Journal of Cleaner Production 573 (2026) 148971

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Calculating balance of cumulative non-fossil methane emissions over consecutive or non-consecutive periods of livestock production

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HIGHLIGHTS

- A novel methane burden or removal calculation in livestock production was developed.
- The developed method can be applied to any global livestock population or sector.
- Slovenian dairy cows contributed to methane removal and non-dairy cattle to burden.
- The method's simplicity enables basis for tool development for farmers.

ARTICLE INFO

Keywords:
Emissions
Livestock
Methane decay
Methods
Mitigation
Tools

ABSTRACT

Methane (CH_4) emissions from livestock production are conventionally reported as annual methane emissions (AME) or converted to carbon dioxide equivalents. However, these assessments cannot determine the methane burden or removal in the atmosphere, as they do not account for continuous methane removal and short-term accumulation. Consequently, they may obscure the identification of livestock (sub)sectors or (sub)populations with methane burden or removal, thereby limiting optimal mitigation efforts. Here, a novel method is developed and demonstrated to calculate the balance of cumulative non-fossil methane emissions (BME) over consecutive or non-consecutive livestock production periods, considering the atmospheric methane decay. Two BME approaches are defined: BME with a chain base (BME_C), which allows comparison of two cumulative methane emissions (CME) in consecutive years i and i + 1; and BME with a fixed base (BME_F), which allows comparison of CME in year j (where j can range from -∞ to ∞) with a fixed CME in year i. The average BME_F for Slovenian dairy cows and non-dairy cattle between 2018 and 2022, compared to the fixed year 2001, was −46.45 kt CH_4 and 19.76 kt CH_4, indicating a long-term methane removal and burden, respectively, from these sectors. For practical use, BME_C and BME_F can be applied across livestock farming systems to assess and monitor short-term and long-term efficiency, respectively, in any (sub)sector or (sub)population. In addition, BME provides a template for developing novel tools for farmers and enables the incorporation of reduced AME through methane mitigation measures.

1. Introduction

Assessing the contribution of livestock production to methane burden or removal is essential for mitigating emissions while maintaining food security and sustainable production in a warming climate. Livestock farming produces enteric and manure methane, contributing to one-third of global anthropogenic methane emissions (Saunois et al., 2024; Zhang et al., 2022), yet limiting further warming remains a global priority (UNCC, 2015; UNSD, 2015) and hunger affects more than 295 million people across 53 countries (GRFC, 2025). To address these issues, recent methods capture better the environmental impact of livestock farming by considering methane's properties (Lynch et al., 2021). However, among the available metrics and models, there is currently no approach to calculate the long- or short-term methane balance (net burden or removal) considering continuous methane removal at a small scale (e.g. farm) using limited methane data between periods of production. Such an approach would allow more accurate assessments of production efficiency and sustainability. It would also provide insights into the application of methane mitigation measures and serve as a tool for stakeholders, such as farmers, to evaluate methane balance.

To assess the impact of livestock production on the climate, data on

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https://doi.org/10.1016/j.jclepro.2026.148971
Received 3 November 2025; Received in revised form 6 May 2026; Accepted 12 July 2026
Available online 15 July 2026

emissions released by animals need to be obtained. Data can be collected at the animal level using technologies (e.g. Garnsworthy et al., 2019; Zhao et al., 2020; Laubach et al., 2024), for example the respiratory cage (Machado et al., 2016; Ma et al., 2024), GreenFeed (Huhtanen et al., 2019), sniffer (Løvendahl et al., 2024), laser techniques (Sorg et al., 2018; Kang et al., 2022), milk MIR spectroscopy (Dehareng et al., 2012), and novel sensors (e.g., Schaller and Harison, 2025). All these technologies have become more prevalent in recent years and will continue to enable data collection for modeling in the future. However, to assess long-term trends (e.g. $\geq$ 20 years) that provide insight into the atmospheric methane balance or warming-equivalent emissions, methods that allow the obtaining of data on past emissions are needed. For this purpose, the IPCC approaches (e.g., IPCC et al., 2021: Tier 1, Tier 2 or Tier 3) remain the gold standard. These approaches are based on animal production parameters or farm technologies, which are more accessible for longer historical periods than emission measurements. However, the issue with data on annual methane emissions (AME), whether obtained from measurements or calculations, is that they do not reflect the actual methane burden or removal from livestock production, but represent total emissions from various sources. Therefore, any interpretations of burden or removal based on these calculations fail to consider that methane is continuously removed from the atmosphere. When comparing different periods of livestock production and assessing climate impact, methane's atmospheric removal should be taken into account. This can be modelled using methane's atmospheric lifetime.

The duration of methane's presence in the atmosphere depends on its chemical removal pathway (IPCC et al., 2021; Saunois et al., 2024). These removal processes are variable and mainly occur through oxidation in the troposphere via hydroxyl radicals (about 90% of all removals; Ehhalt, 1974), photochemistry in the stratosphere through reactions with chlorine atoms (Li et al., 2023) and excited oxygen atoms (O'Brasseur and Solomon, 2005), oxidation in the soil (Curry, 2007), and photochemistry (reaction with Chlorine) in the marine boundary layer (Allan et al., 2005). Based on the removal pathway, the specific lifetime can be calculated (Saunois et al., 2024), which varies significantly depending on the degradation pathway, for example, approximately 9 years for reaction with hydroxyl radicals (IPCC et al., 2021) or 120 ± 24 years for soil oxidation (Myhre et al., 2013). This is still a short period compared to carbon dioxide, which remains in the atmosphere at high levels for up to a millennium (Archer and Brovkin, 2008), and is considered a long-lived climate pollutant. For methane, a perturbation lifetime of 11.8 ± 1.8 years (IPCC et al., 2021) is used in global warming potential (GWP) calculations. Therefore, if during a certain period of livestock production more methane is oxidised than emitted (methane removal) compared to the previous period of the same production, the result is decreased warming contribution, while additional methane (methane burden) leads to warming. More specifically, Cain et al. (2019) reported a methane emission (expressed as CO_2 warming equivalent emissions) decline rate faster than 0.3% per year as cooling relative to the current temperature.

Recently, various methods have been developed to identify methane emitters with positive or negative temperature effects, taking into account methane's lifetime. One such method is based on the internationally established GWP equivalents, namely GWP* (Allen et al., 2018; Cain et al., 2019), which links methane emissions to their temperature outcomes. By enabling the estimation of CO_2 warming equivalent emissions (CO_2-we) from CH_4, GWP* is becoming the gold standard for reporting warming or cooling effects in the livestock science field (e.g. Ridoutt, 2021; Correddu et al., 2023; Berton et al., 2024). Furthermore, assessing warming-equivalent CO_2 emissions using GWP* helps resolve ambiguities arising from applying metrics such as CO_2-e on a population basis, which can provide unclear insights into subpopulation's warming effects, as it overestimates subpopulations with a cooling effect and underestimates those with a warming effect. For example, Ridoutt (2021) calculated a cooling effect for the Australian sheep sector and a warming effect for the chicken meat sector using GWP* and the approach of Lynch et al. (2020). This approach uses GWP_{100} factors and combination of two weighting factors, r and s, given to the impacts of changing the rate of short-lived climate pollutant (SLCP) emissions and to the current emission rate, respectively. Furthermore, Correddu et al. (2023) demonstrated a cooling effect for the dairy cattle sector and a warming effect for the buffalo sector in Italy. These differences are not apparent when calculated at the sectoral level, where different subpopulations contribute to emissions but do not necessarily contribute to additional warming, which is also the focus of climate policy (Cain et al., 2021) such as the Paris Agreement (UNCC, 2015). Moreover, in climate science, where emissions are modelled over hundreds of years, 20 years may not be considered long-term data. However, in livestock science, at various population levels such as regions, categories, or breeds, and especially at the farm level, obtaining 20 years of data, which is necessary for GWP*, may be challenging. As a result, the professional basis for providing information on how to improve production efficiency and sustainability at various levels is lacking.

