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RESEARCH ARTICLE



## Thirty years of global warming potential evolution for the Italian dairy cow sector measured by two different metrics

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### ABSTRACT

This study aimed to provide a comprehensive evaluation of the greenhouse gases (GHG) emission between 1991 and 2021 of both the entire Italian dairy cattle sector (ITA\_POP) and the registered Holstein Friesian population only (HF). An attributional cradle-to-farm gate Life Cycle Assessment was performed, including emissions (methane-CH<sub>4</sub>, nitrous oxide-N<sub>2</sub>O, carbon dioxide-CO<sub>2</sub>) due to animal and manure management, feed production, and farm materials. The functional units were 1 year and 1 kg of fat- and protein-corrected milk. We applied 100-year global warming potential (GWP) metric. For 2011–2021 period, we also applied GWP star (GWP\*). Data originated from Italian GHG accounting and official milk recording systems. From 1991 to 2021, annual GHG emission of ITA\_POP decreased from 20.4 ± 2.7 to 15.5 ± 2.1 Mt CO<sub>2</sub>e and emission intensity (EI) from 1.90 ± 0.25 to 1.17 ± 0.16 kg CO<sub>2</sub>e/kg corrected milk. The share of officially registered HF cows in ITA\_POP increased from 36 to 70%. The annual emission of HF increased by 32% to 12.2 ± 1.8 Mt CO<sub>2</sub>e, but its EI decreased by 34% to 1.09 ± 0.16 kg CO<sub>2</sub>e/kg corrected milk. The accumulation in GHGs in 2011–2021 period due to ITA\_POP (100-year GWP) continuously increased. When considering the short lifetime of CH<sub>4</sub> (GWP\*), the rate of increase in the same years was quite lower, with a flat pattern in the last 5 years. The decrease in CH<sub>4</sub> emission is compensating the accumulation of N<sub>2</sub>O and CO<sub>2</sub> from fossil fuels, highlighting the need of considering GHGs lifetime in the estimation of dairy cow sector emissions.

### HIGHLIGHTS

- Italian dairy cow sector has succeeded in reducing GHG emission per unit of milk.
- Cumulative GHG continuously increased in 2011–2021 period if calculated with conventional 100-y GWP, but not with GWP\*.
- Further improvements achievable focussing on individual GHGs (CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub>) and their lifetime in the atmosphere.

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## Introduction

The Italian dairy sector accounts for over one-third of the economic value of the Italian livestock sector (ISMEA 2022). It is mainly focused on producing high-quality, high-price cheeses, often labelled with PDO certifications by the European Union (European Union 2012; Bittante et al. 2022). In the last 30 years, the Italian dairy sector has undergone significant changes due to different factors, such as the reformation of the EU's common agricultural policy, the abolition of the milk quota, the progressive shift towards farm environmental sustainability that led to the Farm-to-Fork

strategy (European Parliament 2020), the evolution of consumer attitudes toward greater environmental sustainability of food products (Canavari and Coderoni 2020), and the improvements in cows' genetic background and herd management, which led to a progressive increase in their productivity (AIA 2023). The number of dairy farms has decreased from over 200,000 to nearly 25,000 in the last three decades, with a concurrent decrease of nearly 40% in dairy cows, reaching nearly 1.6 million heads, three-quarters of which are concentrated in northern Italy (ISTAT 2022). At the same time, the Italian production of milk has remained rather unchanged (Eurostat 2023)

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because of the increase in individual milk yield (MY) due to genetic selection and because of a progressive increase of Holstein Friesian (HF) cows at the expense of other dairy and dual-purpose breeds formerly kept in national dairy herds. The number of HF cows under the official milk recording system has increased in Italy from nearly 46% to over 80% of the total dairy cows registered from 1990 to 2022 (ISTAT 2022; AIA 2023).

During the same period, awareness of the environmental impact associated with animal production, particularly in the dairy sector, has notably increased. Life Cycle Assessment (ISO 2006) has emerged as a quantitative method to evaluate the environmental impact associated with production systems and the options for its reduction and mitigation (Baldini et al. 2017; Mazzetto et al. 2022).

Among the different impacts associated with animal production, the emission of greenhouse gases (GHG), strictly associated with the increase in the mean global temperature, has been the most evaluated (McClelland et al. 2018). Conventionally, LCA practitioners in agro-livestock sector have used the 100-year global warming potential (GWP<sub>100</sub>; IPCC 2021) metric to standardize and compare the various GHGs (Lynch 2019). The most important GHGs associated with livestock sector are methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and carbon dioxide (CO<sub>2</sub>) (Gerber et al. 2013), each of them being characterized by different residence times and capacity to have a warming effect in the atmosphere. In particular, CH<sub>4</sub> has a short residence time (almost a decade), whereas N<sub>2</sub>O and CO<sub>2</sub> can be detected even after a century after their release into the atmosphere (Masson-Delmotte et al. 2018). This different temporal framework has been gaining attention in the last years because different mixes of GHG could have different climate impacts, with consequent implications in the achievement of the target to limit the increase in the mean global temperature to 1.5–2.0 °C (IPCC 2022). As the atmospheric concentration of each GHG is the result of the balance between emissions and removals, the short persistence of CH<sub>4</sub> implies that reductions in the present-day emission rate can lead to an observable reduction in its atmospheric concentration in the very following years, as the CH<sub>4</sub> removed would be substituted by a lower amount of new CH<sub>4</sub>.

Since the conventional GWP<sub>100</sub> does not include this temporal framework, alternative metrics, such as Global Temperature Potential (GTP; IPCC 2021) or GWP-star (GWP\*; Allen et al. 2018; Cain et al. 2019; Smith et al. 2021) have been proposed. Both GTP and GWP\* consider the different behaviour of the various

GHGs in terms of warming potential and lifetime; however, only GWP\* specifically deals with the low persistence of CH<sub>4</sub> and considers also the differences between fluxes (i.e. how much gas is released into the atmosphere in a reference period) and stocks (i.e. how much gas can be found in the atmosphere in a reference period). In particular, GWP\* weights the different GHGs in terms of 'warming-equivalents' (we) with respect to CO<sub>2</sub>, taken as reference in the same way as done in GWP<sub>100</sub>. Recent studies have explored the use of GWP\* as an alternative to GWP<sub>100</sub> to evaluate the GWP associated with different livestock systems, such as beef and dairy sectors in the USA (Place and Mitloehner 2021), dairy and beef cattle and pigs in Austria (Hörtenhuber et al. 2022), all Italian livestock supply chains in Italy (Correddu et al. 2023) and, more recently, the whole Irish livestock populations in Ireland (McKenna and Banwart 2024).

Focusing on Italy, Correddu et al. (2023) evaluated the GHG emissions associated with different Italian livestock sectors (dairy, beef, pig, poultry, buffalo, goat, sheep, horses, mules and asses, and rabbits) and the relative trend of CH<sub>4</sub> originating from animals and CH<sub>4</sub> and nitrous oxide (N<sub>2</sub>O) originating from manure storage between 1990 and 2020. However, since this study was based on the national GHG inventory framework, it did not consider specific aspects that are of interest in a LCA perspective, such as the role of feed production as a GHG emission source, including the evolution of diet composition over time, and the CO<sub>2</sub> from anthropogenic sources associated with the livestock systems.

