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Implementing IPCC 2019 Guidelines into a National Inventory: Impacts of Key Changes in Austrian Cattle and Pig Farming

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Abstract: This study examined enteric and excreta emissions from cattle and pigs with a focus on effects of changed feeding practices. We assessed the impact of a revision of the Austrian Greenhouse Gas and Air Pollutant Inventory (national method, NM), i.e., the implementation of the Tier2-method of the IPCC-2019 guidelines, to a more dynamic integration of past and present feeding practices. Cattle—in particular, dairy cows—had the highest contribution to enteric CH_4 emissions and to nitrogen (N_{ex}) and volatile-solid (VS_{ex}) excretion, independent of the assessment method (NM or IPCC-2019). These emissions as well as excreta quantities are directly associated with feeding. The most relevant changes from implementing IPCC-2019 were (i) reduced enteric CH_4 over the entire time series and (ii) increased N_{ex} and VS_{ex}, especially for the period from 1990 to 2005. Additionally, uncertainties in the emissions and excreta were analyzed and related to the quantities of protein consumed. From 1990 to 2020, favorable trends per unit of protein were shown due to increased performance and concomitantly reduced animal numbers. The changes were especially pronounced for CH_4, N_{ex}, and VS_{ex} from dairy cows (−40% to −46%) but also substantial for other cattle (−26% to −31%), breeding pigs (−12% to −28%), and partially growing-fattening pigs (−3% to −20%). Future mitigation potential may result from reduced dietary crude-protein content, especially in pigs, and the use of feed additives. Feed additives for ruminants with enteric CH_4-mitigating effects showed a particularly high reduction potential for the total amount of greenhouse gases from the livestock sector.

Keywords: GHG; greenhouse gas; livestock; mitigation

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1. Introduction

Climate-change impacts and the reduction of greenhouse-gas (GHG) emissions are considered among the greatest challenges for anthropogenic and natural biological systems [1]. In the context of GHG emissions and other environmental impacts such as air-pollutant emissions and acidification due to ammonia, livestock, and particularly ruminants, play an important role [2,3]. Although large proportions of GHG emissions arise from other sources in industrialized countries such as those in Western Europe, agriculture is still among the five sectors with the highest emissions [4,5]. Global livestock production is a major contributor to anthropogenic methane (CH_4) emissions, with 32% of CH_4 arising from livestock production [6]. To tackle this issue, UNEP [6] recommends the mitigation of one-sixth to one-seventh of the CH_4 emissions from livestock production until 2030. Moreover, agriculture is the greatest emitter of nitrous oxide (N_2O), with 60% of global N_2O, and ammonia (NH_3) [7]. The latter indirectly causes climate-relevant N_2O emissions [3,8].

National Inventory Reports (NIRs; on GHG emissions) and Informative Inventory Reports (IIRs; on air-pollutant emissions) are generated every year to evaluate the progress of the mitigation measures for emissions of GHGs, NH_3, NO_X, and non-methane volatile organic compounds (NMVOCs). The calculation methods follow either international guidelines or nationally established methods. The default calculation methods (Tier1 for non-key sources and Tier2 for key livestock categories, depending on the country) ensure transparent reporting and comparability between different countries' NIRs and IIRs [9–11]. The latest and most comprehensive calculation procedures are the refined IPCC-2019 guidelines [11], which describe the calculation of NIRs' Tier1 and Tier2 estimates. It is essential that NIRs are representative of the specific annual conditions. This requires regular revisions of the database and methodological updates of calculations incorporating changes in the management of livestock-production systems. Revisions of inventories are essential, on the one hand, to improve accuracy and concomitantly decrease uncertainties, and on the other hand, to better reflect emission mitigation by using detailed and dynamic emission models [10]. Recent revisions of the Austrian Air Pollutant Inventory focused on manure and fertilizer management [10]. In the current study, we focus on cattle and pigs, which are key species in Western European countries such as Austria and Germany [9,10]. In the last two decades, the feeding management for these two species has changed substantially in Austria; however, many data in the NIR and the IIR remained static for most livestock categories. Variation in performance traits was previously not considered for feeding parameters, with the exception of milk-yield-based feeding parameters for dairy and suckler cows. Implementation of the IPCC-2019 guidelines in NIRs is still rare [12]. In this respect, our novel application may provide benefits for other national inventories and studies, including life-cycle analysis. There is a lack of publications on the effects of an implementation of the IPCC-2019 guidelines on national GHG emissions from agriculture and livestock. One recent paper discussed the guidelines' changes for manure-related CH_4 emissions in Canada but failed to address feed-related issues [13].

The aims of this study comprise an update of the basis for calculations regarding livestock feeding to properly estimate annual GHGs and air pollutants emitted by livestock. Therefore, a calculation of current mitigation potentials, a comparison of the results of updated calculations with previous estimates, and the identification of future mitigation potentials, such as the use of feed additives, was performed. Regarding improvement potentials, we focused on the updated modeling of enteric CH_4 emissions; N_{ex} as a basis for NH_3, N_2O, and NO_X; and the VS_{ex} for CH_4 emissions from manure management. Our research questions are as follows: (1) What are the consequences of switching from the previous national method (NM) to the IPCC-2019 Tier2 for both cattle and pigs? (2) What are the reduction potentials of the selected mitigation measures? More specifically, (2a) what is the reduction potential of improved efficiency (emissions and excretion per kg protein in milk, beef, and pork) from 1990 to 2020? (2b) What are the reduction potentials of reduced dietary crude protein (CP) for dairy cows, fattening bulls, and fattening pigs? (2c) What are the reduction potentials of supplementing cattle and pig diets with feed additives?

2. Materials and Methods

The feeding-related aspects of previous calculations according to the NM and the updated calculations according to the IPCC-2019 guidelines [11] are described herein.

2.1. Materials

Animal numbers were derived from official statistics [14] and were used similarly for both the calculation with the previous NM and the IPCC-2019 method. For IPCC-2019, cattle were divided into 25 categories (Supplementary Material Figure S1) and pigs were re-categorized into breeding pigs, i.e., sows, including piglets until weaning and boars, weaned piglets, and fattening pigs. Data for separating the animal categories were obtained from official statistics [14] and expert assessment [15]. For these categories, we calculated the emissions and averaged on a pro-rata basis for the respective summarized categories.

Part of the livestock data was modeled with underlying parameters, which were collected from official statistics and literature (described in Table S1 in the Supplementary Material, see e.g., Refs. [16–32], and references herein) to calculate category-specific annual averages for each parameter based on record-date values (see Section 2.2 Methods, Figures 1 and 2).