Data on methane emissions provide valuable insights for developing tools for farmers at various levels of livestock production. Therefore, it is sometimes not relevant to convert methane emissions into CO_2 equivalents. At the animal level, methane emissions serve as indicators of feeding status, nutrient utilisation efficiency (Manzanilla-Pech et al., 2022; Chang et al., 2021), energy balance (Judy et al., 2018; Morgavi et al., 2023), and the interaction between animals and rumen microbiota (Thacharodi et al., 2024; Kang et al., 2025). At the farm level, they inform adjustments to feed rations (Hristov, 2024; Managos et al., 2025) and fertiliser management (Dalby et al., 2021). Further, it is also a parameter of the efficiency of nutrients from feed. At the population and animal-livestock category level, they support the development of traits for selecting animals in the next generation with lower emissions (Pickering et al., 2015; Lassen and Difford, 2020; de Haas et al., 2021; Heringstad and Bakke, 2025). Nonetheless, if methane emission data are recalculated to CO_2 equivalents, these data may become more confusing for experts working on farms or with farmers. In addition, research on tools development is nascent, where methods to calculate methane balance are missing. Therefore, a practical method for calculating methane's short- and long-term atmospheric balance is needed to support cleaner livestock production and serve as an environmental indicator to monitor the sustainability of livestock production.

The aim of this study is to develop a novel method to calculate the balance of cumulative non-fossil methane emissions (BME) over consecutive or non-consecutive livestock production periods. The method aims to bridge the gap between available environmental techniques, methane's atmospheric pathways and the needs of farmers and breeding organisations. Furthermore, BME quantifies and identifies the net atmospheric burden or removal over consecutive or non-consecutive livestock production periods. Two cases are considered because it is not possible to track both long-term and short-term progress in livestock production efficiency using only one of the cases. It integrates methane's short atmospheric lifetime and continuous atmospheric chemical removal and is applicable on different levels (farm, animal breed, category or species, and region). Approaches are presented to calculate cumulative methane emissions (CME) for periods of livestock production from annual methane emissions (AME), accounting for the portion of past methane emissions that have already been removed from the atmosphere. The method is derived and demonstrated through case studies. Additional novelties include adjusting the method for different methane lifetimes and comparing various livestock periods to assess short- and long-term trends in methane balance using chain-base and fixed-base BME, respectively. Chain-based BME allows comparison of accumulated emissions in consecutive periods, while fixed-based BME allows comparison of accumulated emissions in periods that may be either close together or further apart. Furthermore, examples are provided of applying methane mitigation measures and assessing them using the BME method.

2. Material and methods

2.1. *Calculating balance of cumulative non-fossil methane emissions*

The value of BME is calculated from CME over two production periods for the same livestock methane emitter, considering the continuous removal of methane from the atmosphere (Fig. 1). A livestock farming period is defined as a span of years equal to the methane lifetime, during which most methane emissions accumulate. A period length of 12 years is chosen because the average methane lifetime proposed by the latest (sixth) IPCC Assessment Report (2021) is 11.8 ± 1.8 years, which is rounded to 12 years here to simplify the BME calculation. Firstly, AME data for the livestock production period is obtained either through previous calculations (e.g. IPCC Tier 1, Tier 2, or Tier 3) or measurements (e.g. sniffer, laser methane detector). Secondly, CME (Table 1) are calculated using AME data and the methane decay function. The decay function allows calculation of the probability P(t) that AME remains in the atmosphere in the years following emission. The probability P(t) is calculated as

$$P(t) = \exp(-t/\tau), \quad \text{(eq. 1)}$$

Table 1
Terminology clarification box.

Terminology	Definition	Reference
Burden	The total mass of a substance of concern in the atmosphere.	IPCC et al., 2021
Cumulative emissions[a]	The total amount of emissions released over a specified period of time.	IPCC et al., 2021
Emissions	The release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time.	UNFCCC (1992)
Removals	Physical quantities of GHGs removed from the atmosphere.	UNCC (2023)
Sink	Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.	UNFCCC (1992)
Source	Any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere.	UNFCCC (1992)

[a] In this study, the calculation of cumulative methane emissions includes methane removals during the period of livestock production; GHGs - greenhouse gases.