Therefore, this study aims to (i) provide a comprehensive evaluation of the long-term pattern of GHG emissions associated with the entire Italian dairy cattle sector considering its major causes of variation, (ii) develop a specific focus on the HF population only, because of its growing contribution to national milk production, and (iii) compare the results obtained by traditional GWP<sub>100</sub> and new GWP\* accounting methods.

## Materials and methods

### Goal and scope definition

The LCA model was developed according to the general recommendations of the FAO-LEAP guidelines (FAO 2020). The LCA model was of the attributional type and was applied separately for each year from 1991 to 2021. The functional units were 1 year and 1 kg of fat- and protein-corrected milk (FPCM, correction at 3.3% protein and 4.0% fat, according to Gerber

et al. 2010). The impact category considered was GWP (kg CO<sub>2</sub>e for GWP<sub>100</sub> and kg CO<sub>2</sub>we for GWP\*). The whole impact was allocated to milk by applying an average allocation ratio of 85% (IDF 2015; Kyttä et al. 2022). Furthermore, the system boundaries included emissions related to animal handling, manure storage, and on- and off-farm feed production for dairy cows and replacement heifers. In accordance with previous similar assessments (Hörtenhuber et al. 2022), emissions due to transports and farm materials (energy sources and bedding materials), described in specific sections of National Inventory Reports, were included by applying to each year an average factor. This value (10.4% of the total emission) was obtained by averaging the percentage contributions of transport and materials on the total emission derived from previous LCA studies on Italian dairy chain (Famiglietti et al. 2019; Lovarelli et al. 2019; Pirlo and Lolli 2019; Berton et al. 2023).

### Data collection and editing

Two different datasets were collected for GWP calculation. The first concerned the Italian dairy cattle population (ITA\_POP), following the Italian National Inventory Report (Romano et al. 2023). The second dataset dealt with the HF cow population under the official milk recording system (HF\_POP). For both datasets, the temporal period considered was 1991–2021. The year 2022 was not included in this study because data for GHG computations were not fully available. However, available data on the population size in 2022 were used to increase the robustness of data editing. Data on the number of animals are reported in Figure 1, whereas the main information on MY, milk components, and productive traits of ITA\_POP and HF\_POP dairy cows is reported in Table 1. Finally, the data on replacement heifers are reported in Table 2 (Supplementary Tables 1–4 for year-to-year data). Because some data were available only for the most recent years, the framework of the equations developed to estimate animal numbers and productive traits when direct data were not available is reported in Table 3.

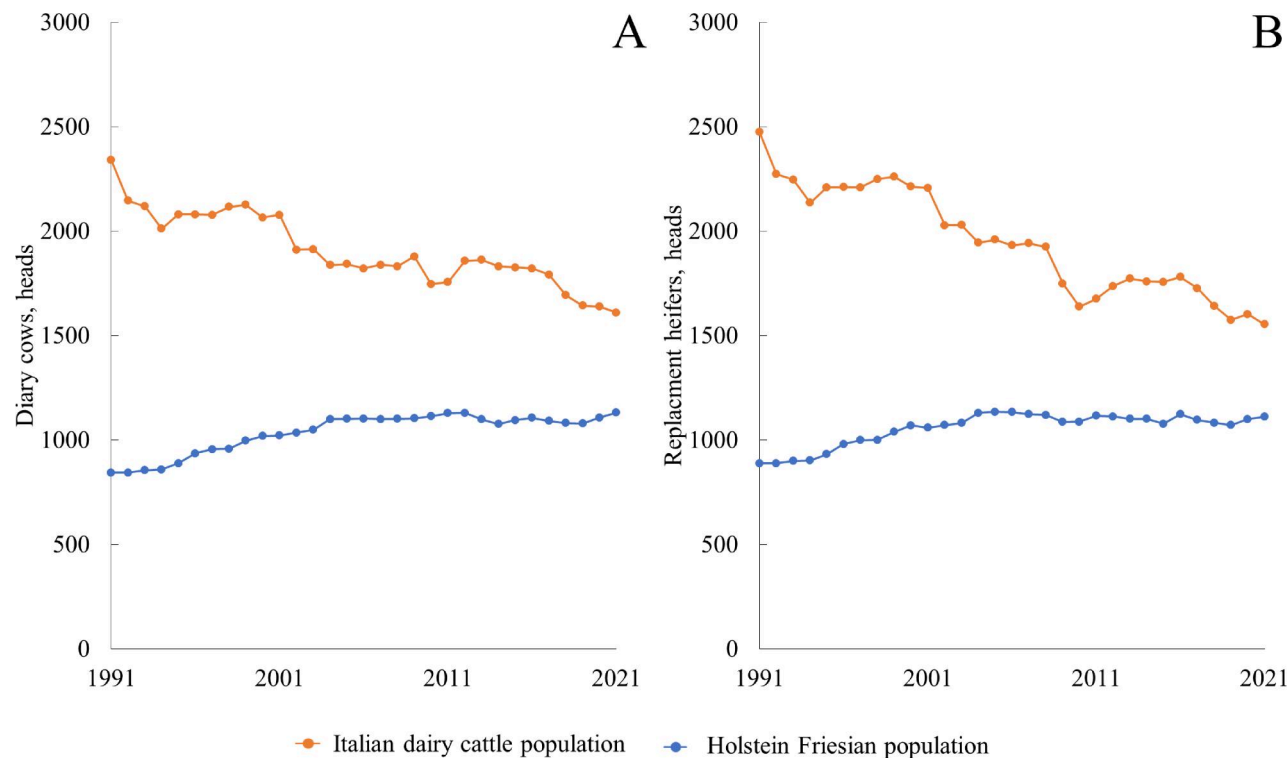
Regarding ITA\_POP, data on the number of dairy cows were derived from the National Inventory Report (Romano et al. 2023) and data on milk production from Eurostat (2023). The milk protein content for 2004–2022 was derived from the official milk recording system (AIA 2023), and for 1991–2003 it was linearly projected based on the 2004–2022 trend. Milk fat content was obtained from AIA (2023) and

Romano et al. (2023). The dry matter intake (DMI) of dairy cows was estimated based on the daily gross energy intake (GEI) divided by 18.45 MJ/kg dry matter (DM) following the IPCC method (IPCC 2019). The GEI was derived from the time series available in the National Inventory Report (Romano et al. 2023) and calculated following the IPCC (2019) method based on the animal daily net energy requirement (NER, computed by summing the requirements due to maintenance, growth, activity, milk production, and pregnancy) and the percentage of dietary digestible energy (DE\_perc). Similarly, the annual amount of nitrogen (N) excreted per dairy cow was derived from the National Inventory Report (Romano et al. 2023).

Data related to replacement heifers for ITA\_POP were derived from the Italian Veterinary Database (BDN 2023), where the number of heifers aged <1, 1–2, and >2 years ( $H_{0-12}$ ,  $H_{12-24}$ ,  $H_{>24}$ , respectively) was available for the 2009–2022 period. For each year of the 1991–2008 period,  $H_{0-12}$ ,  $H_{12-24}$ ,  $H_{>24}$  were computed based on the regression analysis of the 2009–2022 period data (equations are reported in Table 3). The time series of GEI and N excretion for heifers were derived from the National Inventory Report (Romano et al. 2023). Heifers' mean daily feed intake from birth to first calving was computed similarly to that described for dairy cows.