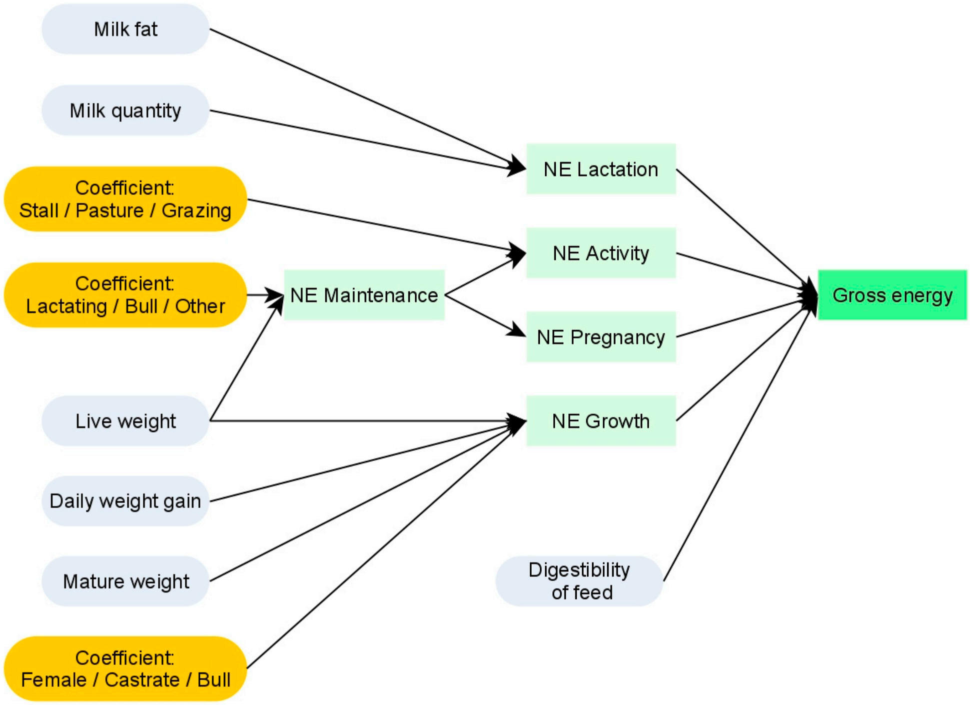

Figure 1. Process diagram for the calculation of cattle's feed gross energy demand, based on the updated IPCC-2019 method [11]. National average data per livestock category (in blue) and IPCC-2019 coefficients (in yellow) are used to calculate net and gross energy demand (in green).

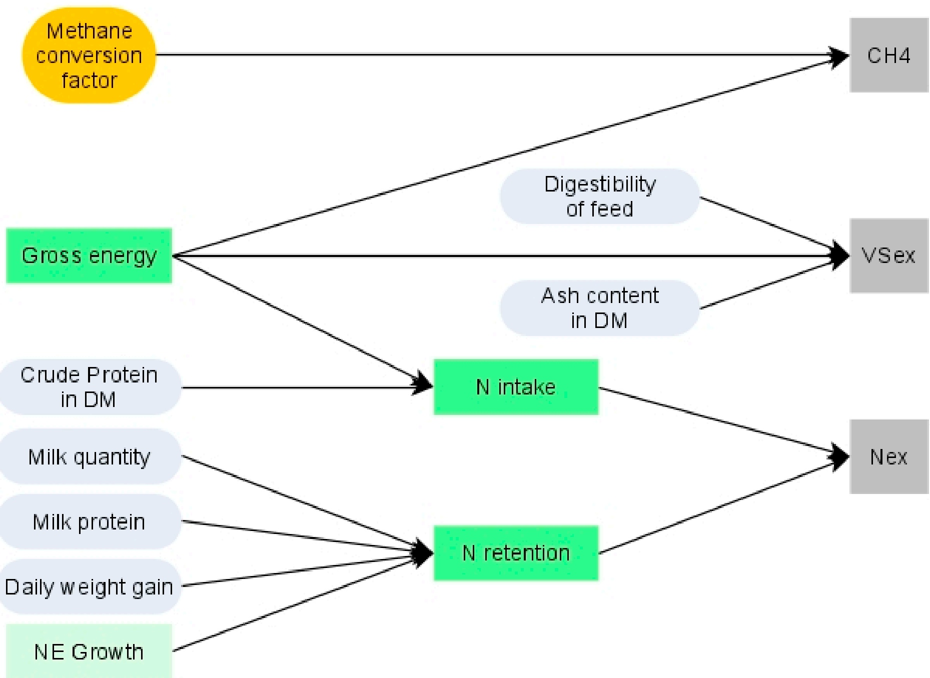

Figure 2. Process diagram for the calculation of cattle's enteric CH_4 emissions, N_{ex}, and VS_{ex} according to the updated IPCC-2019 method [11]. National average data per livestock category (in blue), the IPCC-2019 conversion factor (in yellow) and the gross energy amount, net energy for growth, and N intake and retention (in green) are used to assess emissions (CH_4) and excretion (VS_{ex}, N_{ex}) (in grey).

The calculation method is presented in detail for dairy cows and fattening pigs, which constitute the most important categories of all livestock species in terms of emissions; further model input data can be found in the Supplementary Material. Finally, the results for subdivided categories were merged according to the categories used in the NM (cattle < 1 year, breeding cattle 1–2 years, fattening cattle 1–2 years, fattening pigs, breeding pigs, etc.), as these categories are used in the subsequent post-excretion calculation for the manure-management system [10].

2.2. Methods

2.2.1. The IPCC-2019 Calculation Procedure

The following flowcharts give an overview of the updated IPCC-2019 calculation with cattle as an example: Figure 1 shows the calculation of feed gross energy demand and Figure 2 visualizes the calculation of enteric CH_4, VS_{ex}, and N_{ex}.

The data sources used to calculate the parameters and functions in Figures 1 and 2 for the data series from 1990 to 2020 are shown in Table S1 in the Supplementary Material.

In order to better illustrate the IPCC-2019 method, its input data are described below for the examples of the animal categories of dairy cows (Section 2.2.2) and fattening pigs (Section 2.2.3), which are highly relevant for Austrian livestock emissions. Based on this, the derived intermediate results for cattle and pigs are shown in Section 2.2.4.

2.2.2. Input Parameters for the Assessment of Dairy Cows According to IPCC-2019

Body mass: The development of the average body mass ("weight" according to the IPCC-2019 terminology, e.g., in Figure 1) is the basis for the calculation of the maintenance net energy. The annual body mass of the average cow was derived from Austrian studies based on the breeds Simmental, Brown Swiss, and Holstein Friesian, and 10 other less relevant breeds [33–36]. The average body mass increased by 6% between 1990 and 2020, from 676 kg to 719 kg.

Housing, pasture, and alpine pasture: Keeping cows indoors, grazing on pasture, or grazing on extensive alpine pastures affects their net energy requirement for activity. Thus, the average dairy cow was characterized according to the proportion of dairy cows in each system as well as the proportion of time spent in each system per year. Representative proportions of cows' grazing times weighted by the average numbers of grazing hours per day and the number of grazing days per year were available for the years 2005 [37] and 2017 [38]. For 1990, an expert estimate [39] was used for the proportion of dairy cows on pasture. Data for years between surveys or expert estimates (1990, 2005, 2017) were interpolated. The number of days grazing on alpine pastures was taken from a study [40] and from the official Austrian report on agriculture [41]. The remaining annual budget was allocated to the different housing systems without affecting energy demands. The trends regarding housing systems can be found in Supplementary Material Figure S2.

Milk yield, fat, and protein content of cow milk: Cows' annual milk yield and milk-fat content were used to calculate the net energy requirement for lactation. The protein content of the milk was used for the calculation of N retention. Data on milk yield were based on the annual milk yield (kg) per dairy cow from 1990 to 2020 and obtained from official Austrian statistics [42]. Data on the average milk fat and protein content for the years 1991 to 2020 were also derived from official numbers [43]. Due to missing data for the year 1990, the value of 1991 was adopted. The data on the annual average milk yield, fat content, and protein content for dairy cows are visualized in Figure S3 in the Supplementary Material.

Gestation: The proportion of gestating animals per year was used to calculate the net energy requirement for gestation. The proportion of gestating cows was calculated by dividing 365 days by the calving interval (calculated per breed and weighted for breeds), based on the data from the annual Austrian breeding reports [44,45]. The derived values showed a rather constant gestation energy demand since 1990.