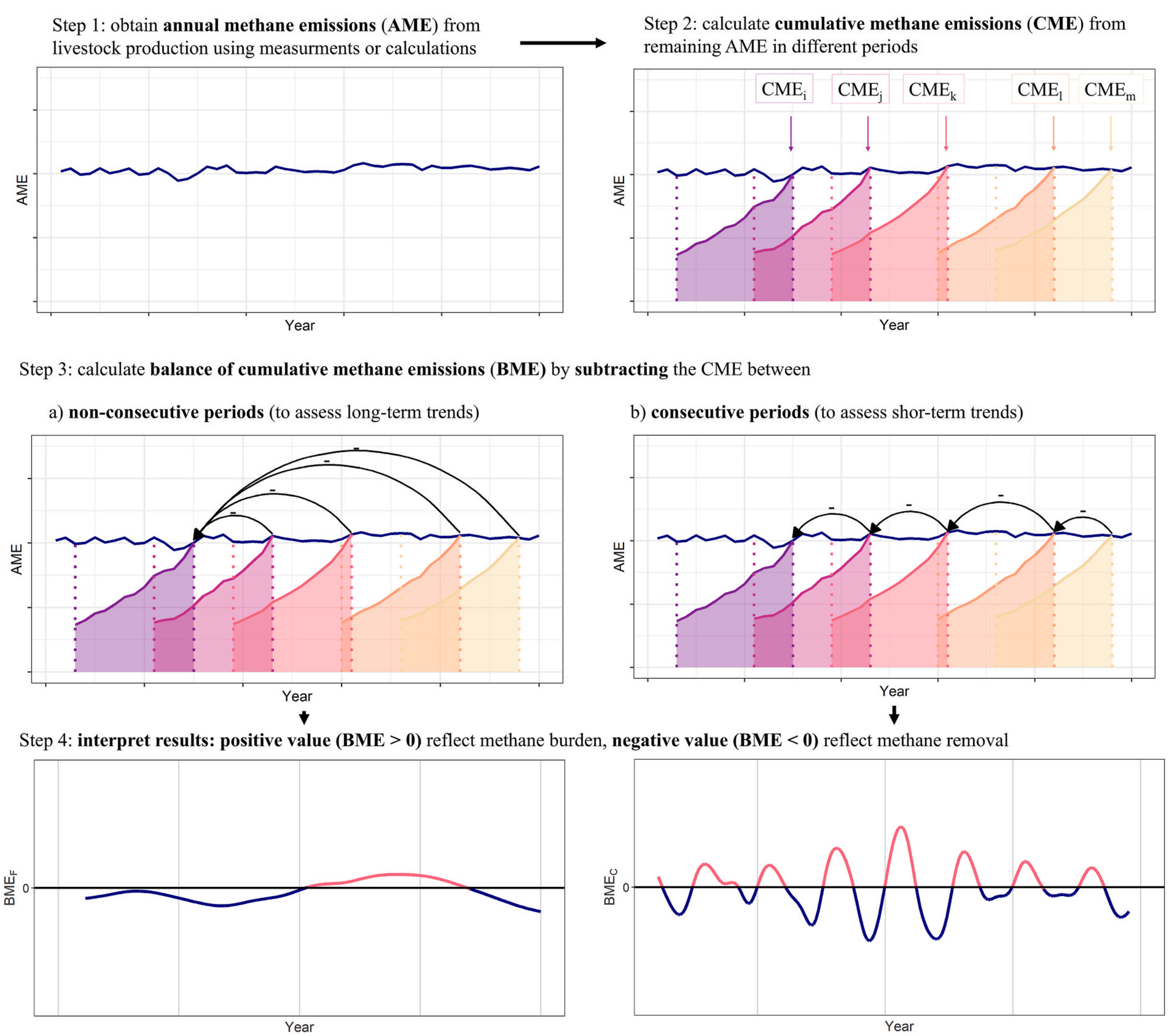

Fig. 1. A schematic representation of balance of cumulative non-fossil methane emissions (BME) calculations. In Step 1, annual methane emissions (AME) are obtained. In Step 2, cumulative methane emissions (CME) are calculated, and in five random years, CME values are marked. The coloured area under the curve represents the CME in years when the AME of the previous 12 years were accumulated. CME are marked for five years with individual indexes. In Step 3, examples of chain-base balance (BME_C) and fixed-base balance (BME_F) are provided for consecutive and non-consecutive livestock production periods, respectively. In the final step, interpretation of the values is provided.

Table 2
Probability of methane remaining in the atmosphere in the year i from the past year t (P(t)), taking into account different atmospheric lifetimes of methane.

Year (t)	P(t) within different methane lifetimes				
	10	11	12	13	14
0	1.000000	1.000000	1.000000	1.000000	1.000000
1	0.904837	0.913101	0.920044	0.925961	0.931063
2	0.818731	0.833753	0.846482	0.857404	0.866878
3	0.740818	0.761300	0.778801	0.793923	0.807118
4	0.670320	0.695144	0.716531	0.735141	0.751477
5	0.606531	0.634736	0.659241	0.680712	0.699673
6	0.548812	0.579578	0.606531	0.630313	0.651439
7	0.496585	0.529213	0.558035	0.583645	0.606531
8	0.449329	0.483225	0.513417	0.540433	0.564718
9	0.406570	0.441233	0.472367	0.500420	0.525788
10	0.367879	0.402890	0.434598	0.463369	0.489542
11	0.332871	0.367879	0.399850	0.429062	0.455794

where t is the consecutive historic year (ranging from 0 to 11 if a 12-year period is studied) since the reference year and τ is the methane's atmospheric lifetime. Table 2 shows calculated P(t) for τ between 10 and 14 (using eq. (1)). Using these probabilities, CME are calculated as the sum of the AME values multiplied by the probability that the corresponding emissions remain in the atmosphere in a given year, using the following equation for a 12-year period: $CME_i = AME_{i-0} \times P_0 + AME_{i-1} \times P_1 + \ldots + AME_{i-10} \times P_{10} + AME_{i-11} \times P_{11}$. The equation is written as follows:

$$CME_i = \sum_{t=0}^{11} AME_{i-t} \text{ x } P_t, \qquad \text{(eq. 2)}$$

where i is the observed year, t is historic (past) year from 0 to 11 and $i > 11$. In the subsequent year j, CME can be calculated as follows:

$$CME_j = \sum_{t=0}^{11} AME_{j-t} \text{ x } P_t, \qquad \text{(eq. 3)}$$

where j is the observed year, t is historic (past) year from 0 to 11 and $j > 11$. If year j follows year i, then $CME_i < CME_j$ indicates a methane burden and $CME_i > CME_j$ indicates a methane removal. Thirdly, the subtraction $CME_i – CME_j$ from previous step was divided with CME_i and obtain BME as follows:

$$BME_j = \left(CME_j - CME_i\right) \text{ x } \left(CME_i\right)^{-1} \text{x } 100 \qquad \text{(eq. 4)}$$

Using this equation, the relative BME (in %) between the two periods of CME is obtained. To obtain the absolute value, Eq. (4) is further simplified, where BME is calculated (e.g. in kilograms or tons), and CME_j is subtracted from CME_i as follows:

$$BME_j = CME_j - CME_i, \qquad \text{(eq. 5)}$$

where BME >0 presents methane burden and BME <0 presents methane removal. A schematic representation of BME is in Fig. 1, and an example of CME and BME calculation with intermediate steps is in Fig. 2.

2.2. *Using BME to assess short- and long-term efficiency of livestock production*

The value of CME in year i includes the remaining AME from the previous 12 years, assuming a 12-year production period. Theoretically, two types of CME comparisons between livestock periods are defined: consecutive and non-consecutive. Consecutive CME are defined as AME in CME_{i+1} followed by AME in CME_i. In non-consecutive CME comparisons, CME_{i+1} do not follow CME_i and are further divided into partially overlapping and non-overlapping CME. Partially overlapping CME are defined where at least two AME are present in both CME_i and CME_j periods, while non-overlapping CME are where AME in CME_i are not present in CME_j. Indexes *i* and *j* represent observed years in which methane emissions accumulated.

For practical purposes, two types of BME are defined: chain-base and fixed-base (Fig. 1). Chain-base BME (BME_C) allows comparison of consecutive CME values (CME_i and CME_{i+1}). Fixed-base BME (BME_F)

Step 1: Obtain **AME data**

Year (i)	1	2	3	4	5	6	7	8	9	10	11	12	13
AME (kt)	52.32	52.30	51.90	51.85	51.42	51.00	48.58	48.52	47.20	46.88	46.58	46.32	45.20

Step 2: Calculate **probabilites** of **remaining AME in observed year** using **methane decay function:** $P(t) = e^{-\frac{t}{\tau}}$, where $\tau = 12$

Year (t)	0	1	2	3	4	5	6	7	8	9	10	11
P (t)	1.00	0.92	0.85	0.78	0.72	0.66	0.61	0.56	0.51	0.47	0.43	0.40

Step 3: Calculate **CME** as follows: $CME_i = \sum_{t=0}^{11} AME_{i-t} \text{ x } P_t$, where $i \geq 12$ and $0 \leq t \leq 11$, for

a) **the first observed period** (CME_{12}):