Regarding HF\_POP, the number of dairy cows was derived from the Italian milk recording system for the 2004–2022 period, as well as the average MY, milk fat, and protein contents, average age at first calving, and average replacement rate. For the 1991–2003 period, the sizes of HF\_POP and MY were retrieved from Magliano (2017), whereas milk fat and protein content, age at first calving, and replacement rate were estimated using a linear regression of data related to the 2004–2022 period. The annual number of pregnant heifers was calculated as dairy cows  $\times$  replacement rate and was assumed to be equal to  $H_{>24}$  (age at first calving was always >24 months). The number of  $H_{0-12}$  and  $H_{12-24}$  per year was derived from the BDN (2023) for the 2009–2022 period, whereas for 1991–2008, they were estimated by linear regression.

The average DMI of dairy cows was calculated as NER divided by the net energy content of the diet (NE\_DM). The NER was estimated following the NRC (2001) procedure for maintenance, activity, and lactation requirements and the IPCC (2019) for growth and pregnancy requirements. The mean BW of dairy cows and replacement heifers was assumed to be equal to that reported in the National Inventory Report (Romano et al. 2023) (dairy cows: 603 kg, heifers:



**Figure 1.** Number of dairy cows (A) and replacement heifers (B) for the Italian dairy cattle sector and the registered Holstein Friesian population from 1991 to 2021.

**Table 1.** Statistics on milk and animal traits for the entire Italian dairy cattle sector (ITA\_POP) and the registered Holstein Friesian population (HF\_POP).

Variable	Unit	1991	2001	2011	2021
ITA_POP <sup>a</sup>					
Milk yield, on 365 days	kg/cow/d	13.00	14.90	18.50	25.00
Milk fat content	%	3.63	3.63	3.70	3.82
Milk protein content	%	3.27	3.27	3.33	3.36
Gross energy intake	MJ/cow/d	273.20	290.50	305.20	355.30
Digestibility, on gross energy	%	65.00	65.00	67.70	68.70
Enteric methane conversion factor	% GEI	6.50	6.50	6.07	5.99
Nitrogen excretion	kg/cow/y	108.30	105.10	101.40	110.90
HF_POP <sup>b</sup>					
HF cows under Italian official recording system, proportion on ITA_POP	%	36.00	49.00	64.00	70.00
Milk yield, on 365 days	kg/cow/d	19.70	22.50	24.70	27.90
Milk fat content	%	3.48	3.59	3.66	3.83
Milk protein content	%	3.11	3.18	3.30	3.34
Gross energy intake	MJ/cow/d	312.50	320.40	330.90	362.10
Digestibility, on gross energy	%	66.70	67.90	68.80	70.20
Enteric methane conversion factor	% GEI	6.090	5.95	5.85	5.69
Nitrogen excretion	kg/cow/y	130.20	134.40	136.60	141.30

<sup>a</sup>Data retrieved from Eurostat (2023) and Romano et al. (2023). Milk protein content data in 1991 and 2011 was obtained through linear regression estimated on the 2004–2022 data derived from AIA (2023).

<sup>b</sup>Data on Holstein Friesian cow consistency and milk yield were derived from AIA (2023) for 2011 and 2021 and Magliano (2017) for 1991 and 2001. Data on milk fat and protein contents were derived from AIA (2023) for 2011 and 2021, whereas data for 1991 and 2001 was estimated through linear regression based on data from AIA (2023). Gross energy intake was computed based on NRC (2001) and IPCC (2019). Digestibility and enteric methane conversion ratio were estimated based on linear regression between these variable and milk yield from Berton et al. (2021, 2023). Nitrogen excretion was computed following Ketelaars and Van der Meer (1999).

298 kg). The NE\_DM was estimated by linear regression between MY and NE\_DM obtained from the datasets of Berton et al. (2021, 2023), related to 103 farms with a wide range of MY and diet compositions. Similarly, we estimated DE\_perc. The average

DMI of replacement heifers was calculated following the IPCC (2019), with NER computed as the sum of the energy requirements related to maintenance, activity, growth, and pregnancy, and DE\_perc derived from Berton et al. (2023) for 2021 and



**Table 2.** Statistics on animal traits for the replacement heifers of the entire Italian dairy cattle sector (ITA\_POP) and of the registered Holstein Friesian population (HF\_POP).

Variable	Unit	1991	2001	2011	2021
ITA_POP <sup>a</sup>					
Age at first calving	mo	31.90	30.30	28.70	27.40
Heifers 0–12 months/heifers 12–24 months		0.99	0.94	0.87	0.82
Heifers >24 months/dairy cows		0.32	0.28	0.24	0.17
Gross energy intake	MJ/head/d	145.90	144.70	144.70	143.00
Enteric methane conversion factor	% GEI	5.22	5.16	5.11	5.01
Nitrogen excretion	kg/head/y	49.50	49.50	49.20	52.60
HF_POP <sup>b</sup>					
Age at first calving	mo	31.30	29.70	28.20	26.70
Replacement rate	%	28.70	32.60	35.60	35.70
Gross energy intake	MJ/head/d	148.80	146.60	145.60	144.30
Digestibility, on gross energy	%	59.70	60.80	61.60	62.60
Enteric methane conversion factor	% GEI	5.11	5.14	5.17	5.16
Nitrogen excretion	kg/head/y	49.50	49.90	50.70	51.60

<sup>a</sup>Data were derived from Romano et al. (2023), except for data on age at first calving, derived from AIA (2023) for 2011 and 2021 and from linear regression based on data from AIA (2023) for 1991 and 2001 and for heifers' consistency proportions, derived from BDN (2023) for 2011 and 2021 and from linear regressions for 1991 and 2001.

<sup>b</sup>Data on age at first calving and replacement rate were derived from AIA (2023) for 2011 and 2021 and estimated with linear regression for 1991 and 2001. Gross energy intake was computed based on NRC (2001) and IPCC (2019). Digestibility for 2021 was derived from Berton et al. (2023) and projected on 1991, 2001, and 2011 by using the same linear trend obtained for dairy cows. Enteric methane conversion ratio was computed on IPCC (2019). Nitrogen excretion was computed following Ketelaars and Van der Meer (1999).

estimated for the other years by applying the same trend obtained for DE\_perc associated with dairy cows (Table 2).

The N input-output balance of dairy cows and heifers was computed based on Ketelaars and Van der Meer (1999). The N intake of dairy cows per year was calculated as  $DMI \times \text{dietary N content} \times 365 \text{ d}$ , where the dietary N content for each year was estimated based on a linear regression analysis performed on data from Berton et al. (2021, 2023) between dietary N content and milk yield. Some studies reported a linear relation between milk yield and dietary crude protein content (Yang et al. 2022; Erickson et al. 2024), whereas others found a quadratic relation (Colmenero and Broderick 2006; Katongole and Yan 2020). In this study, we tested both approaches with nearly identical final results. Thus, we opted for keeping the linear relationship. The N content of the diet fed to replacement heifers per year was assumed to be 1.92% DM for 2021 (Berton et al. 2023) and was calculated using the same 1991–2021 trend rate obtained for dairy cows for the other years. The N retention was calculated as the sum of retention due to milk, growth, and pregnancy (retention coefficients per livestock category were derived from Ketelaars and Van der Meer 1999). Nitrogen excretion was calculated as N intake – N retention.

