environments

MDPI

Article

Retrospective Assessment of Greenhouse Gas Emissions from the Beef Sector in Greece and Potential Mitigation Scenarios

Stephanos Azoukis, Konstantina Akamati, Iosif Bizelis and George P. Laliotis *

Laboratory of Animal Breeding and Husbandry, Department of Animal Science, Agricultural University of Athens, 75 Iera Odos, GR 11855 Athens, Greece
* Correspondence: glaliotis@aua.gr; Tel.: +30-210-5294458

Abstract: Although beef production is one of the most valuable drivers of the global livestock economy, it is considered the main contributor to GHG emissions derived from livestock. This study's objectives were to estimate the GHG emissions (expressed in carbon dioxide equivalents; CO_2-eq) from the beef sector in Greece at the national and prefecture levels during the period 2011–2021 and to explore potential mitigation scenarios. The Tier 1 and 2 methodologies were implemented to estimate the GHG emissions. The total estimated emissions increased over the study period. Although both methodologies captured similar trends in the changes in GHG emissions, the Tier 2 estimations revealed lower emissions and fluctuations due to the different and more precise computational approaches. At the prefecture level, fluctuations in emissions were also noted. However, specific regions showed higher increases in emissions. The observed increase in emissions, in terms of either absolute values (Gg CO_2-eq) or intensities (Kg CO_2-eq/Kg produced beef carcass), is of utmost importance, and further mitigation strategies should be considered. The regression analysis showed a good predictive ability for emissions, using the number of livestock animals as the input. The equations derived from this analysis could be further used as first-approach tools for capturing future emissions at the national level before proceeding with more elaborate approaches. The different scenarios examined in response to the sector's challenges showed moderate changes in GHG emissions. Depending on national priorities, such scenarios could serve as pilot case studies, which may assist stakeholders in improving the sustainability of the sector in the future.

Keywords: beef cattle; cow; climate change; greenhouse gas emissions (GHG); livestock; mitigation; Greek beef sector

Citation: Azoukis, S.; Akamati, K.; Bizelis, I.; Laliotis, G.P. Retrospective Assessment of Greenhouse Gas Emissions from the Beef Sector in Greece and Potential Mitigation Scenarios. *Environments* **2023**, *10*, 144. https://doi.org/10.3390/environments10080144

Academic Editor: Dino Musmarra

Received: 28 May 2023
Revised: 2 August 2023
Accepted: 8 August 2023
Published: 13 August 2023

1. Introduction

The livestock sector is one of the major drivers of economic development in most countries globally, contributing to the cohesion of many areas that cannot be used for other human activities, either because of geographical barriers or because of their inappropriate geomorphological or marginal shape. In addition, 33% of the protein and 17% of the calories consumed globally by humans come from livestock [1], ensuring therefore apart from income and livelihood, food adequacy, and nutritional security.

Despite its importance in daily life, livestock is facing contemporary challenges, such as climate change and population increases, which increase the need to cover future nutrient demands. Therefore, livestock should be adapted to the projected changes in climate (extreme temperatures, variations in precipitation, high humidity, etc.) to continue producing adequate quantities of livestock products globally. Additionally, husbandry practices should be adapted in such a way as to eliminate the negative effect of livestock on the environment. Globally, 14.5% of human greenhouse gas emissions (GHG) originate from the livestock sector [2,3]. However, if further human population expansion occurs, this impact will be greater. In particular, the human population is anticipated to reach approximately 9 billion by 2050 [3,4], which will result in a doubling of the demand for livestock products [3]. Therefore, it appears that livestock are driven to an environmental "dead-end." This means that, on the one hand, the rising demand must be met, but on the other hand, the environmental impact will be greater because more natural resources will be used to meet this demand [5].

According to FAO, the livestock sector produces approximately 8.1 Gtn of carbon dioxide equivalents (CO_2-eq) every year. The GHG emissions from the livestock sector account for carbon dioxide ($CO_{2)}$, methane (CH_4), and nitrous oxide (N_2O) [2,3]. Enteric fermentation, feed production and processing, manure management, transportation, and the further processing of animal products are the main drivers of these emissions. In terms of species contribution, 62% of all livestock emissions are derived from cattle. Other species (pigs, poultry, buffaloes, and small ruminants) contribute to lower percentages, ranging from 7% to 11%. The beef sector makes the highest contribution to livestock's GHGs (41%), followed by the dairy sector (21%) [2,3]. Therefore, the beef sector emits 2–9 times the greenhouse gases (GHGs) of other animal products per kg or produced product and >50 times the GHGs of most plant-based foods per unit of protein [6–8]. Beef production is also a major driver of global deforestation and land degradation [9,10].

However, beef production is considered one of the most valuable drivers of the global livestock economy, with important contributions to national and/or international trade. The European Union is ranked third in beef production, after the United States and Brazil. These three regions account for approximately 50% of beef production worldwide [11]. In Greece, the beef sector is not well developed, and the country's self-sufficiency in this sector is approximately 20–25% [12]. The sector shows considerable heterogeneity and faces the problem of limited competitiveness. Two main types of husbandry systems are implemented. The first type is the intensive calf-fattening system. Many modern large-sized farms implement this type of system, and the majority of fattening calves reared into stalls for further slaughtering belong to meat-type breeds (Limousin, Blond d' Aquitaine, etc.) and their crosses, or crosses of meat-type breeds with local breeds (i.e., Brachycheros) or dual-purpose breeds [13–15]. Some farmers may also use meat-type calves imported from other European countries (France, Romania, etc.) at the age of 8–10 months for fattening purposes up to the age of 14–19 months approximately, or male calves derived from the dairy sector for the same or even longer fattening period (up to 22–24 months of age). Diets are exclusively based on roughage and concentrate feeds, which can be either purchased or partly produced by farmers. The second type of husbandry system refers to the breeding of cows to produce calves for fattening (the so-called "reproduction-beef cattle farming"). This type of system is not very well developed, its productivity is very low, and the animals are reared under (semi)-extensive systems. Such animals are usually retained because the main target is not directly the production and slaughter of high-quality certified meat but the collection of subsidies that are an incentive for keeping their animals alive. Animals reared under this system usually belong to autochthonous breeds or crosses of local breeds with foreign dual-purpose breeds (i.e., Brown Swiss). Calves that are born under this system are usually fattened under intensive conditions after weaning (6–8 months) as described previously, except for those animals that are retained for replacement purposes, which continue to be reared under (semi)-extensive systems. Adult animals (>2 years old) are reared by farmers under extensive systems as a means of diminishing production costs, except during periods of extreme weather (i.e., snow), when the animals are fed small amounts of concentrated feed and/or silage.

Even though the beef sector is one of the major contributors to total greenhouse gas emissions globally [16], it is important to focus on country-level emissions to acquire more detailed information and provide further mitigation measures. Moreover, little information exists concerning the impact of the Greek beef sector on climate change in terms of GHG emissions. Therefore, the study of GHG emissions could assist in composing a better value-added concerning the specific sector at the country level. In this context, the objectives of this study were to first retrospectively estimate the sector's GHG emissions following the methodology recommended by the IPCC [17,18] and then to further explore scenarios that may improve the sector's assessed impact. This is the first systematic attempt, to the best of the authors' knowledge, to quantify the emissions of the beef sector at the national level (Greece), highlight its carbon footprint, and explore potential strategies that could assist in eliminating the impact of the sector. The results may assist stakeholders in the sector in driving more elaborate measures in the future.

2. Materials and Methods

2.1. Area of Study

This study assessed the GHG emissions of the Greek beef sector from 2011 to 2021, following the guidelines reported by the IPCC [17,18] at the national level as well as at prefecture regions, using the Tier methodologies.

2.2. Animal Numbers

The number of animals for the studied period was retrieved using secondary sources of data. Specifically, animal population data for the beef sector were retrieved from the official site of the Greek Payment and Control Agency for Guidance and Guarantee Community Aid (OPEKEPE) [19]. OPEKEPE is the unique body in Greece responsible for the Common Agricultural Policy (C.A.P.) aid schemes and the Paying Authority responsible for the funds related to the European Agricultural Guarantee Fund (E.A.G.F.), the European Agricultural Fund for Rural Development (E.A.F.R.D.), and the European Fisheries Fund (E.F.F.). Every year, farmers officially declare their livestock populations to ensure subsidies. Although other authorities like the Hellenic Statistical Authority (ELSTAT), the European Statistical Office (EUROSTAT), and the statistical database of the Food and Agriculture Organization of the United Nations (FAOSTAT) retain available livestock data, these sources did not report clear discrimination of the productive orientation (i.e., meat or milk production) and/or of the discrimination of breeds (i.e., meat-oriented breeds).

Therefore, for the studied period at the national and regional levels, the number of animals entirely related to meat production orientation and meat-oriented breeds was collected from the OPEKEPE database (Supplementary Tables S1 and S2). According to the database, the following categories of animals reared for meat production are recorded: (a) males and females less than one month old; (b) males and females between the ages of 1 and 6 months; (c) males and females between the ages of 6 and 24 months; (d) males and females between 2 and 6 years old; and (e) males and females over 6 years old. Animals belonging to the first three categories (a–c) were considered to be reared under intensive conditions, while those belonging to the remaining two (d and e) were considered to be reared under (semi-) extensive conditions. In addition, a replacement rate of 15%, an average fattening period of five months, and a 90% fertility rate were considered in further estimations of animal categories representing the average values of the targeted region [20].