$CME_{12} = AME_{12-0} \times P_0 + AME_{12-1} \times P_1 + \ldots + AME_{12-11} \times P_{11}$
$= AME_{12} \times P_0 + AME_{11} \times P_1 + \ldots + AME_1 \times P_{11}$
$= 46.32 \text{ kt} \times 1.00 + 46.58 \text{ kt} \times 0.92 + \ldots + 52.32 \text{ kt} \times 0.40$
$= 387 \text{ kt}$

b) **the second observed period** (CME_{13}):

$CME_{13} = AME_{13-0} \times P_0 + AME_{13-1} \times P_1 + \ldots + AME_{13-11} \times P_{11}$
$= AME_{13} \times P_0 + AME_{12} \times P_1 + \ldots + AME_2 \times P_{11}$
$= 45.20 \text{ kt} \times 1.00 + 46.32 \text{ kt} \times 0.92 + \ldots + 52.30 \text{ kt} \times 0.40$
$= 382 \text{ kt}$

Step 4: Calculate **BME (BME_{13})** by **subtracting** the CME between both periods:

$BME_{13} = CME_{13} - CME_{12} = 382 \text{ kt} - 387 \text{ kt} = -5 \text{ kt}$

Step 5: **Interpretations**

The negative result of -5 kt indicates that, when comparing the two livestock production periods, 5 kt more methane emissions was removed from the atmosphere than emitted (methane removal). If the result was positive (+5 kt), it would mean that, when comparing the two livestock production periods, 5 kt more methane emissions was added to the atmosphere than removed (methane burden).

Fig. 2. Practical training on the calculation of CME and BME of livestock production periods. Abbreviations: AME – annual methane emissions; BME – balance of cumulative non-fossil methane emissions; CME – cumulative methane emissions; P – probability that methane in observed year i from past year t remained in the atmosphere.

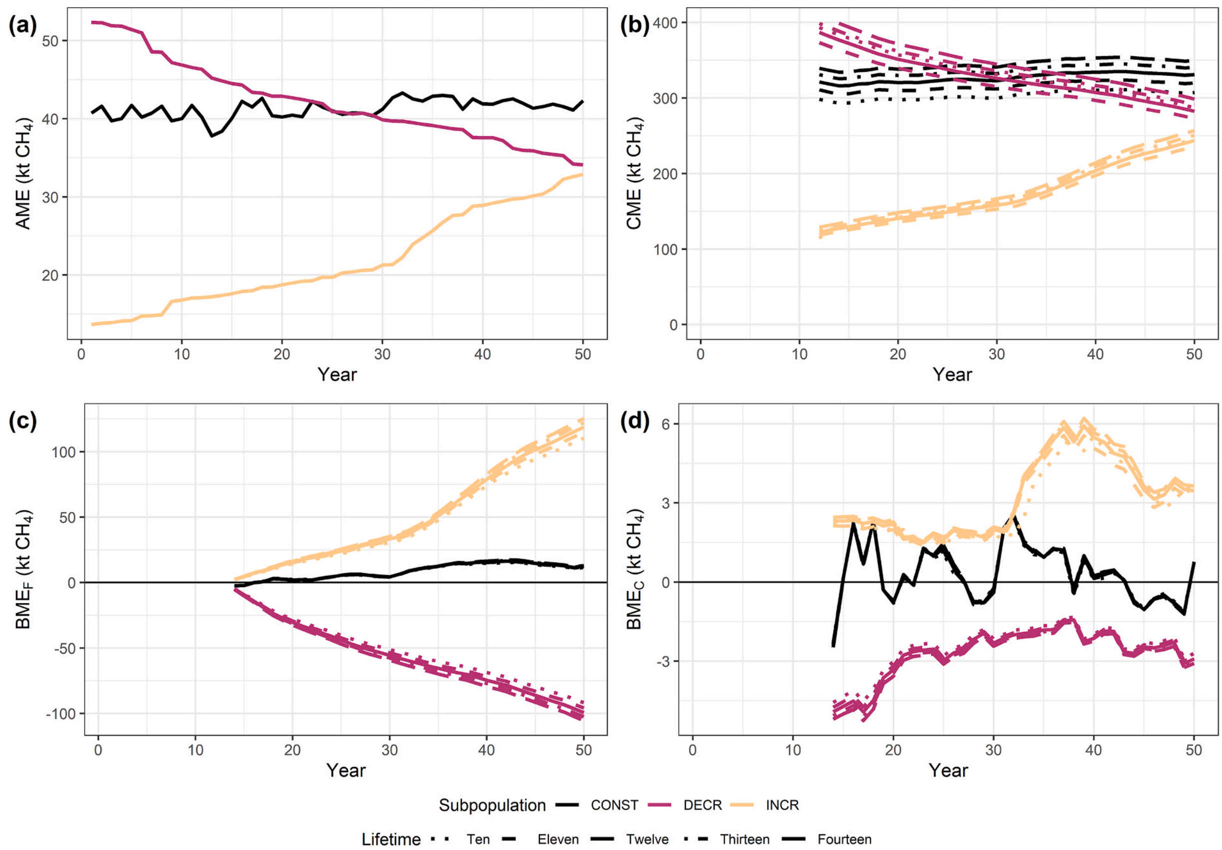

Fig. 3. Trends from year 1 to 50 in a subpopulation with decreasing (DECR), increasing (INCR), and constant (CONST) methane emissions for: (a) annual methane emissions (AME); (b) cumulative methane emissions (CME) calculated for 12-year periods; (c) fixed base balance of cumulative non-fossil methane emissions (BME_F); and (d) chain base balance of cumulative non-fossil methane emissions (BME_C). In (b), (c), and (d), the lifetime of methane is simulated between 10 and 14 years.

allows comparison of non-consecutive CME values: CME_j (where j can be between -∞ and ∞) with a fixed CME_i. Both BME_F and BME_C are calculated using the equation $BME_j = CME_j - CME_i$. The difference is that when calculating BME_F, CME_i is fixed, while when calculating BME_C, CME_i follows CME_{i-1}. For example, if a period of 50 years for livestock production is assumed, 50 years of AME data is needed for further calculation. When calculating BME_F, for each year in the period between years 13 and 50, CME_{12} is subtracted from CME_{13}, CME_{14}, …, CME_{50} as follows: $BME_{13} = CME_{13} - CME_{12}$, $BME_{14} = CME_{14} - CME_{12}$, …, $BME_{50} = CME_{50} - CME_{12}$. When calculating BME_C, consecutive CME values are subtracted as follows: $BME_{13} = CME_{13} - CME_{12}$, $BME_{14} = CME_{14} - CME_{13}$, …, $BME_{50} = CME_{50} - CME_{49}$ (Fig. 2). An example of CME and BME calculations is presented in Fig. 2.

