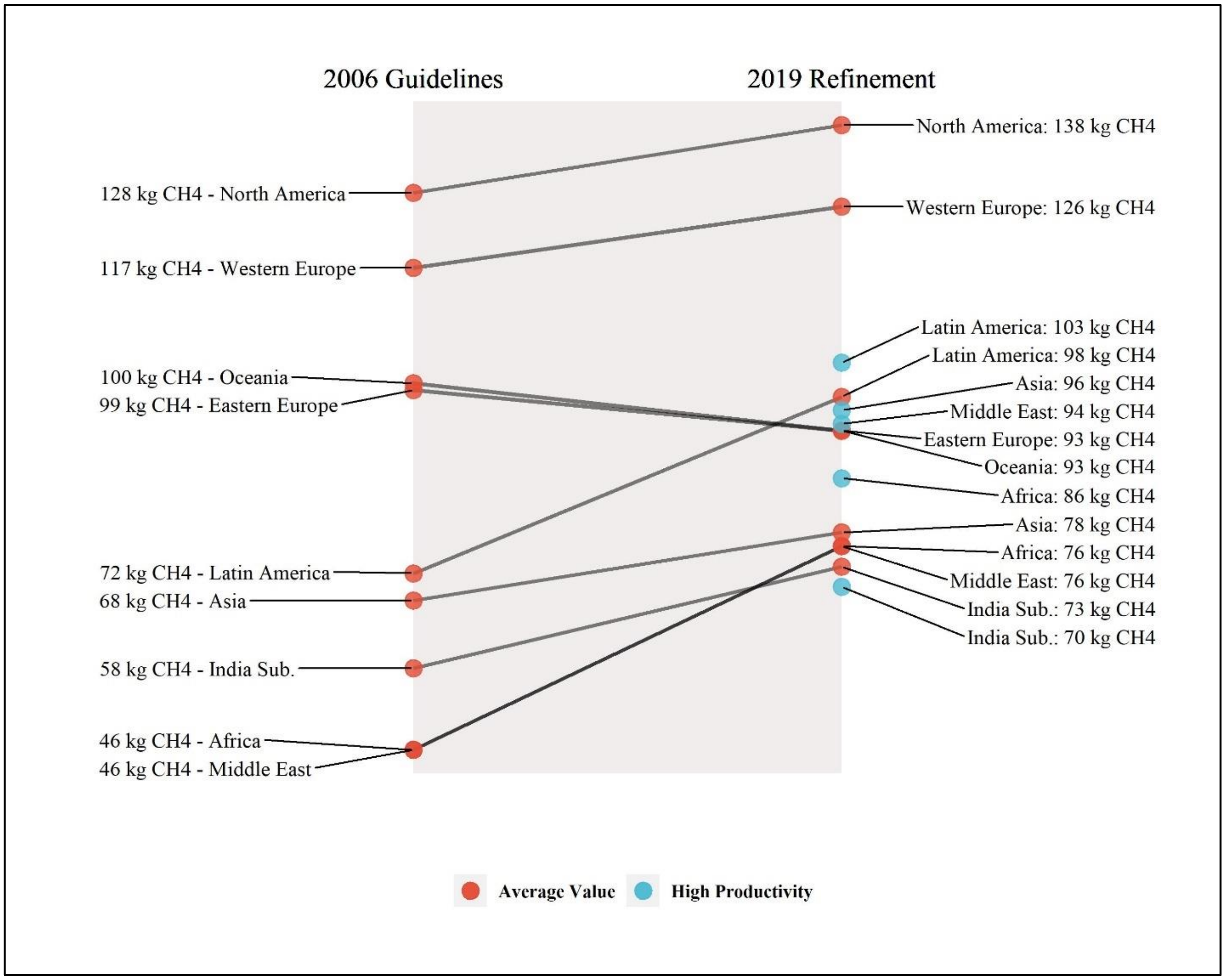
Group	Measure	Variable	Units	1990	2000	2010	2019	Change Since 1990
Annex I	Total	Population	x1000 head	288,669	241,735	227,737	230,827	-20.0%
		Total Emissions	kt CH4	14815.5	13106.4	12662.7	12916.9	-12.8%
		Total Production	Mt live Weight	107407.0	96811.4	93496.9	95554.8	-11.0%
	Average	Emission Factor	kg CH4 head^{-1} yr^{-1}	51.3	54.2	55.6	56.0	9.0%
		Weight	kg	372.1	400.5	410.5	414.0	11.3%
		DE	%	65.9	66.0	66.1	66.4	0.8%
		Ym	%	6.356	6.275	6.267	6.243	-1.8%
		Emission Intensity	kg CH4 t weight^{-1}	140.254	137.614	137.304	136.930	-2.4%
Canada	Total	Population	x1000 head	10520	12989	12217	10927	3.9%
		Total Emissions	kt CH4	706.6	933.5	842.6	779.7	10.3%
		Total Production	Mt live Weight	5943.80	8209.05	7733.36	7211.82	21.3%
		Emission Factor	kg CH4 head^{-1} yr^{-1}	67.2	71.9	69.0	71.4	6.3%
		Weight	kg	565.0	632.0	633.0	660.0	16.8%
		DE	%	63.1	63.3	63.9	63.7	1.0%
		Ym	%	5.8	5.8	5.7	5.7	-1.7%
		Emission Intensity	kg CH4 t weight^{-1}	118.9	113.8	109.0	108.1	-9.1%

Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure

Figure 1

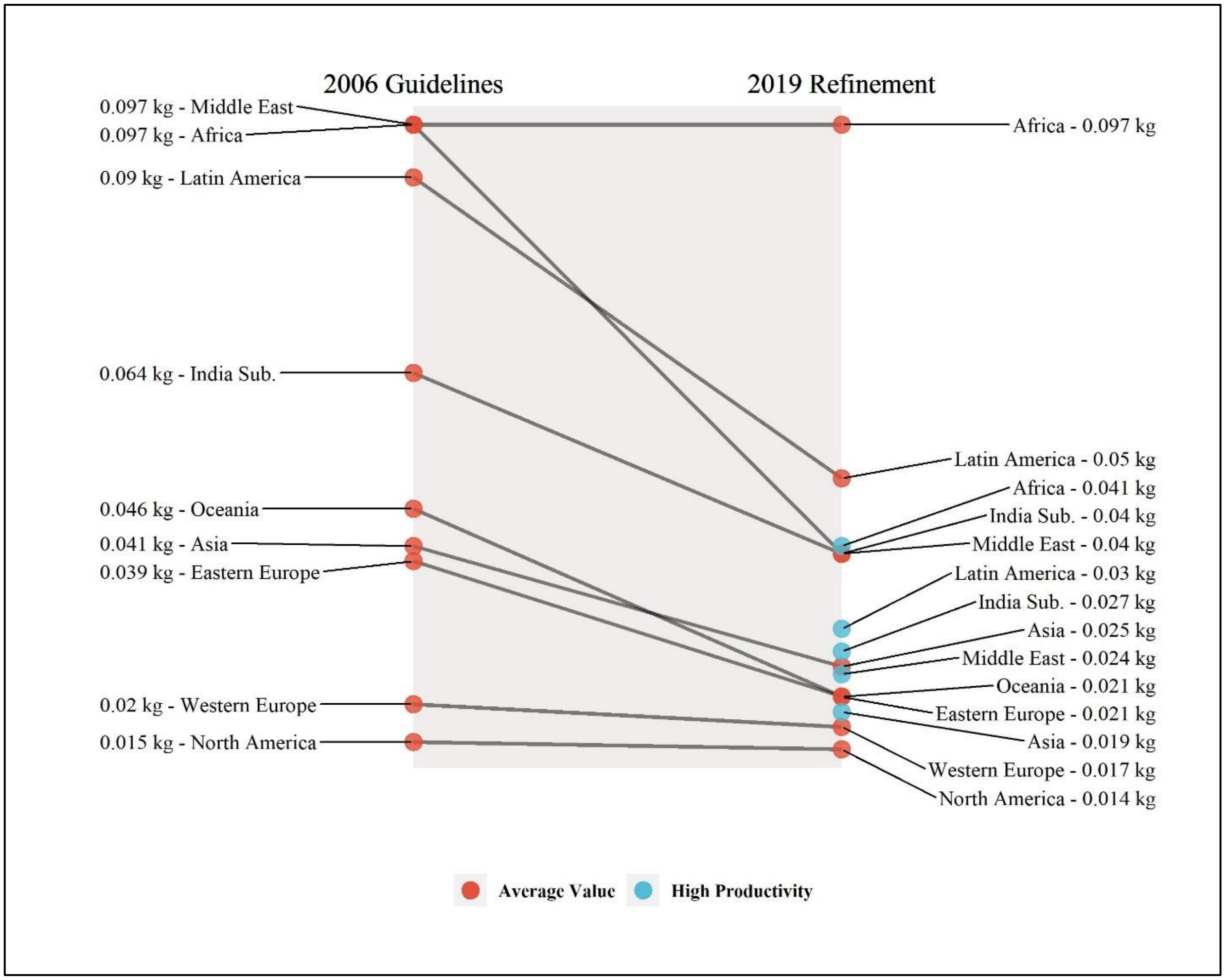
IPCC Regional Default Values: Dairy Cattle Implied Emission Factors (CH_4 head^{-1}year^{-1})