2.3. GHG Emissions Estimation Using Tier Methodologies

The estimation of GHG emissions (methane and nitrous oxide) was assessed following the guidelines and equations reported by the IPCC [17,19] for each gas category. Tier 1 methodology was used to estimate GHG emissions for the whole target period (years 2011–2021) as well as for each prefecture for the years 2011 (the initial of the studied period), 2016 (the middle of the period), and 2021 (the end of the period). A Tier 2 methodology was also applied to estimate emissions for the whole studied period at the national level to compute more accurately the estimations of GHG emissions, according to the IPCC recommendations [18]. To use the equations reported by the IPCC, basic characteristics related to the area's climate, manure treatment, and feeding practices are required to choose the proper values for the parameters required by the equations or further estimations [18]. Therefore, the climate zone for the target area (Greece) was considered warm and temperate (dry). Regarding the allocation of manure, the implemented manure system for animals reared intensively (feeding in stalls with no grazing) was solid storage. For animals that were reared semi-extensively, 50% of the produced manure was assumed to be spread in pastures (as they spent at least 50% of the daytime in pasture), and the rest to be treated in solid storage. In the case of animals reared in pastures (extensive system), a 100% daily spread of manure in pastures was considered (100% of the daytime spent in pastures). In addition, under an intensive system, animals were fed an 85% concentrate or high-grain diet (i.e., corn, soy, etc.), with the rest consisting of roughage and/or silage. Animals reared under a semi-extensive system were considered to be fed in pastures with low- to middle-quality forage (70% of the diet) and having supplementary diets consisting of concentrate feeds (mixed-diet-fed animals). In the case of an extensive system, the diet was exclusively based on the grazing of pastures with low-to-middle quality forage.

2.3.1. Methane (CH_4) Emissions

Tier 1 Approach

The following equation was applied following the IPCC recommendations to estimate the total annual methane emissions from intestinal fermentation using a Tier 1 approach [18]:

$$\text{Enteric CH}_4\text{ Emissions } = \sum\left(\text{EF } \times \left(\frac{\text{N}}{10^6}\right)\right) \tag{1}$$

where:

CH_4 Emissions = emissions derived from enteric fermentation (Gg CH_4);
EF = defined country emission factor for the livestock population (kg $CH_4\cdot head^{-1}\cdot yr^{-1}$);
N = the number of heads of livestock population.

To determine methane emissions derived from manure, the following equations were used [18]:

$$\text{Manure CH}_4\text{ emissions} = \left[\sum\frac{(\text{N} \times \text{VS} \times \text{AWMS} \times \text{EF})}{1000}\right] \tag{2}$$

where:

CH_4 Emissions = emissions derived from manure management (kg$\cdot CH_4$);
N = the number of heads of livestock population;
VS = the annual average Volatile Solid excretion per head of species (kg VS$\cdot animal^{-1}\cdot yr^{-1}$);
AWMS = the fraction of total annual VS for livestock specie that is managed in a manure management system (dimensionless);
EF = emission factor for direct CH_4 emissions from manure management system by animal species (g $CH_4\cdot kg\cdot VS^{-1}$).

The annual average Volatile Solid (VS) excretion was estimated using the following equation:

$$\text{VS} = \left(\text{VS}_{\text{rate}} \times \frac{\text{TAM}}{1000}\right) \times 365 \tag{3}$$

where:

VS_{rate} = default VS excretion rate for the productivity system (kg VS$\cdot$(1000 kg animal mass)$^{-1}\cdot day^{-1}$);
TAM = typical animal mass for livestock species (kg$\cdot animal^{-1}$).

All appropriate factors and parameters used in the equations following the recommendations of the IPCC [18] are presented in Table 1.

Table 1. Basic parameters used for estimating GHG emissions using the Tier 1 and 2 methodologies according to the IPCC refined recommendations [18,19].

Parameter	Methodology	Value	Equation
$EF_{CH4\text{-}enteric}$	Tier 1	52 kg $CH_4 \cdot head^{-1} \cdot yr^{-1}$	(1)
AWMS	Tier 1/2	26% (solid storage); 48% pasture/range	(2)/(5)/(7)/ (11)/(13)
$EF_{CH4\text{-}manure}$	Tier 1	4.8 g CH_4·kg VS^{-1}	(2)
VS_{rate}	Tier 1	5.7 (kg VS·(1000 kg animal mass)$^{-1}$·day^{-1})	(3)
TAM	Tier 1/2	405 kg·animal^{-1}	(3)/(8)
Y_m	Tier 2	6.3 (dimensionless; for the intensive system) 7.0 (dimensionless; for the (semi-)extensive system)	(4)
Bo	Tier 2	0.18 m^3 CH_4·kg^{-1} of VS excreted	(5)
MCF	Tier 2	4% (solid storage) or 0.47% (pasture/range)	(5)
DE	Tier 2	Intensive: 66.5%; semi-extensive: 62%	(6)
UE	Tier 2	0.04 × E	(6)
ASH	Tier 2	0.08	(6)
EF_3	Tier 1	0.01 kg N_2O-N/kg N	(7)
N_{rate}	Tier 1	0.42 kg N·(1000 kg animal mass)$^{-1}$·day^{-1}	(8)
$N_{retention\_frac}$	Tier 2	Mature females (pasture): 0.08; mature males (pasture): 0; replacement/growing (pasture) = 0.04; calves on milk (stall): 0.10; other: 0.11 (dimensionless)	(9)
CP%	Tier2	Mature animals (pasture): 14.7%; replacing/growing (pasture): 16.5%; calves on milk (stall): 17.1%; other: 16.1%	(10)
EF_4	Tier 1/2	0.01 kg N_2O-N/kg N	(11)
$Frac_{GasMS}$	Tier 1/2	0.45 (dimensionless)	(12)
EF_5	Tier 1/2	0.011 kg N_2O-N/kg N	(13)
$Frac_{LeachMS}$	Tier 1/2	0.02 (dimensionless)	(14)

Tier 2 Approach

Methane emissions from enteric fermentation within each animal category were calculated using Equation (1), but for the EF parameter instead of using default values for the target region, it was calculated using the following equation [18]:

$$EF = \frac{GE \times \left(\frac{Y_m}{100}\right) \times 365}{55.65} \tag{4}$$

where:

EF = emission factor (kg $CH_4 \cdot head^{-1} \cdot yr^{-1}$);
GE = gross energy intake (MJ·head^{-1}·day^{-1});
Y_m = methane conversion factor, percent of gross energy in feed converted to methane. The factor 55.65 (MJ/kg CH_4) is the energy content of methane.

The GE was calculated using the following equation based on the reported guidelines of IPCC [18]:

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_p}{REM}\right) + \left(\frac{NE_g}{REG}\right)}{DE}\right] \tag{4a}$$

where:

GE = gross energy (MJ·day^{-1});
NE_m = net energy required by the animal for maintenance (MJ·day^{-1});
NE_a = net energy for animal activity (MJ·day^{-1});
NE_l = net energy for lactation (MJ·day^{-1});
NE_p = net energy required for pregnancy (MJ·day^{-1});
REM = ratio of net energy available in a diet to maintenance of digestible energy;
NE_g = net energy needed for growth (MJ day^{-1});
REG = ratio of net energy available for growth in a diet to digestible energy consumed;
DE = digestibility of feed expressed as a fraction of gross energy.

The estimation of parameters related to GE calculation (NE_m, NE_a, NE_l, NE_{work}, NE_m, and NE_g) was conducted following the guidelines and respective equations reported by the IPCC [18]. Further analytic description of the equations used is shown in Supplementary File S3.

Regarding methane emissions derived from manure within each animal category, Equations (2) and (3) were used, but the EF and VS factors were estimated as follows [18]:

$$\mathrm{EF} = (\mathrm{VS} \times 365) \times \left[\mathrm{B_0} \times 0.67 \times \sum \frac{\mathrm{MCF}}{100} \times \mathrm{AWMS}\right] \quad (5)$$

where:

EF = annual CH4 emission factor for livestock population (kg CH_4·animal^{-1}·yr^{-1});
VS = daily volatile solid excreted for livestock population (kg dry matter·animal^{-1}·day^{-1});
365 = basis for calculating annual VS production (days·yr^{-1});
B_0 = maximum methane-producing capacity for manure produced by livestock population (m^3 CH_4·kg^{-1} of VS excreted);
MCF = methane conversion factors for each manure management system in the climate region (percent);
AWMS = the fraction of total annual VS for livestock species that is managed in a manure management system (dimensionless).

and

$$\mathrm{VS} = \left[\mathrm{GE} \times \left(1 - \frac{\mathrm{DE}}{100}\right) + (\mathrm{UE} \times \mathrm{GE})\right] \times \left[\left(\frac{1 - \mathrm{ASH}}{18.45}\right)\right] \quad (6)$$

where:

VS = volatile solid excretion per day on a dry-organic matter basis (kg VS·day^{-1});
GE = gross energy intake (MJ·day^{-1});
DE = digestibility of the feed in percent;
(UE × GE) = urinary energy expressed as a fraction of GE;
ASH = the ash content of feed calculated as a fraction of the dry matter feed intake;
18.45 = the conversion factor for dietary GE per kg of dry matter (MJ·kg^{-1}).

