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Assessing the contribution of enteric methane emissions from Uruguayan livestock to global warming using an alternative metric

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Abstract

For years, livestock production has been accused of having a supposed impact on global warming. This message permeated broad sectors of public opinion. Recently, questions have arisen about the metrics used to determine the potential contribution of different greenhouse gases. The differences between the atmospheric decays of short- and long-lived climate forcers (SLCFs and LLCFs) and the inadequacy of single-pulse metrics, such as the global warming potential (GWP), to describe sustained emission sources over time, prompted the development of new estimators to compare the warming potential of gases other than CO_2. Alternatives such as GWP* show a considerable reduction in the contribution of SLCFs compared to GWP_{100}. This article assesses the differential warming contribution of enteric methane emissions from Uruguayan cattle from 1900 to 2023 using GWP and GWP* and their potential usefulness in negotiating future emission reduction commitments. Data on livestock population and feed were used to calculate annual feed intake and methane emissions. The total cumulative emissions, as calculated using the GWP* method, represented 56% of the CO_2-equivalent value estimated using the traditional metric (1,139 versus 2,027 Mt CO_2e). Furthermore, the downward trend in annual CO_2 warming-equivalent emissions over the past three decades (-60.6%) has been accompanied by a significant reduction in emissions intensity (-13.0%). Considering GWP* as an additional metric can contribute to Uruguay's positioning for future commitments and provide evidence of its compliance.

Keywords: climate change, enteric methane, global warming potential, GWP*, Uruguayan livestock emissions

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Estimación de la contribución de las emisiones de metano entérico de la ganadería uruguaya al calentamiento global utilizando una métrica alternativa

Resumen

Durante años, la ganadería ha sido culpada por su supuesto impacto en el calentamiento global. Este mensaje permeó a amplios sectores de la opinión pública. Recientemente han surgido cuestionamientos a las métricas utilizadas para determinar la contribución potencial de los diferentes gases de efecto invernadero. Las diferencias entre las desintegraciones atmosféricas de forzantes climáticos de vida corta y larga (FCVC y FCVL) y la insuficiencia de métricas de pulso único, como el potencial de calentamiento global (GWP), para describir fuentes de emisión sostenidas en el tiempo, impulsaron el desarrollo de nuevos estimadores para comparar el potencial de calentamiento de gases distintos al CO_2. Alternativas como el GWP* muestran una reducción considerable de la contribución de FCVC frente al GWP_{100}. Este artículo evalúa la contribución diferencial de las emisiones de metano entérico del ganado uruguayo desde 1900 a 2023 usando GWP y GWP* y su potencial utilidad en la negociación de compromisos futuros de reducción de emisiones. Datos de existencias de ganado y alimento fueron usados para estimar consumo y emisiones de metano. Las emisiones totales acumuladas utilizando el GWP* representaron el 56% del valor de CO_2-equivalente estimado por la métrica tradicional (1.139 frente a 2.027 Mt de CO_2e). Además, la reducción de las emisiones anuales de CO_2 calentamiento-equivalente en las últimas tres décadas (-60,6%) ha sido acompañada por una importante reducción en la intensidad de emisiones (-13,0%). La consideración de GWP* como métrica adicional puede contribuir al posicionamiento de Uruguay frente a compromisos futuros y proporcionar evidencia de su cumplimiento.

Palabras clave: cambio climático, metano entérico, potencial de calentamiento global, GWP*, emisiones ganadería uruguaya

Avaliando a contribuição das emissões de metano entérico da pecuária uruguaia a o aquecimento global usando uma métrica alternativa

Resumo

Durante anos, a pecuária foi acusada de ter um suposto impacto no aquecimento global. Essa mensagem permeou amplos setores da opinião pública. Recentemente, surgiram questionamentos sobre as métricas usadas para determinar a contribuição potencial dos diferentes gases de efeito estufa. As diferenças entre os decaimentos atmosféricos de fatores de força climática de curta e longa vida (FCCV e FCLV) e a inadequação de métricas de pulso único, como o potencial de aquecimento global (GWP), para descrever fontes de emissão sustentadas ao longo do tempo levaram ao desenvolvimento de novos estimadores para comparar o potencial de aquecimento de gases diferentes do CO_2. Alternativas como o GWP* mostram uma redução considerável na contribuição dos FCCV em comparação ao GWP100. Este artigo avalia a contribuição diferencial das emissões entéricas de metano do gado uruguaio de 1900 a 2023 usando GWP e GWP* e sua potencial utilidade na negociação de compromissos futuros de redução de emissões. Dados do rebanho e do alimento foram usados para estimar o consumo e as emissões de metano. As emissões acumuladas totais, calculadas pelo método GWP*, representou 56% do valor de CO_2-equivalente estimado pela métrica tradicional (1.139 versus 2.027 Mt CO_2e). Além disso, a tendência de queda nas emissões anuais de CO_2 aquecimento-equivalente nas últimas três décadas (-60,6%) foi acompanhada por uma redução significativa na intensidade das emissões (-13,0%). Considerar o GWP* como métrica adicional pode contribuir para o posicionamento do Uruguai em relação a compromissos futuros e fornecer evidências de seu cumprimento.

Palavras-chave: mudança climáticas, metano entérico, potencial de aquecimento global, GWP*, emissões da pecuária uruguaia

1. Introduction

For decades, there has been a debate about the origins of climate change (CC) and the relationship between the emission of greenhouse gases (GHG) and global warming (GW). Found naturally in the atmosphere, GHG emissions have increased substantially since the mid-20th century due to human activity[(1)]. Although not satisfactorily settled by science and other theories have also been proposed[(2)(3)(4)(5)(6)(7)(8)(9)(10)(11)(12)], the predominant view has pointed to them as the main cause of the rise in the planet's average temperature. Initially focused on carbon dioxide (CO_2), the discussion was extended to methane (CH_4) and nitrous oxide (N_2O), aiming primarily at domestic livestock, especially ruminants, as the determining emission source. Since then, livestock production has been blamed for allegedly devastating impacts on global warming. This message permeated vast sectors of public opinion and a “long shadow” of stigmatization fell over the entire sector[(13)]. With this vision, the international community tries to reach a consensus on implementing public policies to reduce GHG emissions, including livestock emissions.

Livestock[I] has been in the Pampa biome for more than 400 years[(14)(15)]. They are long before the records of increases in CO_2 and temperature beginning in the 1950s, which gave rise to theories about anthropogenic climate change. Furthermore, enteric CH_4 emitted by livestock does not come from fossil sources; it is part of the biogenic carbon cycle captured by plants during photosynthesis and then consumed by ruminants[(16)]. IPCC[(1)] estimated global CH_4 emissions of about 727 Tg CH_4/yr (2008-2017), 51% from natural sources and 49% from human activity (bottom-up estimates). In the agriculture and waste sectors, livestock production was the largest emissions source (109 Tg CH_4/yr) dominated by enteric fermentation by about 90%. This figure accounts for 5.7% of global CO_2 equivalent anthropogenic emissions (5.0% from enteric fermentation and 0.7% from manure management).

The Uruguayan government signed the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and the Kyoto's Protocol in 2000. In compliance, the country has been committed to periodically submitting its National GHG Inventory Reports (NIR). Beginning in 1997 with the 1990 report, there have been 9 reports issued up to date with data on emissions from 16 past years. Developed by Shine and others[(17)(18)], the Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) are the commonly used metric coefficients to convert non-CO_2 GHGs into their CO_2 equivalent. Total country CH_4 emissions reached 767 Gg in 2020 from energy, AFOLU, and waste management sectors, representing 59% of total GHG emissions (CO_2e GWP_{100AR5})[(19)]. Livestock emission estimates reached 689 Gg of CH_4 (98% enteric and 2% manure), 90% of CH_4 emissions, and 53% of the country's total annual CO_2 equivalent emissions. Additionally, in the Second Nationally Determined Contribution (NDC) in 2022, within the framework of the provisions of the Paris Agreement, Uruguay committed to achieving unconditional GHG emission targets by 2030[(20)]. Concerning CH_4 emissions from energy, AFOLU, and waste management sectors, a maximum emission of 808 Gg was set for 2030. Particularly for non-dairy cattle, a commitment to reduce emissions intensity from enteric fermentation and manure management (units of CH_4/unit of beef produced) by 35% compared to 1990 was established.

These emission reduction commitments are based on the differential contribution to global warming of the different GHGs. In this context, it is important to acknowledge the criticism raised against the use of the GWP for SLCF and evaluate alternative metrics to estimate the long-term contribution of Uruguayan livestock to global warming and its evolution over time. This information can play a key role in improving the country's position in future negotiations.

[I] In this article “livestock” refers to cattle and sheep.

In this article, we assess the differential contribution to global warming of long-term enteric methane emissions from Uruguayan livestock using GWP and GWP* metrics, discuss its potential usefulness within the framework of the country's emission reduction commitments, and briefly address the implications for policy design in livestock production.

1.1 Quantifying the Contribution of Methane to Global Warming

Any emissions reduction policy not based on solid scientific evidence can have unforeseen negative consequences, both social and economic. To inform these policies, it is necessary to compare the warming potential of the different GHGs, based on their radiative forcing capacity. The most popular indicator is the GWP (Global Warming Potential).