Note. Data used in this figure was collected from Table 10.A.1 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 2

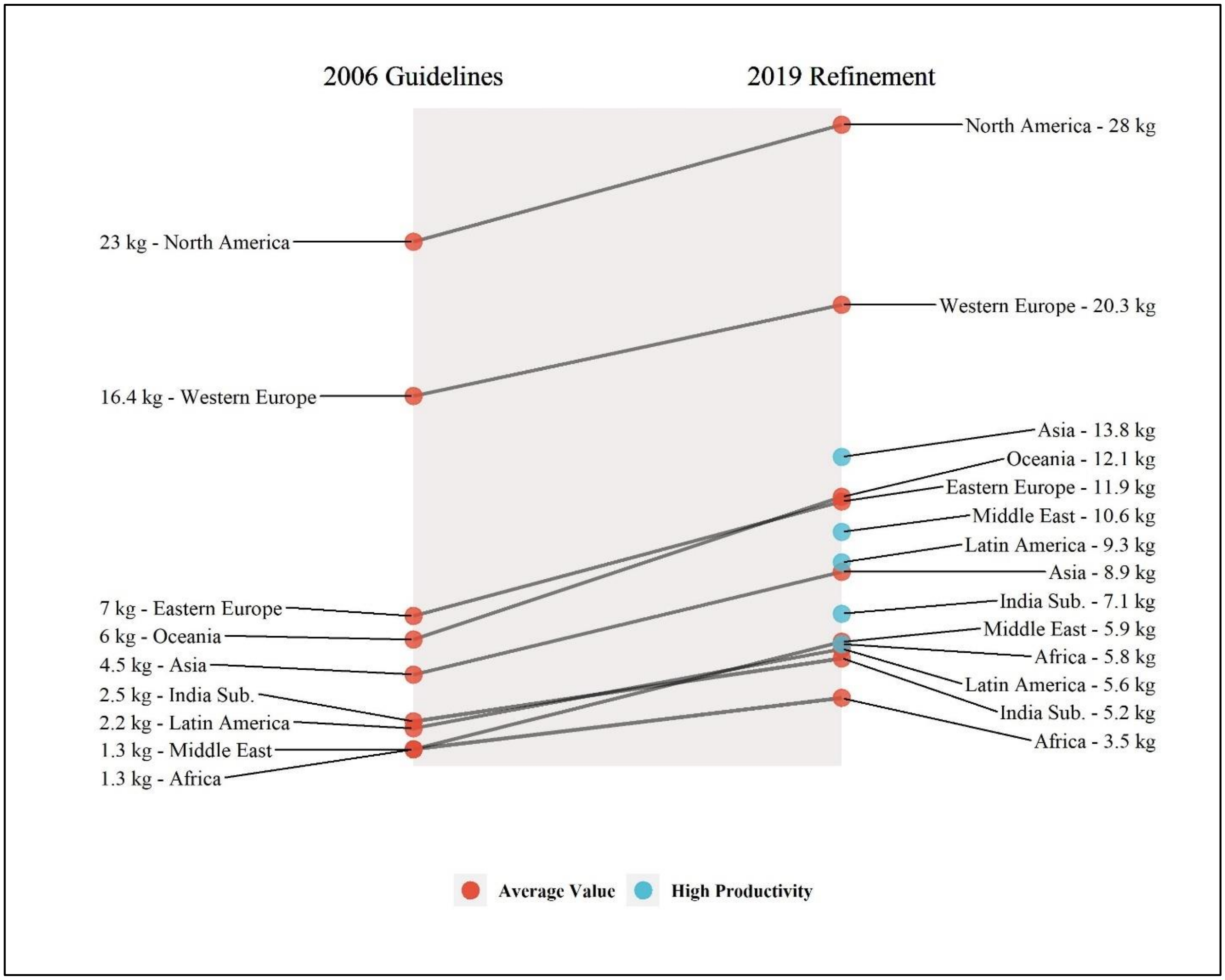
IPCC Regional Default Values: Dairy Cattle Emission Intensity Estimates (CH_4 kg Milk $^{-1}$)



Note: Data used in this figure was collected from Table 10.A.1 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 3

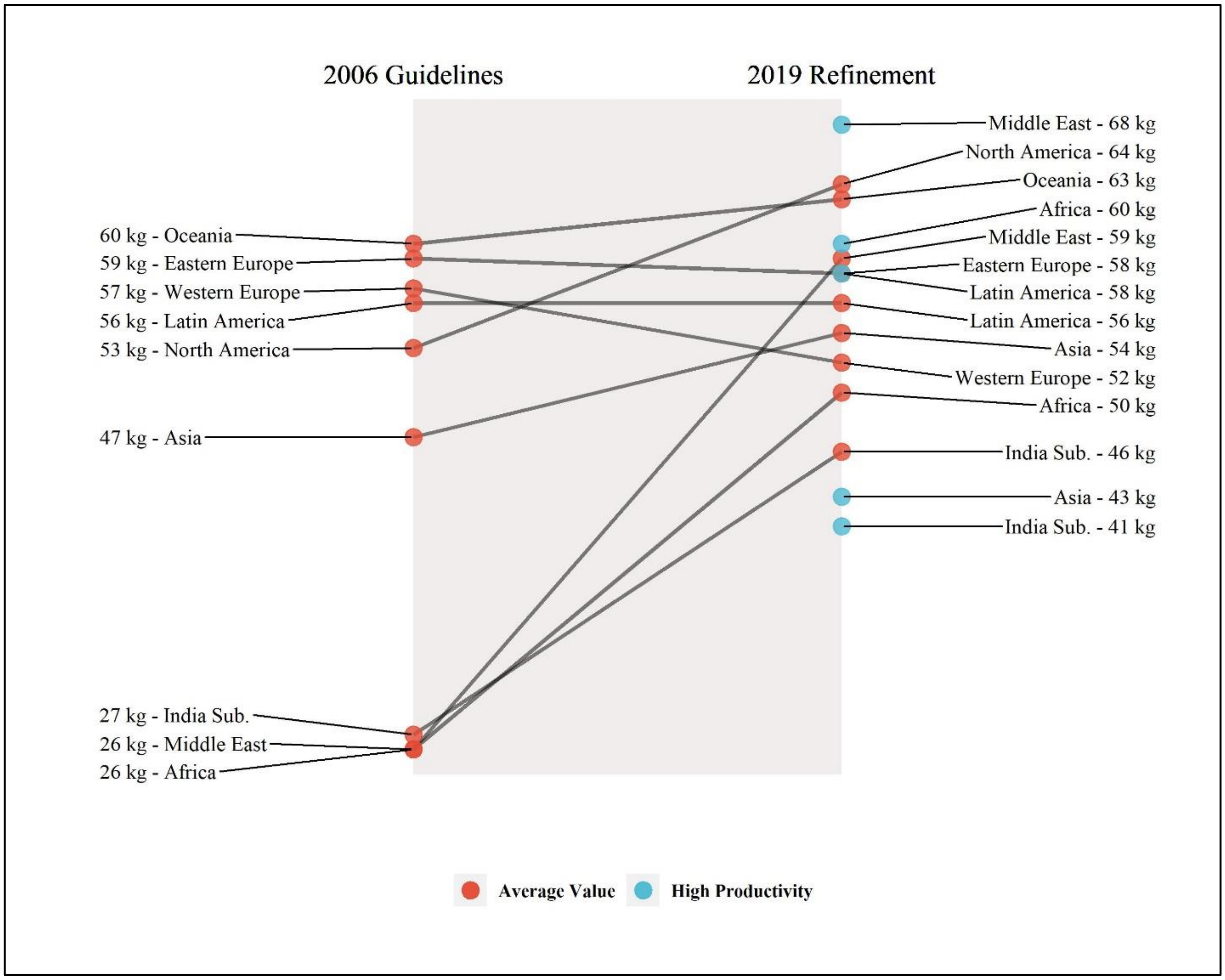
IPCC Regional Default Values: Dairy Cattle Daily Milk Production (kg Milk Produced Day^{-1})