Energy demands, crude protein intake, ash intake, and digestibility: The calculation of N intake was based on the proportion of the average crude protein (CP) content of dry matter (DM), and the calculation of VS_{ex} further required the proportion of ash in feed DM [11]. The digestibility of the average diets was included in the calculation of the gross energy. Dairy cows' annual average CP content in feed DM was calculated using a regression equation for the years 2016 to 2019 based on [33], depending on the average Austrian annual milk yield. Values for 1990 to 2002 were based on the mean values from two studies: One assessed the diets of 30 dairy farms in Austria [46], and one surveyed diets on 40 Austrian dairy farms [47]. The average percentage of CP in DM in these two studies was 13.7%. The values between 2002 and 2016 were interpolated in relation to the average national daily milk quantity. CP content in DM has increased over the years (Figure S4 in the Supplementary Material). The proportion of ash in feed DM was obtained from the same studies for 1990 to 2002 [46,47]. For 2016, the proportion of ash in feed DM was derived from [33]. For the period in between, data were interpolated. The average digestibility of dairy cows' diets was estimated based on model calculations on feed intake (proportions of roughage and concentrates), adjusted to the level of the annual milk yield [47], and expressed as a percentage.

Methane conversion factor: The methane-conversion factor (Y_M) was derived from [11]: For 2020, a Y_M of 6.3 for medium-producing cows was assumed based on the annual milk yield of 7286 kg and diet digestibility of 71.7% for Austrian dairy cows. For 1990, a methane-conversion factor for low-producing cows of 6.5 was assumed based on the annual milk yield of 3791 kg of Austrian dairy cows. The methane-conversion factor was chosen primarily on the basis of the milk yield, as these are the most reliable data, but feed digestibility was also considered. Thus, the methane-conversion factor in the updated version is lower than in the previous NM, in which a Y_M of 6.5 was assumed throughout the time series from 1990 to 2019.

2.2.3. Input Parameters for the Assessment of Fattening Pigs According to IPCC-2019

Body mass, housing systems: The annual average body mass of fattening pigs at slaughter was derived from official Austrian statistics [14]. As almost all fattening pigs are kept in fully confined houses, energy demand did not have to be adjusted to free-range conditions.

Fattening-pigs' performance was calculated based on annual data from the Association of Austrian Pig Farmers (annual reports, e.g., [48]) and annual official data on livestock numbers and body mass at slaughter, e.g., [49], for the year 2020. Data on body mass were re-allocated to commonly used categories, for instance "fattening pigs above 32 kg to the end of fattening" or "piglets from 8 to 32 kg".

Energy demands and nutrient intake: The annual feed-energy requirement of fattening pigs, which defines the feed intake, was calculated according to [50]. Protein content was based on average diets and the feed components' typical protein contents. If available for Austria, representative values were used [51]; otherwise, default values [52] were used instead. Furthermore, on many farms, protein content of feed and the number of pigs kept per hectare of land are oriented towards the Austrian national limits regarding N-fertilization [53]. These limits changed over the time series and were partially reflected in the calculation by a trend towards reduced dietary crude-protein intake.

Methane-conversion factor: With a combination of updated annual gross energy intake of pigs and methane-conversion factors (MCFs) from [54] (4.6 kJ MJ^{-1} for fattening pigs), enteric fermentation could be calculated dynamically using the IPCC Tier2 method over the time series.

2.2.4. Gross Energy Requirement, Digestibility, and Crude-Protein and Ash Contents for Cattle and Pig Categories

Using the IPCC-2019 method [11] and representative input data for all cattle and pig categories (see Sections 2.2.2 and 2.2.3, respectively), the values in Table 1 were calculated for daily gross energy requirements, digestibility, and dietary crude-protein and ash contents.

Table 1. Daily gross energy requirement, diet digestibility, and dietary crude-protein and ash contents for different cattle and pig categories.

	Year	Dairy Cows	Suckler Cows	Breeding Heifers 1–2 Years	Fattening Heifers, Bulls, and Oxen [1] 1–2 yr	Cattle < 1 Year	Cattle > 2 Year	Breeding Sows	Fattening Pigs	Piglets
GE [2] intake (MJ/day)	1990	253.8	231.8	175.4	178.1	75.9	163.4	43.7	10.9	1.88
	2005	290.6	247.6	171.2	175.5	83.7	158.6	45.1	10.8	1.88
	2020	315.3	252.8	176.1	177.1	82.3	167.1	51.2	11.1	1.84
MCF [3] Y_M (%)	1990	6.50	6.50	6.30	6.30	4.34	6.30	2.04	1.00	0.33
	2005	6.40	6.50	6.30	6.30	4.49	6.30	2.10	1.03	0.36
	2020	6.30	6.50	6.30	6.30	3.84	6.30	2.38	1.07	0.34
Digestibility (%)	1990	66.5	65.3	65.1	73.5	83.5	66.7	75.2	79.9	78.4
	2005	69.4	66.0	65.1	73.0	80.8	65.7	75.3	80.1	78.4
	2020	71.6	66.0	65.1	72.1	82.8	66.0	76.3	82.0	80.8
Ash content (kg/kg)	1990	0.083	0.110	0.102	0.069	0.081	0.090	0.066	0.047	0.059
	2005	0.082	0.110	0.102	0.072	0.085	0.092	0.057	0.047	0.059
	2020	0.081	0.110	0.102	0.079	0.083	0.088	0.058	0.048	0.059
Crude-protein content (kg/kg)	1990	0.137	0.119	0.118	0.121	0.171	0.119	0.174	0.181	0.183
	2005	0.139	0.120	0.118	0.120	0.169	0.119	0.165	0.175	0.179
	2020	0.146	0.120	0.118	0.119	0.175	0.119	0.149	0.161	0.171

[1] Including steers; [2] GE = gross energy; [3] MCF = methane conversion factor.

The gross energy requirement is a decisive input parameter for the calculation of CH_4 emissions, N_{ex}, and VS_{ex}. It is composed of different net energy requirements (Figure 1). For example, in dairy cows, the overall gross energy requirements increased by 24% after 1990 due to higher net energy for maintenance (+5%), lactation (+97%), and gestation (+5%). The energy requirement for activity decreased after 1990 (−53%), as fewer dairy cows were kept in pasture, leading to a low impact on gross energy requirement. The dietary gross energy requirement for fattening pigs was relatively constant, showing just a slight increase of 1% between 1990 and 2020 (Figure 3; Table 1).

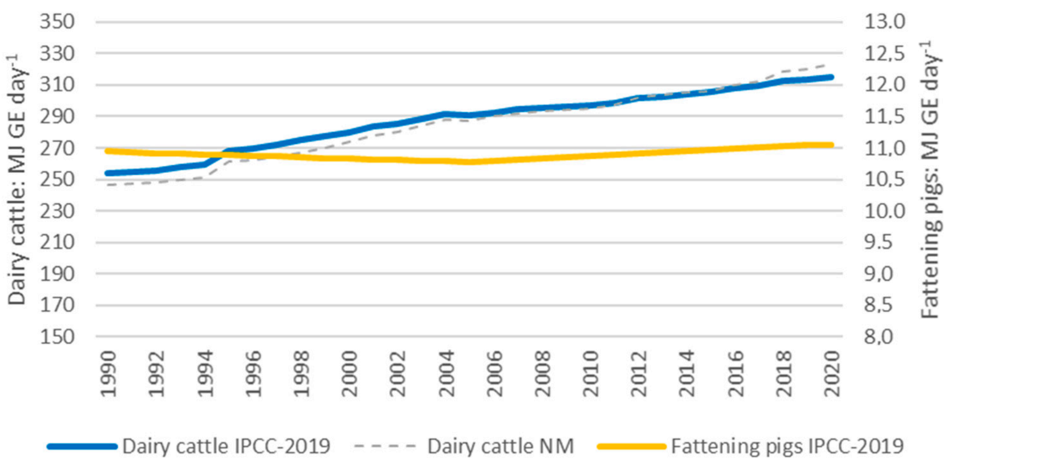

Figure 3. Calculated gross energy requirements of dairy cows (y1-axis) and fattening pigs (y2-axis) between 1990 and 2020. For a comparison, the grey dashed line shows the calculated gross energy requirement of dairy cows according to the previous national method (NM). In fattening pigs, gross energy requirements were not calculated in the previous NM.

