Original Study • DOI: 10.15212/ijafr-2023-0107 IJAFR • 62(1) • 2023 • 96-107

Irish Journal of Agricultural and Food Research

Reassessing the warming impact of methane emissions from Irish livestock using GWP*: historical trends and sustainable futures

P. McKenna[1,2†], S. Banwart[1]

[1]*Global Food and Environment Institute, University of Leeds, Leeds, UK*
[2]*Cranfield University, Bedford, UK*

Abstract

Methane from livestock production contributes significantly to Ireland's greenhouse gas emissions. Methane emissions are generally expressed as carbon dioxide equivalents (CO_2e) using the global warming potential (GWP) metric, but this conversion may result in an inaccurate assessment, because methane has a much shorter atmospheric lifespan than CO_2. This study calculated the CO_2e of methane emissions from Irish livestock using the GWP and GWP* metrics, the latter of which accounts for the short-lived nature of atmospheric methane. Methane emissions from all Irish livestock (1961–2020) were included and three projected scenarios to 2050 were hypothesised: increasing emissions, decreasing emissions and constant emissions. The CO_2e of methane from Irish livestock was found to be influenced by changes in the rate of emission over the preceding decades. Using the GWP* metric, declining populations of donkeys and horses from 1961 to 2000 were shown to cause atmospheric removals of methane when expressed as CO_2e. Increasing populations of swine and non-dairy cattle (in response to industrial changes and European Union [EU] regulations) saw significant increases in the CO_2e of methane emissions from these sources. Milk quotas caused a significant reduction in the CO_2e of methane emissions from dairy cows, and atmospheric removals were observed in the years 1990–2012. GWP* indicated that the constant and decreasing future emission scenarios gave more significant reductions in CO_2e than the GWP. These results indicate the importance of the effect of emission rate on the CO_2e of methane from Irish livestock, which is accounted for using GWP*, but not by the conventional GWP.

Keywords

Climate change • enteric fermentation • livestock • methane • sustainable agriculture

Introduction

Livestock production is practiced globally. It converts natural resources and crop residues into food, fibre, fuel and fertiliser, and in doing so provides life and livelihood for billions of people, many of whom are among the poorest in the world (FAO, 2006). Livestock occupy ~65% of the world's agricultural land and the services and products they generate are significant in the economies of many countries. Livestock can also cause significant environmental damage through the pollution associated with their manures and the reduction in biodiversity caused by grazing (Abbasi & Abbasi, 2016). Livestock production is the dominant form of agriculture in many parts of the world, for example, in Ireland, where grassland-based livestock systems occupy 90% of agricultural land, and 88% of gross agricultural output comes from livestock products (O'Mara *et al.*, 2021). Pasture in Ireland predominantly produces cattle for beef and dairy, and also sheep for lamb and mutton (Hanrahan, 2020). The agricultural sector in Ireland employs 7.1% of the population and Irish livestock products are highly regarded by international markets (Department of Agriculture, 2020).

Livestock production can provide ecosystem services, such as the maintenance of soil organic carbon (Tracy & Zhang, 2008), but it also contributes to global warming through methane (CH_4) emissions from ruminants, and nitrous oxide (NO_2) emissions from the excreta. These emissions contribute significantly to national greenhouse gas (GHG) inventories, because global livestock production has increased exponentially in the past century (Weis, 2013). Livestock production in the developing world particularly has increased significantly in recent years (Steinfeld, 2006). Projections indicate this will continue in the coming decades, as the global population continues to urbanise and become wealthier (Alexandratos and Bruinsma, 2012). It is essential that livestock farmers globally are provided with the knowledge and technology necessary to

---

†Corresponding author: P. McKenna
E-mail: patchmck@gmail.com

mitigate emissions, so livestock farming can make the required changes and continue to provide food, fuel and fertiliser in a sustainable manner.

Methane emissions from ruminants are cited as being among the most significant sources of GHGs from livestock, both in Ireland and globally. Figure 1 shows estimates of ‘farm-gate’ GHG emissions from both Ireland and the world. These data are taken from the Food and Agriculture Organization Statistics (FAOSTAT), the database of agricultural statistics published by the FAO (Food and Agriculture Organization of the United Nations, 1997). ‘Farm-gate’ emissions refer to only on-farm sources of GHGs and omit food transport/retail and land-use change. These estimates indicate that CH_4 from ruminants in Ireland is agriculture’s single largest source of GHGs, accounting for 49% of the total number. It is also more than twice that of the next single biggest animal source – nitrous oxide from manure left on pasture – which also comes from livestock. Ruminant CH_4 accounts for 24% of global farm-gate emissions, almost equivalent to the single biggest contributor, which is net-forest conversion (the GHG emissions when forests are converted to agriculture). The mitigation of CH_4 emissions from ruminants is a challenge facing livestock farmers, and this is even more pertinent in countries such as Ireland, where farming relies so heavily on ruminant livestock production, and where CH_4 is such a significant proportion of farming GHGs.

The data given in Figure 1 use 100-Year Global Warming Potential (GWP100 – hereafter GWP) to express non-CO_2 GHGs such as CH_4 and NO_2 as equivalents of CO_2 (CO_2e). This is the established convention in reporting GHG inventories as it facilitates the comparison of CO_2 with non-CO_2 GHGs (IPCC, 2021). The conventional GWP of any GHG accounts for its radiative efficiency (the heat energy absorbed and warming caused) compared with CO_2. Methane has a radiative efficiency which is 28 times higher than CO_2 and is assigned a GWP of 28, whilst N_2O is higher still and is assigned a GWP of 265 (IPCC, 2021). This, however, may be inaccurate with respect to CH_4, because it has an atmospheric half-life of ~10 yrs (Cain *et al.*, 2022).

Important temporal dynamics may be unaccounted for when using the conventional GWP. Methane is a short-lived climate