Note: Data used in this figure was collected from Table 10.A.1 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 4

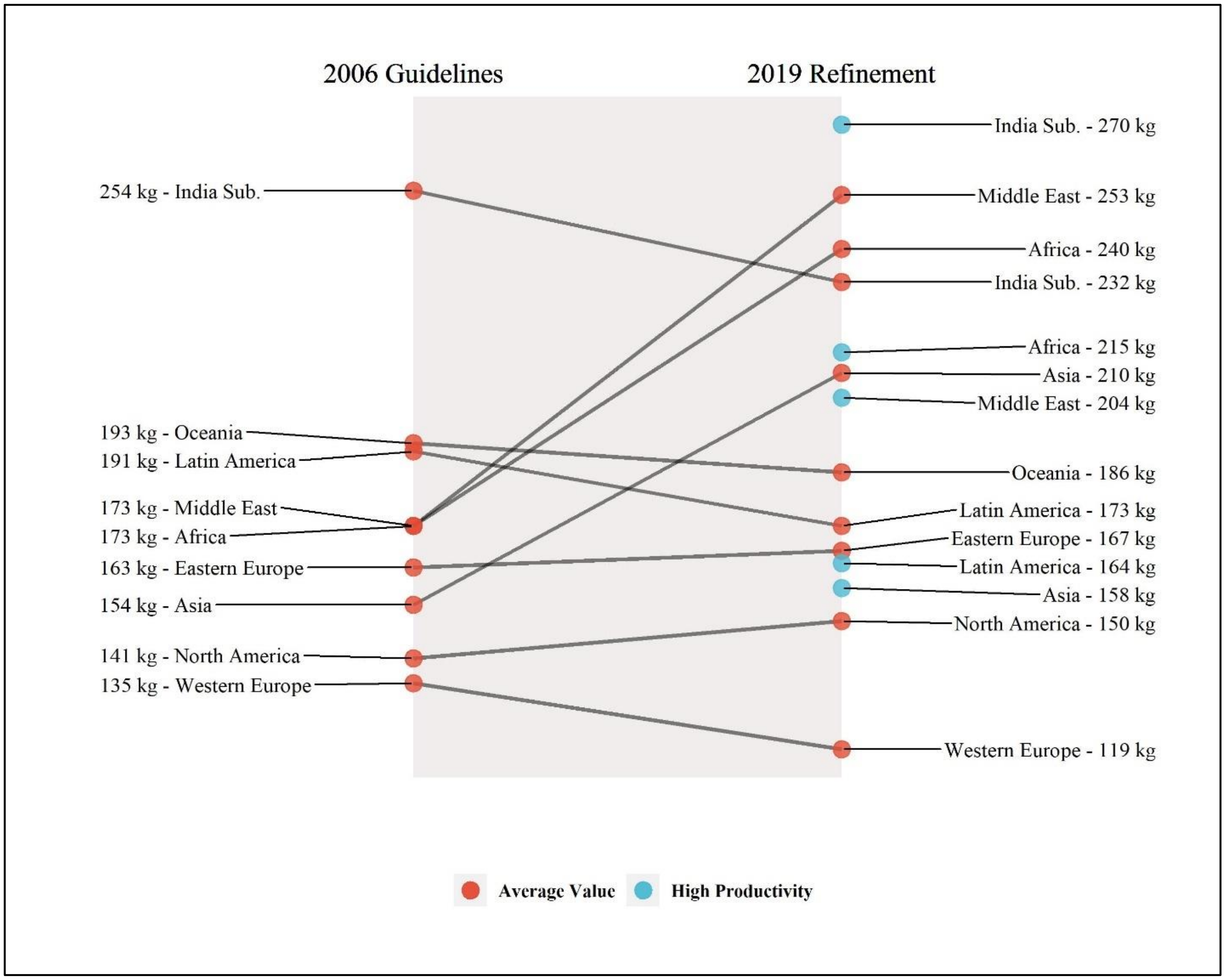
IPCC Regional Default Values: Dairy Cattle Implied Emission Factors (CH_4 head^{-1}year^{-1})



Note: Data used in this figure was collected from Table 10.A.2 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 5

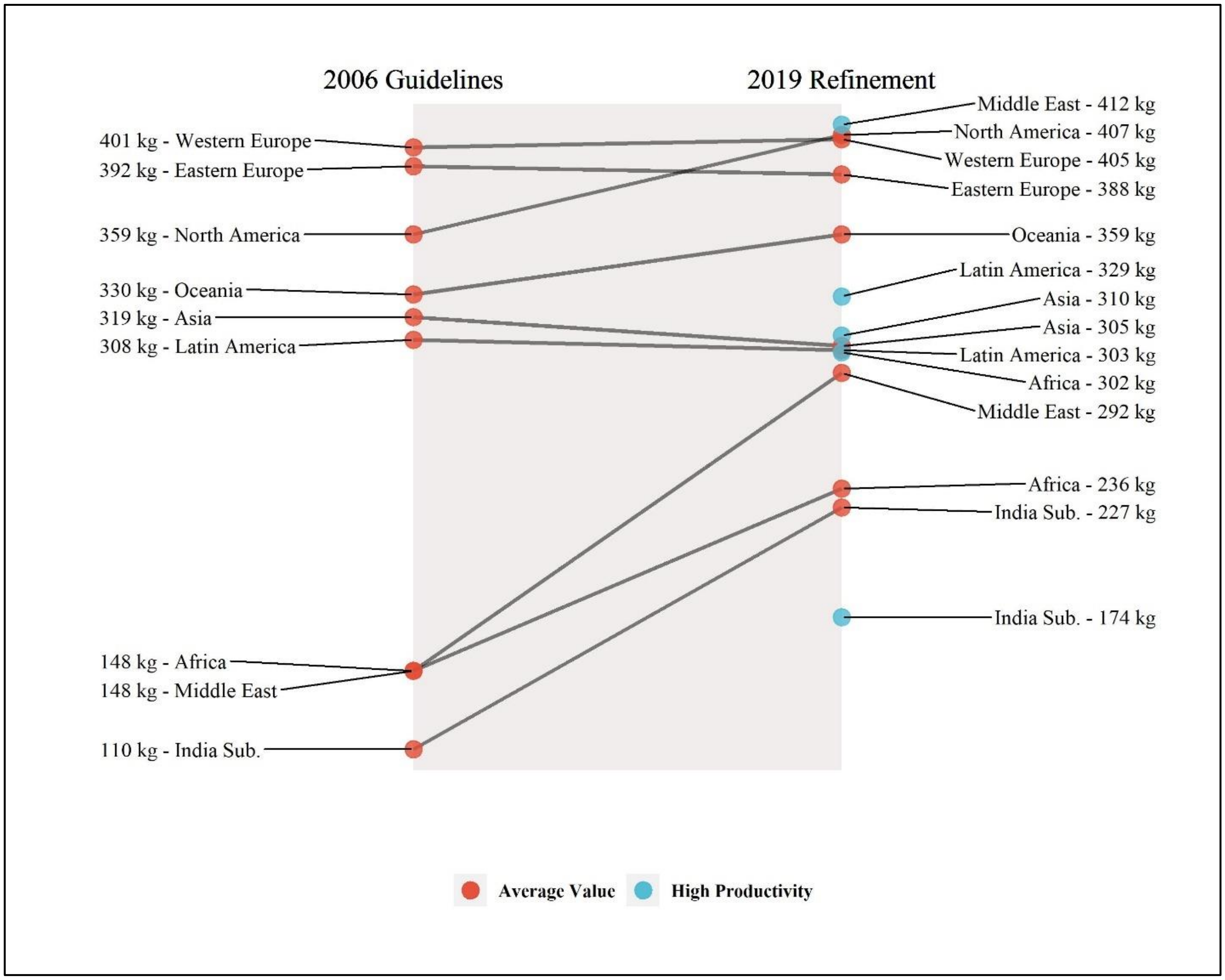
IPCC Regional Default Values: Non-Dairy Emission Intensity Estimates (CH_4 kg t Weight^{-1})