2.3. *Demonstration of BME calculation on examples of increasing, constant and decreasing AME*

To demonstrate BME (BME_F and BME_C), AME was first simulated in three theoretical livestock subpopulations under simple scenarios with increasing, constant, and decreasing kilotonnes of methane over a period of 50 years. The three theoretical populations differ in their approach to emission mitigation measures and herd management: the first population is characterised by poor implementation of measures, use of poor practices, and uncontrolled herd growth, which causes emissions to increase; the second population does not introduce emission mitigation measures, maintains a constant herd size and production, so emissions remain roughly constant; and the third population effectively and consistently introduces emission mitigation measures and achieves mitigation through improved management. Methane emissions in real populations can vary significantly, from gigatonnes at the country level to kilograms at the farm level. Here, kilotonnes were chosen to present the method. In the first subpopulation (DECR), it was postulated that AME decreased from 52 kt to 34 kt; in the second subpopulation (CONST), which represents a subpopulation with roughly constant emissions, AME values of 40 ± 2 kt were used; and in the third subpopulation (INCR), it was designated that AME increased from 13 kt to 33 kt (Fig. 3(a)). All AME data for simulations and results are provided in Supplementary Table 1. Next, CME, BME_F, and BME_C are calculated based on AME for all three subpopulations using equations (1)–(3) and (5).

Additionally, to demonstrate the effect of methane lifetime on BME, and to show how to modify methane lifetime in the BME equations, CME is calculated by varying methane lifetime from 10 to 14 (12 ± 2) years. If the end user wants to use a different lifetime from 12 years in the calculations, the probabilities of remaining methane must be recalculated using the decay function (Eq. (1)). Examples of recalculated probabilities for methane lifetimes ranging from 10 to 14 years are shown in Table 2. These probabilities are used in the calculations of CME (Eq. (2), Fig. 2). Additionally, a quantitative comparison of BME with GWP* was performed using Smith et al. (2021) equation:

$$E(t)^* = 128 \times E(t) - 120 \times E(t\text{-}20), \quad \text{(eq. 6)}$$

where E(t) represents methane emissions in year t and E(t-20) represents methane emissions in year t-20. The annual GWP* results are provided in the Supplementary Table 1.

2.4. *Demonstration of application of BME on subpopulation level; case study on Slovenian livestock categories*

To provide an example of applying BME at the real-life subpopulation level, reported emissions at the livestock-category level were used as a case study. The AME data were summarised from the Common Reporting Tables (CRT) tables that we reported in the annual national inventory report (Mekinda Majaron et al., 2025) and were calculated using IPCC (2019) Tier 2 approach. The AME from enteric fermentation and manure management were summarised by livestock category (goats, horses, mature dairy cattle, non-dairy cattle, other cows, poultry, sheep, swine) for the period from 1990 to 2023. For the category 'other cows', data was available from 1991 onwards. Total methane emissions were calculated as the sum of enteric emissions and manure management for all categories per year. The values of CME, BME_F, and BME_C were calculated using the approaches presented in Fig. 2 (using Eqs. (1)–(5)). For calculating BME_F, the year 2001 was fixed (for the category other cows 2002 was fixed because the AME data is available with a one-year lag). All AME data, including livestock-category results, are provided in Supplementary Table 2.

2.5. Demonstration of assessing mitigation measures in CME and BME calculations; case study on short scale AME data

The effect of emission mitigation measures on the methane balance can be captured using BME. To demonstrate how to include mitigation measures in BME calculations, various scenarios were created. Methane mitigation measures are considered when calculating AME. Mitigated methane emissions in a given year were subtracted from the AME. The remaining emissions, as AME, were then used in further calculations of CME and BME. For demonstration, a period of 15 years of AME was simulated, and mitigation measures were assessed through three scenarios: 1) no mitigation; 2) 5 kt methane emission mitigation in year 14; 3) 5 kt methane mitigation in years 12 and 14. Finally, the calculations of CME and BME were performed using equations (1)–(5). The calculated values are provided in Supplementary Table 3.

3. Results

3.1. Scenario analysis: How BME responds to emission trends

Methane balances were assessed for simulated populations, comparable to real ones, with varying annual trends. Specifically, three populations with decreasing (DECR), constant (CONST), or increasing (INCR) AME were simulated (Fig. 3) over a period of 50 years. To examine the effects on BME_F and BME_C in greater detail, these populations were also simulated with different regression coefficients within individual periods of the total timeframe. In the case of increasing emissions (Fig. 3(a)), emissions increased from year 1 to 8 with a linear regression coefficient of 0.19 kt/year, from year 8 to 31 by 0.23 kt/year, from year 32 to 41 by 0.76 kt/year, and from year 41 to 50 by 0.44 kt/year. The fastest increase in AME occurred between years 32 and 40 (Fig. 3(a)). In the population of decreasing emissions, there was a significant decrease from year 1 to 7, namely by −0.51 kt/year; from year 7 to 37, the decrease was −0.32 kt/year; and from year 37 to 50, it was −0.35 kt/year.

CME followed a similar trend direction to AME (Fig. 3(b)). Notably, as CME increased, their variability with respect to methane lifetime also increased. For example, in the population with increasing AME, the variability during the lifetime was 114.3 kt CH_4 at lifetime ten in year 12, 122.5 kt CH_4 at lifetime twelve, and 129.0 kt CH_4 at lifetime fourteen. Thus, over lifetimes of 12 ± 2 years, the variability increased by approximately ±8 kt CH_4 (between ±6.7%). In contrast, for the population with decreasing AME, the variability was 358.4 kt CH_4 at lifetime ten in year 12, 386.8 kt CH_4 at lifetime twelve, and 409.3 kt CH_4 at lifetime fourteen. Here, the difference over 12 ± 2 years was approximately ±22 kt CH_4 (between ±7.3%).

Populations with decreasing AME indicate a methane removal, while populations with increasing AME indicate a methane burden (Fig. 3(c)). In populations with approximately constant emissions, methane is roughly net zero. The trend in BME_F was −2.41 kt/year, 3.29 kt/year, and 0.50 kt/year in populations DECR, INCR, and CONST, respectively. Compared to 2001, BME_F decreased by 99.38 kt CH_4 in 2023 in DECR population, and increased by 118.75 kt CH_4 and 12.38 kt CH_4 in populations INCR and CONST, respectively. As BME_F diverged from the original value, lifetime variability also increased in INCR and DECR populations. The positive values in the population with approximately constant emissions are due to the nature of the simulated data; if all AME values were identical, BME_F and BME_C would be zero.

In the population with increasing annual emissions, BME_C decreased slightly between years 13 and 31, from 2.40 kt CH_4 to 1.89 kt CH_4 (−21.67%), at a rate of −0.035 kt CH_4/year (Fig. 3(d)). From years 31 to 41, BME_C increased significantly, from 1.89 kt CH_4 to 5.31 kt CH_4 (+284%) at a rate of 0.34 kt CH_4/year. This was due to a significant increase in AME during the same period. Between years 39 and 50, BME_C decreased from 5.92 kt CH_4 in year 39 to 3.46 kt CH_4 in year 50 (−41.50%; −0.24 kt CH_4/year) due to a slower increase in AME during the same period, but remained positive, i.e. it contributed to the methane burden.