### Greenhouse gas emission computation

The emissions were related to CH<sub>4</sub> from rumen fermentation and manure storage, N<sub>2</sub>O (direct and

indirect) from manure storage, as well as N<sub>2</sub>O (direct and indirect) and CO<sub>2</sub> (due to the production of agro-nomical inputs, such as fertilizers, pesticides, and fuel) associated with feed production. The emission of CO<sub>2</sub> due to land use change was not considered because of a lack of specific data about the inclusion of feeds associated with that emission in 1991–2021. Moreover, this assumption allows us to extend the usability of the results of this study for future comparisons, as EU bans the import of goods not certified as deforestation-free products starting from 2025 (EU Reg 2023/1115; European Union 2023).

Regarding the ITA\_POP dataset, emissions from all sources, except for feed production, were derived from the National Inventory Report (Romano et al. 2023). About the feed production, the emission factors (EF) per unit of diet (EF<sub>feed</sub>, kg GHG/kg DM of diet) were estimated as follows. For 2019–2021 period, a global EF<sub>feed</sub> that considered both N<sub>2</sub>O and CO<sub>2</sub> (as CO<sub>2</sub>e) was calculated as the average of a group of recent studies on Italian dairy systems (Famiglietti et al. 2019; Lovarelli et al. 2019; Pirlo and Lolli 2019; Gislon et al. 2020; Berton et al. 2023). The EF<sub>feed</sub> related to the single GHG (N<sub>2</sub>O: EF<sub>feed,N2O</sub>; CO<sub>2</sub>: EF<sub>feed,CO2</sub>) was obtained by multiplying EF<sub>feed</sub> for the average percentage contribution due to N<sub>2</sub>O and CO<sub>2</sub>, obtained from Berton et al. (2021, 2023). The EF<sub>feed,N2O</sub> and EF<sub>feed,CO2</sub> for the 1991–2018 period were estimated based on linear regressions of EF<sub>feed,N2O</sub> and EF<sub>feed,CO2</sub> with DE\_perc data obtained from Berton et al. (2021, 2023) (Table 3), adjusted for the increase in crop productivity observed in the same period,

**Table 3.** Origin of the data and equations developed for the estimation of the number of animals and the productive traits.

Variable	Acronym	Unit	Period of years for developing equations	Equation developed	Period of years on which the equations were applied	R <sup>2</sup>	p-Value	Source of data
ITA_POP								
Italian dairy cows	IDC	n						ISTAT 2022
Heifers from birth to 12 months	H <sub>0-12</sub>	n	2009–2022		–			BDN 2023
Ratio between H <sub>0-12</sub> and IDC	Hei_Dairy_ratio		2009–2022	$= 0.0024 \times \text{year} - 4.4409$		0.71	<0.001	BDN 2023
Predicted heifers from birth to 12 months	H <sub>0-12</sub>		–	$= \text{IDC} * \text{Hei\_Dairy\_ratio}$	1991–2008			–
Heifers from 12 to 24 months	H <sub>12-24</sub>	n	2009–2022	Originated from data set	–			BDN 2023
Ratio between H <sub>0-12</sub> and H <sub>12-24</sub>	Hei_ratio		2009–2022	$= -0.006 \times \text{year} + 12.954$		0.74	<0.001	BDN 2023
Predicted heifers from 12 to 24 months	H <sub>12-24</sub>	n	–	$= H_{0-12} (n) * \text{Hei\_ratio}$	1991–2008			–
Heifers with >24 months	H <sub>&gt;24</sub>	n	2009–2022		–			BDN 2023
Predicted heifers with >24 months	H <sub>&gt;24</sub>		2009–2022	$= -16274 \times \text{year} + 33,168,717$	1991–2008	0.94	<0.001	
Age at first calving		mo	2004–2022	Originated from data set	–			AIA 2023
Predicted age at first calving		mo	–	$= -0.1563 \times \text{year} + 343.1$	1991–2003	0.97	<0.001	
HF_POP								
Age at first calving		mo	2004–2022	Originated from data set	–			AIA 2023
Predicted age at first calving		mo	–	$= -0.1619 \times \text{year} + 353.63$	1991–2003	0.95	<0.001	
Replacement rate		%	2004–2022		–			AIA 2023
Predicted replacement rate		%	–	$= 0.0014 \times \text{year} - 2.5412$	1991–2003	0.65	<0.001	
Heifers from birth to 12 months	H <sub>0-12</sub>	n	2009–2022		–			BDN 2023
Heifers from birth to 12 months	H <sub>0-12</sub>	n	–	$= 1965 \times \text{year} - 3,459,973$	1991–2008	0.57	<0.001	
Ratio between H <sub>0-12</sub> and H <sub>12-24</sub>	Hei_ratio_HF		2009–2022	$= 0.89$	–			BDN 2023
Heifers from 12 to 24 months	H <sub>12-24</sub>		–	$= H_{0-12} (n) * \text{Hei\_ratio\_HF}$	1991–2008			
Net energy content of dairy cows' diet	NE_DM	MJ/kg DM	–	$= 0.0688 \times \text{milk yield (kg/cow/d on 365 d)} + 3.994$	1991–2021	0.44	<0.001	Berton et al. 2021, 2023
Digestibility of dietary gross energy	DE_perc	%	–	$= 0.0051 \times \text{milk yield (kg/cow/d on 365 d)} + 0.5826$	1991–2021	0.40	0.001	Berton et al. 2021, 2023
Dietary nitrogen of dairy cows diet		%	–	$= (0.080 \times \text{milk yield (kg/cow/d on 365 d)} + 1.0501) / \text{dry matter intake} / 6.25$	1991–2021	0.78	<0.001	Berton et al. 2023
Enteric methane conversion factor of dairy cows diet	Ym	%	–	$= -0.0429 \times \text{DE\_perc} + 9.00$	1991–2021	0.97	<0.001	IPCC 2019 (Table 10.12)
ITA_POP and HF_POP								
Feed production, not considering changes in crop yield and management during 1991–2021	EF <sub>feed, N2O</sub>	kg N <sub>2</sub> O/kg DM	–	$= 0.7814 \times \text{DE\_perc} - 0.3862$	1991–2021	0.64	<0.001	Berton et al. 2021, 2023
Feed production, not considering changes in crop yield and management during 1991–2021	EF <sub>feed, CO2</sub>	kg CO <sub>2</sub> /kg DM	–	$= 0.9808 \times \text{DE\_perc} - 0.4737$	1991–2021	0.40	<0.001	Berton et al. 2021, 2023

ITA\_POP: Italian dairy cattle population; HF\_POP: Holstein Friesian cow population under the official milk recording system.