Note: Data used in this figure was collected from Table 10.A.2 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 6

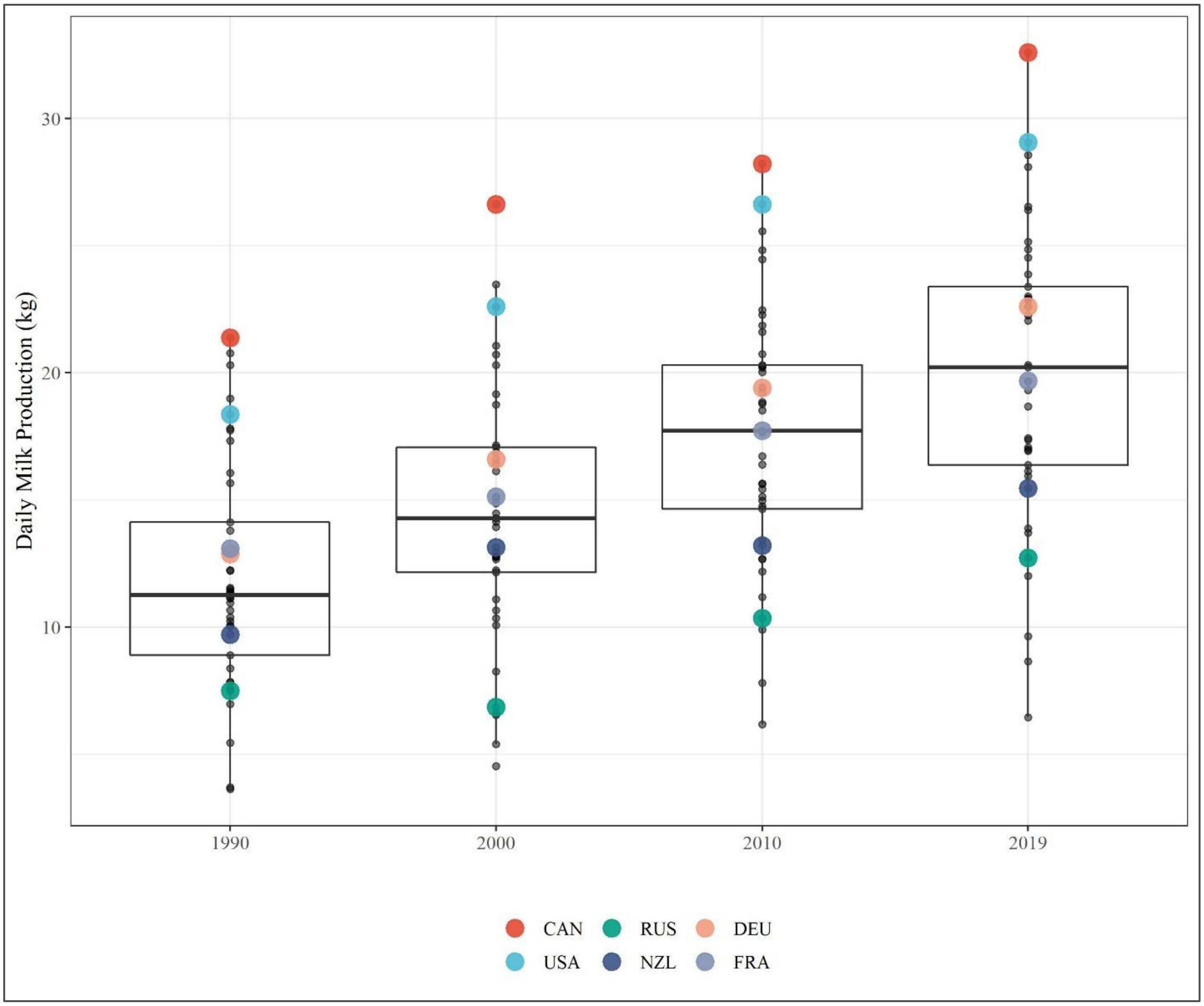
IPCC Regional Default Values: Non-Dairy Cattle Weight (kg Weight)



Note: Data used in this figure was collected from Table 10.A.2 from Volume 4 of the 2006 Guidelines and 2019 Refinement (Dong et al., 2006; Gavrilova et al., 2019).

Figure 7

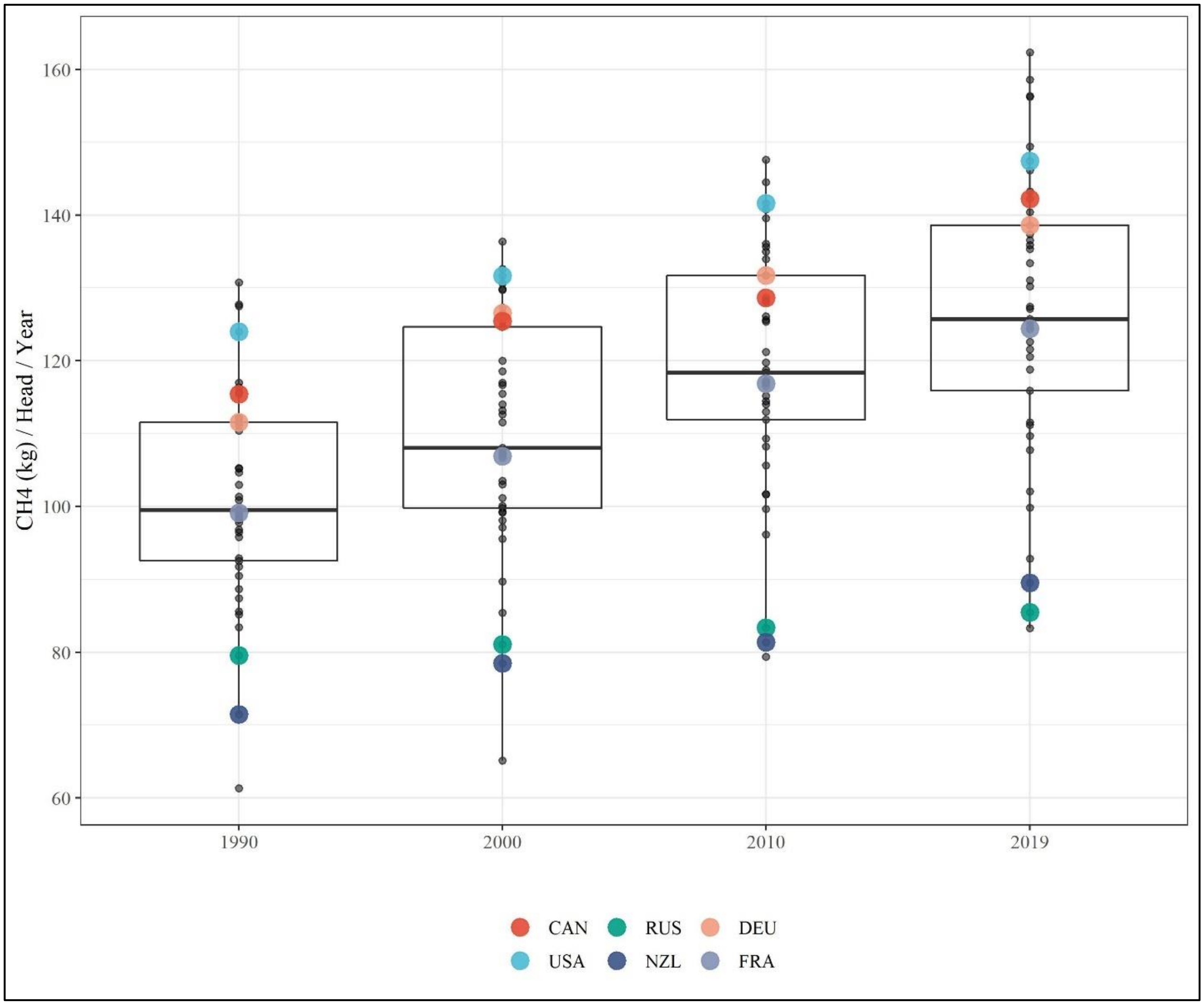
Dairy Cattle Daily Milk Production: 1990-2019