In the population with decreasing emissions, BME_C increased most rapidly from year 13 to 29, rising from −4.98 kt CH_4 to −1.95 kt CH_4 at a rate of 0.200 kt CH_4/year (Fig. 3(d)). It reached its highest value in year 38, at −1.43 kt CH_4, and then decreased at a rate of −0.089 kt CH_4/year until year 50, reaching −2.91 kt CH_4. In periods when the consecutive CME differences were larger, the BME_C was smaller, and vice versa. Throughout the period, BME_C remained below 0 kt CH_4, indicating that this population contributed to the methane removal. The BME_C results can be compared with and used for policy reporting alongside GWP*, which, like BME_C, uses a chain base approach. The DECR population had negative values throughout the entire period, regardless of whether the BME_C or GWP* approach was used, while the INCR population had positive values throughout the entire period (Table 3). Whether a population with relatively constant emissions contributes to the methane burden or acts as a removal depends in real time on short-term trends. In subpopulation three, there were more pronounced increases in BME_C in years 18 (2.31 kt CH_4), 25 (1.29 kt CH_4), and 32 (2.53 kt CH_4) (Fig. 3(d)); in these years, the values were mostly above zero and contributed most to the methane burden. Conversely, the values were lower and

Table 3
Comparison of five-year averages of BME_C with GWP* for three simulated subpopulations.

Years	Subpopulation					
	DECR		INCR		CONST	
	BME_C (kt CH_4)	GWP* (kt CO_2-we)	BME_C (kt CH_4)	GWP* (kt CO_2-we)	BME_C (kt CH_4)	GWP* (kt CO_2-we)
16-20	−4.18	/	2.24	/	0.83	/
21-25	−2.70	−853.33	1.63	808.92	0.73	369.03
26-30	−2.34	−629.60	1.86	773.28	−0.25	359.31
31-35	−1.96	−407.12	3.53	946.04	1.63	714.10
36-40	−1.82	−301.89	5.60	1,381.43	0.65	447.43
41-45	−2.31	−364.06	4.52	1,470.78	−0.20	446.10
46-50	−2.64	−388.02	3.45	1,598.72	−0.47	447.62

DECR – subpopulation with decreasing annual methane emission; INCR – subpopulation with increasing annual methane emissions; CONST – subpopulation with roughly constant annual methane emissions; BME_C - balance of cumulative non-fossil methane emission with chain base; GWP* - global warming potential "star"; CH_4 – methane; CO_2-we – carbon dioxide warming equivalents;/– not obtainable.

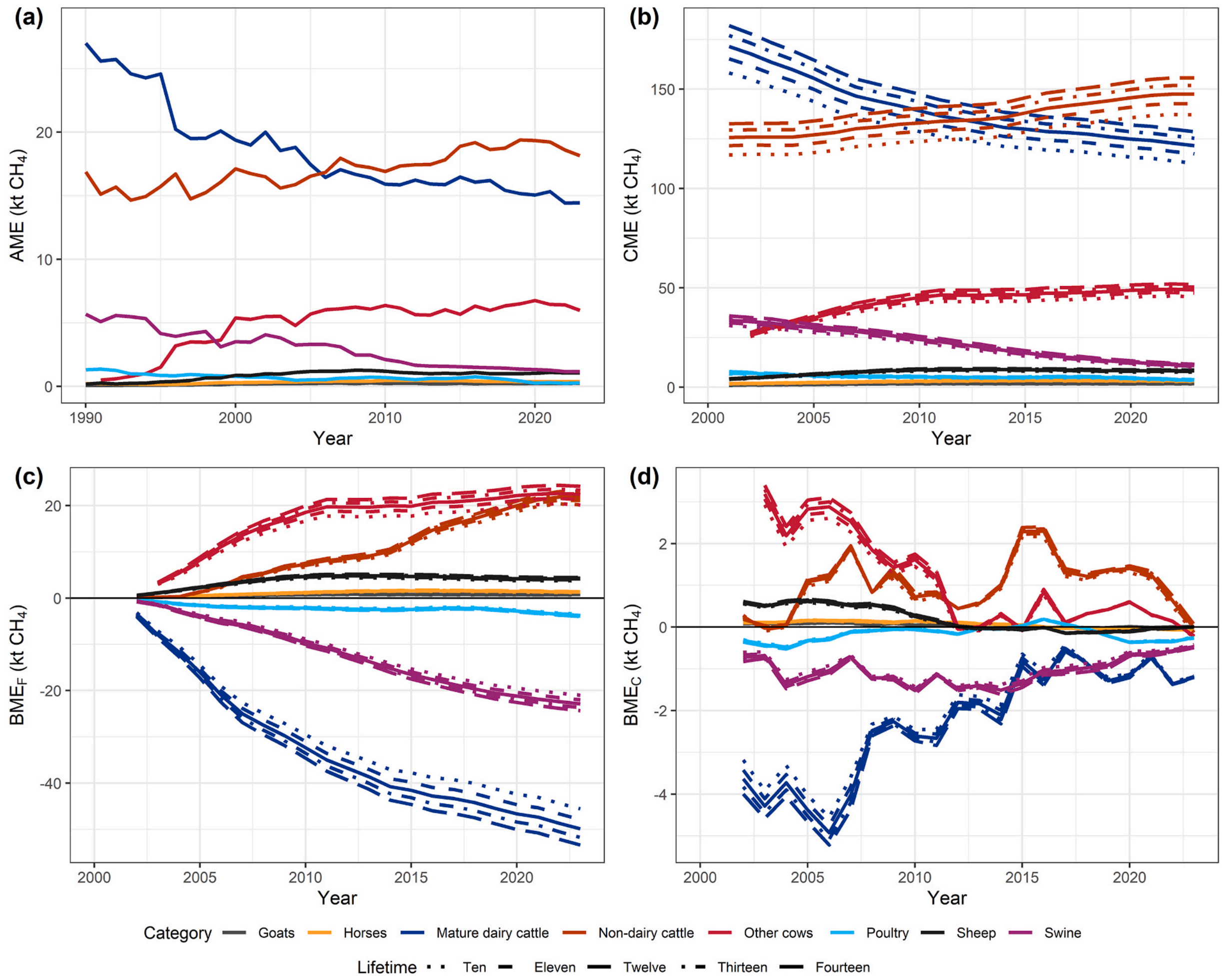

Fig. 4. Assessing methane emissions from Slovenian livestock production at the animal category level: (a) annual methane emissions (AME) summarised from Mekinda Majaron et al. (2025); (b) cumulative methane emissions (CME) calculated for 12-year periods; (c) balance of cumulative non-fossil methane emissions using a fixed base (BME_F); (d) balance of cumulative non-fossil methane emissions using a chained base (BME_C). For (b), (c) and (d), additional assessments are provided by adjusting methane lifetime between 10 and 14 years.

negative in years 13 (−2.86 kt CH_4), 14 (−2.38 kt CH_4), 20 (−0.75 kt CH_4), 28 and 29 (−0.78 kt CH_4 and -0.77 kt CH_4, respectively), and towards the end of the period in years 45 and 49 (−1.03 kt CH_4 and -1.15 kt CH_4, respectively). In these years, a methane removal was present in the population.