This indicator relates the "capacity to retain energy", the radiative forcing (RF), of a unit of mass of a GHG (x) with that of CO_2(r) over a given time horizon (H), expressing it in terms of CO_2 equivalent (CO_2e or CO_2eq) (**Equation 1**)[(21)]. The radiative forcing integrated at different time horizons determines the potential contribution to global warming at that moment known as Absolute Global Warming Potential (AGWP). This does not necessarily represent the final effective warming as it depends on many other factors. The relationship between the AGWP of a certain gas with that of CO_2 for a given time horizon is known as GWP. Traditionally, future horizons of 20 and 100 years have been taken to present this relationship, although the chosen time horizon does not have a clear connection with the temperature trajectories.

The RF for a certain incremental mass of a particular GHG in the atmosphere can be estimated from its radiative efficiency and the decay function of the gas over time. The RF indicates the expected total change in the energy flux delivered to the Earth's surface because of the increased retained energy that has not dissipated into space (**Equation 2**)[(21)]. The radiative efficiency (A) is a measure of the RF increase per unit mass change of a single GHG in the atmosphere.

The radiative efficiency for each GHG decays over time in a particular way depending on its transformation rate in the atmosphere, giving place to a specific decay function. For CH_4, the decay time constant of this function (mean lifetime in the atmosphere) is 11.8 years, while for CO_2 it is centuries[(22)II]. **Figure 1**a shows the decay curves (fraction of gas remaining) after an emission pulse at time t = 0 over time T for three GHGs: methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). After 20 years, only 20% of the CH_4 emitted remains as such, while almost 40% of CO_2 is still present after 100 years.

$$GWP_x(T)= \frac{\int_0^T A_x.f_x(t)dt}{\int_0^T A_r.f_r(t)dt}$$ (**Equation 1**)[(21)]

$$RF_x(t)= A_x.f_x(t).m_x$$ (**Equation 2**)[(21)]

Where:

T: defined time horizon (years),
A_i: radiative efficiency per unit mass of gas i ($W.m^{-2}.ppb^{-1}$),
RF_i: radiative forcing of gas i ($W.m^{-2}$),
$f_i(t)$: decay function for gas i over time,
t: time since the release of gas i into the atmosphere (years),
m_i: mass of gas i released into the atmosphere at t = 0 (grams),
for i = x, r.

[II]The "mean lifetime" in an exponential decay curve corresponds to the period in which the initial quantity is reduced to 36.7% (1/e = 0.3678 79441). The "half-life" (time in which 50% of the initial amount emitted is reached) is estimated between 9 and 10 years for CH_4 and 120 years for CO_2. Both figures depend on the initial concentration in the atmosphere and other factors.

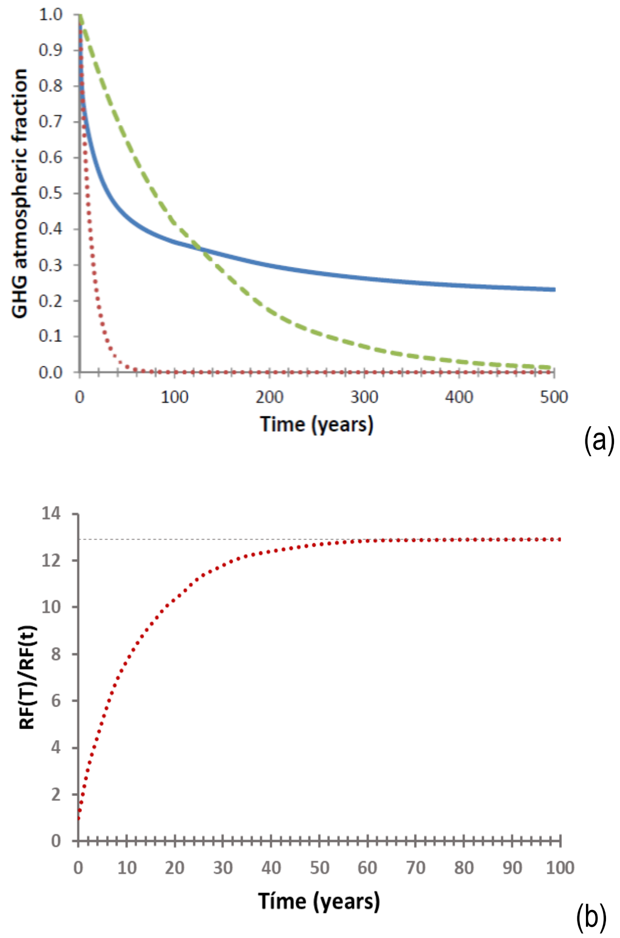


Figure 1. (a) Atmospheric decays after a pulse emission at year t = 0 for CH_4 (red dotted line), CO_2 (blue solid line) and N_2O (green dashed line); and **(b)** saturation of radiative forcing from continuous emission of CH_4 (red dotted line) at a constant rate ($RF_{(T)}/RF_{(t)}$: Accumulated RF at time T/ RF from fraction emitted in year t)

1.2 Shortcomings of a "Pulse" Emission Metric

GWP is a "single pulse" metric, a certain amount of gas issued once and only. It is inadequate to describe the impact of time-dependent emission sources, or those having a significant duration. Constant emissions of so-called short-lived climate forcing gases (e.g. CH_4) result in saturation of the radiative forcing. This saturation is determined by the dynamic balance between its emission and decay rates. A constant annual emission of methane does not determine an indefinite growth of its AGWP, since approximately at an average time of 12 years after the beginning of emissions a balance is reached between the amount of gas emitted at that time and that emitted in year 0, almost no longer present in the atmosphere. The AGWP exponential function for a continuous emission of methane at a constant rate reaches 95% of its limit after 36 years (Figure 1b)[23].

Recently, the debate regarding the appropriateness of the metrics used to determine the contributions of different GHGs to global warming has taken on greater relevance[24][25][26][27]. Differences between atmospheric decays of short- and long-lived climate forcers (SLCFs and LLCFs, respectively), the insufficiency of single pulse-type metrics (e.g. GWP) to describe time-dependent emission sources, particularly of SLCFs resulting in saturation of radiative forcing, as well as the potential misleading caused by the different time horizons led to new estimators of the warming equivalents of non-CO_2 gas emissions.

Under sustained emissions scenarios alternative metrics show a considerable reduction in the warming contribution of SLCFs with that estimated through the GWP, particularly in the case of enteric methane[28]. Forster and others[29] (AR6) highlight that the impact of constant CH_4 emission on temperature might be exaggerated by a factor of 3 to 4 when using CO_2e (GWP) estimates. In contrast, any new CH_4 emission source would be underestimated by a factor of 4 to 5 in the first 20 years following its introduction. In the same way, the impact of a reduction in CH_4 emissions would be understated. Some authors even point out that the GWP lacks some consistency, as it will invariably indicate increased warming under all scenarios where SLCF emissions rates are falling[(30)].

1.3 Alternative Emission Metrics

Many alternatives to the GWP have been proposed and discussed over the years with different data requirements and calculation complexity. Balcombe and others[(31)] report on a wide range of alternative metrics and categorize them based on key factors: CO_2 equivalency value, their physical basis, whether they are static or dynamic metrics, cumulative or end-point estimates, and their level of uncertainty. Besides the authors' recommendations of appropriate metrics for specific assessments and different time-horizons analysis, they conclude: *"The use of climate metrics in GHG estimation must be carried out with great care and the standard usage of a single global warming potential is not acceptable as it may hide key trade-offs between short and long-term climate impacts. To counter this, transparent reporting of CH_4 and CO_2 emissions is required"*[(31)].

Besides GWP, Global Temperature change Potential (GTP) developed by Shine and others[(18)] is the most used alternative metric and is included in the IPCC Assessment Reports. It is defined as the change in mean earth surface temperature after a specified time due to a pulse emission, relative to the effect from an equivalent pulse emission of CO_2. The GTP estimation incorporates some additional assumptions, such as climate sensitivity and the exchange of heat between the atmosphere and the ocean[(32)]. Consequently, this brings more uncertainty compared to GWP (± 75 vs ± 40 for GTP_{100} and GWP_{100}, respectively)[(22)].

Also, some alternatives to GTP based on a cost-effectiveness approach estimated using optimizing climate-economy models with selected set targets, like the Global Cost Potential (GCP) and the related Cost-Effective Temperature Potential (CETP) that have been proposed[(33)]. Unlike GTP, both GCP and CEPT depend on the discount rate used for estimation of net present values of GHG abatement costs relative to CO_2.

The Combined GWP (CGWP) metric, also included in the IPCC AR6[(29)], estimates the years necessary to equal the RF of a permanent change in the emission rate of an SLCF to a single emission pulse of CO_2. Unlike GWP endpoint values, that vary strongly with the time horizon, CGWP is more stable over time horizons of interest, making it especially suitable for policy goals evaluation[(34)].