Note: Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 8

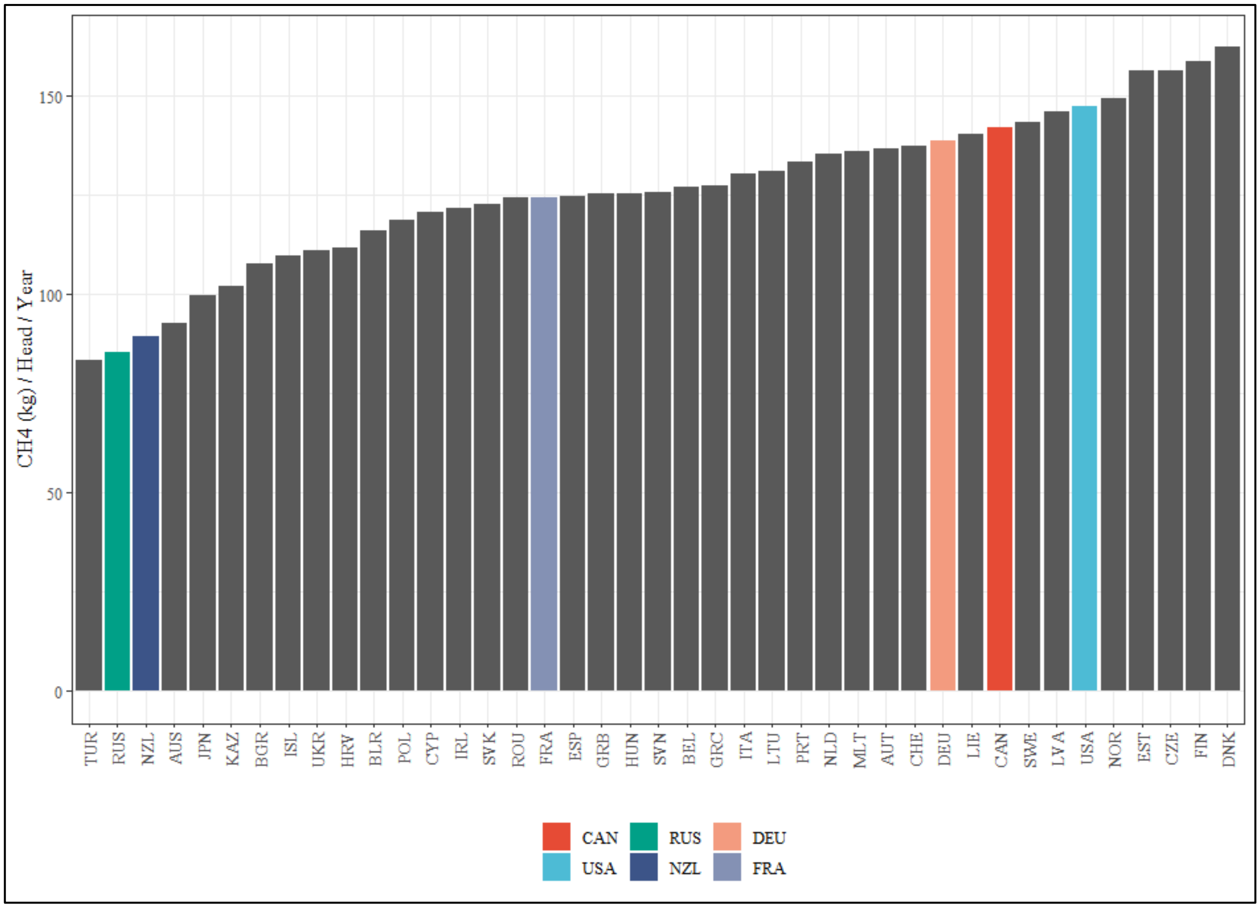
Dairy Cattle Implied Emission Factors: 1990-2019



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 9

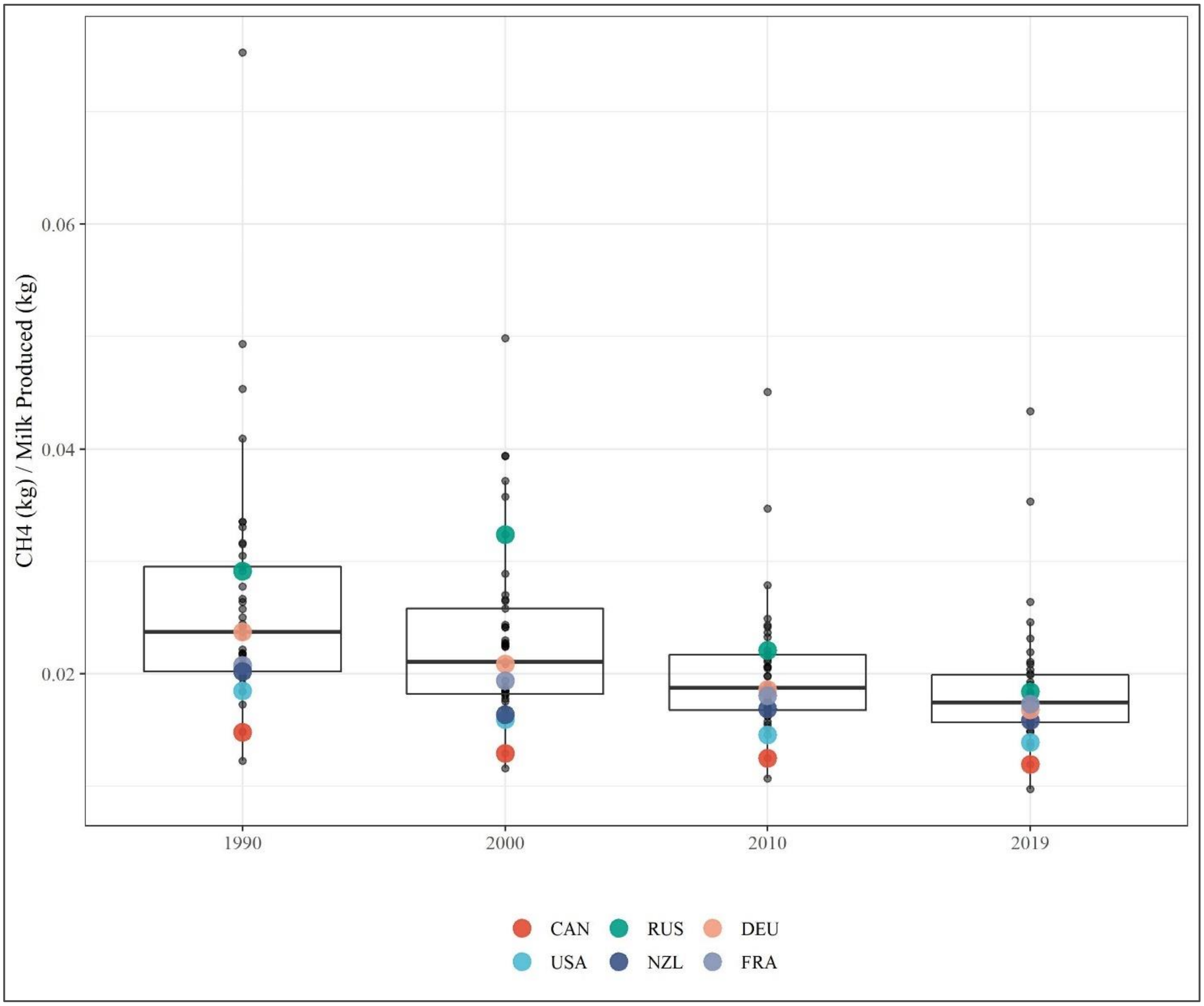
2019: Dairy Cattle Implied Emission Factor Ranking