2.2.5. For Comparison: The Previous National Method

Information on feeding parameters in the previous NM can be found mainly in the previous NIRs [4], with the most important data described in [55–59]. Regarding feed intake, crude protein, ash, and energy requirements, previous calculations were based on calculation of theoretical demands [60] for cattle. For pigs, a mix of measured values for VS_{ex} [61], Tier1 values according to IPCC-2019 [62,63], and nationally calculated values for N_{ex} [64] was used.

2.2.6. Calculation of Emissions Related to Crude-Protein Yields over the Time Series, Lower CP Intake, and the Use of Feed Additives

To analyze the increasing efficiency of livestock over the time series, both N_{ex} per head and year and the N_{ex} per kg of CP in milk, beef, and pork were assessed with the updated method. The same applied to VS_{ex} and enteric CH_4 emissions. CP yielded from dairy cows was calculated from average CP contents of the milk delivered to dairies according to [43], multiplied by the milk quantity produced per cow and year. For the calculation of CP in beef from cull cows, their lifetime was taken into consideration. For growing and fattening cattle and pigs, the CP amounts in the animals were calculated based on the CP retained in the carcass multiplied by the number of animals.

To estimate the reduction potentials of reduced CP intake, a 5% reduction in CP intake was assumed for dairy cows, fattening bulls, and fattening pigs. The assessment of reduction potential of the use of feed additives considered a theoretical reduction of 5%, 10%, and 20% of enteric CH_4 for Austrian cattle. The 5% reduction potential was based on experimental data, which can be realized by phytogenic feed additives [65–67]. These phytogenic feed additives are—with a low application rate—already used in the livestock sector in Austria and other European countries. The 20% was derived from data on the synthetic additive 3-nitrooxypropanol (3-NOP) [68] and the 10% was a mixture of phytogenic and synthetic feed additives that can be found throughout the whole market.

3. Results

3.1. The Effects of Changing from the Previous Austrian National Method to IPCC-2019

Overall, both methods resulted in similar quantities of emitted enteric CH_4, N_{ex}, and VS_{ex}. Temporal trends were similar, with the exception of the animal category "Other cattle" (i.e., all cattle except dairy cows; Figures 4–6).

Based on the updated calculations, over the 30-year period, on average, 53% of the total CH_4 of the cattle and pig sector was emitted by dairy cows, 45% by other cattle, and only 2% by breeding and fattening pigs. Enteric methane emissions were lower when calculated with IPCC-2019 than with NM throughout all categories and years, with the exception of dairy cows in 1990 (Figure 4). The most notable drop in enteric methane emissions was seen in the category "Other cattle" across all years.

Uncertainty ranges were calculated for the results derived with the IPCC-2019 method for the years 1990, 2005, and 2020. They showed standard deviations of approximately 10% for dairy cows and other cattle and approximately 20% for breeding and fattening pigs for each of the three years (see Supplementary Material Table S2).

Regarding an average (1990, 2005, and 2020) of cattle's and pigs' N_{ex} calculated with the NM, 37% derived from dairy cows, 43% from other cattle, just 4% from breeding pigs (excluding gilts that are not inseminated), and 16% from fattening pigs. With IPCC-2019, the quantities of N_{ex} were higher in all categories, with the exception of dairy cows in 2020 and breeding sows across all years (Figure 5). For pigs, lower N_{ex} in breeding pigs and higher N_{ex} in fattening pigs was observed when comparing emission quantities from the NM and IPCC-2019. In addition, IPCC-2019 resulted in higher N_{ex} of fattening pigs.

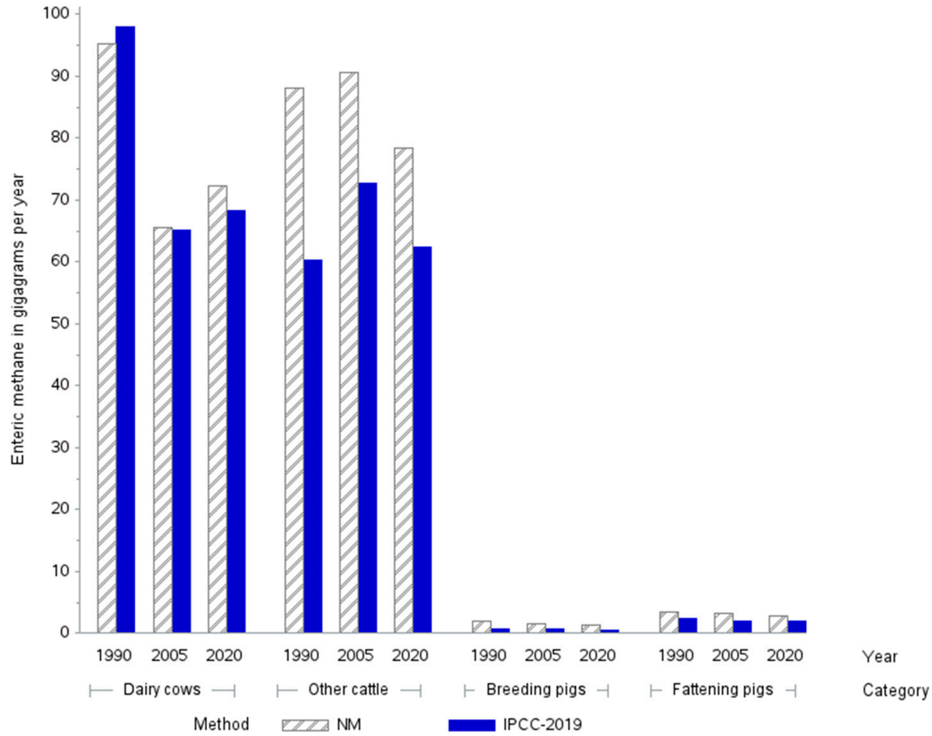

Figure 4. Comparison of enteric CH_4 emissions of different animal categories and years calculated with the (previous) national method (NM) and the IPCC-2019 method.