**Table 4.** Equations for the computation of greenhouse gas emissions.

Pollutant	Equation	References
Enteric fermentation CH <sub>4</sub> (kg/head/y)	$= ((GEI \times Y_m)/55.65) \times 365$ <p>GEI: gross energy intake (MJ/d); Y<sub>m</sub>: methane conversion factor (%)</p> $GEI = (((NEm + NEa + NEI + NEp)/REM) + (NEg/REG))/(DE\_perc/100)$ <p>NEm: net energy requirements for maintenance (MJ/d) = <math>0.386 \times 0.386 \times \text{Body weight}^{0.75}</math></p> <p>NEa: net energy requirements for activity (MJ/d) = <math>NEm \times 0.10</math></p> <p>NEI: net energy requirements for lactation (MJ/d) = <math>(4.184 \times (0.0929 \times \% \text{ fat content} + 0.0547 \times \% \text{ protein content} + 0.192) \times \text{milk yield})</math></p> <p>NEp: net energy requirements for pregnancy (MJ/d) = <math>NEm \times 0.10</math></p> <p>NEg: net energy requirements for growth (MJ/d) = <math>22.02 \times (\text{Body weight}/(0.8 \times 700))^{0.75} \times ADG^{1.097}</math> (ADG: average daily gain)</p> $REM = 1.123 - (4.092 \times 10^{-3}) \times DE\_perc + (1.126 \times 10^{-5}) \times DE\_perc^2 - (25.4/DE\_perc)$ $REG = 1.164 - ((5.16 \times 10^{-3}) \times DE\_perc) + ((1.308 \times 10^{-5}) \times DE\_perc^2) - (37.4/DE\_perc)$ <p>DE_perc: digestibility of gross energy</p>	IPCC 2019 Tier 2 IPCC 2019 Tier 2
Manure management CH <sub>4</sub> (kg/year)	$= (VS \times 365) \times (Bo_{(T)} \times 0.67 \text{ (kg/m}^3) \times \sum (MCF_{S,k}/100)$ $VS = (GEI \times (1 - DE\_perc/100) + (UE \times GEI)) \times ((1 - ASH)/GE_{DM})$ <p>UE: urinary energy fraction; ASH: ash content of manure; ASH = 0.08; GE<sub>DM</sub>: Gross Energy per kg of DM, MJ/kg DM; Bo<sub>(T)</sub> = m<sup>3</sup> CH<sub>4</sub>/kg of VS excreted (0.24 for dairy cows, 0.18 for heifers); maximum methane producing capacity for manure produced by livestock category T; MCF<sub>S,k</sub>: methane conversion factor for manure management system</p>	IPCC 2019 Tier 2
N <sub>2</sub> O direct (kg/year)	$= (\text{Head} \times \text{Nex}) \times 0.005 \times 44/28$ <p>Head: number of animals per each category; Nex: N excreted plus N in bedding material, kg/head/year</p>	IPCC 2019 Tier 2
N <sub>2</sub> O indirect due to volatilization, kg/year	$= N_{\text{volatilisation}} \times 0.01 \times 44/28$ <p>N<sub>volatilisation</sub>: kg/year</p>	Romano et al. 2023 IPCC 2019 Tier2

GEI: gross energy intake; REG: ratio of net energy available for growth in a diet to digestible energy consumed; REM: ratio of net energy available in a diet for maintenance to digestible energy.

based on data retrieved from FAOSTAT (2023) and ISTAT (2023) (Supplementary Table 5). Regarding replacement heifers, EF<sub>feed,N2O</sub> and EF<sub>feed,CO2</sub> were derived from Berton et al. (2023) for the 2019–2021 period and scaled for other years, following the trend obtained for dairy cows.

For HF\_POP, CH<sub>4</sub> emissions due to rumen fermentation were calculated by multiplying the GEI by the percentage of GEI emitted as CH<sub>4</sub> from rumen fermentation (Y<sub>m</sub>), which was estimated based on data provided by IPCC (2019) in terms of gross energy digestibility and CH<sub>4</sub> emission (Table 3). Furthermore, emissions (CH<sub>4</sub> and N<sub>2</sub>O) from manure storage were estimated following the IPCC (2019), using the CH<sub>4</sub> conversion factor (kg CH<sub>4</sub>/kg volatile solids from manure) and the N volatilization rate (kg N volatilized/kg N excreted) derived from Romano et al. (2023). The EF<sub>feed,N2O</sub> and EF<sub>feed,CO2</sub> were calculated following the abovementioned procedure used in ITA\_POP (Supplementary Table 6).

### Life cycle impact assessment

The amount of single GHGs was converted to the common unit of the GWP category (kg CO<sub>2</sub>e for GWP<sub>100</sub> and kg CO<sub>2</sub>-we for GWP\*) using characterization factors from Myhre et al. (2013) for GWP<sub>100</sub>

(CH<sub>4</sub>:28, N<sub>2</sub>O: 265, CO<sub>2</sub>: 1). We also applied the recent metric GWP\* (CH<sub>4</sub>: CH<sub>4</sub>:  $28 \times [4.53 \times CH_{4,t} - 4.25 \times CH_{4,t-20}]$ , where  $t$  = year and  $t - 20 = 20$  years previous year  $t$ , N<sub>2</sub>O: 265, CO<sub>2</sub>: 1; Smith et al. 2021). As the GWP\* includes a temporal framework of 20 years by definition, it was applied only for the 2011–2021 period (10 years), with respect to the 1991–2001 one.

### Uncertainty analysis

As the EFs applied for the GHG emissions calculation could be associated with an uncertainty range, which can alter the singular evaluation (IPCC 2019), we performed a Monte Carlo analysis using 1000 iterations with a 95% confidence interval (CI). The uncertainty associated with the different emission sources was derived as follows. Regarding the emission of CH<sub>4</sub> from rumen fermentation and manure storage, the uncertainty ranges ( $\pm 20$  and  $\pm 30\%$ , respectively) were derived from IPCC (2019). About N<sub>2</sub>O, the best estimated, minimum and maximum values of the EFs for direct N<sub>2</sub>O emissions (0.5, 0, 1% for manure storage and 1, 0.1, 1.8% for N spread at field), N volatilization [20.6% (from Romano et al. 2023), 10, 40% for manure storage and 16, 5, 31% for N spread at field] and indirect N<sub>2</sub>O emissions due to N volatilization (1, 0.2, 1.8% for both manure storage and N spread



at field) were derived by IPCC (2019) and used to estimate the uncertainty considering a pert-beta distribution (Clark 1962), in accordance with Sykes et al. (2019).

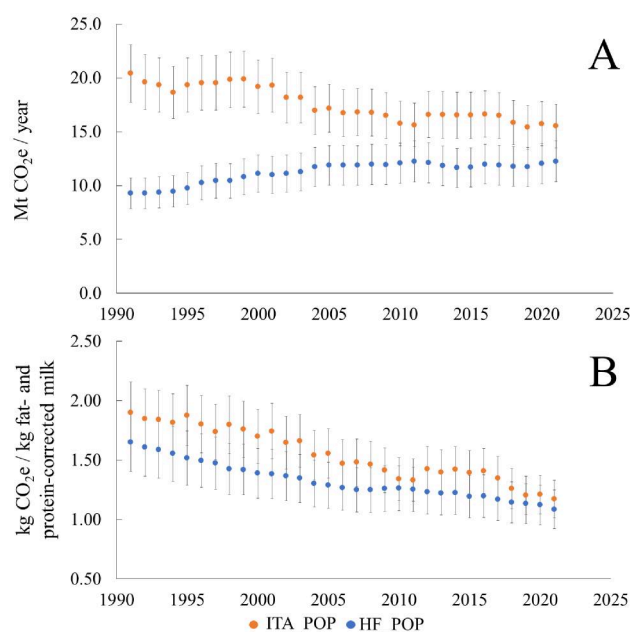
Regarding CO<sub>2</sub>, detailed data about the contribution to feed-related emissions due to the production of fertilizers, pesticides, and fuel use was lacking for the entire 1991–2021 period. For this reason, we applied the procedure proposed by Sykes et al (2019), considering that uncertainty for CO<sub>2</sub> was distributed according to a pert-beta distribution and using the CO<sub>2</sub> emission value estimated in our study as the mean EF value, whereas minimum and maximum values were obtained applied the same uncertainty range associated with average fertilizer production (63–130% as min-max range, with respect to the mean value) as an intermediate between the very low uncertainty related to fuel (100–103%) and the high uncertainty related to pesticides production (25–161%).