For the estimation of GE, the recommendation of the IPCC [18] for non-lactating cows was followed using Equation (4a) as previously described and considering further parameters such as the energy related to maintenance, animal activity, lactation, pregnancy, growth, and digestibility of feed (Supplementary File S3).

Similar to the Tier 1 methodology, all appropriate factors and parameters used in the equations for the Tier 2 calculations followed the recommendations of the IPCC [17,18] and are presented in Table 1.

2.3.2. Estimations of Nitrous Oxide (N_2O) Emissions from Manure Management

Nitrous oxide (N_2O) is produced, directly and indirectly, during the storage and treatment of manure. The calculation of the respective emissions is based on N excretion, emission factors for N_2O emissions, and volatilization and leaching factors [17,18]. Direct

N_2O emissions are produced by the nitrification and denitrification of nitrogen contained in the manure. Volatile nitrogen losses result in indirect emissions that occur primarily in the forms of ammonia and NOx.

Direct Estimations (Tier 1 and 2 Methodology)

Direct nitrogen gases (N_2O) derived from manure management were calculated according to the following equation [18].

$$\text{Manure } N_2O \text{ emissions} = \left[\sum\left[\sum((N \times Nex) \times AWMS)\right] \times\right] \times \frac{44}{28}, \text{ Kg } N_2O \quad (7)$$

where:

N = the number of head of livestock species;
Nex = the annual average N excretion per head of species (kg N·animal^{-1}·yr^{-1});
AWMS = the fraction of total annual nitrogen excretion for the livestock species that is managed in a manure management system (dimensionless);
EF_3 = the emission factor for direct N_2O emissions from manure management system (kg N_2O-N/kg N);
44/28 = factor for the conversion of N_2O-N (mm) emissions to N_2O (mm) emissions.

The implementation of the equation requires calculating the excreted nitrogen per animal (Nex), whereas the emission factor (EF) is provided by the IPCC guidelines [18].

Tier 1 methodology

For the Tier 1 approach, the excreted nitrogen (Nex) was computed using the following equation [18].

$$Nex = N_{rate} \times \frac{TAM}{1000} \times 365 \quad (8)$$

where:

N_{rate} = default N excretion rate (kg N·(1000 kg animal mass)$^{-1}$·day^{-1});
TAM = typical animal mass for livestock species (kg·animal^{-1}).

Tier 2 methodology

The Tier 2 methodology follows a more complex approach that considers parameters related to productive characteristics and nutritional traits. Therefore, the following equation, which takes into account the nitrogen ingested and retained by an animal according to its productive stage, is used to determine the Nex factor [18].

$$Nex = N_{intake} \times (1 - N_{retention\_frac}) \times 365 \quad (9)$$

where:

N_{intake} = the daily N intake per head of animal of species (kg N·animal^{-1}·day^{-1});
$N_{retention\_frac}$ = fraction of daily N intake that is retained by an animal of species (dimensionless);
365 = number of days in a year.

According to the refined guidelines of the IPCC [18], the N_{intake} was estimated using the following equation:

$$N_{intake} = \frac{GE}{18.45} \times \left(\frac{\frac{CP\%}{100}}{6.25}\right) \quad (10)$$

The GE was determined as previously described, and the CP was determined based on the respective information provided by the IPCC guidelines [18] and considering the characteristics of the target region, the farming systems, and the animal category. Similarly, regarding $N_{retention\_frac}$, the respective values were determined according to the recommendations of the IPCC [18].

Indirect Estimations (Tier 1 and 2 Methodology)

The calculation of indirect nitrogen gases (N_2O) refers to the emissions that are volatilized and leached from the manure management system and are estimated using the following equations for both methodologies applied (Tier 1, 2), according to the IPCC [18].

$$N_2O = (N_{volatilization\ MMS} \times EF_4) \times \frac{44}{28} \tag{10}$$

where:

N_2O = indirect N_2O emissions due to volatilization of N from manure management ($kg\ N_2O{\cdot}yr^{-1}$);
EF_4 = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces (kg N_2O-N·(kg NH_3-N + NO_x-Nvolatilised)$^{-1}$);
$N_{volatilization\ MMS}$ = the amount of manure nitrogen that is lost due to volatilization of NH_3 and NO_x, ($kg\ N{\cdot}yr^{-1}$);
44/28 = factor for the conversion of N_2O-N (mm) emissions to N_2O (mm) emissions.

and

$$N_{volatilizationMMS} = \sum\left[\sum\left[(((N \times Nex) \times AWMS)) \times Frac_{GasMS}\right]\right] \tag{11}$$

where:

N = number of head of livestock species;
Nex = annual average N excretion per head of species as estimated for Tier 1 or Tier 2 methodology ($kg\ N{\cdot}animal^{-1}{\cdot}yr^{-1}$);
AWMS = fraction of total annual nitrogen excretion for each livestock species that is managed in manure management (dimensionless);
$Frac_{GasMS}$ = fraction of managed manure nitrogen that volatilizes as NH_3 and NO_x in the manure management system.

Nitrogen gases (N_2O) related to the emissions that are leached are estimated using the following equations [18]:

$$N_2O = \left(N_{leachingMMS} \times EF_5\right) \times \frac{44}{28} \tag{12}$$

where:

N_2O = indirect N_2O emissions due to leaching and runoff from manure management ($kg\ N_2O{\cdot}yr^{-1}$);
EF_5 = emission factor for N_2O emissions from nitrogen leaching and runoff, leached and runoff (kg N_2O-N/kg N);
$N_{leaching\ MMS}$ = amount of manure nitrogen that is lost due to leaching ($kg{\cdot}N{\cdot}yr^{-1}$);
44/28 = factor for the conversion of N_2O-N (mm) emissions to N_2O (mm) emissions.

$$N_{leaching\_MMS} = \sum\left[\sum\left[((N \times Nex \times AWMS)) \times Frac_{LeachMS}\right]\right] \tag{13}$$

where:

$N_{leachingMMS}$ = amount of manure nitrogen that is lost due to leaching ($kg\ N{\cdot}yr^{-1}$);
N = number of head of livestock species;
Nex = annual average N excretion per head of species ($kg\ N{\cdot}animal^{-1}{\cdot}yr^{-1}$);
AWMS = fraction of total annual nitrogen excretion for livestock species (dimensionless);
$Frac_{LeachMS}$ = fraction of managed manure nitrogen for livestock animal category that is leached from the manure management system.

All appropriate factors and parameters used in the aforementioned equations were in line with the recommendations of the IPCC [18] and are presented in Table 1. Emissions are reported as net emissions in total CO_2-eq (Gg), as well as in CO_2-eq/Kg of produced meat (carcass) and CO_2-eq/animal head.

2.4. Explored Mitigation Scenarios

After the estimation of GHG emissions at the national level, four distinct mitigation potentials were examined as separate case studies in an attempt to examine the fluctuations in total GHG emissions. The examined cases were chosen as a potential response of the beef sector towards contemporary challenges. The emissions of the final year of the study period (2021) were chosen as a baseline scenario. The examined scenarios were related to changes in the parameters of animals' numbers, specific management practices (duration of the fattening period), or shifts in favor of a specific production system (i.e., a decrease in the number of animals reared intensively in favor of those reared extensively). All parameters used were assumed to be the same as in the baseline scenario unless otherwise stated. Specifically, the first scenario (Scenario_I; hereafter: S_I) was related to an increase of 25% in the fattening population through imports of calves. The second scenario (Scenario_II; hereafter: S_II) was related to a slight intensification of the sector, considering only an increase in the number of animals reared under an intensive system compared to a (semi-) extensive system (thus, 60–40% vs. 70–30%). No other change related to husbandry practices was considered compared to the baseline scenario. The third scenario (Scenario_III; hereafter: S_III) considered an increase in the extensively reared populations compared to those reared intensively (10–90% vs. 70–30%) without any further change compared to the baseline scenario. The latter scenario (Scenario_IV; hereafter: S_IV) examined the result of the increase in the fattening period (150 days vs. 210 days) on GHG emissions while keeping the same population numbers as in the baseline scenario. In each examined scenario, apart from the highlighted changes, all the rest of the implemented values were the same as in the baseline scenario.

2.5. Data Formatting, Analysis, and Calculations

For each investigated case, data were entered on different sheets. All appropriate estimations were conducted using the appropriate calculations and formulas in an Excel sheet (Supplementary File S2). Once the analysis was completed, descriptive statistics and graphical interpretations followed. The national and regional inventories of GHG emissions were computed in accordance with the refined IPCC 2019 Guidelines [18] and covered all the direct and indirect gases stated in these guidelines. The emissions are presented in Gg CO_2 equivalent (Gg CO_2-eq) for all estimated gases by converting these gases according to their global warming potential (GWP). The respective GWPs were considered to be 25 for CH_4 and 298 for N_2O. A multinomial regression analysis was also conducted using the estimated gas emissions as a dependent value and the heads of animals between years as predictors. Statistical analysis was conducted using SPSS v. 26 [21].