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 10

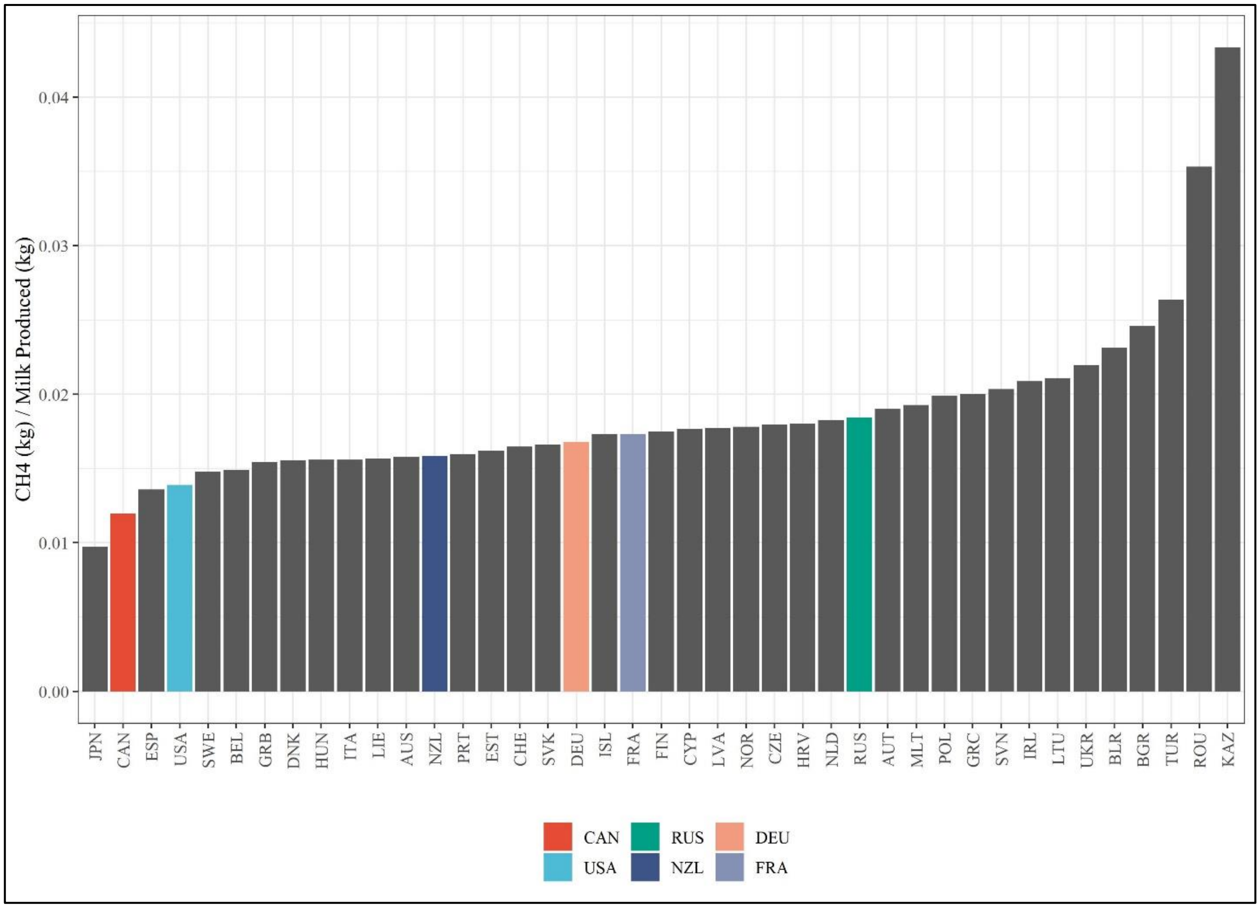
Dairy Cattle Estimated Emission Intensity: 1990-2019



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 11

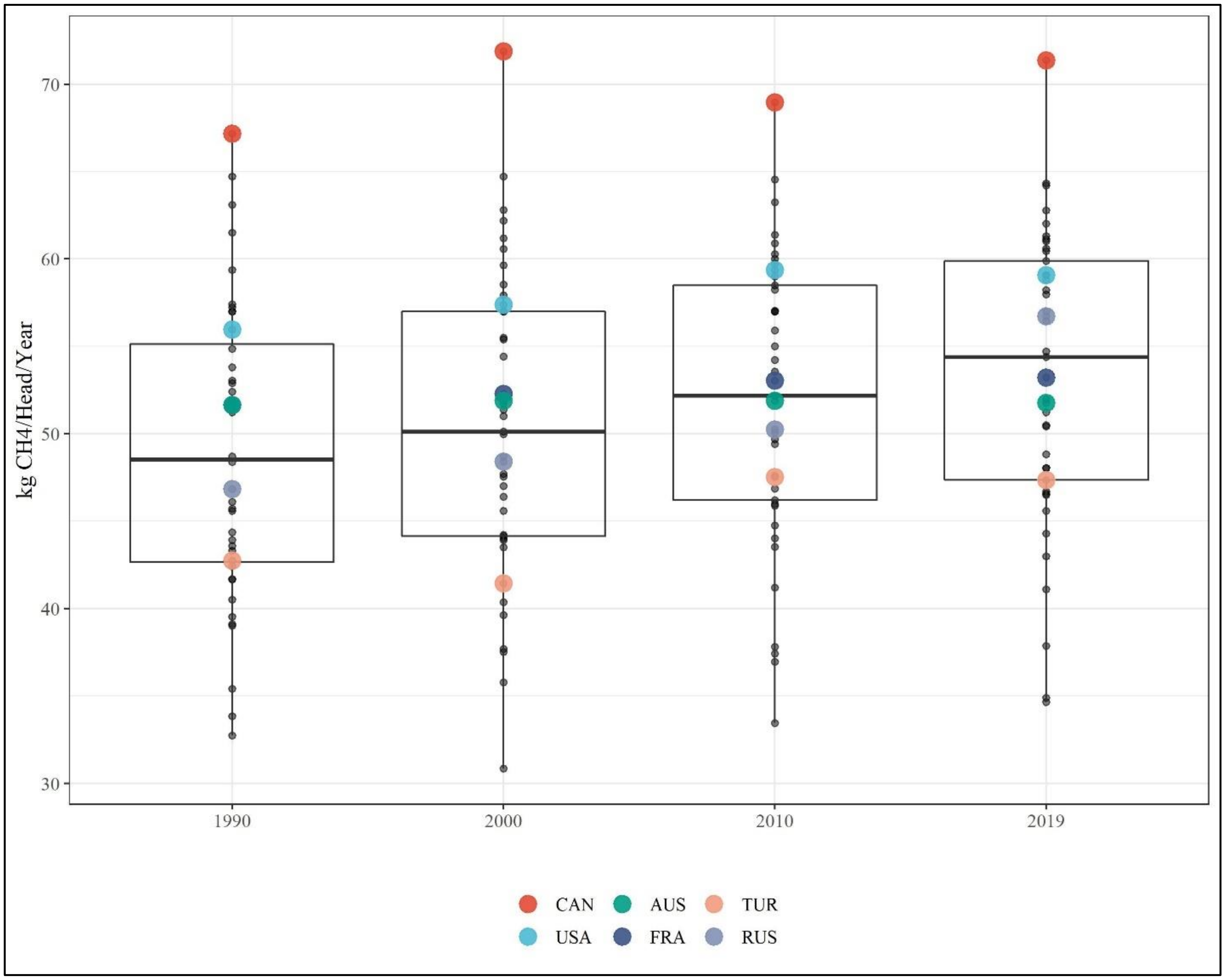
2019: Dairy Cattle Estimated Emission Intensity Ranking