Another relevant alternative metric, GWP*[(35)], evaluates the impact of a change in the emissions rate of an SLCF over a period of 20 years. It uses coefficients estimated from various atmospheric parameters to determine the direct influence of net changes of current emissions and the residual effect of the portion emitted 20 years ago. The 20-year difference introduces an average 10-year lag between changes in SLCF emission rate and their associated CO_2 equivalent calculated emissions, and the subsequent warming impact, consistent with the fact that global temperatures take at least a decade longer to respond to a step-change in SLCF emission rates than a pulse emission of CO_2. The GWP* metric defines an equivalence better associated with the temperature change contribution than the traditional single pulse CO_2e, hence named CO_2 warming-equivalent (CO_2we). A time horizon of 100 years is maintained for estimating the possible impacts.

Further improvements have been made to the original GWP* calculation method to assess a still slightly underestimation of the impact of SLCFs and to provide an all-SLCFs suitable calculation system[(28)(30)(36)].

The commonly used calculation method for CO_2e emissions (E_{CO2e}) for CH_4 by GWP is shown in **Equation 3**[(21)]. Following Smith and others[(36)], **Equation 4** indicates the updated calculation formula for CO_2we emissions using GWP* (E^*_{CO2we}) for year t, considering a time horizon (H) of 100 years.

$$E_{CO2e\ (t)} = E_{CH4\ (t)} \times GWP_{100} \qquad \text{(Equation 3)}$$

$$E^{*}_{CO2we\ (t)} = \left(4.53 \times E_{CH4\ (t)} - 4.25 \times E_{CH4\ (t-20)}\right) \times GWP_{100} \qquad \text{(Equation 4)}$$

Where:

$E_{CO2e\ (t)}$: CO_2 equivalent emissions in year t
$E^{*}_{CO2we\ (t)}$: CO_2 warming equivalent emissions in year t
$E_{CH4\ (t)}$: methane emissions in year t
$E_{CH4\ (t-20)}$: methane emissions in year t-20
GWP_{100}: 27; default GWP IPCC AR6 value for non-fossil CH_4 at a time horizon (H) of 100 years

The coefficient difference for t and t-20 methane emissions in **Equation 4** accounts for the long-term warming effect due to the lag of the climate system to find a new equilibrium to a past increase in SLCF emissions. Therefore, not only present changes in SLCF emissions rates are considered but also a stock effect for past increases.

Considering CH_4 and a time horizon H = 100, if emissions in year t and t-20 are equal, **Equation 4** is simplified to $E^{*}CO_{2we\ (t)} = E_{CH4\ (t)} \times 7.56$. Therefore, E_{CO2e} would be overestimating the effect on warming by about 3.6 times (27 ÷ 7.56). If emissions increase over 20 years, any incremental CH_4 emissions in time t are multiplied by a factor of 4.53 times the GWP_{100} value (4.53 × 27). If emissions fall by 6.2% after 20 years (-0.32% annually), equivalent warming emissions are zero and there is no contribution to warming. GWP is not capable of reflecting on this situation.

Figure 2 shows the example of a starting situation of zero emissions at t = 0 that changes to a constant annual emission of CH_4 from t = 1 onwards. Calculations of warming potential using **Equation 3** and **Equation 4** show different annual contributions. The GWP* indicator emphasizes the contribution in CO_2we emissions in the first years after the step-change to sustained emissions. Therefore, since annual CH_4 flux is constant, RF saturation due to gas decomposition causes annual CO_2we emissions to tend to zero. The accumulated emissions over time are lower than those estimated by GWP CO_2e, where each annual emission produces the same contribution, so the added effect over time is always incremental.

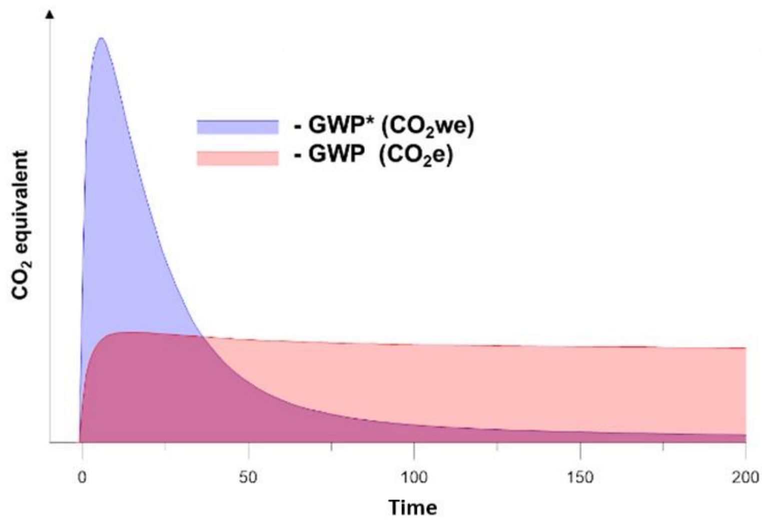


Figure 2. A demonstration of a step-change to sustained CH_4 emissions and the differences in corresponding annual CO_2-equivalent emissions using GWP_{100} or GWP* metrics (red and blue areas, respectively)

2. Materials and Methods

Annual enteric methane emissions from Uruguay cattle and sheep were calculated based on annual feed intake and feed quality estimates. IPCC's simplified Tier 2 method was used to estimate annual feed intake[(37)]. Dry matter intake (DMI) prediction for calves and growing cattle was based on the average live weight (LW) of the animals and net energy of maintenance concentration of the feed (NEmf) (Equations 10.17 and 10.18 as numbered in the original source)[(37)]. For lactating cows, DMI was estimated based on LW and fat-corrected milk production (FCM) (Equation 10.18B as numbered in the original source)[(37)].

NEmf, when necessary to estimate DMI (calves and growing cattle), was calculated from the digestibility of the feed (DE) using the ratio of net energy available in the diet for maintenance to digestible energy consumed (REM) formula (Equation 10.14 and Equation on Table 10.8A as numbered in the original source)[(37)].

For mature cattle (cows, bulls, and oxen) and sheep, DMI as a percentage of average LW based on feed DE assessments by period was used, according to IPCC guidelines (Table 10.8 as numbered in the original source)[(37)] and local reported information. An average DMI of 2.3% of LW was considered for the whole period for mature cows[(38)], bulls, and oxen; for cull cows and sheep[(39)], it was 2.5% LW.

Feedlot cattle could not be distinguished from general grazing cattle for DMI estimation given the lack of information on total confined animals by subcategory. For DMI estimation purposes they were treated like any other growing cattle on a forage-based diet. This may lead to underestimating the per-head emission factor, while emission intensity is overestimated, particularly over the last decade, when confined cattle gained relevance. This limitation should not affect the comparison between GWP and GWP* values.

Data on livestock population from 1880 to 2023 was collected from different sources[(40)(41)(42)(43)(44)(45)(46)(47)(48)(49)(50)(51)(52)(53)(54)(55)(56)(57)(58)(59)(60)(61)]. When not available, total animal inventory data was estimated using interannual linear interpolation and animals by category according to average livestock coefficients (see details of sources in Supplementary Material, **Table S1**). Based on available data, efforts were made to separate lactating dairy cows from the rest of the cattle. Specifically, from 1930 they were considered in a separate subcategory since daily production per milking cow was reported to exceed an estimated beef cows' average of 4.0 l/day[(62)]. Milk production and milk fat content data were collected from various sources[(56)(57)(58)(59)(60)(61)(62)(63)(64)(65)]. When not available, data was interpolated.

Given that the average ratio of "animal units per bovine head/animal units per ovine head" for the period 1880-2023 is 5.1, a Bovine Equivalent (BE) index was adopted to have a single expression reference, where BE = [Bovine heads + (Sheep heads/5)]. Animal unit (UG) is a commonly used livestock head equivalence reference based on annual requirements. 1.0 UG represents a mature beef cow raising and weaning a calf, while a lactating dairy cow is equivalent to 1.6 UG and a mature mated ewe is 0.15 UG[(66)]. To estimate annual average livestock stock and total DMI, animal inventory for each subcategory at the end of each fiscal year was averaged with the inventory of the next younger category at the end of the previous year, so that animals slaughtered during the past year were considered.

Time series data on pasture areas by type (native and improved grasslands, improved perennial, and annual pastures) was collected from official sources and estimated when data was unavailable[(52)(53)(54)(55)(56)(57)(58)(59)(60)(61)(62)(64)(67)(68)(69)(70)(71)] (summary data used on Supplementary Material, **Table S2**). Pastures annual production and forage DE by period were derived from literature and expert opinion[(72)(73)(74)(75)(76)(77)(78)(79)(80)(81)]. Information on estimations used by period and sources is presented in the Supplementary Material (**Table S3** and **Table S4**). Data and estimates on pastures and grasslands areas, annual production and digestibility were averaged over different time periods according to their variability, availability and dynamics of technological advances adoption reported by Moraes[(67)] and Alvarez[(68)]. Besides a small area of annual pastures for dairy cattle (lactating cows), only native grasslands forage was available until 1960.

Average diets by period for each category of cattle (proportion of DMI of each type of pasture assigned by category) were developed to estimate the diet average DE. Diets were constructed prioritizing the animal category requirements and its proximity to being marketed. Grains and by-product supplementation estimates for grazing cattle were also considered based on reported dairy and beef sectors' apparent consumption data from Pizzanelli[(82)] and Methol and others[(83)]. Detailed diet composition and digestibility of assigned diets are shown in the Supplementary Material (**Table S5**).