3. Results

During the examined period, the number of meat-type animals at the national level followed an increase except for the years 2017–2019, which remained relatively stable (Figure 1).

From 2011 to 2021, the heads of meat-type cattle increased by approximately 46.3%. From 2019 to 2020 and 2020 to 2021, an increase of 12.1% and 9.6% was noted, respectively. Between the years 2016 and 2019, a slight increase (1%) was observed. Figure 2 presents the changes in the respective total GHG emissions (CO_2-eq) between the years of the examined period (2011–2021). The estimated emissions followed a similar trend to those of population changes. Specifically, during the eleven years, an increase of 44% in total GHG emissions was observed. The highest increase was noted between 2019 and 2020 (13%) and 2020 and 2021 (9%), while the highest decrease was estimated between the years 2011 and 2012 (−10%), followed by that of the years 2016 and 2017 (−1.9%). During the studied period, total emissions per beef head ranged from 11.1×10^{-4} to 11.6×10^{-4} Gg CO_2-eq. Adult females (>2 years old) were the major contributors to total absolute emissions, followed by adult males (>2 years old; Supplementary File S1: Tables S3 and S4). Total GHG emission intensity ranged from 6.45 to 21.79 Kg CO_2-eq/Kg of produced beef meat during the examined period, following an increasing trend over the examined years (Supplementary File S1: Table S3).

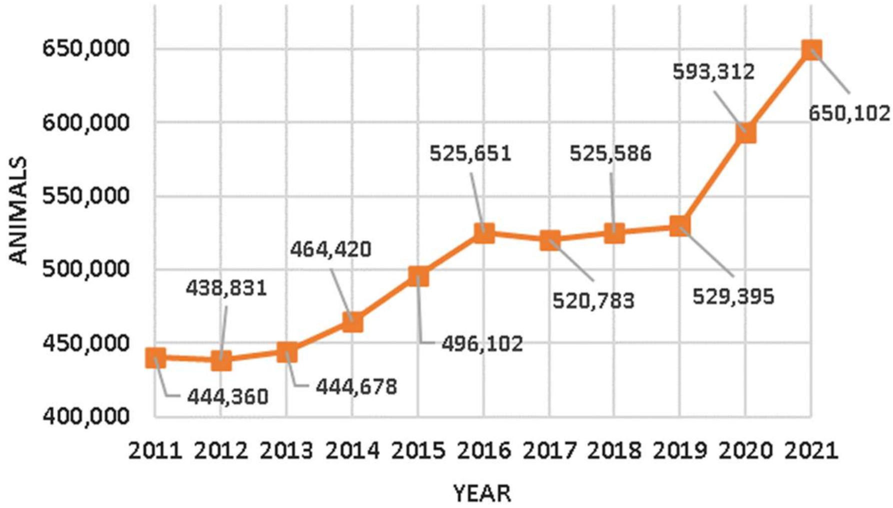

Figure 1. Animal population changes in meat-oriented cattle during the examined period.

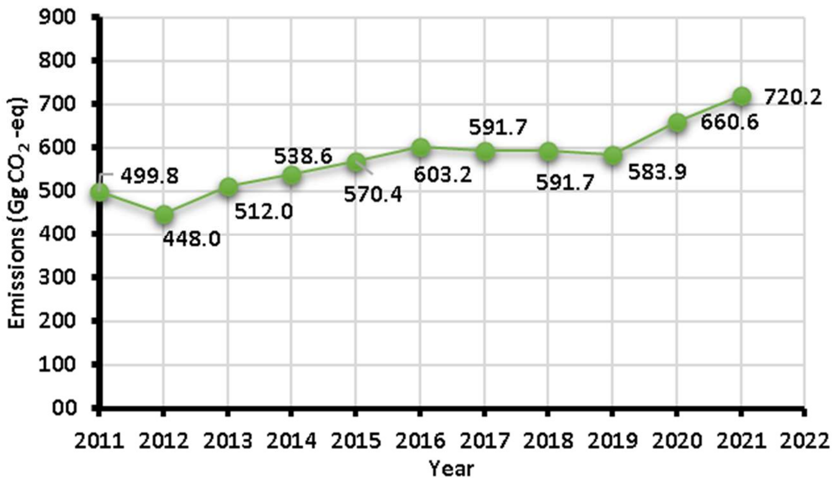

Figure 2. GHG emission (Gg CO_2-eq) changes during the examined period (2011–2021) using the Tier 1 methodology.

Concerning the methane and nitrogen gases, their changes during the examined period are shown in Table 2. In all cases, an increase from 2011 to 2021 was noted.

Table 2. Methane and nitrogen emissions from enteric fermentation and manure management (Tier 1) at the national level from 2011 to 2021. Values within brackets represent the equivalents in CO_2 (Gg CO_2-eq).

Year	CH_4 Enteric Fermentation	CH_4 Manure Management	Direct N_2O Manure Management	Indirect N_2O Manure Management
	Kg CH_4/Year		Kg N/Year	
2011	18,079,815.2 (451.99 Gg CO_2-eq)	365,618.3 (9.14 Gg CO_2-eq)	88,197.4 (26.28 Gg CO_2-eq)	41,629.2 (12.40 Gg CO_2-eq)
2012	16,204,212.8 (405.10 Gg CO_2-eq)	327,689.04 (8.19 Gg CO_2-eq)	79,047.8 (23.55 Gg CO_2-eq)	37,310.55 (11.11 Gg CO_2-eq)

Table 2. *Cont.*

Year	CH_4 Enteric Fermentation	CH_4 Manure Management	Direct N_2O Manure Management	Indirect N_2O Manure Management
	Kg CH_4/Year		Kg N/Year	
2013	18,520,002.8 (463 Gg CO_2-eq)	374,520.0 (9.63 Gg CO_2-eq)	90,344.7 (29.92 Gg CO_2-eq)	40,805.4 (12.16 Gg CO_2-eq)
2014	19,483,424.4 (487.09 Gg CO_2-eq)	394,002.8 (9.85 x Gg CO_2-eq)	95,044.5 (28.32 Gg CO_2-eq)	42,929.9 (12.79 Gg CO_2-eq)
2015	20,631,421.1 (515.79 $\times 10^6$ Gg CO_2-eq)	417,218.1 (10.43 $\times 10^6$ Gg CO_2-eq)	100,644.7 (29.99 $\times 10^6$ Gg CO_2-eq)	45,477.9 (13.55 Gg CO_2-eq)
2016	21,820,497.8 (545.51 Gg CO_2-eq)	441,264.1 (11.03 Gg CO_2-eq)	106,445.3 (31.72 Gg CO_2-eq)	48,101.8 (14.33 Gg CO_2-eq)
2017	21,401,827.3 (535.04 Gg CO_2-eq)	432,797.6 (10.81 Gg CO_2-eq)	104,402.9 (31.11 Gg CO_2-eq)	49,278.2 (14.68 Gg CO_2-eq)
2018	21,402,604.7 (535.07 Gg CO_2-eq)	432,813.3 (10.82 Gg CO_2-eq)	104,406.7 (31.11 Gg CO_2-eq)	47,144.4 (14.05 Gg CO_2-eq)
2019	21,121,435.2 (528.04 $\times 10^6$ Gg CO_2-eq)	427,127.4 (10.68 $\times 10^6$ Gg CO_2-eq)	103,035.1 (30.70 $\times 10^6$ Gg CO_2-eq)	46,541.7 (13.87 $\times 10^6$ Gg CO_2-eq)
2020	23,895,637.5 (597.39 Gg CO_2-eq)	483,228.6 (12.08 Gg CO_2-eq)	116,568.3 (34.74 Gg CO_2-eq)	52,649.4 (15.69 Gg CO_2-eq)
2021	26,050,751.9 (651.27 Gg CO_2-eq)	526,810.3 (13.17 Gg CO_2-eq)	127,081.4 (37.87 Gg CO_2-eq)	57,406.3 (17.11 Gg CO_2-eq)

Figure 3 depicts the results of the regression analysis as well as the projected equation between the estimated GHG emission values (Tier 1) and the available number of animals at the national level. The estimated R^2 of the model was 0.95 ($p < 0.001$), the constant (a) of the regression equation was estimated at 4.19, and the slope (b) of the regression line was estimated at 0.001 ($p < 0.001$).