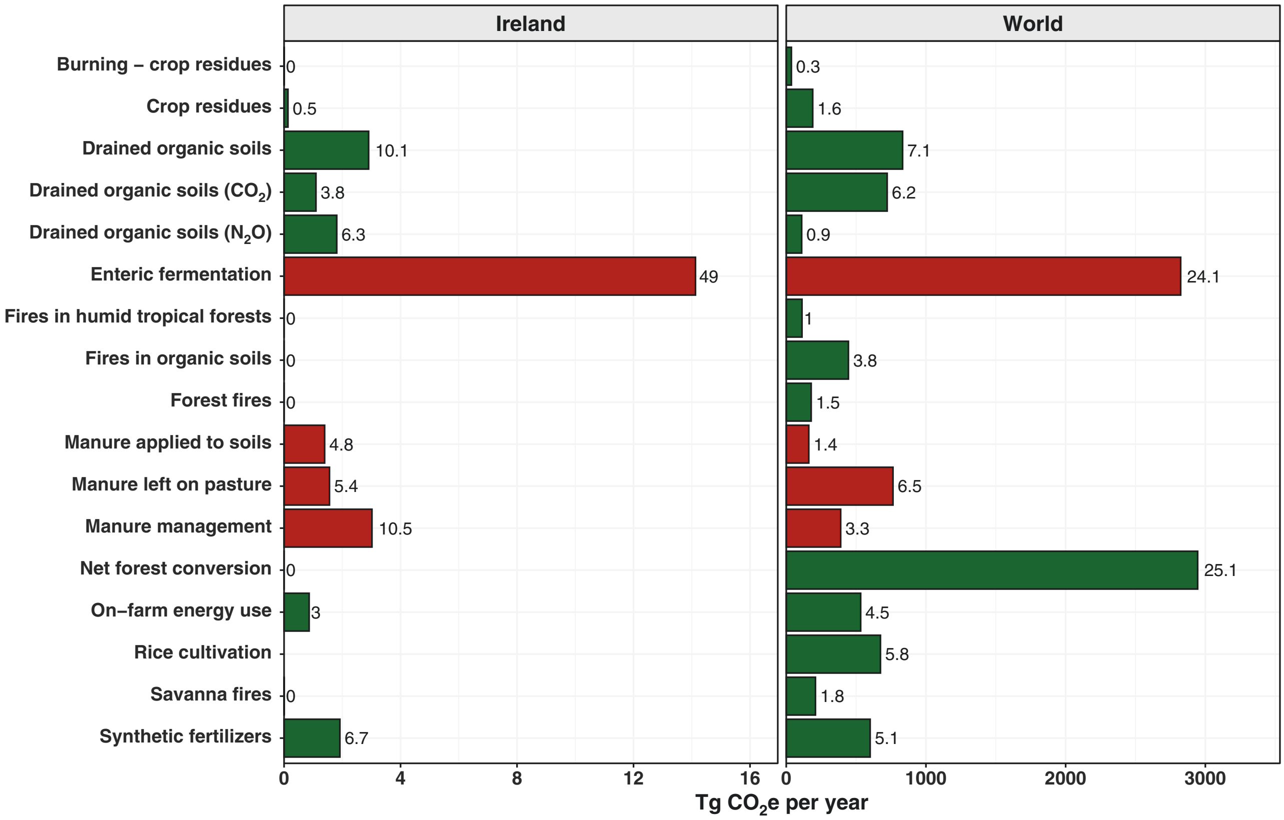

Figure 1. Farm-gate greenhouse gas emissions from Ireland and the World in 2019 using conventional GWP metrics. Direct livestock emissions are given in red, non-livestock emissions are given in green. Percentage breakdown of each component is given in the bar labels. GWP, global warming potential.

pollutant (SLCP) with lower atmospheric persistence than CO_2. Methane is oxidised in the atmosphere and breaks down into CO_2 and water. When livestock CH_4 oxidises into CO_2, it has a warming effect but it is not considered a GHG because the carbon contained is biogenic and part of the natural short-term cycling of carbon through the biosphere and atmosphere (Stocker *et al.*, 2014). The ephemeral nature of atmospheric CH_4 (~20 yrs) stands in contrast to the enduring nature of atmospheric CO_2 (>1,000 yrs), and the warming caused by constant CH_4 emissions can in some cases be balanced by atmospheric removal. This is the case with non-anthropogenic CH_4 emissions from anaerobic environments such as wetlands and bogs. Non-anthropogenic CH_4 emissions comprise ~40% of the total annual 550–594 Tg CH_4 emitted to the atmosphere (Saunois *et al.*, 2020). These natural emissions have contributed significantly to global warming, but they do not continue to cause additional warming, because they have been roughly constant for long enough that the climate system has reached an equilibrium, that is, annual emissions are balanced by natural removals in the atmosphere and no additional warming takes place (van Amstel, 2012). This is not the case with CO_2, as this GHG persists in the atmosphere and therefore emissions will always cause additional warming in the absence of significant increases in terrestrial C sequestration.

The temporal element of the warming effects of SLCPs such as CH_4 is not accounted for with the conventional GWP metric, and this may lead to a misunderstanding of the warming effects of CH_4 emissions. This is particularly relevant when addressing farm-gate GHG emissions in Ireland, as CH_4 from ruminants comprise half of the total when the conventional GWP metric is used (Figure 1). Various reduction targets for Irish agricultural GHGs have been set by both European (European Union Climate and Energy Framework, European Green Deal) and Irish organisations (Climate Action and Low Carbon Development Bill, Ag Climatise and the National Climate Plan (Lanigan, 2019)). The Climate Action and Low Carbon Development Bill was passed by the Irish parliament in 2021 and legislates for national carbon budgeting, which sets targets of a 25% reduction of GHGs by 2030 from 2018 levels. Legal and policy frameworks such as these, however, have all used the conventional GWP metric, which does not account for the temporal element. Omitting the short-lived nature of CH_4, and the role that the rate of emission plays may be ‘unfair, inefficient and dangerous’ (Lynch *et al.*, 2020); unfair because it does not accurately link emissions and climate impact, inefficient because it may overstate the level of action required to offset long-term sustained CH_4 emissions, and dangerous because it may greatly underestimate the climate impacts of increasing CH_4 emissions.

Another metric known as GWP* has been described to address this problem (Lynch *et al.*, 2020). This allows emissions of SLCPs, such as CH_4, and emissions of long-lived climate pollutants, such as CO_2, to be more accurately expressed within a single metric, by equating a change in the emission rate of an SLCP as equivalent to a single emission pulse of a long-lived pollutant. The use of this metric is likely to provide more accurate inferences about the warming effects of CH_4 from livestock systems in Ireland, because these emissions have not been constant over time. Changes in livestock populations caused by the growing export market, economic drivers and policy directives, for example, the introduction and removal of European Union (EU) milk quotas, have changed the rate of CH_4 emissions over time, and this has a significant effect on the expected warming caused.

The goal of this study is to improve the understanding of the warming effects of CH_4 from Irish ruminants by calculating the carbon dioxide equivalents (CO_2e) of these emissions using the GWP* metric. The conventional GWP metric is also included for comparison. Future hypothetical scenarios of increasing, constant and decreasing emissions over a 10-yr period are also included to investigate what effect changes in emission rates are likely to have, and what effect climate mitigation strategies would have. The focus is on CH_4 from ruminants exclusively and all livestock significantly present in Ireland are included.

Methods

Data on livestock populations and animal CH_4 emissions from Irish livestock were taken from FAOSTAT (Food and Agriculture Organization of the United Nations, 1997). These data are based on livestock population data provided by CSO, which dates to 1926 (CSO, 2023). Irish livestock populations were surveyed in 1960 and then every 5 yrs until 1980, after which they were surveyed every year. The missing data from the 1960–1980 period is modelled from national export data by FAOSTAT.

Livestock CH_4 was estimated using Tier 1 Methodology for data within the 1961–2005 year range, whilst Tier 2 Methodology was used for the 2006–2020 year range. Both methods are described by the Intergovernmental Panel on Climate Change (IPCC, 2006). Tier 1 is a basic calculation using livestock populations and a region-specific emission factor supplied by IPPC. Tier 2 is a detailed calculation incorporating animal age, feed, gross energy intake and so on. Tier 1 was selected for 1961–2005, because nutritional information and specifics around livestock age/breed were unavailable. Tier 2 was selected thereafter, as this information became available in the early 2000s. Animals which are not present in Ireland in significant numbers such as camels, buffalo and goats were not included. Poultry was also not included as monogastrics with small stomachs are not believed to emit CH_4 in significant amounts. The animals selected were donkeys, cattle (dairy cows and non-dairy cattle), horses, mules, hinnies, sheep and swine (breeding and market). Donkeys, mules and hinnies were aggregated into one category (hereafter referred to as donkeys, mules and hinnies), as were breeding and market swine (hereafter referred to as swine). The studied animals were split into two categories, 'minor' animals (donkeys, mules & hinnies, horses and swine) and 'major' animals (dairy cows, non-dairy cattle and sheep). The CO_2e of these emissions was then calculated using both the conventional GWP metric and the GWP* metric. The conventional GWP was calculated by multiplying the emission per animal per year amount by 28 (IPCC, 2021). The GWP* was calculated by applying the following formula, as described by Cain *et al*. (2022):

$$E*(t) = [4.53 \times E_{100}(t)] - [4.25 \times E_{100}(t-20)]$$

where $E^*(t)$ is the CO_2e of the emissions, $E_{100}(t)$ is emissions calculated using the conventional GWP metric from year t (the year for which CO_2e emissions are being calculated), and E_{100} (t-20) is the emissions calculated using the conventional GWP metric in the year t-20 (20 yrs prior). The 4.53 and 4.25 factors are derived from climate models and represent the immediate and residual warming effects of CH_4 emissions in years t and t-20. Multiplying by these factors and then subtracting the 20-yr-old emissions from the studied year allows for calculation of the studied year's emissions to account for removal of the emissions from 20 yrs previously.