Livestock subcategory average LW by period was estimated from cattle slaughter weights and age data supplemented with expert opinion or obtained from livestock auction records available from 2000 to 2023 (summary data used on Supplementary Material, **Table S6**)[(64)(67)(84)(85)(86)(87)(88)].

Annual enteric methane emissions were calculated from DMI estimations using a general value of gross energy (GE) content of 18.45 Mj/kg DM for all diets. This value is assumed by IPCC[(37)] and CSIRO[(89)] for a wide range of forages and feeds. Specific energy to methane conversion factors (Ym) for each livestock category were used. For general cattle, Ym was estimated using **Equation 5** as reported by Gere and others[(90)], as a function of the digestibility of the diet (DE), from experiments in South America (AR, BR, and UY) and Canada. Suggested IPCC[(37)] Ym values for low to medium-range producing lactating dairy cows were used (6.5, 6.4, and 6.3%) for the periods up to 1969, 1970 to 1999, and 2000 to 2023, respectively, and a general single value of 6.7% for sheep for the entire time series.

$$Ym\ (\%) = 11.555 - 0.091 \times DE \quad (\textbf{Equation 5})$$

Annual enteric methane emissions were then transformed to CO_2 equivalent emissions using the GWP and GWP* metrics (**Equation 3** and **Equation 4**). A non-fossil methane $GWP_{100\ AR6}$ value of 27 was used[(29)]. CO_2 warming-equivalent for GWP* metric was calculated considering a 20-year difference to define rates of change in methane emissions.

The temperature change due to cumulative emissions was calculated using the Transient Climate Response to Cumulative CO_2 Emissions (TCRE) coefficient (1.65 °C/Tt C), assuming the relation is linear and only dependent on CO_2 emissions[(91)].

3. Results

3.1 Methane Annual Emissions

Uruguay's livestock (cattle and sheep) stock has been stable since after the first third of the 20th century and particularly so far in the 21st with an average of approximately 13 million bovine equivalent (BE) heads from 1935 to 2023, with small variations (**Figure 3**). In 1990 cattle herd was 6.83 million heads and sheep 18.61 million (6.83 and 3.72 million BE, respectively). By 2023 cattle herds reached 11.69 million heads. Sheep peaked at 25.03 million in 1992 and have continuously dropped to 5.85 million animals in 2023 (1.17 million BE). As a result, although cattle numbers have been growing steadily, since approximately 1990, there has been a slight decrease in the BE animal population caused by the sheep stock drop (see Supplementary Material, **Figure S1**). During most of the period, annual CH_4 emissions match the growing evolution of the animal population, exhibiting a more neutral trend in the past three decades, following the decrease in the number of BE heads.

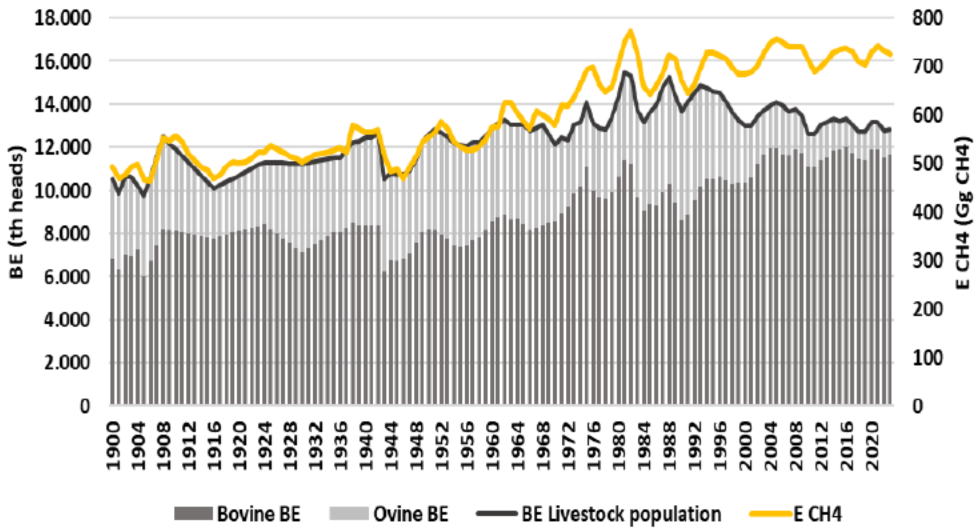


Figure 3. Bovine and ovine (BE; stacked dark and light grey bars respectively, left axis), total livestock population (BE; black line, left axis), and enteric CH_4 annual emissions (E_{CH4}; yellow line, right axis)

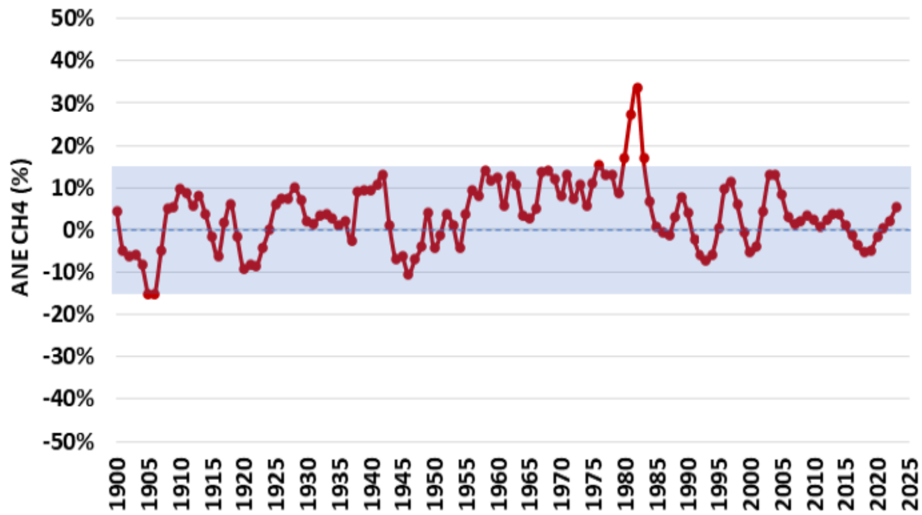


Figure 4. Enteric CH_4 annual emissions change in year t relative to year t-12 (ANE_{CH4} (t) %)

Considering an average lifespan in the atmosphere of 12 years, CH_4 annual net emissions (ANE) were calculated. Emission in year t ($E_{CH4\ (t)}$) was subtracted the emission that occurred 12 years before ($E_{CH4\ (t-12)}$), already transformed by oxidation to CO_2 and water vapor. The resulting annual change between year t and year t-12 ($ANE_{(t)} = E_{(t)} - E_{(t-12)}$) is shown in **Figure 4** as a percentage change over the corresponding base year (t-12).

ANE reasonably tracks the changes in animal stock in **Figure 3**. Variation can be explained by changes in the herd size and composition over the years (sheep/cattle ratio, aging structure of the herd, etc.). When the animal BE heads increase, net emission also increases, and the opposite occurs when the stock decreases compared to its value 12 years earlier, resulting in negative sign ANE values. Since 1900, ANE rarely exceeded ± 15%, with an average of 3.6%, and a lower value of 2.2% over the last three decades. Taking the full period (1900-2023), the average CH_4 ANE value is 19.80 Gg CH_4, while in the past three decades (1994-2023) it decreased to 13.96 Gg CH_4 average change in emissions every 12 years.

3.2 CO_2 Equivalent Annual Emissions

Figure 5 shows annual CH_4 emissions expressed as CO_2e (GWP_{100}) or CO_2we (GPW*) according to **Equation 3** and **Equation 4** above. Since the GPW* reflects the change in emissions over 20-year periods, it shows important interannual variations. The 20-year moving average of CO_2we emissions (GPW*) is also depicted in **Figure 5** to follow its long-term behavior. Taking 1900 as a starting point, estimates of CO_2 equivalent emissions have differed significantly between both metrics since then. Towards the end of the 19th century and early 20th century, there was significant growth in the livestock stock, trying to rebuild the wealth lost during the intensive jerky (dried-salted beef) exporting cycle (1800 to 1880) and the struggles for the country's independence[III]. Increased livestock population produced a significant jump in the flow of annual methane emissions reflected in a higher value or GWP* compared to GWP_{100} in 1900. After the first quarter of the 20th century, with the stabilization of the herd, a decrease occurred in methane emissions, and the resulting annual CO_2we stabilized and showed values lower than those estimated as CO_2e (GWP_{100}). Around 1990, there was a break in the increasing trend in annual CO_2we emissions that began 30 years earlier (1965) because of the rising livestock population. This decreasing path in annual CO_2we emissions continues to the present; however, it is not reflected in the same way in the CO_2 equivalent emissions estimated with the GWP_{100} (CO_2e) metric.