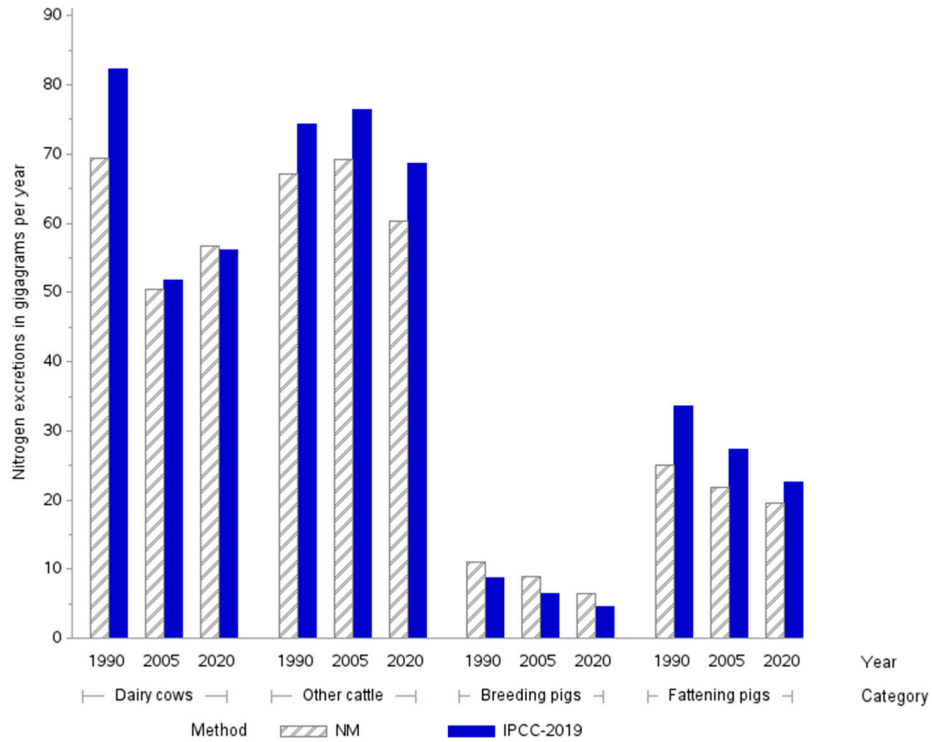

Figure 5. Comparison of nitrogen excretions (N_{ex}) of different animal categories and years calculated with the national method (NM) and the IPCC-2019 method.

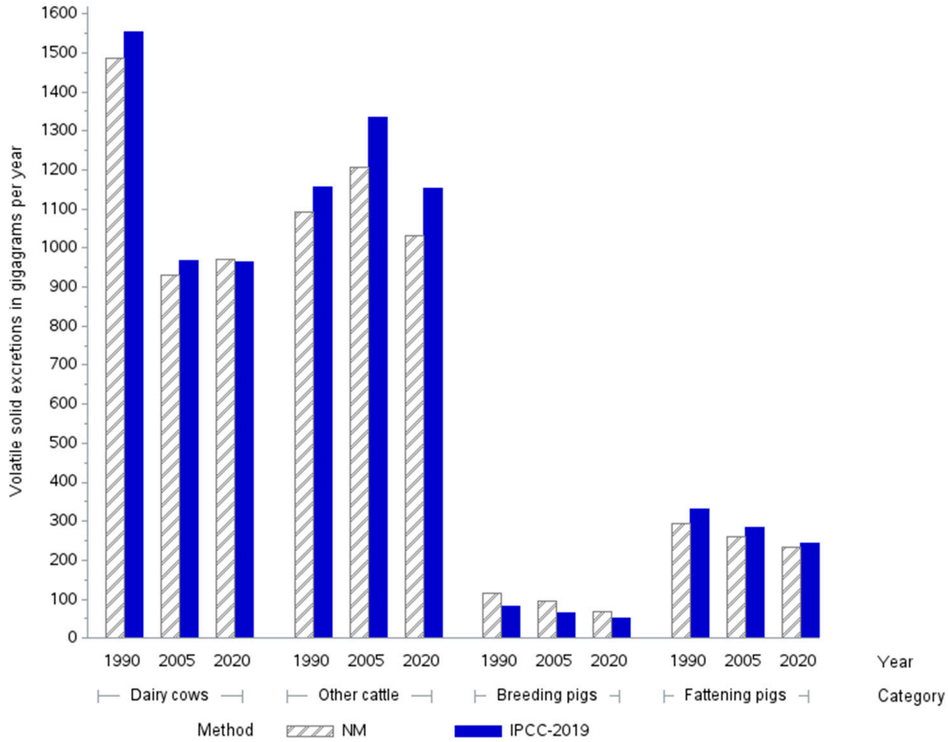

Figure 6. Comparison of volatile-solid excretions (VS_{ex}) of different animal categories and years calculated with the national method (NM) and the IPCC-2019 method.

The margin of uncertainty estimated for the IPCC-2019 method for the years 1990, 2005, and 2020 resulted in standard deviations of approximately 9% for dairy cows and other cattle and approximately 7% for breeding and fattening pigs for each of the three years (see Supplementary Material Table S2).

With the NM, 43% of VS_{ex} from cattle and pigs resulted from dairy cows, 45% from other cattle, 2% from breeding pigs, and 10% from fattening pigs (with gilts that were not inseminated). Calculating VS_{ex} with IPCC-2019 resulted mostly in higher emission quantities, except for the category of "Breeding pigs" (Figure 6).

Uncertainty ranges for VS_{ex}, which were assessed for the IPCC-2019 figures for the years 1990, 2005, and 2020, resulted in standard deviations of approximately 8% for dairy cows and other cattle and approximately 5% for breeding and fattening pigs for each of the three years (see Supplementary Material Table S2).

3.2. Reduction Potential Originating from Increased Animal Efficiency

Comparing the change in emissions per head and year with the change in emissions per kg CP in products (milk, beef, and pork) illustrates developments in the production efficiency of animals (Figure 7; the corresponding values are given in Table S3 in the Supplementary Material). The greatest deviations (measured in percentage change) between emissions per head and year and emissions per kg CP in products are visible for dairy cows and other cattle.

In dairy cows, the annual production of milk and body CP almost doubled from 130.7 kg in 1990 to 260.1 kg in 2020, primarily due to increased milk yield (+127.1 kg CP increase over 30 years) and to a much lesser extent due to higher body mass (+2.3 kg CP). Simultaneously, the performance of dairy cows increased with a concurrent decrease in net energy demand for maintenance per unit of milk produced. Thus, the emissions per kg CP in dairy cows' milk and beef decreased substantially, as shown in Table 1. Similarly, in the category other cattle relative changes in emissions per animal and year increased generally, whereas the emissions per kg CP decreased across the time series. Furthermore, independent of the unit of measurement, all emissions exhibited large fluctuations between

1990 and 2010. In breeding pigs, emissions per head and year increased for enteric CH_4 and VS_{ex} but slightly decreased for N_{ex} due to N-reduction in the animal feed. In contrast, emissions per kg CP decreased across all emission categories as a result of an increase in the produced kg CP per animal (from 14.8 kg in 1990 to 16.7 kg in 2020) due to a higher number of weaned piglets per year. In fattening pigs, only CH_4 increased per animal place and year, whereas N_{ex} and VS_{ex} were almost constant. The production of CP per fattening-pig place grew from 14.8 kg in 1990 to 16.7 kg in 2020 due to a higher body mass at the end of the fattening period as well as increased number of fattening periods per year. Because of this increase, all emissions per kg CP were reduced (Table 1).