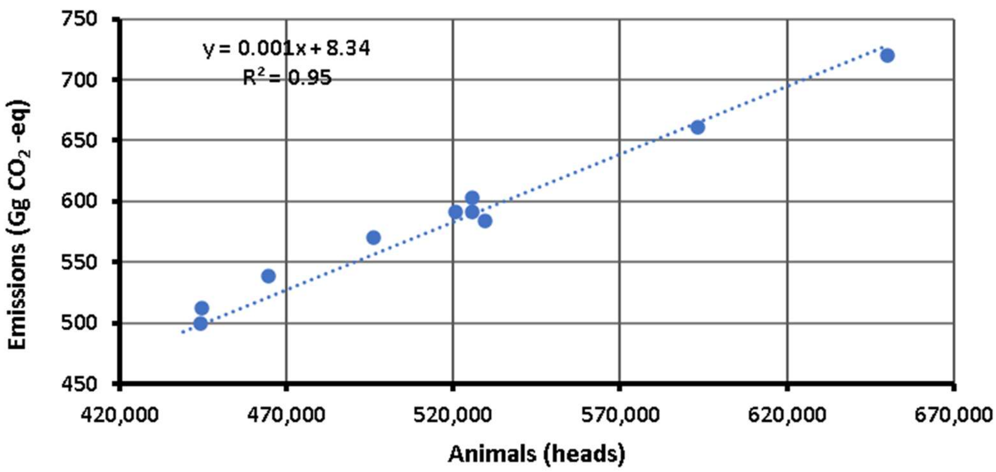

Figure 3. Linear regression analysis for predicting total GHG emissions (Tier 1) based on animals' numbers.

Further to our analysis, GHG emissions were also estimated at the regional (prefecture) level (Figure 4) for the following years: 2011 (initiation of the examined period), 2016 (the middle of the period), and 2021 (end of the period). The region (prefecture) of Thessaly possessed the first position in the respective emissions, followed by the regions of Central Macedonia, Eastern Macedonia and Thrace, Western Greece, and Epirus during the examined years. Between the years 2011 and 2021, an increase of 81.0%, 69.5%, 67.0%, 59.6%, and

39.6% in the total GHG emissions in the regions of Western Macedonia, Epirus, Thessaly, Western Greece, and Central Greece was noted, respectively. Although in the region of Crete, the GHG emissions were noted to be relatively low compared to the rest regions, an increase of 108% was observed between the years 2011 and 2021. In addition, a decrease of 56.8%, 4.8%, and 0.2% in emissions was noted in 2021 in the regions of Attica, North Aegean, and South Aegean, respectively, compared to those emissions estimated at the beginning of the studied period (2011).

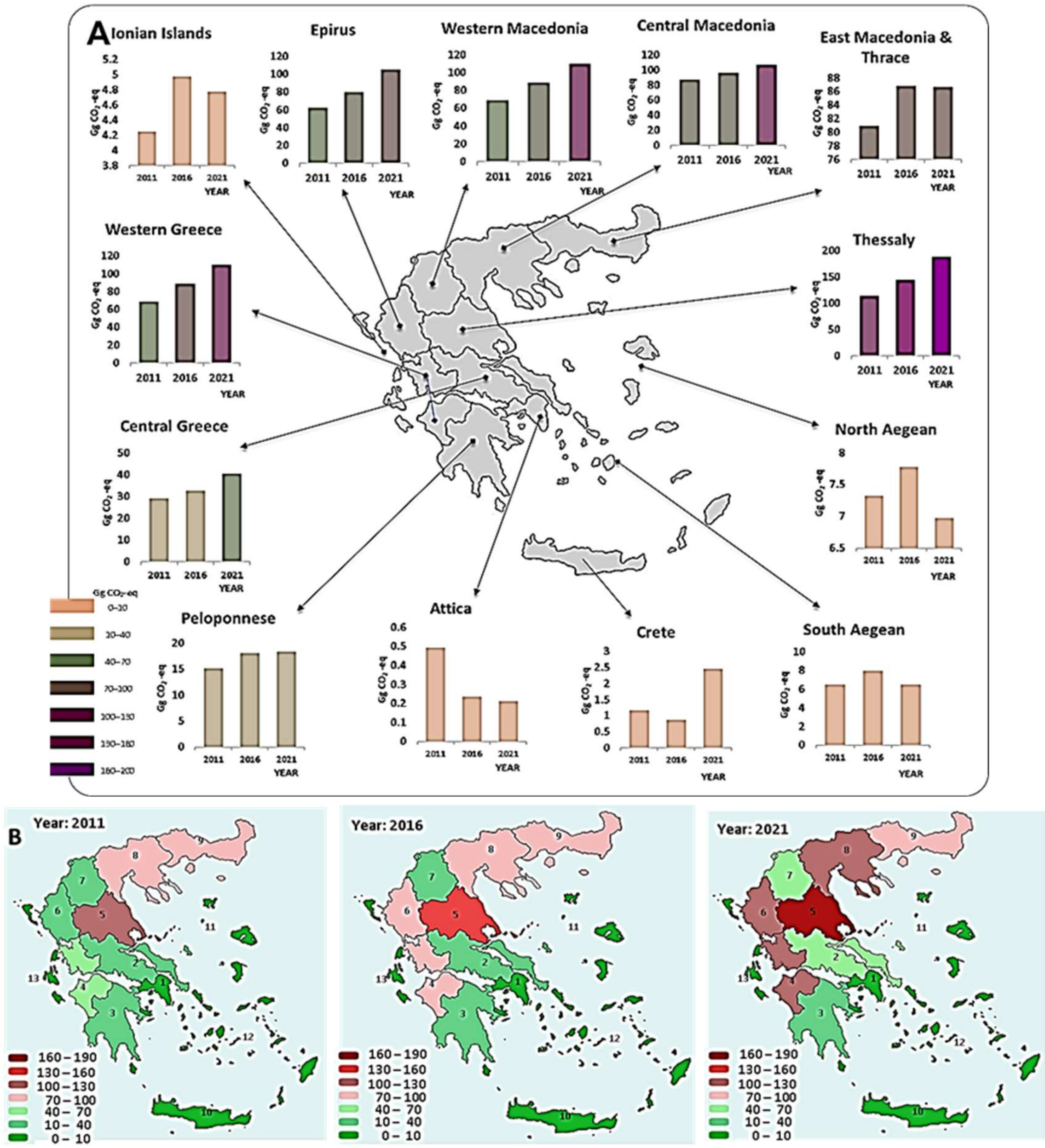

Figure 4. GHG emission changes (Tier 1) at the region (prefecture) level for the studied years (2011, 2016, and 2021). (**A**) Map on which the respective changes in GHG emissions are presented with absolute values (Gg CO_2-eq) for each studied region (prefecture). (**B**) Emissions' changes in each region (prefecture) are presented through a tessellated map projection. Regions: 1: Attica; 2: Central Greece; 3: Peloponnese; 4: Western Greece; 5: Thessaly; 6: Epirus; 7: Western Macedonia; 8: Central Macedonia; 9: Eastern Macedonia and Thrace; 10: Crete; 11: North Aegean; 12: South Aegean; 13: Ionian Islands.

We further estimated the GHG emissions for the studied period using a Tier 2 methodology. According to the estimations (Table 3), the highest increase was observed between the years 2012 and 2013, followed by that between the years 2019 and 2020. An increase of 43% in the total estimated emissions was noted between the years 2011 and 2021 (the beginning and the end of the studied period). Methane emissions were also the highest contributor to the estimated total GHG emissions during the whole study period. In addition, the estimated emissions using a Tier 2 methodology were lower (5.7–11.9%) compared to those estimated by the Tier 1 approach during the studied period. Total emissions per beef head estimated by the Tier 2 methodology were lower compared to those estimated by Tier 1, ranging from 9×10^{-4} to 10.9×10^{-4} Gg CO_2-eq. Similar to the Tier 1 approach, adult females (>2 years old) contributed more to total absolute emissions (Supplementary File S1: Tables S3 and S4). The respective total GHG emission intensity during the studied period ranged from 5.68 to 19.93 Kg CO_2-eq (Supplementary File S1: Table S3).

Table 3. Estimations of GHG emissions (Gg CO_2-eq) of the beef sector using the Tier 2 methodology for the period 2011–2021.

Year	Total GHG Emissions (Gg CO_2-eq)	Total GHG Emissions Change between Years	Tier 2 vs. Tier 1 (Difference in Each Year)	CH_4 Emissions (Gg CO_2-eq)	NO_2 Emissions (Gg CO_2-eq)
2011	460.5	-	−7.9%	450.8	9.7
2012	394.5	−14.3%	−11.9%	386.1	8.4
2013	480.5	21.8%	−6.2%	470.4	10.1
2014	508.1	5.7%	−5.7%	497.5	10.6
2015	536.7	5.6%	−5.9%	525.5	11.2
2016	567.2	5.7%	−6.0%	555.3	11.9
2017	550.6	−2.9%	−6.9%	539.0	11.6
2018	545.5	−0.9%	−7.8%	534.0	11.5
2019	532.0	−2.5%	−8.9%	520.8	11.2
2020	605.6	13.8%	−8.3%	592.8	12.8
2021	658.6	8.8%	−8.6%	644.7	13.9
Average	530.9	-	-	519.7	11.2

We further attempt to predict total GHG emissions using the animal numbers as predictors and based on the estimated emissions. The regression analysis results and the predicted equation between the estimated total GHG emission values (Tier 2) and the number of animals at the national level are shown in Figure 5. The estimated R^2 of the model was 0.87 ($p < 0.001$), the constant (a) of the regression equation was estimated at 18.81, and the slope (b) of the regression line was estimated at 0.001 ($p < 0.001$).