The GWP* metric was calculated from 1981 for all studied livestock, as the data begin in 1961 and it requires a 20-yr period for calculation. Minor animals were considered as animals whose total annual CH_4 emissions were less than 100 kt CO_2e year^{-1} in 2019. Major animals were considered as those whose emissions were greater than 100 kt CO_2e year^{-1}. Cumulative historical emissions for each animal were calculated by summing all values from 1961 to 2019. This was only possible from 1981 to 2019 for GWP* calculations, as this requires 20 yrs of preceding data. Cumulative emissions for the future projections for both GWP and GWP* were also included by summing all values from 2020 to 2050. Calculated CH_4 emissions only refer to enteric fermentation, and not other sources such as manure management.

Three scenarios of future emissions from 2019 to 2050 were then calculated. The scenarios hypothesise changes in livestock populations, which in turn cause changes in livestock CH_4 emissions (no changes in CH_4 emission factors due to management or nutritive factors were assumed in all scenarios). The scenarios hypothesised were as follow:

1. No change in livestock populations and emissions from 2019 to 2050 (hereafter referred to as *constant*);
2. A 1% annual increase in livestock populations and emissions from 2019 to 2030 and then no change from 2030 to 2050 (hereafter referred to as *increasing*);
3. A 1% annual decrease in livestock populations and emissions from 2019 to 2030 and then no change from 2030 to 2050 (hereafter referred to as *decreasing*).

These scenarios were drawn up to assess the effect of potential changes in emission rates on the carbon footprint of Irish livestock farming, which could be due to changing farming practices or policy directives from either Irish or European authorities. All calculations were carried out in the R environment (version 4.2.1 [TEAM, 2020]) and plots were created using the *ggplot2* package.

Results

Historical results – major animals

The comparison of GWP and GWP* metrics when assessing the CO_2e of CH_4 from major Irish livestock showed how the conventional GWP metric overestimated the CO_2e when populations fell over the preceding 20-yr period, and underestimated the CO_2e when populations rose over the preceding 20-yr period. Cattle were found to emit more CH_4 than sheep when the conventional GWP was used, and non-dairy were found to emit more than dairy cattle (Figure 2). The GWP* metric calculated much lower CO_2e values for dairy cows than the GWP over the historical period (1961–2019), with some atmospheric removal, but the inverse was true for non-dairy cattle in the same period. Populations of non-dairy cattle increased as the dairy cow population decreased in the 1980s (Figure 4) and the GWP* metric indicated that their CH_4 emissions peaked following this in the early 2000s (hitting ~12,500 kt CO_2e year^{-1}, more than twice that of dairy cows at its peak).

Sheep were shown to have higher CO_2e CH_4 emissions in the years 1981–2019 when using the GWP* metric. Rising sheep populations in the 1980s and mid-1990s caused emissions to increase in this period, and when assessed by GWP* the CO_2e was >5,000 kt in the year 2000, more than twice of what was assessed by GWP in the same year. Declining sheep populations after the year 2000 caused sheep CH_4 emissions in the years 2010–2019 to be balanced by atmospheric removals in the GWP* assessment, as the calculated CO_2e values when GWP* was used ran close to zero in this period.

Historical results – minor animals

Methane emissions from minor animals were not significant when compared with those of major animals in any year from 1961 to 2019 (e.g., when using GWP, in 1961 horses produced ~100 kt CO_2e (Figure 3) whilst dairy cows produced ~5,000 kt CO_2e (Figure 2)). The CH_4 emissions from donkeys, horses

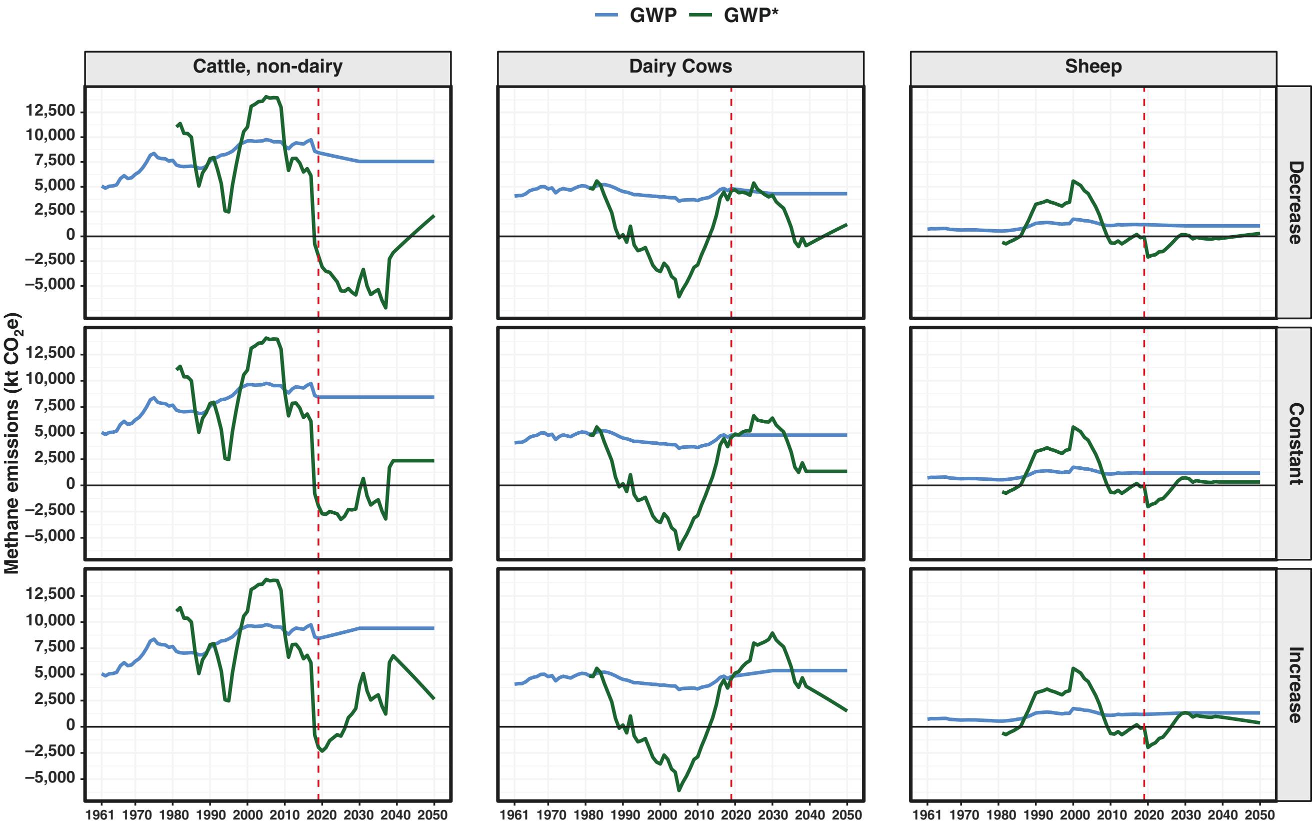

Figure 2. Livestock methane emissions from major sources in Ireland from 1961 to 2050 using GWP and GWP* metrics. Red line indicates the beginning of the future scenarios. GWP, global warming potential.