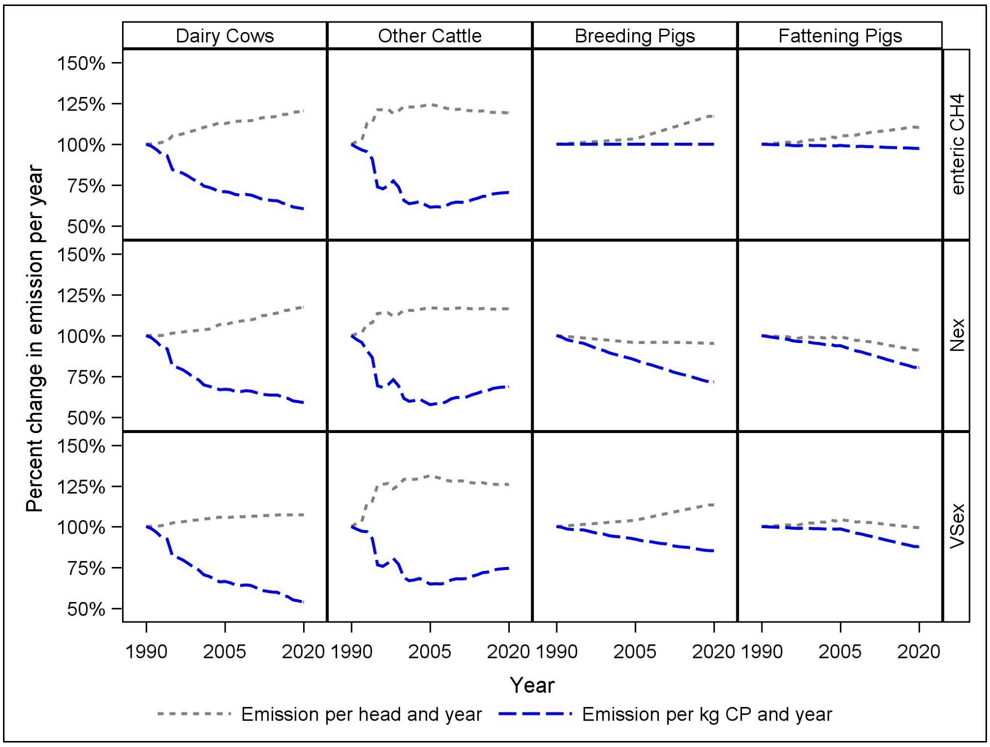

Figure 7. Comparison of relative changes of emissions per head and year and per kg CP of enteric CH_4, N_{ex}, and VS_{ex} across years for different animal categories following IPCC-2019. Emissions from the year 1990 were used as the initial state with 100%.

3.3. Reduction Potential of Reducing Dietary Crude-Protein Content and of Using Feed Additives

The amount of CP in the ration is a determining factor for N_{ex} rates. While the annual average CP content of dairy cows' diets increased by 7% from 1990 to 2020 due to milk-yield increase, it remained constant for other cattle (see Table 1). In contrast, average CP content decreased by 17% for breeding pigs, 12% for fattening pigs, and 7% for weaned piglets. Overall, for pig feed, an average of a 12% CP decrease represents a considerable reduction for NH_3 or N_2O emissions.

Under current conditions, reducing the CP content in dairy cows by 5% from 14.6% to 13.9% would reduce N_{ex} by −6.8% from 106.9 kg to 99.6 kg. In fattening bulls from birth to slaughter, a reduction of CP by 5% in all life phases would result in an average CP content of 13.9% instead of 14.7%, leading to a drop in N_{ex} of 6.3% from 61.5 kg to 57.7 kg. In fattening pigs, lowering the CP content from 16.4% to 15.6% would reduce N_{ex} by 8.33% from 4.51 kg to 4.14 kg (Figure 8).

Phytogenic feed additives are used by a rather small proportion of Austrian dairy- and beef-cattle, pig, and poultry farms. A potential reduction of enteric CH_4 emissions from all cattle by 5% due to the use of phytogenic feed additives in 2020 would diminish CH_4 by 6.5 Mg. A theoretical application of a mixture of 50% each of phytogenic and synthetic feed additives (the latter with at least 20% reduction potential) on Austrian cattle farms for all cattle would result in a 13 Mg reduction, and a full application of synthetic additives would decrease enteric CH_4 by 26 Mg.

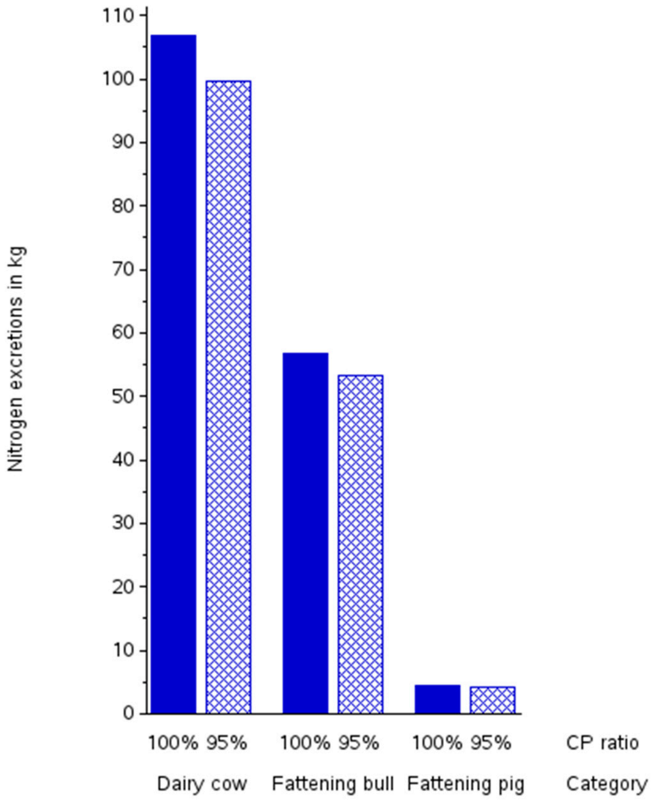

Figure 8. Nitrogen excretion in kg per animal and production cycle with the average diet (100%) and with a CP-reduced diet (−5%) for dairy cows, fattening bulls, and fattening pigs.

4. Discussion

4.1. Differences in Results When Using the Previous and the Updated Method

4.1.1. Changing Trends over the Time Series from 1990 to 2020

Across all emission categories, dairy cows were the main source of higher emissions in 1990 and of lower emissions in 2020 when calculated with IPCC-2019 rather than with the NM. In 2005, dairy cows emitted less CH_4 and more N_{ex} and VS_{ex} when based on IPCC-2019. These differences originate from changes in gross energy demand and underlying data: In the NM, gross energy was based on model diets derived from theoretical requirements, probably underestimating the actual intake. With the updated method, gross energy demand was calculated according to the IPCC-2019 methodology and based on on-farm data from several collections, e.g., the average CP-intake was based on on-farm surveys with data from [33,46,47] instead of theoretical CP requirements. This, on average, resulted in higher CP intake in 1990 and slightly lower CP intake in 2020 for cattle and pigs. Using empirical data is in accordance with the EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 [9], which links to "animal nutrition analyses" and thus data, which are derived from feeding trials or on-farm experiments rather than theoretically assessing the (minimum) CP requirement. Consequently, and especially for dairy cows and fattening pigs, the trends for N_{ex} (Figure 5) and VS_{ex} (Figure 6) showed a steeper decline compared to the previous NM. In addition to absolute-emission targets, the role of relative targets is critical for the present as well as the future (see, e.g., National Emission Ceilings (NEC) EU directive 2016/2284) [69]. Therefore, the switch to the updated method allows for better assessment of mitigation options for on-farm implementation.

An important methodological improvement is the replacement of static values by more accurate, dynamic parameters across all cattle and pig categories, which allowed the calculation of annual changes and more pronounced trends over the time series [10]. In our method update, changes in average body mass for dairy cows and every category of other cattle due to altered proportions of cattle breeds and changes in genetics are incorporated into the calculation. In line with this, varying fat and protein contents of cow milk and effects of increasing fattening performance in beef cattle, which were not included in the NM, are now evaluated. As a result, the method better considers changing circumstances across time. Similarly, reduction options can be analyzed more accurately to inform farmers and advisors. This was also pointed out by other reports and studies, e.g., [10,11,70].

The analysis of (linear) trends from 2011 to 2020 showed that more intensive fattening with higher CP output of fattening bulls would decrease CH_4 emissions but increase N_{ex} and VS_{ex} emissions (data not presented here). For fattening pigs and dairy cows, more intensive production with increased CP output reduced all these emissions. However, it should be considered that mitigation trends of intensification are not the same in all regions and production systems and are not linear anymore for continuing intensification in high-output systems [71]. Thus, the trends from 1990 (to 2000, 2010, or 2020) were more pronounced than those from 2011 to 2020.