3.2. Case study: Slovenian livestock categories

The BME method was applied at the Slovenian livestock-category level to assess the methane burden or removal from each category. The highest annual emissions in Slovenia over the past 30 years were from other cows, dairy cattle, non-dairy cattle, and swine (Fig. 4(a)). In dairy cows, annual methane emissions decreased from 26.99 kt CH_4 in 1990 to 14.45 kt CH_4 in 2023 (−46.47%), with an annual trend of −0.33 kt CH_4 per year. Conversely, in non-dairy cattle, emissions increased from 16.88 kt CH_4 to 18.15 kt CH_4 (+7.54%), with an annual trend of 0.12 kt CH_4 over the same period. In other cows, annual emissions increased significantly between 1991 (no data for 1990) and 2000, from 0.50 kt CH_4 to 5.38 kt CH_4 (+972%), with an annual trend of 0.53 kt CH_4. From 2000 to 2023, emissions were relatively constant or increased slightly, from 5.38 kt CH_4 to 5.98 kt CH_4 (+11%), with an annual trend of 0.05 kt CH_4. Emissions from pigs decreased significantly, from 5.67 kt CH_4 to 1.16 kt CH_4 (−79.56%), or −0.14 kt CH_4 per year. The sheep sector increased emissions from 0.18 kt CH_4 in 1990 to 1.18 CH_4 kt in 2005 (+538.69%), or by 0.07 kt CH_4 per year, and from 2005 to 2023 decreased from 1.18 kt CH_4 to 1.07 kt CH_4 (−10.03%), with an annual trend of −0.011 kt CH_4. Other sectors had low annual emissions throughout the period (Supp. file 2).

The trend directions of CME for the 12-year period were the same as for AME (Fig. 4(b)). Over the period 2001-2023, CME increased mainly for non-dairy cattle, from 125.7 kt CH_4 to 147.5 kt CH_4, an increase of 17.3% or +1.12 kt per year. For other cows, CME increased from 26.69 kt CH_4 in 2001 to 46.35 kt CH_4 in 2012 (+73.69%), or by 2.05 kt CH_4 per year; between 2012 and 2023, it increased from 46.35 kt CH_4 to 49.05 kt CH_4, an increase of 5.8% or 0.31 kt CH_4 per year. In dairy cows and pigs, CME decreased significantly: in mature dairy cows from 171.5 kt CH_4 in 2001 to 121.6 kt CH_4 in 2023 (−29.09%) or −2.16 kt CH_4 per year, and in pigs from 33.77 kt CH_4 to 10.91 kt CH_4 (−67%) or −1.14 kt CH_4 per year. The impact of methane lifetime on the range of cumulative emissions is more pronounced in sectors with higher cumulative emissions. The lowest cumulative emissions are calculated for a 10-year lifetime and the highest for a 14-year lifetime. For mature dairy cows, in 2001, at a lifetime of 12 years, CME are 13.26 kt CH_4 (8.38%) higher compared to a lifetime of 10 years and 10.51 kt CH_4 (5.77%) lower compared to a lifetime of 14 years. In 2023, it is slightly lower: CME at a lifetime of 12 years are 8.9 kt CH_4 (7.90%) higher compared to a lifetime of 10 years and 7.0 kt CH_4 (5.47%) lower compared to a lifetime of 14 years. The impact of lifetime on CME with smaller AME is not as pronounced as in sectors with larger AME.

Applying BME_F through CME enables the assessment of long-term efficiency in subpopulations or subsectors (Fig. 4(c)). Sectors with negative BME_F values contributed to the long-term methane removal, while sectors with positive values contributed to the long-term methane burden. The most pronounced negative BME_F was observed in the mature dairy cows sector, where BME_F decreased from −7.92 kt CH_4 to −49.88 kt CH_4, at a rate of −1.94 kt CH_4 per year between 2002 and 2023. In dairy cows, BME_F decreased over three periods. The most pronounced downward trend occurred between 2003 and 2007, at −4.34 kt CH_4 per year; between 2007 and 2015, the trend was −2.14 kt CH_4 per year; and from 2015 to 2023, it was −1.02 kt CH_4 per year. There was also a significant decrease in pigs, from −1.41 kt CH_4 to −22.85 kt CH_4, or -1.14 kt CH_4 per year. In both sectors, significantly more methane was removed than produced during the period. There was also a negative trend in poultry. The opposite was observed for other cows and non-dairy cattle, which showed a positive long-term trend, indicating additional methane in the atmosphere compared to the previous period, i.e. a methane burden. For other cows, BME_F increased from 3.19 kt CH_4 in 2003 to 18.52 kt CH_4 (+580%) in 2010, with an annual trend of 2.25 kt CH_4; from 2010 to 2023, the growth slowed to 22.36 kt CH_4 (+20.78%) in 2023, with an annual trend of 0.30 kt CH_4 per year and an overall trend of 0.83 kt CH_4 per year between 2003 and 2023. There was also a significant increase for non-dairy cattle, from 0.23 kt CH_4 to 21.83 kt CH_4, with an annual trend of 1.15 kt CH_4 over the entire period. BME_F for other sectors was close to zero compared to cattle, so it did not have a significant impact on methane burden or methane removal. However, it was found that the direction of the BME_F trend follows the trends of AME and CME.

Applying BME_C through CME enables the assessment of short-term efficiency in subpopulations or subsectors (Fig. 4(d)). In dairy cows and swine category, BME_C was negative throughout the study period, indicating that more methane was removed than emitted, resulting in a net methane removal during successive farming periods. In dairy cows, BME_C at lifetime 12 decreased from −3.64 kt CH_4 in 2002 to −4.92 kt CH_4 in 2006, then increased to −1.21 kt CH_4 in 2023, the final period studied. The BME_C for the pig sector also decreased, from −0.73 kt CH_4 in 2002 to −1.52 kt CH_4 in 2010, then increased to −0.46 kt CH_4 in 2023. For both mature dairy cattle and pig sectors, BME_C began to increase as the decrease in AME slowed and annual differences in cumulative emissions became less pronounced. In contrast, the other cows (until 2012) and non-dairy cattle sectors contributed the largest additional methane burden to the atmosphere. For other cows, BME_C was high at the start of the study period, but then showed a significant decrease, from 3.19 kt CH_4 in 2003 to −0.05 kt CH_4 in 2012, after which values remained relatively constant between −0.22 kt CH_4 and 0.84 kt CH_4 until 2023. The high values until 2012 were due to the increase in AME in the preceding period. As AME stabilised after 2010, this led to a continuous balance of approximately net zero. A positive or negative direction of BME_F does not necessarily correspond to a positive or negative direction of BME_C (Fig. 4(c) and (d)). This was evident in the sheep sector, which had a positive BME_F in the long term; compared to the cumulative emissions in 2001, when cumulative emissions were small, they contributed to the methane burden in subsequent years. However, this was not reflected in the BME_C due to relatively constant emissions after 2001. Specifically, BME_C decreased from 0.59 kt CH_4 in 2002 to −0.06 kt CH_4 in 2015, remained negative until 2022 when it reached −0.02 kt CH_4, and increased slightly in 2023 to 0.00 kt CH_4. Thus, even though annual emissions, cumulative emissions, and BME_F are decreasing, BME_C may increase. This does not necessarily indicate a methane burden, as a negative value still represents a methane removal. The value of BME_C may increase because annual emissions decrease with progressively smaller annual differences. However, a methane removal effect remains, as more methane from the past is removed than new methane is emitted.