and swine remain at least an order of magnitude less than the dominant form of livestock husbandry in Ireland, which is pasture-based ruminants. Minor animals such as donkeys, mules & hinnies, and horses, showed negative emission values (atmospheric removal) when using GWP* from 1981 onwards, whereas the GWP metric calculated positive values (Figure 3). Donkeys, mules & hinnies were described as emitting close to zero CO_2e in the year 1981 when the GWP metric was used, but a net removal of ~75 kt CO_2e was calculated for these animals in the same period when using GWP* (Figure 3). A similar pattern was observed in horses, but this was reversed as the horse population increased from 1990 onwards.

Swine were shown to have a higher CO_2e from 1961 to 2019 when using the GWP* metric (Figure 3). The GWP metric indicates a rise in CH_4 emissions in the period 1995–2005, but the GWP* metric indicates that this increase is an underestimation of the true warming effect. The CO_2e emissions from Irish swine, and therefore the warming effect, was shown to be twice as high when using GWP* than when using GWP in this period. The GWP* then calculated that lower CH_4-based CO_2e was emitted in the 2010s than the emissions calculated by the GWP.

Total historical emissions – major and minor animals

Total historical CH_4 emissions (1981–2019) when expressed as CO_2e were considerably lower using the GWP* metric for some animals, for example, donkeys, mules & hinnies, horses and dairy cows (Table 1). The conventional GWP metric calculated 167,828 kt CO_2e for dairy cows from 1981 to 2019, but the GWP* metric calculated −8,805 kt CO_2e for this period, marking some atmospheric removal, or a cooling, in this time period. This effect was not observed for non-dairy cattle, for which both GWP and GWP* gave almost the same value (Table 1). Total emissions for Irish livestock were calculated as 538,072 kt CO_2e in the years 1981–2019 by the conventional GWP, and the GWP* metric calculated 380,370 kt CO_2e for this period. Only sheep were observed to emit a higher amount of CH_4-based CO_2e when assessed using GWP* (GWP calculated 46,354 kt CO_2e, whereas the GWP* calculated 67,496 kt CO_2e). Total emissions for all studied Irish livestock when converted to CO_2e were lower when using

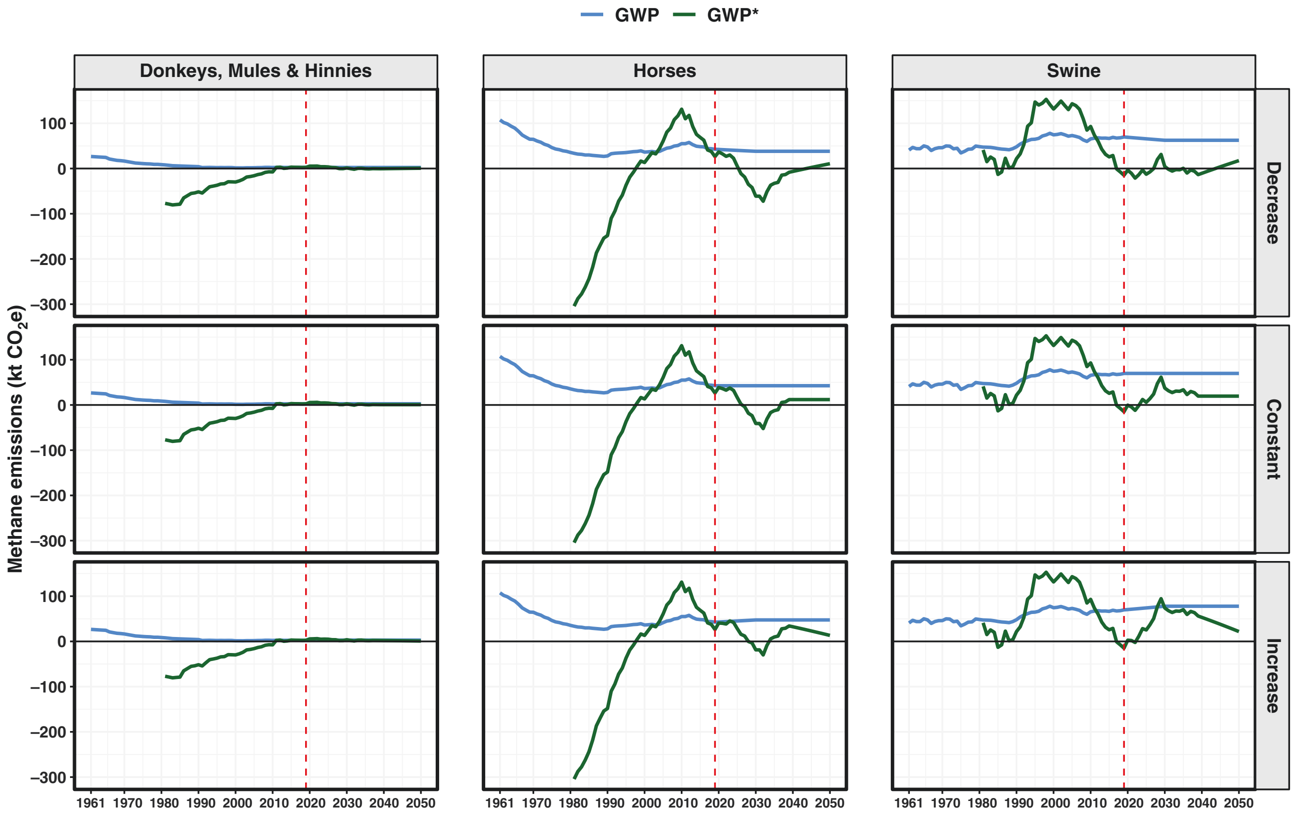

Figure 3. Livestock methane emissions from minor sources in Ireland from 1961 to 2050 using GWP and GWP* metrics. Red line indicates the beginning of the future scenarios. GWP, global warming potential.

GWP* in the period 1981–2019 (391,557 kt when using GWP* and 553,898 kt when using GWP).

Future scenarios – major and minor animals

Methane emissions under scenarios of unchanging and decreasing animal populations (constant and decreasing scenarios) were lower in the GWP* metric than the GWP with respect to all animals apart from dairy cows (Figure 2), which gave higher CO_2e emissions in the constant scenario immediately after 2019, before declining to less than the values calculated for GWP around 2030. This was caused by the increasing numbers of dairy cows in Ireland from 2010 onwards (Figure 4), in response to the milk quota removal in this period. Other animals were shown to emit less CH_4 expressed as CO_2e under the GWP* metric in the constant scenario, some significantly less so. Constant emissions from non-dairy cattle were shown to cause atmospheric removal in the studied time period (2019–2050), and decreasing emissions were shown to cause even more significant removal. The decreasing scenario was shown to cause a peak of ~10,000 kt CO_2e net removal in the mid-years between 2025 and 2050, a figure comparable to the additions caused by dairy cows in the years 2000–2010 when the conventional GWP metric was used.