An updated and more detailed method needs more specific data over the entire time series. Collecting these data can sometimes be difficult, particularly for the beginning of the time series. If no data are available, data can be extrapolated or set constant, experts can be consulted [11], and this information can be combined with trends derived from existing data in later years. The latter approach was used for a few specific aspects in the present study, e.g., the proportion of time dairy cows spent in pasture and the distribution of cattle across confined husbandry systems in 1990.

4.1.2. Changes within Other Cattle Due to Re-Categorization and Detailed Calculation

The largest discrepancies between IPCC-2019 and the NM occurred for other cattle with lower enteric CH_4 emissions and higher N_{ex} and VS_{ex} when calculated with the updated method. These discrepancies were a consequence of subdividing the different cattle categories for more precise calculations, which was suggested in the EMEP Guidebook [9]: Livestock should be split into homogenous groups "with respect to feeding, excretion and age/weight range." In the NM, the subcategory of cattle younger than one year (cattle < 1) was calculated based on an average weaned calf six months old, whereas in IPCC-2019, cattle < 1 were subdivided into 14 subcategories, wherein milk-fed calves did not contribute to enteric CH_4 emissions. Higher N_{ex} from other cattle estimated according to IPCC-2019 reflect the inclusion of the milk phase of calves as well as the higher gross energy requirements of breeding and fattening cattle 1–2 years old and cattle > 2 years old. Moreover, the further subdivision and characterization of categories usually resulted in lower digestibility of the average diet, causing considerably higher VS_{ex} in cattle 1–2 years old and cattle > 2 years old.

4.1.3. Changes for Pigs Due to Tier2 Methods and Re-Categorization

CH_4 emissions were lower for both breeding and fattening pigs when calculated with IPCC-2019. This is due to the fact that in the previous NM, CH_4 emissions were assessed with Tier1 values, whereas in the updated calculations the IPC-2019 Tier2 method with specific feed rations was implemented. Regarding N_{ex} and VS_{ex}, updating the methodology resulted in lower emissions for all breeding pigs and higher emissions for all fattening pigs. This was partly due to a change in the allocation of animal subcategories: Replacement gilts before the first insemination were deducted from gilts and added to fattening pigs, as they are fed similarly. Furthermore, the consideration of diets that are fed on practical farms to weaned piglets 8–32 kg (subcategory of fattening pigs) resulted in a higher proportion of dietary CP and thus in an increase in N_{ex}. Likewise, lower VS_{ex} quantities in breeding pigs and higher VS_{ex} quantities in fattening pigs were due to considering specific diets in IPCC-2019 compared to measured values from [61] in the previous NM.

4.2. Efficiency Improvement and Other Mitigation Measures

4.2.1. Productivity, Efficiency, and Sustainability

Although emissions per head of livestock increased, they decreased per kg product CP over the time series (Figure 7). Per kg of CP in milk and body-mass gain, CH_4, N_{ex}, and VS_{ex} were reduced on average by over 40% (dairy cows) and by almost 30% (other cattle) since 1990. For breeding and fattening pigs, lower but notable efficiency gains per kg CP in body mass gain were found, resulting in a reduction of enteric CH_4 by 12% and 3% and a N_{ex} reduction of 28% and 20%, respectively. These efficiency increases since 1990 were responsible for almost two thirds of overall pigs' N_{ex} reductions.

Although the CP content of average diets increased since 1990 for dairy cows along with increasing performance, it remained constant for other cattle and decreased considerably for pigs. With a 12% reduction in the average CP content of overall pig feed (including piglet diets), more than one third of the overall pigs' N_{ex} reduction could be attributed to reduced CP contents of breeding and fattening pigs' diets.

Overall, global livestock production became more efficient during the last few decades, especially in countries of the Global North [72]. With a growing world population, unchanged consumption patterns in the Global North, and a trend towards an increasing consumption of livestock products in the Global South, increased efficiency of livestock and feed production is essential to achieving higher product output while maintaining or reducing emissions [73,74]. However, any process of intensifying production needs to be thoroughly vetted for its impact on different areas of sustainability, which is often not done properly [74]. Potential trade-offs with efficiency gains, particularly when assessed within narrow system boundaries, are of particular concern. For instance, improving efficiency at the animal level can lead to reduced biodiversity and resilience, and increased diversification does not necessarily conflict with efficiency. Analysis at a high level with comprehensive system boundaries, e.g., overall resource-use efficiency and land-use diversity, point at the absence of major conflicts [75,76].

At the animal level, efforts to improve productivity and efficiency are probably reaching their limits in modern livestock systems: Increased productivity led, inter alia, to a more frequent occurrence of metabolic disorders, e.g., subacute ruminal acidosis [77–79] and oxidative stress [80]; welfare issues, e.g., lameness [81–83]; and genetic disorders, e.g., complex vertebral malformation in dairy cattle [84] and stress syndrome (PSS) in pigs [85]. Another limitation to productivity is heat stress, which is mainly driven by metabolic heat load due to high milk and meat yields [86,87]. The risk of heat stress has to be taken into consideration for high-yielding animals such as dairy cows, sows, and fattening pigs at high ambient temperatures. Heat stress has recently received more attention and will likely gain more importance in the near future as temperatures increase [88].

In feed production, increasing productivity and efficiency will likely lead to trade-offs such as a loss in soil fertility [89] and a reduced provision of regulative and cultural ecosystem services such as conservation of biodiversity, water quality, or carbon storage [90–92]. The use of concentrate feedstuffs to improve productivity of ruminants is likely to increase feed–food competition [93,94].

In general, the greatest and quickest reductions in enteric CH_4, N_{ex} (NH_3, NO_X, and N_2O), and VS_{ex}, causing manure-based CH_4, could be achieved by decreasing animal numbers. This option is discussed in other studies as well, e.g., by [95], who postulated that a stabilization of the global climate for at least 30 years could be achieved by abandoning all livestock. However, this would impede socio-economic and food-security goals [96,97].

4.2.2. Reducing Crude-Protein Intake and Imported Emissions

A reduced CP intake, which is compensated for by supplementation with synthetic amino acids, can reduce N_{ex} and environmentally relevant N losses without a reduction in livestock performance. This is especially important for monogastric animals (pigs and poultry) and more difficult for ruminants. Furthermore, lower N_{ex} could occur without any economic trade-offs and could even result, depending on the price of protein sources, in lower costs [98]. An experiment with four groups of growing–fattening pigs receiving amino-acid supplementations with different CP levels showed high potential [99]: A 12% reduction in CP intake in a maximum N-reduced diet (average of 13.5% CP) reduced N_{ex} by a further 19% per animal or per kg of weight gain when compared to a strongly N-reduced diet (average of 15.3% CP). Although the maximum CP reduction resulted in 3% less body-mass gain per animal per day, no statistically significant difference was detected in feed-conversion efficiency. Furthermore, relevant carcass characteristics, such as the lean-meat content, were not or only slightly affected by the crude-protein reduction. A decrease in CP content by one percentage point resulted in an average NH_3 reduction of 17% (±6%) for cattle and −11% (±6%) for pigs [100]. A similar magnitude was found in another study [101].

Replacing imported high-protein feed with locally or regionally produced feed and partially supplementing with synthetic amino acids was shown to significantly reduce environmental impacts such as GHG emissions [102–104]. An analysis of this mitigation option is outside the scope and the system boundaries of the present study, which covers interactions between feeding, excretions, and enteric emissions. Unlike a life-cycle assessment (LCA), IIRs and NIRs are based on calculation procedures developed by, e.g., EMEP/EEA [9] and IPCC [11], and do not directly relate environmental impacts of domestic-feed production such as greenhouse-gas emissions to the livestock consuming the feed. Furthermore, it is currently not possible to calculate the environmental impacts of feed imported from other nations and account for them in the NIR and the IIR of the importing country. The environmental impacts and other sustainability aspects of domestic and international feed-supply chains should thus be analyzed in future LCA studies.