## Results

### *Evolution of Italian dairy cattle population and trend of production*

From 1991 to 2021, the Italian cows showed a nearly 30% decrease (from 2.34 to 1.61 million dairy cows; Figure 1), whereas HF cows showed a corresponding increase (from 0.84 to 1.13 million). Indeed, during these 30 years, the share of HF-POP in the total Italian dairy cow population doubled from 36 to 70%, and currently, HF cows account for nearly 90% of Italian dairy cows under the official milk recording system.

In the 30 years considered, the milk yield of ITA\_POP (Table 1) nearly doubled, moving from 6492 to 9564 kg/lactation per cow, including the dry period, which means an increase from 13 to 25 kg/d per cow. Likewise, the milk yield of HF\_POP increased by over 40%. Furthermore, milk fat and protein content progressively increased over the period considered, with greater enhancement observed for HF\_POP than for ITA\_POP. Consequently, increases in gross energy intake were also observed in both populations (+30 and +12%, respectively) because of the concurrent increase in energy requirements for milk production and the increase in digestibility of diets. The age at first calving progressively decreased in ITA\_POP and HF\_POP, reaching the current average values of 27.4 and 26.7 months, respectively (Table 2). Conversely, the replacement rate of HF\_POP increased over the years, exceeding 35% over the last decade.

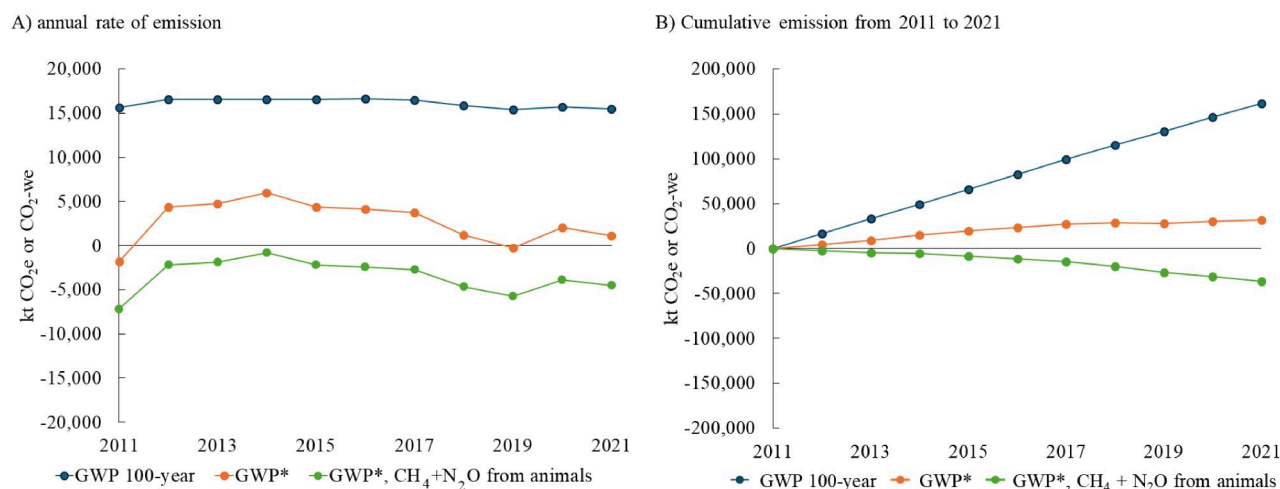


**Figure 2.** Annual mean value and standard deviation (error bars) of total national greenhouse gases (A) and of emission intensity per kg of fat and protein corrected milk (B) of the Italian dairy cattle sector (ITA\_POP) and of the registered Holstein Friesian population (HF\_POP) (100-year global warming potential, using the following conversion factors: CH<sub>4</sub>: 28, N<sub>2</sub>O: 265; CO<sub>2</sub>: 1).

### *Evolution of global warming potential of Italian dairy cattle population*

The GWP<sub>100</sub> patterns (total national values and values per kg FPCM) associated with ITA\_POP and HF\_POP are reported in Figure 2. The total GWP emission of ITA\_POP linearly decreased in the 30 years considered, moving from around  $20.4 \pm 2.7$  Mt CO<sub>2</sub>e in 1991 to nearly  $15.5 \pm 2.1$  Mt CO<sub>2</sub>e in 2021, thus evidencing a cumulative decrease of nearly 30%. Conversely, the absolute emission associated with HF\_POP was estimated to be equal to  $9.3 \pm 1.4$  Mt CO<sub>2</sub>e in 1991 and linearly increased up to  $12.2 \pm 1.8$  Mt CO<sub>2</sub>e in 2021 (+37%). Consequently, the relative share of absolute emissions due to HF\_POP increased from 46 to 78%, clearly following the population size dynamics during the period considered.

When expressed per unit of milk produced, the emission associated with 1 kg FPCM provided by the Italian dairy sector was  $1.90 \pm 0.25$  kg CO<sub>2</sub>e in 1991 and  $1.17 \pm 0.16$  kg CO<sub>2</sub>e in 2021, evidencing a linear decrease of 39% in 30 years. The HF\_POP evidenced a similar trend, with one kg FPCM associated with the emission of  $1.65 \pm 0.24$  kg CO<sub>2</sub>e in 1991 and  $1.09 \pm 0.16$  kg CO<sub>2</sub>e in 2021. The difference between ITA\_POP and HF\_POP in terms of emission per 1 kg of FPCM was  $\sim 0.25$  kg CO<sub>2</sub>e in 1991 but progressively



**Figure 3.** Annual rate (A) and cumulative (B) emission of GWP-100years and GWP\* [sum of methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and carbon dioxide ( $\text{CO}_2$ )] computed for the Italian dairy cattle sector in the 2011–2021 period. In computing GWP 100-year, we used as conversion factors 28 for  $\text{CH}_4$ , 265 for  $\text{N}_2\text{O}$  and 1 for  $\text{CO}_2$ ; in computing GWP\*, we used as conversion factors  $(4.53 \times \text{CH}_4, t(x) - 4.25 \times \text{CH}_4, t(x-20) \times 28)$  for  $\text{CH}_4$ ; 265 for  $\text{N}_2\text{O}$  and 1 for  $\text{CO}_2$ . Cumulative emissions of GWP-100years and GWP\* has been expressed as an index taking the value of 2011 year equal to zero. The GWP-100years or GWP\* pertinent to the year  $t$  represents the amount of greenhouse gases ( $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and  $\text{CO}_2$ ) present in the atmosphere in that year, computed as the amount of GHGs remained from the previous year ( $t - 1$ ) plus the GHGs emitted in the year  $t$ .

declined with time, so the GHG emission intensity was more similar in the two populations in 2021. The 1991–2021 trend for single gases ( $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and  $\text{CO}_2$ ) was like that observed for  $\text{GWP}_{100}$  in the ITA\_POP and HF\_POP datasets (Supplementary Figure 1).