Future emission scenarios (total) – major and minor animals

Differences in the total emissions of the projected scenarios (2019–2050) of increasing, constant or decreasing emission rates were marginal when using GWP. For example, non-dairy cattle were shown to emit 286,745 kt CO_2e in the increasing scenario, 261,475 kt CO_2e in the constant scenario and 238,433 kt CO_2e in the decreasing scenario (Table 2). The effect of these projected scenarios was much more significant when using GWP*, for example, non-dairy cattle were shown to emit 82,520 kt CO_2e in the increasing scenario, −7,484 kt CO_2e in the constant scenario and −88,972 kt CO_2e in the decreasing scenario (Table 1). These negative values for both constant and decreasing scenarios mark a net removal of CH_4 in these projections. This effect of future scenarios or constant or decreasing emissions causing net removal was also observed for other animals, for example, horses and sheep (Table 1). This was not the case with dairy cows, where

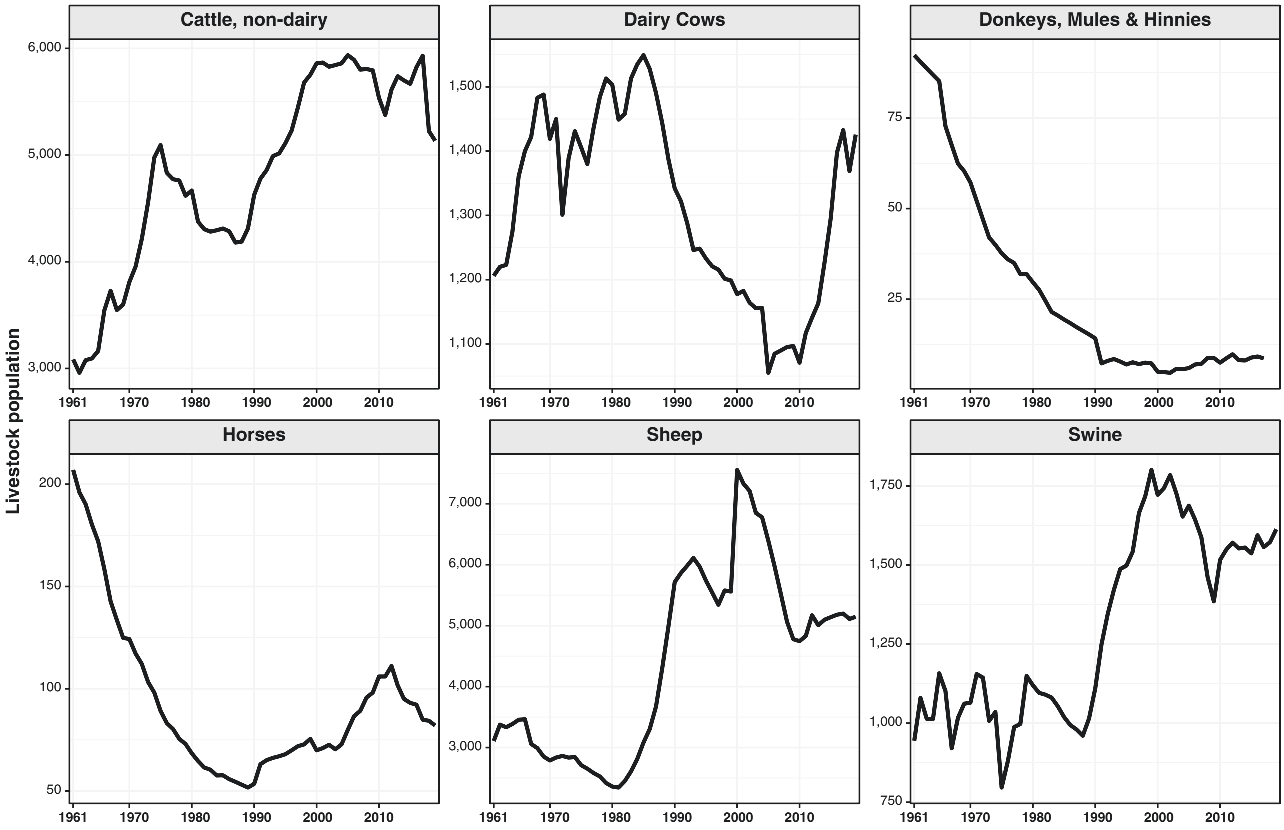

Figure 4. Livestock populations in Ireland, 1961–2019. Units are 1,000 animals.

Table 1: Cumulative CO_2e of historical (1961–2019) CH_4 emissions from all Irish livestock using both GWP and GWP* metrics. GWP* is only calculated from 1981 as it requires 20 yrs of preceding data. All units are kt CH_4 expressed as CO_2e

	GWP		GWP*
	1961–1980	1981–2019	1981–2019
Donkeys, mules & hinnies	329	119	−1,187
Dairy cows	93,718	167,828	−8,805
Cattle, non-dairy	131,536	335,590	332,579
Horses	1,313	1,532	−1,263
Sheep	13,475	46,354	67,496
Swine	893	2,427	2,768
Total	241,263	553,898	391,557

GWP, global warming potential.

constant and decreasing scenarios gave lower total CO_2e emissions under the GWP* than the GWP metric, but not negative values.

The total CH_4 emitted by Irish livestock when expressed as CO_2e was lower when using GWP* for all future scenarios, and the difference was more pronounced in scenarios of constant and decreasing emissions than increasing (Table 2). The GWP metric calculated total CO_2e to be 450,910 kt, but the GWP* calculated only 100,633 kt. Under the decreasing scenario the GWP metric calculated total CO_2e to be 411,175 kt, but the GWP* calculated −39,893 kt.

Discussion

Historical emissions – major animals

There are more non-dairy cattle than dairy cows in Ireland (Figure 4) and cattle generally emit more methane than sheep due to their larger stomach capacity (Broucek, 2014). Methane

Table 2: Cumulative CO_2e of projected CH_4 emissions from all Irish livestock using GWP and GWP*. Scenarios include increasing, constant and decreasing. All units are kt CH_4 expressed as CO_2e

	Increasing scenario (2020–2050)		Constant scenario (2020–2050)		Decreasing scenario (2020–2050)	
	GWP	GWP*	GWP	GWP*	GWP	GWP*
Donkeys, mules & hinnies	86	81	79	55	72	30
Dairy cows	163,458	159,237	149,053	107,931	135,918	61,478
Cattle, non-dairy	286,745	82,520	261,475	−7,484	238,433	−88,972
Horses	1,446	554	1,319	100	1,202	−311
Sheep	40,339	12,033	36,783	−629	33,542	−12,093
Swine	2,372	1,396	2,163	652	1,971	−22
	0	0	0	0	0	0
Total	494,488	255,843	450,910	100,633	411,175	−39,893

CO_2e, carbon dioxide equivalents; CH_4, methane; GWP, global warming potential.

emissions from cattle make up most of the CH_4 emitted from Irish agriculture, but the use of the GWP* metric shows how our understanding of the warming effects of these emissions can be improved, and how policy measures can help farmers to reduce the climate impact of dairy and beef production.