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 12

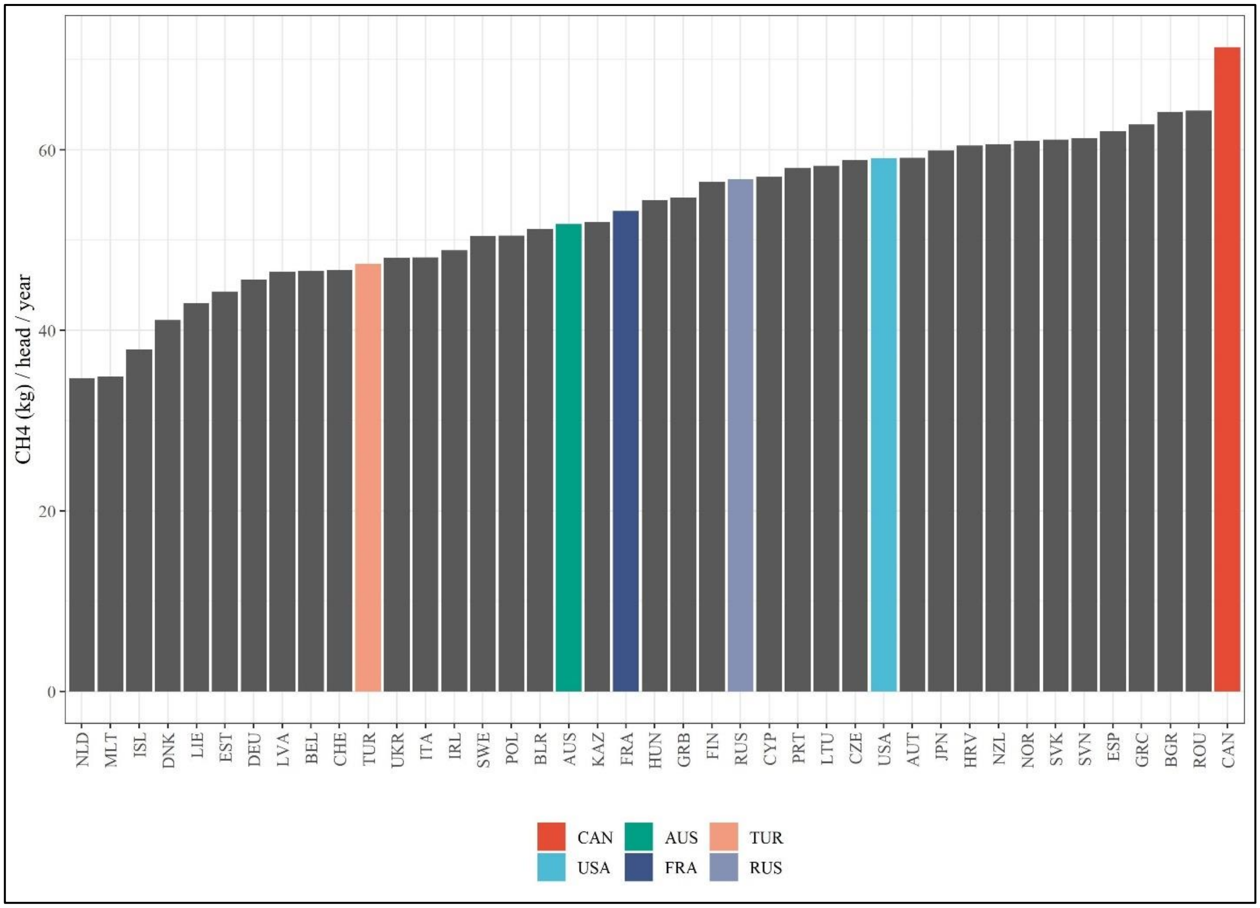
Non-Dairy Cattle Implied Emission Factors: 1990-2019



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 13

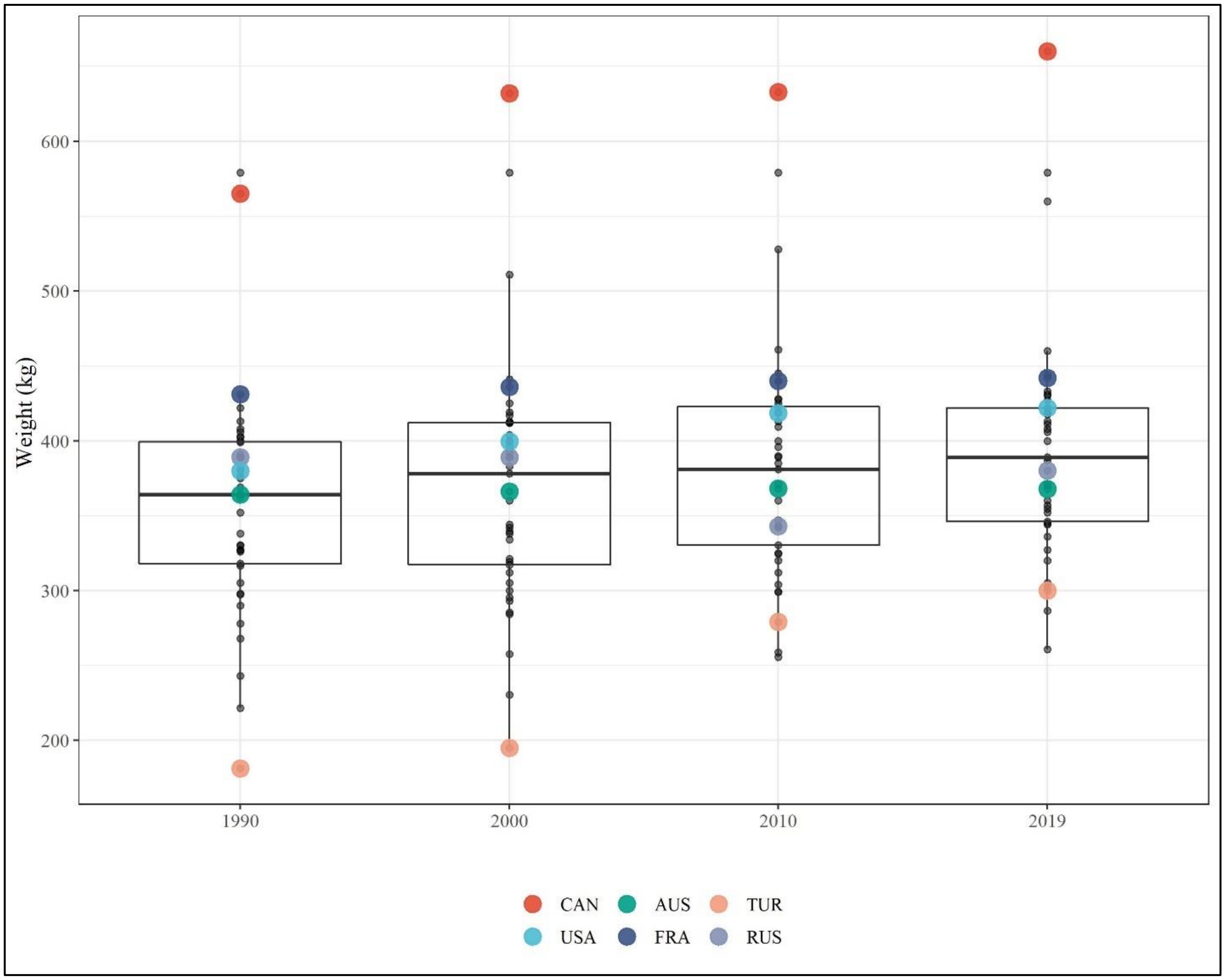
2019: Non-Dairy Cattle Implied Emission Factor Ranking