4.2.3. Use of Feed Additives

Feed additives for improved N-use efficiency and lower N_{ex} in farm manure or lower NH_3 formation due to urease inhibitors, e.g., benzoic acid, are described, for instance, in [105,106]. According to these studies, pigs have the second highest mitigation potential regarding feed additives, following cattle. In addition to chemical feed additives, plant constituents such as saponins or essential oils have the potential to reduce ammonia emissions; possible molecular modes of action are described by [107]. However, contradictory results can be found in the literature. For example, one study reported an average of −23% NH_3 emissions from the addition of benzoic acid, with a high variation of between +116% and −71% [105], whereas another study confirmed highly effective mitigation effects of CP reduction in finishing pigs but reported no significant effect of adding 1% benzoic acid to the diet [101].

For cattle and from a GHG perspective, feed additives are primarily relevant for reducing enteric CH_4 emissions. In this context, 3-nitrooxypropanol (3-NOP) promises a substantial reduction potential. In vitro as well as in vivo studies confirm this effect. A total of 100 mg of 3-NOP per kg feed DM intake can reduce CH_4 by about 20%, although the efficiency of the additive seems to decrease with an increase in dietary crude-fiber content [68]. A significant effect was found for an incorporation rate of 53 mg per kg in mixed rations (at 88% reference dry matter). At the maximum recommended incorporation rate of 100 mg 3-NOP per kg DM feed, no risks, neither for the animal nor the consumer, were found [68].

Plant-based feed additives with lower effects are already used on farms, e.g., essential oils [65] and mixtures of tannins, essential oils, saponins, and other active plant ingredients [66,67]. For a daily application rate of 1 g per cow, a 9.9% decrease in CH_4 emissions per kg of energy-corrected milk was reported in a meta-analysis for an essential-oils additive [65]. Another meta-analysis [108] reported reductions in enteric CH_4 of 2.5% to 15% per kg milk but pointed out that some of the beneficial effects are temporary and diminish over time, as the rumen microbial flora become accustomed to active ingredients in feed additives. Not all designated plant-based substances show clear and consistent results [109], especially when the CH_4 reduction is related to units of animal products (milk, meat) [110]. A potentially reduced digestibility of fiber-rich feed ingredients due to the use of specific additives such as tannins [109] has to be considered and should be investigated in future studies. There is also evidence that a reduction of enteric CH_4 by feed additives may result in compensatory CH_4 losses from manure [110,111]. Therefore, the overall potential of feed additives over the entire life cycle remains rather unclear.

With a more widespread use of feed additives in agricultural practice and a better understanding of their impacts, it is recommended that their effects be cautiously addressed as a potential mitigation measure in the Austrian NIR and the IIR, unless their effect is already accounted for in reduced N_{ex}. From our calculations, it can be concluded that the potential reduction of effective feed additives may be substantially higher than the mitigation caused by reduced N_{ex}. The latter calculation took into account the average national emission factor for N_2O from breeding- and fattening-pig manure-management systems (0.5%) [4] and assumed that 1% of the field-spread and atmospherically deposited N forms as N_2O [11]. Even if they only played a minor role, all options in every sector and for every livestock category should be implemented to reduce environmental impacts such as GHG emissions, acidification, and nutrient losses to water bodies as much as possible. Except for GHG emissions, N_{ex} reduction plays an important role in many environmental aspects, including biodiversity [3].

4.3. Limitations and Further Improvements

It is not possible to directly compare uncertainties of the previous NM with those of the updated IPCC-2019-based calculations, since the uncertainties of the previous NM were derived from the activity data of animals and emission factors. The uncertainty ranges presented in Section 3.1 are similar to those reported by others, e.g., a 95% confidence interval for enteric CH_4 emissions from −11% to +18% [112].

Practices of feed conservation and preparation as well as the composition of diets and nutrients are constantly changing in animal feeding. It would be sensible to periodically revise the inventory to incorporate these changes. Overall, IPCC-2019 proposed continuously updating methods for more accurate and less uncertain results [113]. Estimating the consequences of changing feeding practices along the whole manure chain, including feed production, was outside the scope of this study. With unchanged on-farm manure-management systems, a proportional decrease in NH_3-, N_2O-, and CH_4- emissions can be assumed in accordance with a decrease in N_{ex} and VS_{ex} but needs to be verified in future studies.

5. Conclusions

Updating the previous NM to the IPCC-2019 Tier2 method allowed for a more accurate and dynamic estimation of emissions and their reduction potentials. These improvements originate from several elements: Firstly, a re-allocation (pigs) or further segmentation (cattle) of animal numbers to specific subgroups result in a more detailed characterization of animal categories; secondly, calculating N_{ex} as the difference between the performance-dependent N intake and N in retention and products represents N_{ex} in a way that reflects practice conditions more accurately; and thirdly, the possibility to annually adjust emission factors according to background data on feeding practices, e.g., the CH_4 emission (conversion) factor, which is adjusted for dairy cows' performance and diet composition, incorporates reduction potentials that arise in practice through, e.g., improved feeding. Efficiency increases, caused by the improved productivity of a consequently declining livestock population, show the highest reduction potential for emissions of Austrian livestock production. Per kg of CP in milk and body-mass gain, CH_4, N_{ex}, and VS_{ex} of dairy cows and other cattle were on average reduced by more than 40% CH_4 and almost 30% for N_{ex} and VS_{ex} since 1990. For breeding pigs and fattening pigs, notable efficiency gains were found per kg CP in body-mass gain, resulting in a reduction of enteric CH_4 by 12% and 3% and a N_{ex} reduction of 28% and 20%, respectively. Additionally, more than one third of the overall pigs' N_{ex} reduction can be attributed to reduced CP contents of breeding- and fattening-pigs' diets, representing another important strategy for reduction of (pig-related) NH_3 and N_2O emissions. Further substantial emission mitigation might be achieved by the use of effective feed additives, primarily targeting enteric CH_4 in cattle. Data uncertainties regarding the impact of feed additives under on-farm conditions and characteristics of diets fed in practice represent the main limitations of the present study. Thus, emission reductions induced by a widespread application of feed additives, adjustments to diet composition and nutrient content, and the impacts of changed N_{ex} and VS_{ex} on NH_3, N_2O, and manure-related CH_4 emissions need to be assessed in future studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15064814/s1, Table S1: Parameters and functions as well as their data sources relevant for calculation of enteric CH_4 emissions and N_{ex} and VS_{ex} for cattle and pigs; Figure S1: Differentiation of cattle categories for the updated IPCC-2019-based analysis; Figure S2: Share of dairy cattle indoors, in pasture, and in alpine pasture (equal to "Grazing large areas", according to IPCC 2019) from 1990 to 2020; Figure S3: Average milk yield in kg per animal per day (y1-axis) and the average fat and protein content of the milk (y2-axis) of dairy cows between 1990 and 2020; Figure S4: The proportion of crude protein and crude ash in the dry matter (y1-axis) and the feed digestibility (y2-axis) of dairy cows between 1990 and 2020; Figure S5: Calculated net-energy requirements for maintenance, activity, lactation, and pregnancy of dairy cows between 1990 and 2020. Table S2: Uncertainty ranges for the IPCC-2019 results for the years 1990, 2005, and 2020. Table S3: Relative changes of protein (N) retention and of emissions per head and year and per kg CP of enteric CH_4, N_{ex}, and VS_{ex} in 2020 compared to 1990 for different animal categories.

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