The population of dairy cows in Ireland has shifted in response to economic changes following accession to the EU in 1973. Common market access increased the demand for Irish dairy products internationally and farmers doubled milk production between 1970 and 1984 by improving the output per cow and increasing the dairy cow population (Donnellan, 2015). Intensive production in Ireland and the rest of the EU into the 1980s gave way to falling prices and market saturation, which caused the EU to impose restrictions on milk production (known as quotas) from 1984 (Läpple *et al.*, 2022). The restrictions remained in place until 2015 when demand in emerging international markets for European dairy products reached the point where the bloc could absorb a surplus. The effect of this on the Irish dairy cow population is shown in Figure 4: the numbers drop after 1984 and only begin to rise again around 2015 when the quotas were removed. The effect on CH_4 emissions is also clear when using the GWP metric, but the GWP* metric gives a more accurate understanding of the warming effects of these shifts in agricultural policy.

The sensitivity of GWP* to a declining annual emission rate illustrates how the climate impact of livestock can be mitigated by reducing populations. The fall in CH_4 from Irish dairy cows, when assessed using GWP*, was precipitous from the 1990s onwards, and a cooling or net removal took place in this period, because annual emissions throughout this period were substantially lower than the overall removals from this same source. This was most significant in the early 2000s, where a net removal of ~5,000 kt CO_2e year^{-1} was observed (Figure 2). This effect was also observed in other studies on dairy cows, for example, the national dairy industry in the USA was found to have a neutral impact on global warming (with respect to CH_4) in the years 1986–2017 (Liu *et al.*, 2021). This was caused by a decline in populations from the 1960s until 2017. The significant effect of declining populations on CH_4 when converted to CO_2e using GWP* has also been described in Italian dairy cows, which were also shown to have negative emission values for the years 2010–2020 due to declining populations (Correddu *et al.*, 2023). This 'cooling' effect has also been observed in other studies using GWP*, particularly those with similar livestock population dynamics. For example, sheep in Australia were shown to have caused a net removal in recent years due to a declining sheep population (Ridoutt, 2021). A similar study on the goat and sheep dairy sector in Europe saw the same effect in the years 1990–2018, again due to declining livestock populations (Del Prado *et al.*, 2021). The use of conventional GWP to assess the CH_4 emissions of declining livestock populations over time may overestimate the warming effect, but the data for Irish non-dairy cattle in Figure 2 indicate that it may also *underestimate* the climate impact of livestock when populations, and therefore emissions, are increasing over time. Methane emissions from non-dairy cattle in Ireland were found to be higher than dairy when using either GWP or GWP* metrics (Figure 2). This is not surprising considering the greater populations (Figure 4) and the role beef production plays in the Irish economy. It produces 30% of the value of Irish farming products and has a significant international market in the EU (90% of beef produced in Ireland is exported (Hanrahan, 2020)). The peak rapidly dropped back down as the emission rate levelled off. The GWP* assessment of both non-dairy cattle and sheep shows how the warming caused by livestock can spike quickly following an increase in the animal populations and associated emissions, and how this is more significant than the GWP assessment indicates. It also shows how these rapid increases are mitigated by reducing the rate of increase or returning to a constant rate of emission.

Historical emissions – minor animals

Donkeys, mules, hinnies and horses were much more commonly found in Irish farming systems in 1961 and before, than they are in modern times. They were traditionally kept as draught animals to carry goods and till fields, but they were displaced by tractors and motorcars as Irish society industrialised from the 1960s onwards (Smyth, 2014). The declining population of these animals over time is given in Figure 4, and this results in a concomitant decline in annual CH_4 emissions when using GWP as a metric for assessing their CO_2e (Figure 2). However, the decline in emission rate has a more significant effect when using GWP*, where a cooling effect was observed, similar to dairy cows in the years 1990–2020. This cooling effect when using GWP* was also seen for horses up until the year 2000, but increasing populations of these animals after this year saw emissions rise again in the new millennium.

As with non-dairy cattle, the CO_2e of CH_4 from Irish swine was shown to be underestimated by the conventional GWP (Figure 3). The Irish pork industry transitioned throughout the 1980s from an industry dominated by small producers scattered throughout the country, to large-scale production at a small number of centralised facilities (Boyle *et al.*, 2022). With this came investment in the sector and the establishment of an internationally competitive export market, which increased the population from 1990 onwards (Figure 4). This effect has also been observed in other parts of the world when assessing the CH_4 emissions from animals over time. For example, between 1970 and 2008, the CO_2e of CH_4 emissions from the Californian dairy industry when calculated using GWP* was shown to be three times higher than when calculated using GWP (Liu *et al.*, 2021). This was caused by changes in industrial practices and increasing populations, similar to those which occurred in the Irish pork industry in the 1980s. The GWP* data for swine indicated that CO_2e emissions dropped significantly after 2005, as the rate of emission tapered off in the preceding 20-yr period, leading to some atmospheric removal at this time. These emissions were minor when compared with cattle or sheep, but the use of the GWP* metric illustrates how the conventional GWP metric can underestimate the warming effects of livestock CH_4 when the populations, and therefore CH_4 emissions, are increasing over time.

Total historical emissions – major and minor animals

Populations of Irish livestock have shifted up and down in the years 1961–2019 (Figure 4). Shifts in populations at different times have been responses to various industrial, policy and economic changes, for example, the milk quotas for cattle and the industrialisation of the pork industry for swine. The effect of these changes in populations, and therefore CH_4 emissions, on the CO_2e of these emissions is more accurately described by the GWP* metric. Declining populations of dairy cows from the 1980s until 2010 caused a net removal of 8,805 kt CO_2e in the years 1981–2019 (as calculated by the GWP* metric – Table 1). A similar effect was also observed in animals with declining populations in this period, for example, horses and donkeys, mules and hinnies. These declining populations causing net atmospheric removal have also been observed for other countries, for example, Italy, where declining populations of dairy cows were found to cause a net removal of 53,786 kt CO_2e over the time period, 1981–2019 (Correddu *et al.*, 2023).

The effect of increasing populations can also be significant, and the conventional GWP metric can underestimate the CO_2e of emissions when the emission rate is increasing. This was observed in Ireland for sheep in the period 1981–2019, where populations increased from ~4.5 million to ~6 million in the early 2000s. The GWP* metric estimated that the warming effect of this increase was more significant than the conventional GWP metric suggested. These results are in contrast to a similar study carried out in Australia, which described the CH_4 emissions from sheep using both metrics and found that GWP* gave much lower results than GWP, due to the declining populations of Australian sheep over the preceding decades (Ridoutt, 2021).

Future emission scenarios – major and minor animals

The scenarios of future CH_4 emissions from Irish livestock presented in this paper are hypothesised to investigate the climate impact of Irish livestock under likely outcomes of agricultural development or climate mitigation policy efforts. Ireland was given a target of 30% reduction of agricultural CH_4 from 2005 levels by 2030 by the EU 2020 Climate and Energy Package, but the smaller reduction hypothesised in this study may be a more realistic target given the central role livestock farming plays in the export economy of Ireland, the outlook for increased production in the absence of policy constraints and the limited capacity of other industrial sectors to provide significant GHG reductions (Lanigan, 2019). The target also uses the GWP metric, and therefore may not accurately reflect the reduction in emissions required to curtail the warming effects of CH_4 emissions, as Figures 2 and 3 have suggested. Here we propose scenarios of *no change* after 2019, *increasing* by 1% year^{-1} up to 2030 and then maintaining a constant rate, and *decreasing* by 1% year^{-1} up to 2030 and then maintaining a constant rate.