Finally, four scenarios were explored to examine potential fluctuations in total GHG emissions using a Tier 2 approach (Table 4). The GHG emissions of the latest investigated year (2021) were used as a baseline scenario. In the first scenario (S_I; Table 4), changes in the population number of fattening animals are considered. Specifically, a 25% increase in the population of this animal category caused an increase in the overall GHG emissions compared to the corresponding emissions of the baseline scenario (668.1 vs. 658.6 Gg CO_2-eq).

The second scenario (S_II) (an increase in the animals reared intensively and a decrease in those reared semi-extensively) showed a 9.3% reduction in overall GHG emissions compared to the baseline scenario. Considering the opposite scenario (S_3), therefore, a decrease in animals reared intensively and an increase in those reared semi-extensively resulted in an increase in emissions of 14.5% in comparison to the respective emissions of 2021 (baseline). Finally, the increase in the fattening period (S_IV) resulted in a slight increase in the respective total GHG emissions (%).

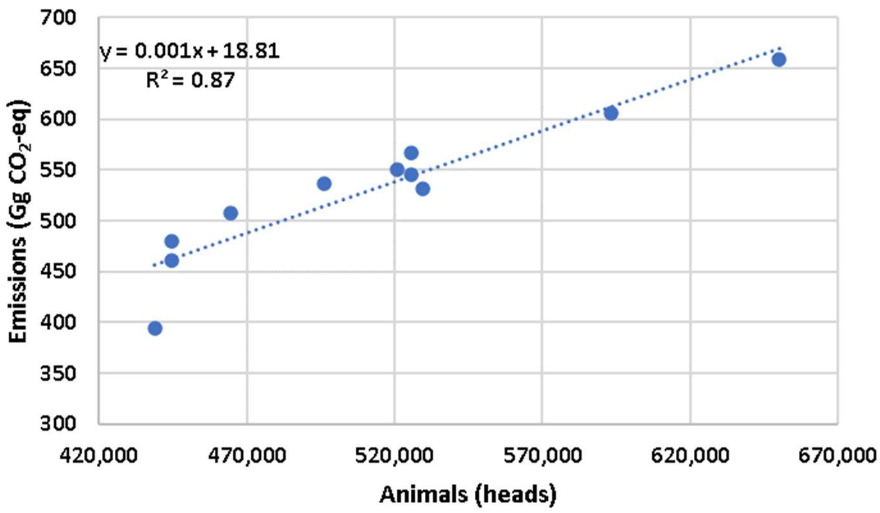

Figure 5. Linear regression analysis for predicting total GHG emissions (Tier 2) based on animals' numbers.

Table 4. Results of different estimated scenarios for exploring changes in total GHG emissions of the beef sector at the national level.

Scenario	Total GHG Emissions (Tier 2; Gg CO_2-eq)	Difference
Baseline (year: 2021)	658.6	---
S_I (an increase of 25% in fattening animals)	668.1	1.4%
S_II (total population: 60% intensively/40% semi-extensively)	606.0	−7.9%
S_III (total population: 10% intensively/90% semi-extensively)	693.7	5.3%
S_IV (change in fattening period: two-month increase)	690.3	4.8%

4. Discussion

Livestock is considered one of the important pillars of the agricultural economy. Projections regarding population growth report that it will reach over 9 million in 2050, incrementally influencing human needs for animal products [16,22]. To meet these needs, the livestock industry will need more natural resources, which will have a greater impact on the environment [16]. Therefore, the GHG emissions derived from livestock production are of major importance as they significantly contribute to the total anthropogenic GHG emissions [2,3,16]. Among livestock sectors, the beef sector is considered the main contributor to GHG emissions [3,16]. The present study reports, for the first time, to the best of our knowledge, a retrospective evaluation of the GHG emissions of the beef sector (exclusively meat-oriented reared animals) in Greece during an eleven-year period (from 2011 to 2021). Both the Tier 1 and Tier 2 approaches were followed according to the IPCC guidelines [17,18]. In addition, hypothetical strategies were explored for self-efficiency in beef products and eliminating the sector's GHG emissions at the national level.

According to our findings, the estimated total GHG emissions increased from 2011 to 2021, regardless of which estimation methodology (Tier 1 or Tier 2) was implemented. This is in line with our expectations owing to the respective increase in the animal population. The observed increase in emissions within the studied period is explained by the respective changes in animal populations. However, the estimated emissions using a Tier 2 methodology, either estimated as absolute emissions or intensity (per Kg of produced beef meat), were lower than those estimated using Tier 1. This is reasonable because of the different equation approaches that the two methodologies follow to calculate specific parameters used for estimation, especially those related to emission factors. The Tier 1 methodology is considered the simplest approach for estimating GHG emissions, and it focuses mainly on the number of animals and on region-defined emission factors either for methane or nitrous oxide emissions for the specific examined animal species. Therefore, the estimated emissions reflect changes only in animal numbers, regardless of age and/or the production stage of animals' categories or territory-level characteristics [18,23]. Contrarily, Tier 2 inventory focuses on detailed data for estimating emissions factors related to methane and nitrous oxide emissions more precisely, allowing for a more accurate approach. Such data consider information regarding herd structure and the respective animals' numbers (classification of different types of livestock categories), production system, animals' weight, animals' diet (i.e., feed digestibility), animals' energy requirements, animal performance (daily growth, weight intake, etc.), in each animal category to estimate their emissions [17,18]. Therefore, Tier 2 inventories intend to capture the estimation of GHG emissions more accurately. Since Tier 1 methodology considers the animals' number and general pre-determined regional emission factors as the only parameters for further estimations, it is obvious that the methodology may overestimate the result compared to Tier 2 inventory. However, according to a previous study [23], in some developing countries, higher Tier 2 emission factors compared to the respective Tier 1 factors have been reported, leading to higher total emissions than those of the Tier 1 inventory. According to the IPCC recommendations, all countries should use higher Tier inventories for GHG estimations as they provide a more precise result. Especially for the beef sector, a Tier 2 inventory is highly preferred, especially when GHG estimations refer to the national level [18].

At the prefecture level, all regions showed fluctuations in GHG emissions during the examined years. Except for three prefectures (Attica, North, and South Aegean), an increase in emissions between 2011 and 2021 was noted (Figure 4A). Attica is mainly an urban and industrialized region, while South and North Aegean prefectures are more tourism-oriented areas and at a greater distance from continental Greece, and therefore, livestock is not very well developed. On the other hand, specific prefectures, namely Western Greece, Thessaly, Epirus, and Central Macedonia, showed an obvious increase in the estimated emissions during the targeted years. These regions are the typical areas where most of the beef-oriented livestock units are located. The observed higher emissions are due to an increase in the number of animals reared in these areas. However, the latter is not a result of a certain national policy (i.e., an increase in self-sufficiency), but it can be explained by the European Community subsidies that are given to the sector, and specifically to measures enforcing the retention of suckling cows and autochthonous (local) breeds. Therefore, if mitigating measures are to lower GHG emissions, the aforementioned regions should be given specific and primary attention.

We further conducted a regression analysis in an attempt to predict GHG emissions using either Tier 1 or Tier 2 methodology and having as an input easily accessible parameters (i.e., the number of animals). The estimated R^2 parameters in both cases revealed a strong ($R^2 < 0.7$) predictive ability [24]. Similar approaches have been previously reported as proxies for estimating either total or methane emissions [25,26], showing either moderate or strong predictive ability ($0.5 < R^2 < 0.7$; $R^2 < 0.7$). In these estimations, the carbon footprint (total CO_2-eq) was predicted using the production level (cattle heads/year) of the targeted area. In any case, the estimated regression equations reported here can be used as a proxy for an easy approach to estimating a country's GHG emissions before applying any further complicated equations that lead to more elaborate calculations.