Considering the annual rate and the cumulative effect of annual GHG emissions in the Italian dairy sector (Figure 3), the application of the GWP\* resulted in a different pattern in the 2011–2021 period with respect to  $\text{GWP}_{100}$ . In terms of annual emission rates (Figure 3(A)),  $\text{GWP}_{100}$ , coherently with Figure 2, evidenced a slow decrease to 15 Mt  $\text{CO}_2\text{e}$ . Likewise, GWP\* showed a general decline up to zero in 2018–2021 period, following the trend observed for GWP\* computed considering only the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emission from animals only (i.e. excluding emissions due to feed production). Setting the cumulative effect of emissions equal to 0 in 2011 (Figure 3(B)), the accumulation in terms of  $\text{GWP}_{100}$  linearly increased in the 2011–2021 period, to almost +160,000 kt  $\text{CO}_2\text{e}$ . In contrast, cumulative GWP\* slightly increased only in the 2011–2017 period and remained quite stable afterward. Removing the contribution due to feed production, the cumulative GWP\* tended to decline, particularly since 2015 afterward, with a reduced accumulation of –36,000 kt  $\text{CO}_2\text{we}$  in 2021 compared to 2011.

## Discussion

Life cycle assessment is a data-demanding methodology, and the results obtained using this procedure

must consider the possible uncertainties associated with the data (ISO 2006). The model developed in this study combined data from different national databases (AIA 2023; Romano et al. 2023) and added a set of equations based on previous studies focused on the environmental impact of the Italian dairy system to evaluate the trend of GHG emissions of the Italian dairy sector over the last 30 years, including all the main emission sources, that is those directly related to the animals (rumen fermentation and manure storage) together with those related to the production of the diets fed to the animals, which are known as a major source of livestock GHG emissions (Mazzetto et al. 2022). The approach applied in this study led to the development of a set of linear equations with fair or good statistical results in terms of significant  $R$ -squares (0.40–0.97) and very low differences with respect to the use of quadratic equations (0–2%), e.g. in the relationship between milk yield and dietary N content in HF\_POP. This is the first study that aimed at evaluating the GHG emissions, and relative trend, of the Italian dairy sector in the last 30 years, and in perspective, new studies are needed to improve the availability of data in terms of the composition of diets fed to different animal categories over the last decades and of farm materials and energy sources, which were not included in this study.

In the EU Green Deal context and within the Farm-to-Fork strategy (European Parliament 2020), all production sectors, including the livestock sector, have been called on to achieve a net-zero emission level in

the following decades. Within the Italian livestock sector, the dairy industry is one of the most important branches in terms of food provision and economic value (ISMEA 2022). Correddu et al. (2023) and Romano et al. (2023) showed that in the last 30 years, the Italian cattle sector was able to reduce CH<sub>4</sub> emissions associated with animal rearing and manure storage (nearly –20%), primarily due to a decrease in the total number of cattle and an increase in productivity. This reduction in CH<sub>4</sub> is the main cause of the decrease in GWP\* observed in the present study in the same years. Previous studies have demonstrated the potential utility of assessing the temporal trend of GHG emissions related to livestock to better quantify the real effects of a sector on global warming and address strategies aimed at further reduction (Capper and Cady 2020; Hörtenhuber et al. 2022; Rotz et al. 2024). In this study, we aimed to evaluate the 1991–2021 Italian dairy sector GHG emission with a comprehensive life cycle approach regarding emission sources, type of GHG, and animal categories.

The results found for the entire Italian dairy cow population (ITA\_POP) evidenced that the Italian dairy sector achieved a reduction in annual GHG emissions in absolute terms from 1991 to 2021 and that this reduction was observed for all the three main GHGs, nominally CH<sub>4</sub>, N<sub>2</sub>O, and CO<sub>2</sub>. The reduction found (–30%) was in line with that reported by Hörtenhuber et al. (2022) in Austria in the 1990–2019 period (nearly 30%) and by Capper and Cady (2020) in the United States in the 2007–2017 period (nearly 20%). On the other hand, Rotz et al. (2024) found a moderate increase in GHG emissions from 1971 to 2020 in the United States (14%), but a strong decrease in the emissions per unit of milk. In addition, the reduction in GHG emissions observed for Italian dairy chain from 1991 to 2021 remained confirmed also considering the results of the uncertainty analysis, thus proving to be a robust estimate. At the same time, the results of the uncertainty analysis suggest that year-to-year comparisons in annual emissions should be done with caution, as uncertainty ranges associated with each specific year could be larger than the year-to-year change. In this sense, these results confirm that future LCA analyses should include the assessment of the uncertainties associated with emissions computation. Moreover, future studies could in perspective take into account factors to allocate the whole impact to the milk that included the potential temporal variations in their calculation, such as the year-to-year reduction of the number of the animals.

The reduction in annual GHG emissions found for ITA\_POP could be attributed to three factors. The first was related to a decrease in the number of animals (dairy cows and heifers), which was strongly correlated with absolute GHG emissions ( $r = 0.98$ ,  $p < 0.001$ ). The second was related to the increase in milk yield of dairy cows (+93%) (Lorenz et al. 2019); considering the dynamics of the average milk yield of Italian dairy cows, the reduction of over 30% of dairy cow population size in the period considered has gone along with an increase of over 30% of milk globally yielded by the Italian sector. Improvements in milk productivity and animal management (e.g. decrease in age at first calving) (Llonch et al. 2017; Berton et al. 2023) determined not only an increase in production efficiency but also the possibility of achieving a given milk production level with a lower number of cows, thus steadily decreasing the emission intensity per milk unit throughout the entire 1991–2021 period. The third contributing factor was the decrease in the EI of producing 1 kg of DM of the animal diet; this was determined by the combination of (i) improvements in agronomical productivity, which has decreased the inputs needed to obtain a feed unit and the related impacts (mean value: –1.5%/year), (ii) increases in forage quality (nutritional value, digestibility) and in its conservation (drying or ensilage) (Capstaff and Miller 2018; Wilkinson and Rinne 2018), and (iii) greater dietary inclusion of high-energy and highly digestible feeds (e.g. concentrates) to sustain milk yield (mean value: +1.07 and +1.11% per year, respectively, for ITA\_POP and HF\_POP), consistent with previous studies (Gonzalez-Mejia et al. 2018; Grodkowski et al. 2023). In addition, the observed reduction in GHG emissions in 1991–2021 period could be slightly underestimated, as an average emission for transports and farm materials, such as fuel and electricity was here applied for the entire period, but improvements in these areas could be detected as well, e.g. in the energy use in agriculture (Caputo 2022).

These improvements have been achieved by implementing breeding selection programs that effectively increase the productive genetic abilities of dairy cows (Brito et al. 2021). The success of these programs has favoured the diffusion of high-yielding dairy breeds, primarily HF. As previously observed, the proportion of HF cows at the national level has steadily increased to 70% of the entire Italian dairy cow population and nearly 90% of the cows herded in farms enrolled in the official Italian milk recording system in 2021 (AIA 2023; Romano et al. 2023). The results of this study showed that the decrease in emission intensity per

milk unit observed from 1991 to 2021 was driven not only by a general improvement in productive traits in the Italian dairy sector but also by the progressive replacement of other dairy and dual-purpose breeds with the HF breed. In fact, the rate of decrease observed for ITA\_POP was contrasted by the increase in HF\_POP, indicating that ITA\_POP gains were also linked to the decrease in the number of cows belonging to less-performing breeds, mainly herded in smaller and less-performing farms, which also dramatically decreased in the last 30 years (ISTAT 2023). These breeds maintained their presence mainly in less favourable areas. In the mountains, breeds of alpine origin (Simmental, Brown Swiss, local breeds) are better suited to summer pastures (Zendri et al. 2016), allowing the production of more appreciated dairy products (Bergamaschi and Bittante 2018; Secchi et al. 2023), and a greater valorisation of vegetal resources not directly usable for human nutrition, thus providing valuable ecological services (Berton et al. 2020).