The climate impact of livestock CH_4 depends on the preceding rate of emissions, and whether this has been roughly constant, increasing or decreasing over the previous 20 yrs. This effect has also been described by Lynch *et al.* (2020).

Where the emission rate has remained roughly constant for decades prior to the scenarios given here (beginning in 2019), then the differences between GWP and GWP* are minimal, for example, in donkeys, mules & hinnies (Figure 3) and to a lesser extent with sheep (Figure 2). Where this rate has increased, then the GWP* predicts higher CO_2e values for increasing emissions (non-dairy cattle) before levelling off, and lower CO_2e values for decreasing emissions (dairy cows). The scale of the difference found between GWP and GWP* in prospective scenarios of CH_4 emissions from non-dairy cattle shows the importance of considering the preceding rate of CH_4 emissions from Irish ruminants.

The GWP* metric indicated that increasing future emissions from dairy cows would cause a greater degree of warming than the conventional GWP implies (Figure 2), peaking at ~8,750 kt CO_2e in the early 2030s before rapidly declining after the emission rate returned to constant. A similar effect was seen in non-dairy cattle. The effect of increasing emissions by 1% in dairy cows when GWP* was used also shows how impactful a small increase in annual emissions can be on CH_4 expressed as CO_2e, as emissions increased from negative 2,500 kt CO_2e to 5,000 kt CO_2e in a ~15-yr period. This implies that increases in CH_4 emissions over time cause more warming than the conventional GWP calculates, but the drop following a return to constant emissions in these scenarios implies this warming can be curtailed if the rate of emissions is returned to constant.

Future emission scenarios (total) – major and minor animals

The predicted impact of livestock CH_4 emissions on climate change is a lynchpin of climate mitigation efforts (Scoones, 2023), but this impact can be misunderstood when looking at long-term impacts if only the conventional GWP is used to concert CH_4 to CO_2e. The effect of maintaining constant emissions on the climate impact of Irish livestock enteric fermentation is understated when the ubiquitous GWP metric is used. If a minor decrease in emissions is applied (the decreasing scenario), we argue that the CH_4 from Irish livestock can be climate neutral by 2050, as the total of projected emissions is calculated as a marginal removal (Table 2). This does not mean the Irish livestock industry will become climate neutral, as emissions from other life-cycle stages, such as feed production, transport, processing, retail, food waste and so on, will remain. However, CH_4 is a significant contributor to GHG emissions from the livestock sector, and here we find a minor reduction could eliminate the warming associated with these emissions if applied between now and 2050.

To our knowledge, there are currently no similar studies on the future scenarios of livestock CH_4 emissions comparing GWP and GWP*; however, studies with data up to the present day in Italy (Correddu *et al.*, 2023), Australia (Ridoutt, 2021) and USA (Liu *et al.*, 2021) might find a similar pattern of negative values calculated for CH_4-based CO_2e if future projections of marginal decreases were included. There are also currently no studies on the impact of future emission scenarios on other countries such as India and Brazil, which have seen significant increases in livestock populations over the past few decades (Food and Agriculture Organization of the United Nations, 1997). This increase is projected to continue in the coming decades (Alexandratos and Bruinsma, 2012), and it may be the case that these countries underestimate the warming impact their livestock industries are likely to have in the future.

Mitigation options

Reducing CH_4 emissions also does not have to mean reducing populations, production and farmer income. A number of ways of reducing CH_4 emissions from ruminants are available, for example, the introduction of forage species containing bioactive tannins (Cooledge, 2022), breeding for digestive efficiency (Manzanilla-Pech *et al.*, 2022) and the inclusion of methanogenesis-inhibiting supplements such as red algae (Ridoutt *et al.*, 2022). The plentiful supply of red algae on Ireland's coastline is being explored as a means to reduce livestock CH_4 emissions by Teagasc in an EU-funded project known as SeaSolutions (Abbott *et al.*, 2020), as well as by the Donegal-based start-up Dúlabio (DúlaBio, 2020). Feed supplements containing seaweed must, however, take care to monitor concentrations of potential toxins such as iodine, which may bioaccumulate in livestock and harm animal and human welfare (Makkar *et al.*, 2016).

Feed-based solutions are only effective as long as they are implemented and their effect can therefore be transient in practice. Other mitigation options include restricting rumen methanogenesis using probiotics or vaccination, and breeding programmes focusing on cattle with low CH_4 emissions (Króliczewska *et al.*, 2023). Poor fertility in dairy cows can also reduce annual and lifetime milk yield, and improving reproductive performance may therefore offer a more permanent mitigation strategy for CH_4 emissions (Garnsworthy, 2004). Methane inhibitors such as nitrooxypropanol have also been shown to reduce livestock CH_4 emissions in indoor systems, and these may be extended to farmers for use in pasture if an appropriate delivery mechanism can be developed (Reisinger *et al.*, 2021).

Conclusions

Methane is a GHG and livestock is a significant source. Countries with a focus on pastoral ruminant production such as Ireland should therefore try to reduce CH_4 emissions, to play their part in holding the increase in the global average temperature below 2°C above pre-industrial levels. However, using the conventional GWP metric to assess the warming effects of SLCPs such as CH_4 may not accurately describe the warming effect, thus confounding climate mitigation policy efforts. Ireland has been given a target reduction of 30% below 2005 levels by 2030 by the EU, but the results calculated using the GWP* metric in this paper indicate that a reduction of this scale may not be necessary to achieve a 30% reduction *in warming*, as CH_4 emissions from Irish livestock have not been consistently increasing since 1961: rather they have increased and decreased in response to societal and policy changes as well as market forces. A modest reduction of 1% per year for an initial 10 yrs and then no change until 2050 for all Irish livestock was calculated here to remove 38,753 kt CO_2e for this time period. This implies that significant reductions in warming associated with CH_4 emissions can be mitigated with marginal reductions in the rate of emission.

To accurately assess the warming effects of CH_4 from livestock, one must account for the historical and projected effects of the changing annual rate of emission – which can be done using GWP*. Mitigation measures combined with more accurate emission assessments provided by GWP* may help Irish farmers to account for the warming associated with CH_4 emissions without compromising on productivity and profitability. The overall contribution of Irish livestock to global warming is non-significant, given how small it is in comparison to emissions from larger countries with large animal populations, particularly those which have been increasing for decades, for example, Brazil or India. But if Ireland can demonstrate how CH_4 emissions can be mitigated and more accurately accounted for, then more significant emitters may be more inclined to follow suit.

References

Abbasi, T. and Abbasi, S.A. 2016. Reducing the global environmental impact of livestock production: the minilivestock option. *Journal of Cleaner Production* **112**: 1754–1766.

Abbott, D.W., Aasen, I.M., Beauchemin, K.A., Grondahl, F., Gruninger, R., Hayes, M., Huws, S., Kenny, D.A., Krizsan, S.J., Kirwan, S.F., Lind, V., Meyer, U., Ramin, M., Theodoridou, K., Von Soosten, D., Walsh, P.J., Waters, S. and Xing, X. 2020. Seaweed and seaweed bioactives for mitigation of enteric methane: challenges and opportunities. *Animals* **10**: 2432.