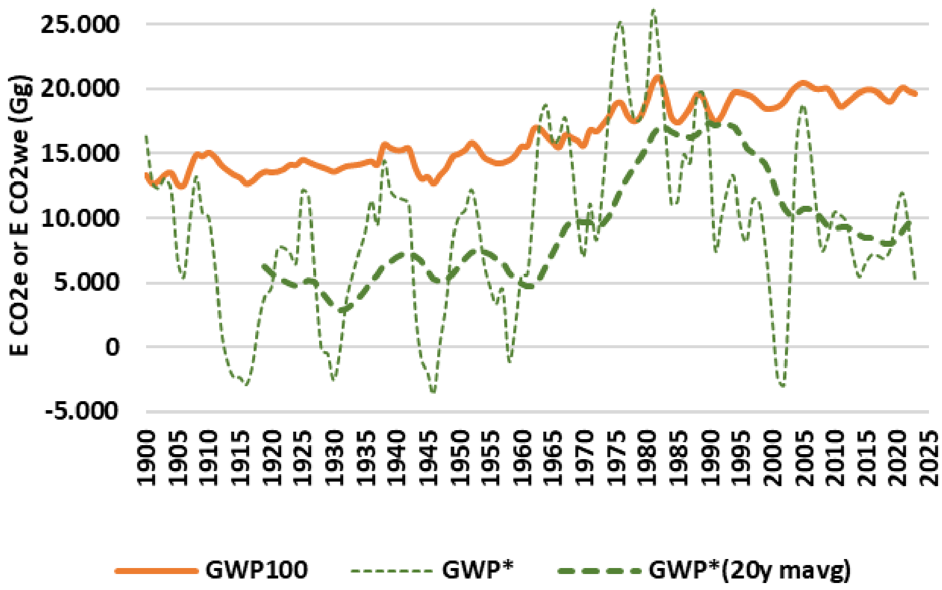


Figure 5. Annual CH_4 emissions expressed as CO_2e (E_{CO2e}, orange solid line) using GWP_{100}; CO_2we (E_{CO2we}; green thin dashed line) calculated by GWP*, and CO_2we 20-year moving average (GWP* (20y mavg) (green thick dashed solid line)

3.3 Warming Contribution

The total cumulative CO_2 equivalent emissions considering enteric CH_4, estimated using the alternative GWP* metric, have been considerably lower (1,139 Mt CO_2we) compared to the data calculated using the GWP_{100} method (2,027 Mt CO_2e).

The contribution of emissions to the increase in global temperature is calculated through the TCRE and the amount of CO_2 equivalent emitted in the period considered. The warming contribution of the total accumulated CO_2we emissions of Uruguayan livestock (**Figure 6**) in the 1990-2023 period (123 years) represented 56% of the value estimated by the traditional metric (0.51 and 0.91 m°C, respectively).

[III]At the end of the 18th century there were already about 11 million heads in the country, which fell to just over 2 million by 1850.

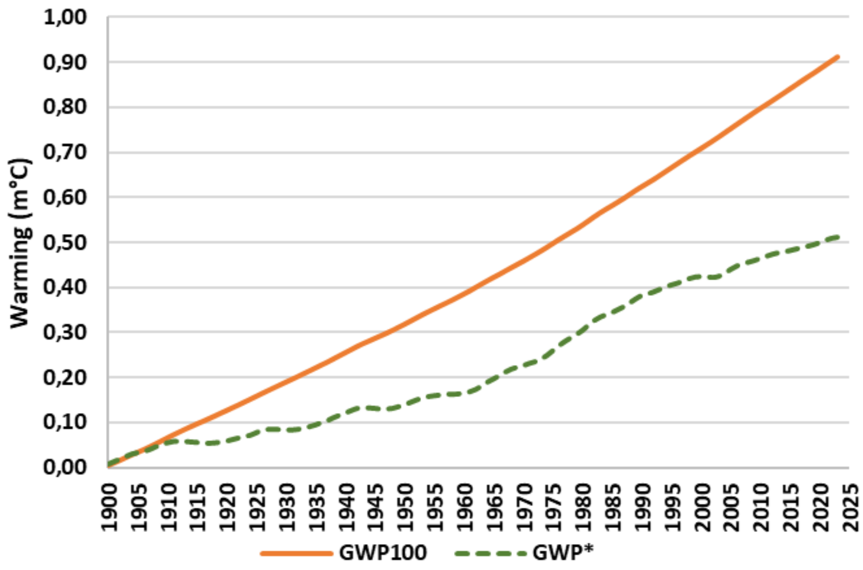


Figure 6. Cumulative contribution to warming (m°C) relative to 1900 using GWP_{100} cumulative CO_2e (orange solid line) and GWP* CO_2we estimates (green dashed line)

4. Discussion

4.1 Methane Annual Emissions

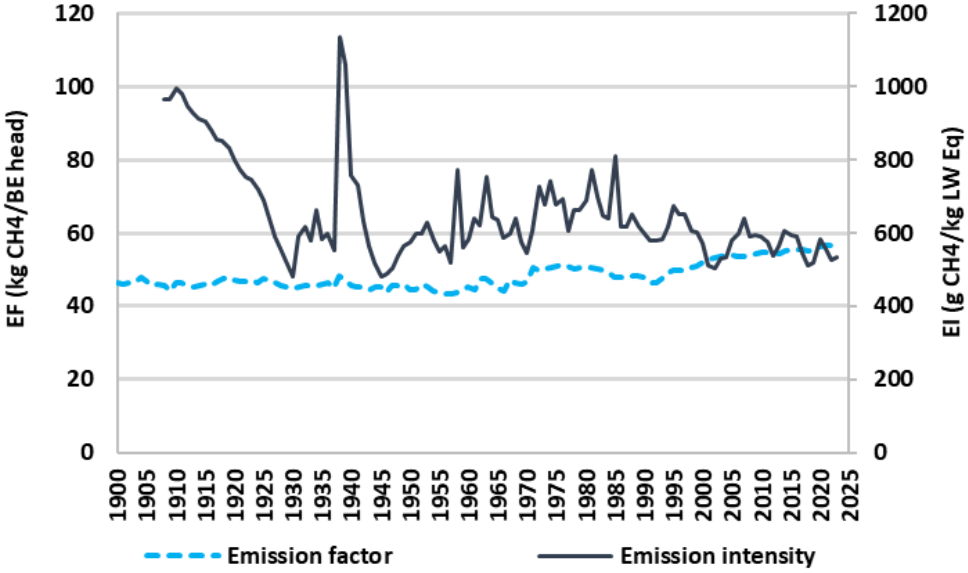
Estimates of annual enteric methane emissions from livestock were by those informed in the National GHG Inventory Reports (NIRs)[19]. The estimated annual CH_4 emissions were in average only 6.4% (±1.1%) higher compared to the official records, for the 16 years for which national inventories have been issued between 1990 and 2020. The main source of this difference lies in sheep's emissions factor estimates. The NIRs have used a default emission factor suggested by the IPCC of 5.0 kg CH_4/head/yr[37], compared to our estimated values of 6.0 and 6.4 kg CH_4/cab/yr (16.4 and 17.6 g CH_4/day) for the 1900-2023 and 1990-2023 periods, respectively, the latter being the same period covered by the NIR records. This higher value is consistent with the estimation obtained using the single updated regression equation proposed by Swainson and others[92] for New Zealand based on data from a wide range of forage intake and quality experimental situations.

Considering a much constant GE content in forages of 18.45 Mj/kg DM and a conversion factor (Ym) of 6.7% of the GE (for a typical 55% DE diet, based on native grassland), the figure estimated by this work for annual emissions corresponds to a DMI of 2.5% of LW (0.800 g DM/day for a 32 kg herd average LW), a figure very consistent with the regular consumption reported on the local literature[39]. The IPCC's default emission factor of 5.0 kg CH_4/head/yr may be underestimating emissions in Uruguay's conditions and be more appropriate for situations where sheep have a lower average body weight, or consumption is limited by a much lower quality of the available forage and a higher conversion factor may apply.

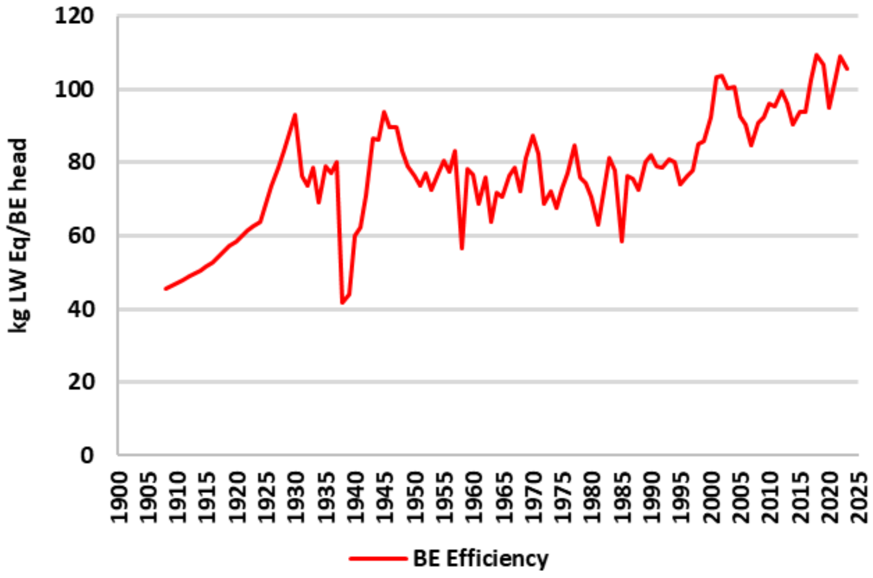
4.2 Emission Intensity and Production Efficiency

Annual CH_4 emissions accompanied the growth of the animal herd until it reached its maximum around 1990 (**Figure 3**). From then on, the livestock population, measured in BE heads, began a decreasing trend and annual methane emissions stabilized to an almost constant value. The decline of the livestock numbers has been caused by a continual decline in sheep stock, particularly since 1990 (see Supplementary Material, **Figure S1**). As the bovine/ovine ratio grew higher, there was an increase in the emission factor (EF) per BE head (**Figure 7**a).