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 14

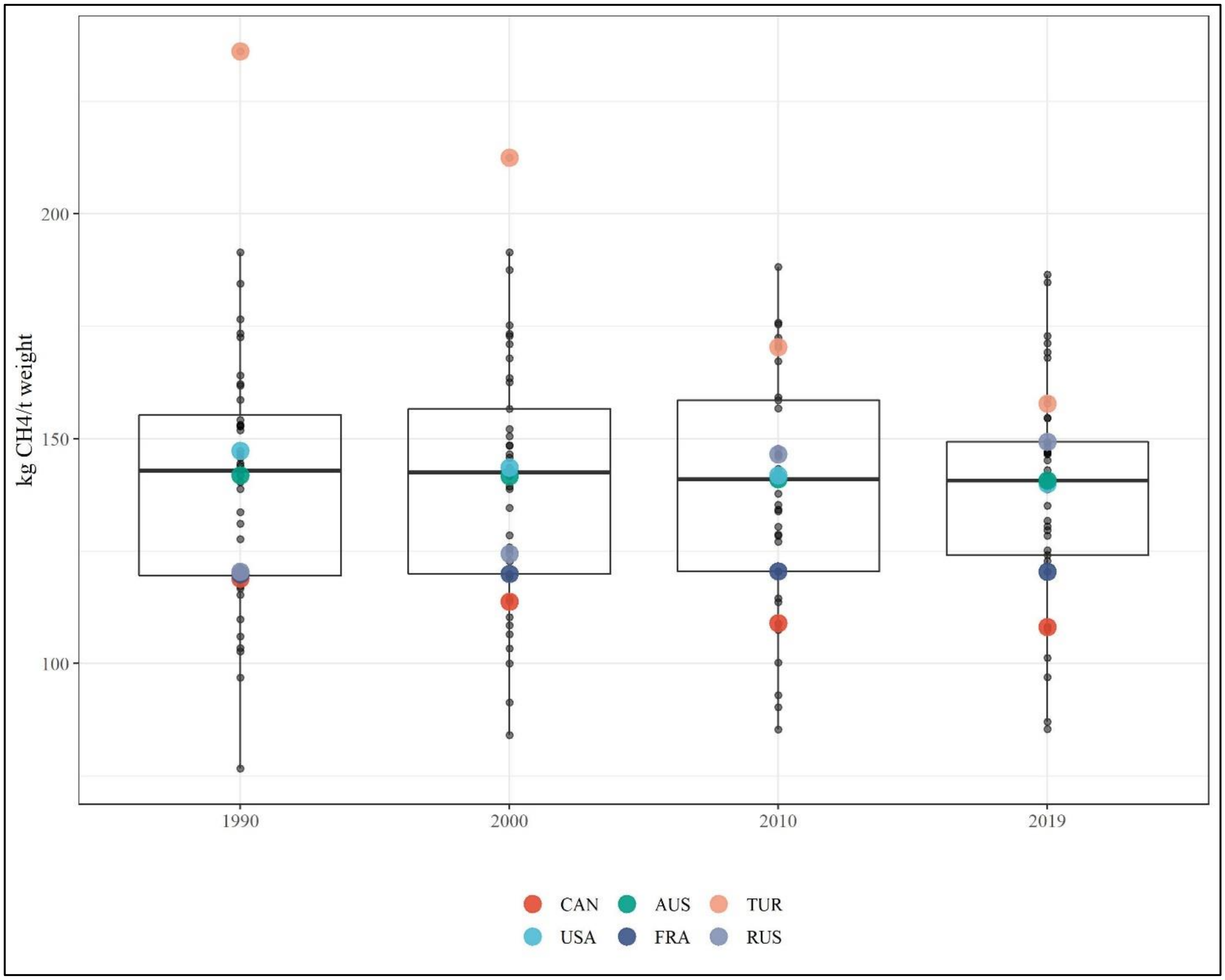
Non-Dairy Cattle Weight: 1990-2019



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 15

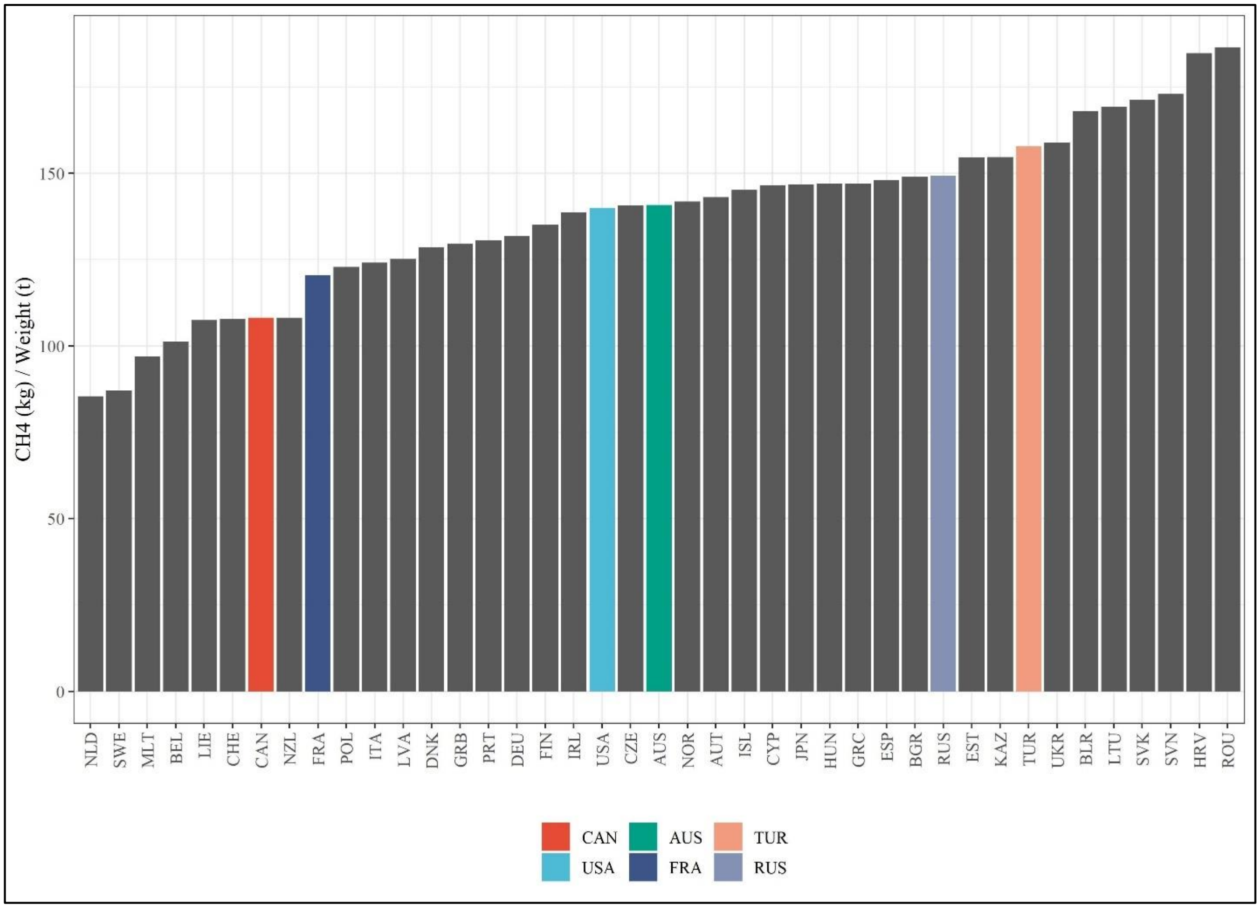
Non-Dairy Cattle Estimated Emission Intensity: 1990-2019



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

Figure 16

2019: Non-Dairy Cattle Estimated Emission Intensity Ranking



Note. Data was Collected from CRF Tables 3.As1 and 3.As2, see Table 1

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