Regarding the total GHG emissions, the attempt to compare our findings with those of previous studies reveals some challenges and constraints. Although many studies have reported the environmental impact of beef livestock, different boundaries and/or different functional units are used to report the estimated emissions. Such variability in functional units and boundaries is of utmost importance because it influences the final estimations, as reported by previous studies [27,28]. According to Andretta et al. [27], proceeding with further transformations between different functional units could not always lead to precise results. Previous studies report a range of GHG emissions per kg of beef carcass from 17 to 37 kg CO_2-eq [29–32]. In addition, a previous study [33] reported an estimated GHG intensity of 22 kg CO_2-eq/kg carcass for beef production in southern Alberta (Canada). Another study [34] also reports a great variation in carbon footprint for the European beef production systems (16.0–27.3 kg CO_2/kg carcass). Therefore, our estimated emissions intensities for the Greek beef sector are in accordance with the ranges of emissions reported in previous studies. However, it should be noted that the beef production (kg of produced carcasses) in Greece was lower compared to other reported areas (i.e., Western or Eastern Europe, North America, South Asia, and Oceania) [3]. The noted increase in the emission intensities between the examined years is a result of the increase in the total reared population in the sector and a diminution in the total produced (Kg) beef carcass (Table S3). In addition, a decrease in the number of slaughtered animals for beef production during the studied period was noted (Table S3), which explains the observed decrease in the produced carcass quantity. Thus, when production is reduced, the intensity of the emissions is increased. It seems that farmers prefer to keep the animals alive to earn the respective subsidies that are given in the sector rather than slaughtering them. Unannounced inspections (audits) that are made by the authorities to check the animal census of farmers could also enhance such practices. In addition, among the animals reared for beef production, there are animals that belong to autochthonous breeds. These farmers receive an extra subsidy for keeping such breeds. Due to this extra aid, many farmers increased the number of animals belonging to this category during the last decade. A noteworthy example is the Brachyceros breed, whose population rose by 2.5-fold between 2011 and 2021, according to DAD-IS [35]. It was also observed that during the studied period, the emissions derived from adult females increased, meaning that the number of respective animals also increased. This can also be explained by the fact that farmers who retain adult female cows that give birth to calves within each current year of aid receive extra financial aid. Therefore, many farmers prefer to keep the adult female population alive rather than slaughter them. During the studied period, many epizootic diseases (i.e., lumpy skin disease) had affected the sector, leading consequently to the decapitation of many herds without these animals being computed as carcasses for human consumption. Therefore, farmers, apart from the incentive of subsidies, had to retain animals to renew their herds, and, thus, carcass beef production was diminished. Although subsidies aim to strengthen the sector, it seems that the farmers opt for larger herds to maximize their income, as these subsidies are structured to reward the number of animals kept alive rather than reinforce the quantity of beef produced. Certain policies should be designed by the stakeholders and official authorities to diminish the GHG intensities of the sector without reducing its production. Further to the reported emissions of the sector, an Irish study [36] estimated the GHG emissions from pasture-based beef cattle production using, however, a different functional unit, noting a range from 7.6 to 11.3 kg CO_2-eq/kg live weight/year. Furthermore, different emissions have been reported for Swedish ranch beef cattle production (28.6 CO_2-eq/kg of bone-free beef meat), for Brazilian and USA Midwestern pasture-based systems (42.45 and 43.7 CO_2-eq/kg of bone-free beef meat, respectively) [37]. According to a Swedish report, the range of greenhouse gases derived from the beef sector was 22–40 kg CO_2-eq/kg meat [38], while in Japan, the respective emissions have been reported to be 32 kg CO_2-eq/kg meat [31], and in Ireland, 28–32 kg CO_2-eq/kg meat [39]. In China, during the period 1961–2010, the methane and nitrous oxide emissions from the beef sector increased from 2.18 Mt to 5.86 Mt and from 7.93 kt to 29.56 kt, respectively, because of the animals' growingpopulation and changes in various management practices [40]. Finally, in the USA, the beef sector contributes 136.5 MMT CO_2-eq [41].

Mitigating the emissions derived from the livestock sector is of great importance at the country level. The choice of implemented strategies is primarily a matter of state and stakeholder policies, but herein we tried to explore four major challenges of the sector that are related to (a) an increase in self-sufficiency in the beef sector (S_I); (b) the intensification of the sector as a proxy for adaptation of extensive systems to climate change (S_II); (c) a shift in favor of extensive reared populations as a means of lowering livestock's input and increasing welfare (S_III); and (d) an increase in the fattening period (2 months increase) as a proxy to produce heavier carcasses. Improving the final productivity by increasing the fattening population (i.e., through imports of beef calves for further fattening at the national level) resulted in an increase of 1.4% compared to the baseline, reflecting that if secure and well-organized policies and specific aid are provided by the state, then self-sufficiency can be increased with a slight change in GHG emissions. In addition, an increase in the number of animals reared in intensive systems over extensively could lead to a decrease in emissions of approximately 8%. This strategy could, also, form a solution for the stakeholders in the sector to adapt their farming systems to climate change because extensive systems are more vulnerable to extreme climatic conditions. Further, a shift from intensive systems to more extensive systems as a proxy firstly, to eliminate livestock inputs (i.e., minimize the cost of feeds) and, secondly, to enhance animal welfare seems to lead to more emissions (5%), mainly due to manure management practices, because in extensive systems the manure is spread daily in pastures, while in intensive systems manure management systems refer mainly to solid storage where emissions are eliminated compared to the spread [42]. Finally, increasing the fattening period to ameliorate the final carcass weight seems to influence GHG emissions, with a similar level of increase in emissions as in S_III. In any case, it should be mentioned that according to national or regional priorities (either of state or farmer associations), the tested ad hoc scenarios could be potentially implemented in the studied sector. They can also serve as case study examples for future implications that policymakers could examine further.

Any possible uncertainties in the total estimated GHG emissions (Tier 1 or 2) are primarily driven by the uncertainties in the used emission factors (EFs) and the possible assumptions made during estimations [17,18]. Uncertainties can also be derived from the animal population. However, the data used (beef cattle population) were derived from an administrative authority (OPEKEPE) of the Greek Ministry of Agriculture and Rural Development, which is responsible for the official recording of livestock populations every year for further E.U. subsidy approval. In addition, other related databases with livestock numbers (i.e., derived from the Hellenic Statistical Authority) do not report the number of fattening calves or the productive orientation. However, the data used herein report the productive orientation, sex, and age of the animals. Therefore, we assume that the uncertainty in the data is minimal. Furthermore, zootechnical indexes related, i.e., to replacement rate or fattening period, follow the officially reported indexes by FAO at the territory level [20]. Animals' weights related to meat-type breeds reared at the national level were retrieved from previously conducted studies [14], reflecting minimal uncertainty. The fact that the beef sector at the country level is mainly conducted in mountainous areas under (semi-)extensive systems [12,13] can explain the choice of 70% of animals' livestock to be characterized as (semi-) extensive production systems. Any possible uncertainty about this percentage, according to the authors' knowledge, is minimal. In any case, any over- or underestimation in GHG emissions is captured by trends that are depicted by the explored scenarios (S-II, S-III, S_IV). However, such an approach (Tier 2) cannot be followed during the analysis at the prefecture level due to missing information as well as differences in geographical characteristics; therefore, only the Tier 1 approach was followed. Future studies at the territory level could focus on capturing more precise data related to diets to improve the precision of EFs estimations, as conducted in previously reported studies [43].

5. Conclusions

GHG emissions from the beef sector in Greece showed an increasing trend over the studied period (2011–2021). Although both the Tier 1 and Tier 2 methodologies captured similar trends, the Tier 2 estimations revealed lower emissions between years, mainly due to the different and more elaborate computational approaches that the methodology follows. At the prefecture level, fluctuations in emissions (either an increase or decrease) were noted between the examined years in each area. However, specific regions showed a higher increase in emissions as a result of an increase in animal population due to specifically implemented subsidies in the beef sector. The noted increase in emissions derived from the sector (both in terms of absolute values and intensities) during the examined period is of utmost importance, and further mitigation strategies should be considered. The equations derived from the regression analysis could be used as an easy tool for capturing future emissions before proceeding with more elaborate computations according to the IPCC guidelines. The different scenarios explored showed a small to moderate change in GHG emissions, depending on the parameters that were changed. The explored scenarios could serve as a pilot case study to assist stakeholders, depending on national priorities, to improve the sector's sustainability in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments10080144/s1, Supplementary File S1: Table S1: Animals number (beef cattle; heads) reared in Greece between 2011 and 2021. Table S2: Animals number (beef cattle; heads) at the prefecture level (regional) during the examined years (2011, 2016, 2021). Table S3: Total GHG emissions per beef head (Gg CO_2-eq) and per produced beef carcass (Kg CO_2-eq/Kg beef carcass) during the examined period (2011–2012) using Tier 1 and 2 methodologies. Table S4: Total GHG emissions (Gg CO_2-eq) for each animal category estimated by using Tier 1 and 2 methodologies during the period 2011–2021. Supplementary File S2: Excel application for estimating GHG emissions of the beef sector using Tier 1 and Tier 2 equations. Supplementary File S3: Gross Energy (GE) calculation for methane emission estimations from enteric fermentation using Tier 2 inventory.

Author Contributions: Conceptualization, G.P.L.; methodology, G.P.L. and I.B.; software, S.A., K.A. and G.P.L.; validation, G.P.L. and S.A.; formal analysis, S.A.; investigation, S.A. and K.A.; resources, G.P.L.; data curation, S.A.; writing—original draft preparation, S.A. and K.A.; writing—review and editing, G.P.L. and I.B.; visualization, S.A. and G.P.L.; supervision, G.P.L.; project administration, G.P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The used data are publicly available. Sources are mentioned in the reference list. Curated data are also available by the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Food and Agriculture Organization of the United Nations FAO. *More Fuel for the Food/Feed Debate*; FAO: Rome, Italy, 2022; Available online: https://www.fao.org/3/cc3134en/cc3134en.pdf (accessed on 2 May 2023).
2. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. *Tackling Climate Change through Livestock—A Global Assessment of Emissions and Mitigation Opportunities*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013; ISBN 978-92-5-107920-1.
3. Rojas-Downing, M.M.; Nejadhashemi, A.P.; Harrigan, T.; Woznicki, S.A. Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag.* **2017**, *16*, 145–163. [CrossRef]
4. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423)*; United Nations: New York, NY, USA, 2019.
5. OECD. *Making Better Policies for Food Systems*; OECD Publishing: Paris, France, 2021. [CrossRef]
6. Clune, S.; Crossin, E.; Verghese, K. Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* **2017**, *140*, 766–783. [CrossRef]
7. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987. [CrossRef] [PubMed]