An upward trend in production efficiency per animal (kg LW equivalent[IV] produced/BE head) was also observed during the same time (**Figure 7**b). Despite some exceptional records during the Second World War and subsequent variable behavior, starting in the mid-1980s, the growth in EF was partially compensated by a constant decrease in emissions intensity (EI), resulting in more stable total CH_4 emissions. Emissions intensity declined 13.0% (-0.41% annual rate) in the 30 years between 1994 and 2023. Clariget and others[(93)] reported a similar behavior of EI over time by analyzing 1950, 1980, and 2012 data from agricultural censuses. A small increase in emissions on a product basis was also found between 1950 and 1980, followed by a downward trend from 1980 to 2012.



(a)



(b)

Figure 7. (a) Enteric CH_4 emissions factor (EF; blue dashed line, left axis) and emissions intensity (EI; black solid line, right axis); and **(b)** production efficiency per BE head (BE Efficiency; red solid line)

Calculated average EI for the last decade (2014-2023) of 557 g CH_4/kg LW Eq is consistent with similar figures reported in the literature, considering that CH_4 emissions from manure were not included in the present article

[IV] kg live weight equivalent produced; kg LW Eq = [kg of beef + kg of sheep meat + (kg of wool × 2.48)][(94)].

estimates. Ministerio de Ambiente and others[95] reported for all GHG an EI for Uruguay in 2019 of 18.4 kg CO_2e/kg LW Eq, considering only on-farm cattle and sheep production processes, approximately 12.5 CO_2e/kg LW Eq (600 g CH_4/kg LW; $GWP_{100\ AR2}$) from methane. Picasso and others[96] used a partial life cycle assessment approach to calculate GHG EI. They estimated methane average intensities values of 16 kg CO_2e/kg LW Eq (640 g CH_4/kg LW Eq; $GWP_{100\ AR4}$) for cow-calf production systems (22 kg on low to 12 kg on high-performance systems) to 9 kg CO_2e/kg LW Eq (360 g CH_4/kg LW Eq) for pasture-based rearing and finishing systems with different combinations of natural and improved grasslands, improved pastures and supplements. Total GHG emissions intensity ranged from approximately 12 to 20 kg CO_2e/kg LW Eq on nine combinations of cow-calf and backgrounding-finishing pasture-based systems tested (the original article includes six combining feedlots options in addition).

The estimated livestock average methane yield and emission factor for the last decade (2014-2023) were 20.9 g CH_4/kg DMI and 55.8 kg CH_4/BE/year (58.3 and 6.6 kg/head/year for cattle and sheep, respectively) for diets with 55 minimum and 66% maximum DE (see Supplementary Material, **Table S5**). Dini Vilar[97] reports methane yields of 23.6 vs 16.8 g CH4/kg DMI for Hereford heifers consuming a low-quality pasture in winter and spring (31.1 and 65.5% DE, respectively), and 21.6 vs 14.3 g CH4/kg DMI for a high-quality pasture (63.3 vs 71.2% DE on winter and spring, respectively). Mieres and others[98] with Holstein heifers consuming improved pasture and range (61.2 and 43.8% DE) obtained methane yields of 17.3 and 24.4 g CH4/kg DMI, attributing the differences to forage quality, particularly to neutral fiber content (67.6 vs 79.2 %).

Production efficiency and emissions intensity can improve due to better diet quality and availability, among other factors. This phenomenon largely occurs through the dilution of the maintenance effect; as nutrient intake increases, the proportion of ingested nutrients used for maintenance functions decreases, leaving a greater proportion of ingested nutrients for animal production[99]. Likewise, data show an important growth of improved pastures and forage crops planted area, and quantity of supplements used starting in the 1990s, coinciding with the increasing individual animal production and declining CH_4 emissions on an animal product basis (EI) observed on **Figure 7**a and **Figure 7**b. This change corresponds to the implementation, at that time, of important reforms in current policies and deregulation of the livestock industry that led to substantial advances in livestock and meat markets and in production technology adoption[45][100]. At the same time, the world experienced an increased demand for food in the context of a global trade liberalization trend. The policy measures and the marketing opportunities had an important traction effect on the livestock industry, increasing production and unintentionally triggering the beginning of a production efficiency and emissions intensity improvement trend.

4.3 CO_2 Equivalent Annual Emissions

Since the animal stock growth rate from 1900 to 2023 has been low (0.16% annually), GWP* CO_2we annual emissions are lower than CO_2e emissions determined by GWP_{100}. Although increasing since 1900, there was a break point around 1990 following a reduction of animal population driven by a declining ovine stock. In the last three decades before 2023, annual CO_2we emissions decreased 60.6%, 3.1% annually, while CO_2e (GWP_{100}) emissions did not change in the same period (-0.4% from end-to-end).

Many examples can be found in the literature reporting a substantial reduction in the cumulative warming contribution of livestock SLCFs when calculated using GWP*, with a declining in livestock population and increased productivity[101][102][103][104]. The proposed GWP* recognizes that a stable environment (e.g. no significant growth or decrease in herd size) results in a balance between emissions and transformation of CH_4. SLCFs incremental contribution to the atmosphere, as measured by GWP*, was smaller than that determined by GWP, suggesting that additional direct global warming would be marginal. The estimated temperature response to accumulated emissions reflects the difference in warming capacity that each metric assigned to SLCFs. Considering the total impact of annual emissions rather than incremental emissions over a period, and the differential short- and long-time warming capacity, produces a much higher estimation of the accumulated temperature response over time.

The average net change in methane emissions every 20 years from 1994 to 2023 was 4.2%, representing an average annual growth rate of 0.14%, a far cry from the -0.32% mentioned above as the annual break-even rate of zero contribution to warming. However, this is a significant reduction compared to the average increment of 8.6% recorded over the previous 93 years. This fall in the rate of change in methane emissions is mainly due to a decrease in animal stocks, mostly sheep, and improvements resulting from increased feed availability and quality may also have contributed.

GWP and other alternative metrics have not been exempted from some criticism. Rogelj and others[105] argued that the dependence of non-CO_2 GHGs under the GWP* metric on past emissions raises questions of equity and fairness when applied on any but a global level. The use of GWP* would put most developing countries at a disadvantage compared to developed countries. When using GWP* countries with high historical emissions of SLCFs are exempted from accounting for avoidable future warming caused by sustaining these emissions. Thus, given the risk of such unfair accounting differences, GWP* should only be used globally.

Meinshausen and others[106] strongly argued GWP* is more a microclimate model, useful for educational purposes and quick temperature projections, than an emissions equivalence metric. When using GWP*, interannual variability is signaled as a limitation regarding policy instruments and Kyoto Protocol five-year commitment periods. Inconsistency with the current Nationally Determined Contributions and the time and effort eventually required to review existing policies and targets are also highlighted. Moreover, they argued that GWP* is not a neutral metric, as it weighs emissions differently depending on a country's emissions history.

Another important limitation affecting all metrics, including GWP, is that they do not recognize the biogenic nature of enteric CH_4 beyond that it is a SLCF. However, biogenic sourced CO_2 is not counted in the atmospheric CO_2 stock and arguments are being made that landfill methane should be carbon neutral[107]. In particular, for countries where livestock production has been a major driver of development since long before the impacts of GHG emissions were debated, budgeting for biogenic CH_4 is a key economic issue.

4.4 Potential Implications of this Study

Uruguay could benefit from including GWP* as an additional metric in its NIR. As a predominantly agricultural country where the livestock industry plays a significant role, methane represents the most important greenhouse gas. This is evident when using GWP_{100} metric, given the high warming potential attributed to methane, even considering long-time horizons.

Figure 8 shows total country emissions from 2010, 2014, 2018, and 2020 NIRs[19] as CO_2e ($GWP_{100\ AR5}$) and re-calculated as CO_2we using GWP* for methane, based on emissions reported in the corresponding NIRs from 20 years earlier. The stabilization of methane emissions over the past three decades (see **Figure 3** and **Figure 4**) resulted in very low net flows, significantly reducing the estimated equivalent emissions (minimum of 16% reduction for 2010 and a maximum of 37% for 2014). If the warming contribution is calculated based on the net flux of short-lived gas emissions, as suggested by GWP*, the reduction in total methane emissions expressed as CO_2 equivalents is substantial.