Alexandratos, N. and Bruinsma, J. 2012. “World Agriculture towards 2030/2050: The 2012 Revision”. Food and Agriculture Organization (FAO), Rome.

Boyle, L.A., Carroll, C., Clarke, L., Garcia Manzanilla, E., Gardiner, G.E., Mccutcheon, G., Mccrum, E., Mckeon, M., Lawlor, P., Lynch, B., O’Doherty, J. and O’Driscoll, K. 2022. An overview of Irish pig production, research and knowledge transfer since 1960. *Irish Journal of Agricultural and Food Research* **61**: 109–125.

Broucek, J. 2014. Production of methane emissions from ruminant husbandry: a review. *Journal of Environmental Protection* **5**: 12.

Cain, M., Jenkins, S., Allen, M.R., Lynch, J., Frame, D.J., Macey, A.H. and Peters, G.P. 2022. Methane and the Paris Agreement temperature goals. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **380**: 20200456.

Cooledge, E.C., Chadwick D.R., Smith, L.M.J., Leake, J.R. and Jones, D.L. 2022. Agronomic and environmental benefits of reintroducing herb- and legume-rich multispecies leys into arable rotations: a review. *Frontiers of Agricultural Science and Engineering* **9**: 245–271.

Correddu, F., Lunesu, M.F., Caratzu, M.F. and Pulina, G. 2023. Recalculating the global warming impact of italian livestock methane emissions with new metrics. *Italian Journal of Animal Science* **22**: 125–135.

CSO. 2023. Livestock survey: 1926–2019. In: “The Central Statistics Office”, Ireland.

Del Prado, A., Manzano, P. and Pardo, G. 2021. The role of the European small ruminant dairy sector in stabilising global temperatures: lessons from GWP* warming-equivalent emission metrics. *The Journal of Dairy Research* **88**: 8–15.

Department of Agriculture, Food and the Marine. 2020. “Fact Sheet on Irish Agriculture”, Ireland.

Donnellan, T., Hennessy, T. and Thorne, F. 2015. “The End of the Quota Era: A History of the Irish Dairy Sector and its Future Prospects”. Teagasc, Agricultural Economics and Farm Surveys Department.

DúlaBio. 2020. “An Irish Seaweed Supplement That Reduces Methane Emissions From Livestock [Online]”.

FAO. 2006. “Livestock’s Long Shadow: Environmental Issues and Options”. Food and Agriculture Organization of the United Nations, Rome.

Food and Agriculture Organization of the United Nations. 1997. “FAOSTAT Statistical Database”. FAO, Rome, c1997.

Garnsworthy, P.C. 2004. The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions. *Animal Feed Science and Technology* **112**: 211–223.

Hanrahan, K. 2020. The significance of beef. “Beef Manual”, Teagasc, Ireland.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme (eds. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe), IGES, Japan.

IPCC. 2021. Climate change 2021: synthesis report. Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change, Switzerland.

Króliczewska, B., Pecka-Kiełb, E. and Bujok, J. 2023. Strategies used to reduce methane emissions from ruminants: controversies and issues. *Agriculture* **13**: 1–26.

Lanigan, G., Donnellan, T., Hanrahan, K., Carsten, P., Shalloo, L., Krol, D., Forrestal, P., Farrelly, N., O’Brien, D., Ryan, M., Murphy, P., Caslin, B., Spink, J., Finnan, J., Boland, A., Upton, J. and Richards, K. 2019. An analysis of abatement potential of greenhouse gas emissions in irish agriculture 2021–2030. “Teagasc Greenhouse Gas Working Group”, (eds. J. Lanigan and T. Donnellan), Teagasc, Ireland.

Läpple, D., Carter, C.A. and Buckley, C. 2022. EU milk quota abolition, dairy expansion, and greenhouse gas emissions. *Agricultural Economics* **53**: 125–142.

Liu, S., Proudman, J. and Mitloehner, F.M. 2021. Rethinking methane from animal agriculture. *CABI Agriculture and Bioscience* **2**: 22.

Lynch, J., Cain, M., Pierrehumbert, R. and Allen, M. 2020. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environmental Research Letters* **15**: 044023.

Makkar, H.P.S., Tran, G., Heuzé, V., Giger-Reverdin, S., Lessire, M., Lebas, F. and Ankers, P. 2016. Seaweeds for livestock diets: a review. *Animal Feed Science and Technology* **212**: 1–17.

Manzanilla-Pech, C.I.V., Stephansen, R.B., Difford, G.F., Løvendahl, P. and Lassen, J. 2022. Selecting for feed efficient cows will help to reduce methane gas emissions. *Frontiers in Genetics* **13**: 885932.

O’Mara, F., Richards, K.G., Shalloo, L., Donnellan, T., Finn, J.A. and Lanigan, G. 2021. Sustainability of ruminant livestock production in Ireland. *Animal Frontiers* **11**: 32–43.

Reisinger, A., Clark, H., Cowie, A.L., Emmet-Booth, J., Gonzalez Fischer, C., Herrero, M., Howden, M. and Leahy, S. 2021. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **379**: 20200452.

Ridoutt, B. 2021. Short communication: climate impact of Australian livestock production assessed using the GWP* climate metric. *Livestock Science* **246**: 104459.

Ridoutt, B., Lehnert, S.A., Denman, S., Charmley, E., Kinley, R. and Dominik, S. 2022. Potential GHG emission benefits of Asparagopsis taxiformis feed supplement in Australian beef cattle feedlots. *Journal of Cleaner Production* **337**: 130499.

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwiler, L., Carlson, K.M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P.M., Covey, K., Curry, C.L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M.I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K.M., Joos, F., Kleinen, T., Krummel, P.B., Langenfelds, R.L., Laruelle, G.G., Liu, L., Machida, T., Maksyutov, S., Mcdonald, K.C., Mcnorton, J., Miller, P.A., Melton, J.R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O’Doherty, S., Parker, R.J., Peng, C., Peng, S., Peters, G.P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W.J., Rosentreter, J.A., Segers, A., Simpson, I.J., Shi, H., Smith, S.J., Steele, L.P., Thornton, B.F., Tian, H., Tohjima, Y., Tubiello, F.N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T.S., van Weele, M., van der Werf, G.R., Weiss, R.F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q. and Zhuang, Q. 2020. The Global Methane Budget 2000–2017. *Earth System Science Data* **12**: 1561–1623.

Scoones, I. 2023. Livestock, methane, and climate change: the politics of global assessments. *Wiley Interdisciplinary Reviews: Climate Change* **14**: e790.

Smyth, J. 2014. The strange history of the irish donkey. *Hydra Mule and Donkey Conference, Hydra*.

Steinfeld, H. 2006. “Livestock’s Long Shadow: Environmental Issues and Options”. Food and Agriculture Organization of the United Nations.

Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M.M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. 2014. Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of IPCC the intergovernmental panel on climate change.

TEAM, R.C. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online: https://www.R-project.org/.

Tracy, B.F. and Zhang, Y. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in illinois. *Crop Science* **48**: 1211–1218.

van Amstel, A. 2012. Methane. A review. *Journal of Integrative Environmental Sciences* **9**: 5–30.

Weis, T. 2013. “The Ecological Hoofprint: The Global Burden of Industrial Livestock Production”, USA, Zed Books.