8. Searchinger, T.; Waite, R.; Hanson, C.; Ranganathan, J.; Dumas, P.; Matthews, E. *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*; World Resources Institute: Washington, DC, USA, 2019; ISBN 978-1-56973-963-1.
9. Bustamante, M.M.C.; Nobre, C.A.; Smeraldi, R.; Aguiar, A.P.D.; Barioni, L.G.; Ferreira, L.G.; Longo, K.; May, P.; Pinto, A.S.; Ometto, J.P.H.B. Estimating greenhouse gas emissions from cattle raising in Brazil. *Clim. Change* **2012**, *115*, 559–577. [CrossRef]
10. Cederberg, C.; Persson, U.M.; Neovius, K.; Molander, S.; Clift, R. Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. *Environ. Sci. Technol.* **2011**, *45*, 1773–1779. [CrossRef] [PubMed]
11. FAOSTAT. Food and Agricultural Organization of the United Nations. Available online: https://www.fao.org/faostat/en (accessed on 3 May 2023).
12. General Secretariat of Research and Technology. Agri-Food Platform Description of ETAK Strategic Actions in Animal Production for the Years 2016–2017. Available online: http://www.gsrt.gr/Financing/Files/ProPeFiles161/%CE%96%CF%89%CE%B9%CE%BA%CE%AE%20%CF%80%CE%B1%CF%81%CE%B1%CE%B3%CF%89%CE%B3%CE%AE.pdf (accessed on 30 April 2023).
13. Zervas, G. Quantifying and optimizing grazing regimes in Greek mountain systems. *J. Appl. Ecol.* **1998**, *35*, 983–986. [CrossRef]
14. Nikolaou, K.; Koutsouli, P.; Bizelis, I. Evaluation of Greek Cattle Carcass Characteristics (Carcass Weight and Age of Slaughter) Based on SEUROP Classification System. *Foods* **2020**, *9*, 1764. [CrossRef]
15. Masouras, P.K.; Nikolaou, K.; Laliotis, G.P.; Koutsouli, P.; Bizelis, I. Relationship between meat quality characteristics, intramuscular fat and marbling in Greek cattle carcasses. *Adv. Anim. Vet. Sci.* **2022**, *10*, 506–513. [CrossRef]
16. Cusack, D.F.; Kazanski, C.E.; Hedgpeth, A.; Chow, K.; Cordeiro, A.L.; Karpman, J.; Ryals, R. Reducing climate impacts of beef production: A synthesis of life cycle assessments across management systems and global regions. *Glob. Change Biol.* **2021**, *27*, 1721–1736. [CrossRef]
17. IPCC. *Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Hayama, Japan, 2006; ISBN 4-88788-032-4.
18. IPCC. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; IGES: Hayama, Japan, 2019; ISBN 978-4-88788-032-4.
19. Greek Payment Authority of Common Agricultural Policy (C.A.P.) Aid Schemes (OPEKEPE). Available online: https://www.opekepe.gr/en/ (accessed on 18 March 2023).
20. FAO. Global Livestock Environmental Assessment Model, Version 2.0. In *Model Description*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2018.
21. IBM Corp. *IBM SPSS Statistics for Windows, Version 26.0*; IBM Corp.: Armonk, NY, USA, 2019.
22. Alexandratos, N.; Bruinsma, J. World Agriculture towards 2030/2050: The 2012 Revision. In *ESA Working Paper 2012, No. 12-03*; FAO: Rome, Italy, 2012.
23. Wilkes, A.; Reisinger, A.; Wollenberg, E.; Van Dijk, S. Measurement. Reporting and Verification of Livestock GHG Emissions by Developing Countries in the UNFCCC: Current Practices and Opportunities for Improvement. In *CCAFS Report No. 17, CGIAR Research Program on Climate Change*; Agriculture and Food Security (CCAFS) and Global Research Alliance for Agricultural Greenhouse Gases (GRA): Wageningen, The Netherlands, 2017.
24. Moore, D.S.; Notz, W.I.; Flinger, M.A. *The Basic Practice of Statistics*, 6th ed.; W.H. Freeman and Company: New York, NY, USA, 2013; p. 138.
25. Atzori, A.S.; Lunesu, M.F.; Correddu, F.; Sau, P.; Cannas, A. Carbon footprint of dairy sheep and goat farms in Mediterranean areas. In Proceedings of the 8th IDF International Symposium on Sheep, Goat and Other Non-Cow Milk, Virtual, 4–6 June 2020.
26. Atzori, A.S.; Lunesu, M.F.; Sau, P.; Pill, D.; Pacchioli, M.T.; Cannas, A. Carbonsheep: AGIS tool based on simplified Life Cycle Assesment to benchmark and spatialize the carbon footprint of sheep farms. In Proceedings of the 72nd Annual Meeting of the European Federation of Animal Science, Davos, Switzerland, 30 August–3 September 2021.
27. Andretta, I.; Hickmann, F.M.W.; Remus, A.; Franceschi, C.H.; Mariani, A.B.; Orso, C.; Kipper, M.; Létourneau-Montminy, M.-P.; Pomar, C. Environmental Impacts of Pig and Poultry Production: Insights From a Systematic Review. *Front. Vet. Sci.* **2021**, *8*, 750733. [CrossRef]
28. Akamati, K.; Laliotis, G.P.; Bizelis, I. Comparative Assessment of Greenhouse Gas Emissions in Pig Farming Using Tier Inventories. *Environments* **2022**, *9*, 59. [CrossRef]
29. Johnson, D.E.; Phetteplace, H.W.; Seidl, A.F.; Schneider, U.A.; McCarl, B.A. Management variations for US beef production systems: Effects on greenhouse gas emissions and profitability. In Proceedings of the 3rd International Methane and Nitrous Oxide Mitigation Conference, Beijing, China, 17–21 November 2003; Coal Information Institute: Beijing, China; pp. 953–961.
30. Casey, J.W.; Holden, N.M. Analysis of greenhouse gas emissions from the average Irish milk production system. *Agric. Syst.* **2005**, *86*, 97–114. [CrossRef]
31. Ogino, A.; Orito, H.; Shimada, K.; Hirooka, H. Evaluating environmental impacts of the Japanese beef cow–calf system by the life cycle assessment method. *Anim. Sci. J.* **2007**, *78*, 424–432. [CrossRef]
32. Vergé, X.P.C.; Dyer, J.A.; Desjardins, R.L.; Worth, D. Greenhouse gas emissions from the Canadian beef industry. *Agr. Syst.* **2008**, *98*, 126–134. [CrossRef]
33. Beauchemin, K.A.; Janzen, H.H.; Little, S.M.; McAllister, T.A.; McGinn, S.M. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. *Agric. Syst.* **2010**, *103*, 371–379. [CrossRef]

34. Nguyen, T.L.T.; Hermansen, J.E.; Mogensen, L. Environmental consequences of different beef production systems in the EU. *J. Clean. Prod.* **2010**, *18*, 756–766. [CrossRef]
35. DAD-IS. Domestic Animal Diversity Information System. Available online: https://www.fao.org/dad-is/en/ (accessed on 12 July 2023).
36. Casey, J.W.; Holden, N.M. Quantification of GHG emissions from sucker-beef production in Ireland. *Agricultural Systems* **2006**, *90*, 79–98. [CrossRef]
37. Lynch, J.; Pierrehumbert, R. Climate Impacts of Cultured Meat and Beef Cattle. *Front. Sustain. Food Syst.* **2019**, *3*, 2019. [CrossRef] [PubMed]
38. Sonesson, U.; Cederberg, C.; Berglund, M. Greenhouse Gas Emissions in Beef Production. Decision Support for Climate Certification. Klimatmarkning for Mat. Report 2009:4. Available online: https://www.klimatmarkningen.se/wp-content/uploads/2009/12/2009-4-beef.pdf (accessed on 15 May 2023).
39. Casey, J.W.; Holden, N.M. GHG emissions from conventional, agri-environmental and organic Irish suckler beef units. *J. Environ. Qual.* **2006**, *35*, 231–239. [CrossRef]
40. Gao, Z.; Zhi, L.; Yang, Y.; Ma, W.; Liao, W.; Li, J.; Roelcke, M. Greenhouse gas emissions from the enteric fermentation and manure storage of dairy and beef cattle in China during 1961–2010. *Environ. Res.* **2014**, *135*, 111–119. [CrossRef]
41. EPA 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020. U.S. Environmental Protection Agency, EPA 430-R-22-003. Available online: https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (accessed on 21 May 2023).
42. Grossi, G.; Goglio, P.; Vitali, A.; Williams, A.G. Livestock and climate change: Impact of livestock on climate and mitigation strategies. *Anim. Front.* **2019**, *9*, 69–76. [CrossRef] [PubMed]
43. Eugène, M.; Sauvant, D.; Nozière, P.; Viallard, D.; Oueslati, K.; Lherm, M.; Mathias, E.; Doreau, M. A new Tier 3 method to calculate methane emission inventory for ruminants. *J. Environ. Manag.* **2019**, *231*, 982–988. [CrossRef] [PubMed]