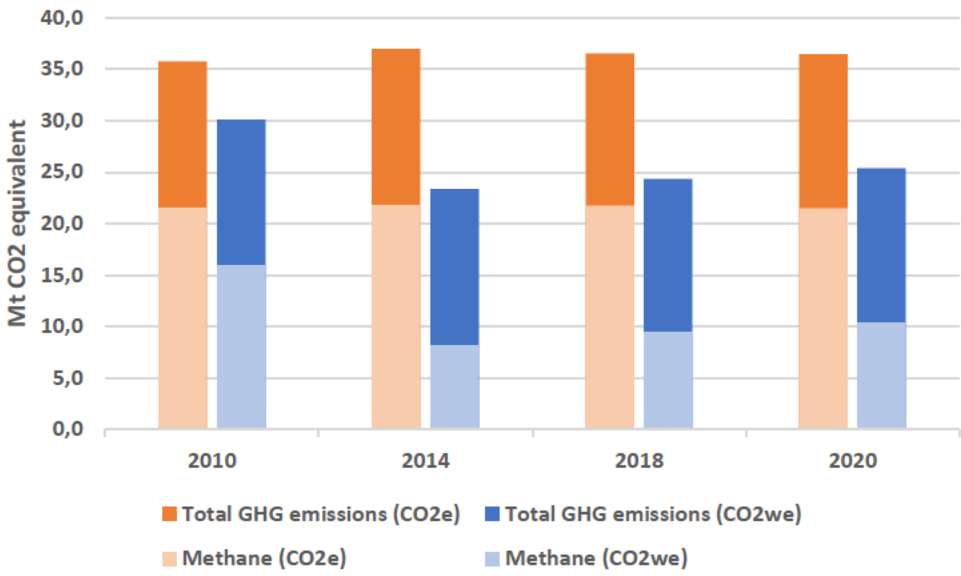


Figure 8. Total emissions from Uruguay National GHG Inventory Reports (CO_2e; orange bars), re-calculated total emissions (CO_2we, blue bars) using GWP* with base data from 1990, 1994, 1998 and 2000 NIRs ($GWP_{100\ AR5}$ = 28) and methane participation (light orange and blue bars). (Land use change emissions/removals are not included)

Establishing specific goals about methane in the NDC was based on the large participation the gas has on the country's CO_2e emissions. Official cattle emissions intensity estimated for 2019 reached 550.9 g CH_4/kg LW (enteric and manure), a 29% reduction from 1990[108]. Meeting the 2030 target implies an additional emissions intensity reduction of 11%, which at first appears to be an achievable goal given the actual reduction trend is maintained. The government is preparing its third NDC, which is expected to set more ambitious goals for the newly defined targets. GWP* adoption as an additional emissions metric has significant implications for public policy design and future commitments under Uruguay's NDCs. The use of GWP* could influence the design of future NDCs by highlighting emissions reduction targets from SLCPs and their impact. Allen and others[109] argued that clarifying the individual contributions of each GHG in future commitments and reporting past emissions would eliminate uncertainties about possible differential impacts on global temperature. This approach would also allow for a more precise evaluation of the non-climate benefits of emission reductions, particularly for methane (sustainable use of native grasslands, soil, water, and other resources).

Research indicates that metrics like GWP* can provide a more accurate representation of the warming effects of different gases, particularly when methane emissions are stable or declining[28]. By focusing on SLCFs, Uruguay could improve visibility of its climate commitments and potentially achieve more substantial short-term benefits. Adoption of GWP* can also enhance public understanding of the livestock sector's role in climate change. By communicating how methane's role in global warming is more accurately quantified, policymakers can foster greater collaboration between government, farmers, and the public in reducing emissions.

Incorporating GWP* into policy design for the livestock sector allows Uruguay to more effectively address methane emissions by using a scientifically accurate measure of its climate impact[35]. This could lead to targeted, transparent, and adaptive policies that support sustainable practices, improve mitigation strategies, and strengthen Uruguay's position in global climate commitments. It also provides a clearer path for the livestock sector to contribute to national climate goals and the global effort to combat climate change. Furthermore, it can increase the willingness of the livestock sector to engage with policies aimed at reducing emissions, knowing that the climate impact of their actions is being measured more accurately.

By acknowledging the actual impact of methane emissions and the contribution the industry can make to fight climate change, farmers could be incentivized to adopt low-emission technologies that focus on reducing short-lived gases. So far, the government has implemented technical assistance and rural extension programs to encourage performance-enhancing technologies, such as strategic supplementary feeding and improved forages, to close productivity gaps and lower methane emissions[110]. Innovative international financing mechanisms link reduced interest rates to overachieving already ambitious environmental goals, including lowering agricultural emissions and providing economic incentives for the country to foster sustainable practices across the agricultural sector.

Several countries have implemented emissions taxes or carbon pricing policies to reduce greenhouse gas emissions, including methane from various sources[111]. Furthermore, tariff barriers and import taxes related to environmental compliance on agricultural products, such as restrictions on products from deforested areas or those requiring adherence to environmental certifications, have been recently proposed by developed countries. In this context, the policies adopted by the Uruguayan government so far may prove to be ineffective in the future. These market restrictions could be perceived as risk enhancers and limit the adoption of technologies that seek to improve productivity, particularly for small farmers. Future policy should consider alternative arrangements, such as time-limited financial incentives, price premiums, or tax breaks for farmers achieving methane-reducing targets by adopting increased productivity technologies, thereby fostering market-driven opportunities and leading to a more sustainable livestock sector. Adoption rates have increased in the past when competitive gains were needed and there were market incentives to meet quality or environmental standards, particularly for export markets[45][100].

5. Conclusions

The primary focus of this paper was to assess the differential marginal warming outcomes that both approaches yield. The marginal warming contribution of Uruguayan livestock enteric methane, even when being half of the country's CO_2 equivalent emissions, was already negligible in the global context. Considering SLCF atmospheric decays, the subsequent radiative forcing saturation and the way relevant new approaches (GWP*, CGWP) have incorporated this knowledge provide a considerably lower warming contribution estimation.

Although some assumptions were made, the calculations for both metrics were based on the same dataset and coefficient estimates. The magnitude of the estimated emissions could be more accurate if more detailed data were available and no estimates to fill gaps were needed. In any case, the relative values of the metrics would be the same and are based on the different warming capacities that each one adjudges to SLCFs.

Uruguay can benefit from using GWP* as an additional metric in its NIR and future NDC commitments, not only to assess the real contribution of the country's GHG emissions to global warming, but also to highlight the contributions of its future achievements in emissions reduction. GWP* offers a nuanced approach to emissions accounting, particularly for SLCFs such as methane, which have distinct impacts on climate compared to long-lived greenhouse gases such as carbon dioxide. This differentiation is crucial for formulating effective climate policies that align with the goals of the Paris Agreement.

The discussions about global policies to reduce GHG emissions through tax burdens and additional costs (taxes, tariff barriers) are based on questionable metrics and ambiguous results. Consequently, the local meat industry could unfairly face incremental costs and potentially weaker demand due to increased environmental regulations and a misleading consumer information campaign. In addition to promoting current technical assistance-oriented programs, future policies should consider innovative incentives and rewards linked to emissions reductions.

There are still some aspects that need to be addressed. A determination must be encouraged regarding the definition of methane from ruminants as being anthropogenic and how these biogenic sources of CH_4 should be considered in global warming potential scenarios.

Considering livestock's long history in the country, the alleged negative environmental or economic impacts from incremental global warming due to methane emissions from Uruguayan livestock are at least debatable. Moreover, if livestock systems continue the same path of efficiency improvement as in recent decades, they could play a relevant role in future climate commitments, provided that the differential warming impact of sustained SLCF emissions is considered.

Finally, the evaluation of emission targets at the national level cannot be undertaken from a scientific perspective only, but also depends on economic, social, and equity considerations. Particularly, the choice of metrics is also a question of political decision and policy targets.

Transparency of Data

Summary data and references to the original data are available in the Supplementary Material.

Author Contribution Statement

	Fernández E	Lanfranco B	Soares de Lima JM	Ferraro B
Conceptualization	■	■	■	■
Data curation	■	■	■	
Formal analysis	■		■	
Funding acquisition				■
Investigation	■	■	■	
Methodology	■	■	■	■
Project administration		■		■
Resources	■	■	■	
Software	■	■	■	
Supervision	■	■		
Validation	■	■	■	■
Visualization	■	■	■	
Writing – original draft	■	■		
Writing – review and editing	■	■	■	■

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Supplementary Material

Table S1. Total and by categories livestock population data sources by year

	Livestock data		
Years	***Animals by category data source***	***Total animal data source***	
1908 **1916** **1924** **1930** **1937** **1943** **1946**	Jarvis[41], Vasallo[42], Bertino and Tajam[43], Nahum[44], Rohner[45]	Jarvis[41], Vasallo[42], Bertino and Tajam[43], Nahum[44], Rohner[45]	61 years (42.4%)
1951	MGA[46]	MGA[46]	
1961	MGA[47]	MGA[47]	
1966	MGA[47]	MGA[47]	
1970	MGA[48]	MGA[48]	
1974-95	MGAP[49][50][52],INAC[53][54][55]	MGAP[49][50][52],INAC[53][54][55]	
1996-22	MGAP[51][56][57][58][59][60]	MGAP[51][56][57][58][59][60]	
2023	MGAP[61]	MGAP[54]	
1875 **1883** **1886** **1892-93** **1900** **1901-05** **1935-36** **1938-42** **1944-45** **1947-50** **1952-60** **1962-65** **1967-69** **1971-73**	Estimated by coefficients	Williman[40], Jarvis[41], Vasallo[42], Bertino and Tajam[43], Nahum[44], Rohner[45]	42 years (29.2%)
1880-82 **1884-85** **1887-91** **1894-99** **1906-07** **1909-15** **1917-23** **1925-29** **1931-34**	Estimated by coefficients	Interpolated	41 years (28.5%)