As a consequence of the abandonment of many traditional dairy farms and the substitution of other breeds with HF, in recent years, the milk emission intensities associated with ITA\_POP and HF\_POP have almost converged to values around 1.1–1.2 kg CO<sub>2</sub>e, so that the absolute GHG emission associated with ITA\_POP has become nearly overlapped with that associated with HF\_POP (Figure 2); this implies that further improvements in GHG emissions would be increasingly related to improvements in HF cow management and genetics, as further improvements in systems already characterized by high-performance levels can become increasingly difficult to obtain (Moallem 2016; Pulina et al. 2020). However, these improvements could be jeopardized because of the negative effects observed on fertility, health, and longevity traits in high-yielding cows (Dezetter et al. 2019; Hazel et al. 2020). Techniques, such as innovative breeding programs (Brito et al. 2021) or strengthening the farm crop-livestock relationship (Battini et al. 2016; Berton et al. 2023) could help the sector continue its environmental impact mitigation. In the intensive dairy farming systems, a possible interesting alternative to HF breeds seems to be the recent spreading of rotational three-breed crossbreeding plans because of the better milk quality (Malchiodi et al. 2014b; Maurmayr et al. 2018; Saha et al. 2020), fertility and longevity (Malchiodi et al. 2014a), and carcass value (Piazza et al. 2023). Concerning environmental issues, better fitness, greater longevity, and improved beef traits may compensate for the slightly lower milk productivity and allow a lower environmental impact per unit

of milk fat plus protein yielded in the lifespan of cross-bred cows compared to purebred HF cows (Gallo et al. 2024; Martínez-Marín et al. 2024).

However, the diversity of the single main GHGs associated with dairy production, particularly their different atmospheric lifetimes, implies that their yearly trends must be assessed together with the GWP<sub>100</sub> trend. Results of the present study suggest that the mix of CH<sub>4</sub>, N<sub>2</sub>O, and CO<sub>2</sub> did not differ much between 1991 and 2021, even though they are affected by the methodology used and probably some information concerning the carbon footprint of feed in different years is incomplete. Anyway, their different cumulative behaviours resulted in a differentiated effect of the Italian dairy sector as a contributor to national GHG total emissions. When we applied the GWP\* model, which considers the short lifetime of CH<sub>4</sub> with respect to N<sub>2</sub>O and CO<sub>2</sub>, the Italian dairy sector showed a stable cumulative GHG effect on global warming in recent years (2017–2021) and, simultaneously, a decline in the cumulative levels of CH<sub>4</sub> and N<sub>2</sub>O from animals (Figure 3). We are aware that a 10-years period is a short time to fully assess the additive warming of the system, and the results of this study need to be consolidated in the next years. However, these data provide preliminary results about the feasibility of the decrease of the contribution due to the livestock sector to the accumulation of GHGs in the atmosphere.

Considering the potential flaws in the application of GWP\* concerning the declaration of 'negative' emissions or the contribution to anthropogenic GHG emission (Meinshausen and Nicholls 2022; Del Prado et al. 2023), the results found in this study evidenced two interesting aspects. The first concerns the opportunity for the dairy sector to continue reducing absolute CH<sub>4</sub> emissions. Since the warming effect of CH<sub>4</sub> depends on its atmospheric concentration and a pulse would be removed in a few decades, future lower emission fluxes and consequent decrease of atmospheric concentration of CH<sub>4</sub> could partially compensate for the increase in the concentration of anthropogenic CO<sub>2</sub> and help the stabilization of the increase in the mean global temperature to 1.5–2.0° C (Rogelj et al. 2018; IPCC 2022). The second relates to the importance of including the emissions due to the feed production, which is the responsible for the divergent cumulative trends shown in Figure 3 between GWP\* and GWP\* associated with GHG directly related to animals. On this aspect, a particular attention should be posed on CO<sub>2</sub>. In fact, as N<sub>2</sub>O, CO<sub>2</sub> is a long-lived compound that, once added to the



atmosphere, can be detected after many centuries (IPCC 2021). Conversely, CO<sub>2</sub> is not directly related to animals and its net addition to atmosphere is mainly due to the use of fossil fuels. In this sense, the increasing attention posed by the dairy cow sector on mitigating CH<sub>4</sub> and N<sub>2</sub>O emissions (Wattiaux et al. 2019; Beauchemin et al. 2020) needs to be accompanied by greater attention to the reduction of CO<sub>2</sub> fossil emissions. This could be done operating both on-farm—e.g. shifting to more energy-efficient equipment (Sanford and Go 2022), renewable energy sources (Qiao et al. 2019), and a lower use of mineral fertilizers, whose high energy production requirements imply notable CO<sub>2</sub> emissions (Sutton et al. 2013)—and off-farm—e.g. including environmental efficiency and fossil fuel use in the criteria used for selecting the purchased inputs (Garcia-Launay et al. 2018). On the other hand, the increasing attention on the potential contribution of farms also in terms of removing CO<sub>2</sub> from the atmosphere and sequestering it in the agricultural soils (i.e. carbon farming; European Commission 2021), although not considered in this study, suggests that actions targeted to reduce emissions and increase removals should be concurrently implemented to maximize the positive contribution of livestock sector.

## Conclusions

The national dairy cow system plays a major productive and economic role in the Italian livestock industry. To limit the human-induced increase in the mean global temperature due to anthropogenic GHG emissions, this study evaluated the pattern of GHG emissions related to the Italian dairy sector over the last 30 years, focusing on the predominantly Holstein Friesian population. Different national databases were combined for this purpose and used to develop a model that includes all the main GHG sources associated with animal production according to an LCA-based approach.

The results of this study show that in the last 30 years, the Italian dairy sector has strongly reduced its GHG footprint in terms of absolute emissions and even more in terms of emission intensity per unit of milk. This reduction has been observed for all the main greenhouse gases and resulted confirmed also considering the uncertainties associated with the different emission sources. This trend was associated with the contemporary reduction in animal numbers, increase in animal productivity, and improvements in animal management, as well as with the increase in the quota covered by the high-performing HF

population in the Italian dairy sector. Furthermore, this study showed that appropriate consideration of the short atmospheric life of CH<sub>4</sub> can provide deeper insights into the cumulative GHG balance in Italian dairy cattle, that appeared stable in the last years when assessed with GWP\* methodology. In addition to emissions directly related to animals, such as CH<sub>4</sub> due to rumen and manure fermentation, more attention should also be paid to indirect emission sources and related gases, such as CO<sub>2</sub>. This with the ultimate goal of continuing the positive decline in greenhouse gas emissions associated with the Italian dairy cow sector and simultaneously supporting its productive and economic value. On the other side, it should be considered the possible negative effects of a full 'holsteinization' of the entire Italian dairy cattle population due to the worsening of fertility, health, and longevity of cows and on abandonment and loss of ecological services, especially in the mountains. Therefore, the evaluation of the impact of global warming due to the dairy sector should be accompanied by a more comprehensive evaluation of other environmental issues and animal welfare.

## Ethical approval

All research reported in this research has been conducted in an ethical and responsible manner and is in full compliance with all relevant codes of experimentation and legislation.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement

The data presented in this study are available on request from the corresponding author upon reasonable request.

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