Table S2. Average pasture areas (% of grazing area[I]) by type and by period

Period	*PP*	*IG*	*FG*	*AP*	*NG*	*Data source*
1880-1959	0.0	0.0	0.0	0.0	100.0	(62)(67)(68)(70)(71)
1960-1969	0,2	0.0	0.4	0.5	98.9	(68)(69)(70)
1970-1979	1.0	1.3	0.7	0.6	96.3	(52)(68)(69)(70)
1980-1989	1.9	1.4	0.6	0.7	95.4	(52)(64)
1990-1999	4.9	2.3	0.6	1.4	90.8	(53)(54)(55)(56)(64)
2000-2009	7.0	5.0	0.7	1.6	85.7	(56)(57)
2010-2019	6.1	4.6	0.9	2.8	85.6	(58)(59)
2020-2023	7.2	4.9	0.9	3.8	83.2	(60)(61)

[I]Excluding grazing area for milk production

PP: Improved Perennial Pastures, IG: Improved Grasslands, FG: Fertilized Grasslands, AP: Annual Pastures, NG: Native Grasslands, Suppl: Supplements (grains and by-products).

Elaborated based on: MGAP(52)(56)(57)(58)(59)(60)(61)(64), INAC(53)(54)(55), Bertino and Tajam(62), Moraes(67), Alvarez(68), Perez Arrate and others(69), Rodriguez and others(70), Bertino and Bucheli G(71).

Table S3. Annual forage dry matter production (kg DM/ha) by pasture type and by period

Period	*PP*	*IG*	*FG*	*AP*	*NG*
1880-1959	-	-	-	-	3000
1960-1979	4500	4000	3500	4500	3000
1980-1999	5500	4500	3800	5000	3200
2000-2023	6500	5000	4000	6000	3500

Elaborated based on: MGAP(72), Crempien(73), García(74)(78), Risso and Berreta(75), Bemhaja and Olmos(76), Bemhaja(77), Mieres and others(79), Risso and others(80), Becoña(81).

Table S4. Average annual forage and supplements dry matter digestibility (DE %) by pasture type and by period

Period	*PP*	*IG*	*FG*	*AP*	*NG*	*Suppl*
1880-1959	-	-	-	-	54	-
1960-1979	62	56	54	65	54	80
1980-1999	64	58	55	65	55	80
2000-2023	65	58	55	68	55	80

Elaborated based on: MGAP(72), Crempien(73), García(74)(78), Risso and Berreta(75), Bemhaja and Olmos(76), Bemhaja(77), Mieres and others(79), Risso and others(80), Becoña(81).

Table S5. Assigned diet composition (% of total DM) and calculated digestibility (DE %) by category and by period

Period	*Pasture type*	*Bulls*	*Oxen*	*Cows*	*Cull cows*	*Steers +3ys*	*Steers 2-3ys*	*Steers 1-2ys*	*Heifers +2ys*	*Heifers 1-2ys*	*Calves*	*Sheep*
1880-1959	**PP**											
	IG											
	FG											
	AP											
	NG	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Supp											
	DE	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0
1960-1969	**PP**					4.5						
	IG											
	FG											
	AP					9.8						
	NG	100.0	100.0	100.0	100.0	85.7	100.0	100.0	100.0	100.0	100.0	100.0
	Supp											
	DE	54.0	54.0	54.0	54.0	56.0	54.0	54.0	54.0	54.0	54.0	54.0
1970-1979	**PP**					18.2						
	IG											
	FG					12.3						
	AP											
	NG	100.0	100.0	100.0	100.0	69.4	100.0	100.0	100.0	100.0	100.0	100.0
	Supp											
	DE	54.0	54.0	54.0	54.0	56.0	54.0	54.0	54.0	54.0	54.0	54.0
1980-1989	**PP**					23.3	9.8					
	IG					12.4	12.1					
	FG					11.2						
	AP											
	NG	100.0	100.0	100.0	100.0	50.4	78.1	100.0	100.0	100.0	100.0	100.0
	Supp					2.7						
	DE	55.0	55.0	55.0	55.0	59.0	56.8	55.0	55.0	55.0	55.0	55.0
1990-1999	**PP**					43.6	41.7					
	IG					16.0	23.0					
	FG						10.8					
	AP					19.5	4.7					
	NG	100.0	100.0	100.0	100.0	15.4	16.5	100.0	100.0	100.0	100.0	100.0
	Supp					5.5	3.3					
	DE	55.0	55.0	55.0	55.0	63.3	61.4	55.0	55.0	55.0	55.0	55.0
2000-2009	**PP**					48.0	53.7	16.5				
	IG					23.1	15.5	17.9	38.2			
	FG							8.7				
	AP					10.8	17.0					
	NG	100.0	100.0	100.0	100.0	13.7	9.5	53.0	58.5	100.0	100.0	100.0
	Supp					4.4	4.4	3.8	3.3			
	DE	55.0	55.0	55.0	55.0	63.7	64.7	59.1	57.2	55.0	55.0	55.0
2010-2019	**PP**					45.3	48.8	14.5				
	IG				56.0			21.9	22.4			
	FG							6.8	9.3			
	AP					21.1	31.9					
	NG	100.0	100.0	100.0	44.0	29.2	13.9	51.9	63.9	100.0	100.0	100.0
	Supp					4.4	5.5	4.9	4.4			
	DE	55.0	55.0	55.0	56.9	64.5	66.0	59.2	57.0	55.0	55.0	55.0
2020-2023	**PP**					47.1	57.2	32.6				
	IG				49.6			16.6	39.1			
	FG							5.3	12.5			
	AP					36.9	29.8	12.8				
	NG	100.0	100.0	100.0	50.4	11.6	7.5	27.8	43.9	96.7	100.0	100.0
	Supp					4.4	5.5	4.9	4.4	3.3		
	DE	55.0	55.0	55.0	56.8	66.1	66.3	62.8	57.5	55.8	55.0	55.0

Table S6. Estimated average live weight (kg/animal) by category and by period

Period	*Lact Dairy cows*	*Bulls*	*Oxen*	*Cows*	*Cull cows*	*Steers +3ys*	*Steers 2-3ys*	*Steers 1-2ys*	*Heifers +2ys*	*Heifers 1-2ys*	*Calves*	*Sheep*	*Data source*
1880-1959	400	500	600	346	360	402	281	200	321	200	120	28	(67)(84)(85)
1960-1969	400	500	600	350	360	364	283	203	325	204	130	30	(64)(85))
1970-1979	400	500	600	360	360	381	301	220	335	214	140	30	(64)
1980-1989	450	500	600	365	360	386	306	225	340	219	145	30	(64)
1990-1999	450	500	600	369	360	402	322	230	334	224	150	30	(64)(86)(87)
2000-2009	500	550	600	375	350	420	340	255	305	225	155	32	(88)
2010-2019	500	550	600	355	380	430	355	270	310	255	170	32	(88)
2020-2023	500	550	600	365	380	440	360	300	320	255	170	34	(88)

Elaborated based on: MGAP(64), Moraes(67), Garavaglia(84), Finch(85), INAC(86)(87), Aguirre and Durán(88).

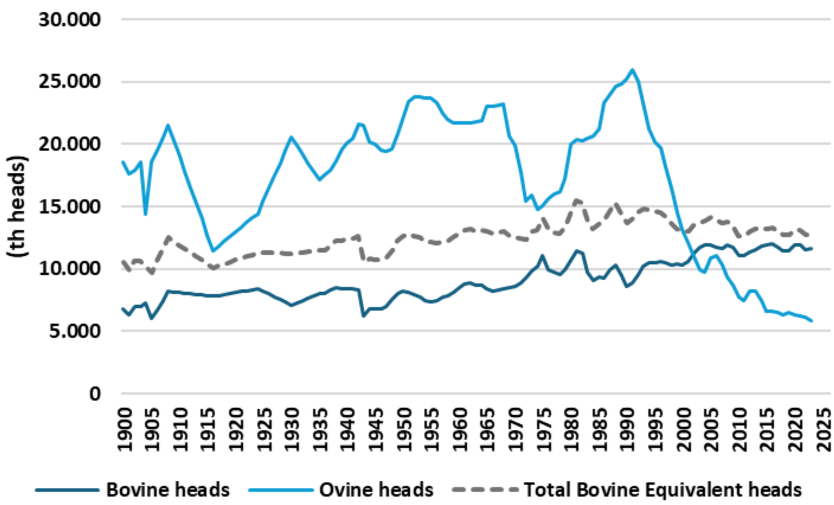

Figure S1. Bovine and ovine heads, and total livestock Bovine Equivalent population