For the eight largest livestock categories, methane parameters as average values for the period 2018–2022 were calculated (Table 4). For BME_F, the CME base in 2001 was taken into account. Within the structure of all categories, AME and CME were highest in non-dairy cattle and mature dairy cattle, at 34.29% and 43.35% respectively, totalling 77.64% of all sectors. The results were different in BME_F and BME_C, where, in mature dairy cows and pigs, the values were much lower than in other sectors. Over the long term (BME_F), both the mature dairy cow and the swine category had a negative balance, at −46.45 kt CH_4 and -21.03 kt CH_4 respectively. The permanent reduction of emissions was also reflected in BME_C, where the five-year average for the same categories was −1.074 kt CH_4 and -0.747 kt CH_4. Conversely, non-dairy cattle and other cows had the largest positive BME_F and BME_C and were the only sectors with a positive BME_C compared to others, making them the only contributors to methane burden on average from 2018 to 2022.

3.3. Mitigation assessment using BME

To assess how mitigation measures affect methane parameters, three scenarios were created, with and without measures, using an example of annual emissions over a 15-year period. The remaining emissions from the previous year t and the cumulative emissions were calculated for years 12 to 15. The remaining emissions in each year were determined using the decay function coefficients ($\tau = 12$; Table 2). For example, in year 12, from year 1, when there were 40.73 kt CH_4 emissions, 16.29 kt CH_4 remained (0.39985 × 40.73 kt CH_4). The same principle was applied to calculate the remaining emissions for other years. The remaining emissions increased from years 2 to 15, as the proportion of remaining emissions grew and equalled the annual emissions in the final year, year 12. Using the same procedure, the remaining emissions were calculated in years 13, 14, and 15 from the previous year t.

In the scenario where 5 kt of emissions were mitigated in year 14, this was reflected in the remaining methane emissions in years 14 and 15, with a reduction from 38.40 kt by 5 kt to 35.40 kt and 30.73 kt, respectively. In the scenario where annual emissions were reduced in two periods, specifically in years 12 and 14, the remaining emissions decreased proportionally (Fig. 5). In year 12, the remaining emissions in years 12, 13, 14, and 15 were 35.20 kt, 32.38 kt, 29.79 kt, and 27.41 kt, respectively. Thus, the differences between years 12 and 13, 13 and 14, and 14 and 15 decreased, namely −2.81 kt CH_4, -2.59 kt CH_4, and -2.38 kt CH_4.

In the next step, the methane following parameters were calculated: CME, BME_F, and BME_C for the period between years 12 and 15, taking into account the mitigation measures, to observe how their application affects the methane burden or removal. In all three scenarios, CME decreased over the years, except in the no mitigation scenario, where it

Table 4
Average BME_F between 2018 and 2022 compared to 2001, and BME_C for the main Slovenian livestock categories.

Category	Goats	Horses	Mature dairy cows	Non-dairy cattle	Other cows	Poultry	Sheep	Swine
AME (kt CH_4)	0.232	0.377	15.078	19.061	6.491	0.366	1.047	1.317
CME (kt CH_4)	1.805	3.295	125.026	145.468	48.658	4.546	8.373	12.655
BME_F (kt CH_4)	0.744	1.445	−46.452	19.764	21.971	−2.830	4.238	−21.115
BME_C (kt CH_4)	−0.005	−0.043	−1.074	1.173	0.358	−0.260	−0.081	−0.747

AME – annual methane emissions; CME – cumulative methane emissions over 12-year periods; BME_C - balance of cumulative non-fossil methane emission with chain base; BME_F – balance of cumulative non-fossil methane emission with fixed base.

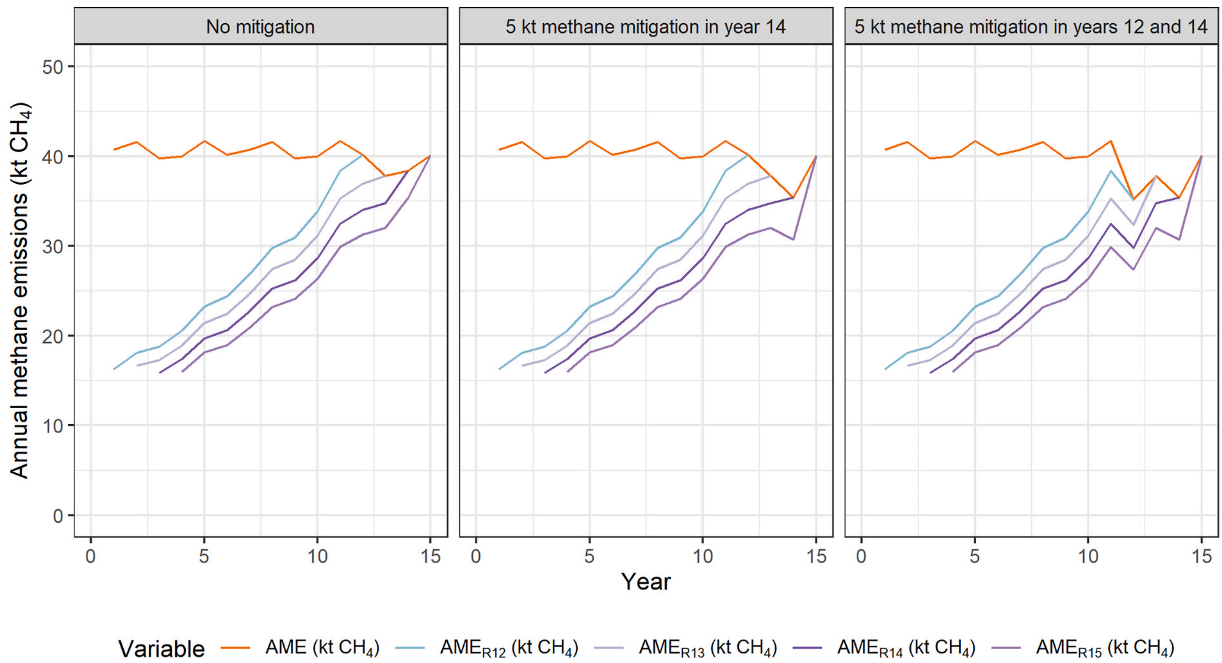

Fig. 5. Assessment of annual methane emissions (AME) focusing on the period 12–15, with and without mitigation measures. The black curve represents AME in year 15 as a fraction of the remained methane in year t over the past 12 years. The remained AME is further used for the calculation of cumulative methane emissions (CME) and balance of cumulative non-fossil methane emissions (BME) (Table 2).

increased between years 14 and 15 due to the increase in AME during the same period. This trend was also reflected in BME_F and BME_C.

The BME_F in the first scenario in year 13 was −2.86 kt CH_4; in the second scenario, it was also −2.86 kt; and in the third scenario, it was −2.46 kt CH_4, i.e. 0.4 kt CH_4 higher than in the first two. This difference was due to the different calculation basis: in the first and second scenarios, the CME in year 12 was 321.42 kt CH_4, while in the third scenario it was 316.4 kt CH_4. Between years 14 and 15, the difference in BME_F in the first scenario was very small (+0.19 kt CH_4), whereas in the second and third scenarios, the methane removal between these years was higher by 1.42 kt CH_4 and 1.08 kt CH_4, respectively. Comparing consecutive periods with BME_C, there was a significant difference in year 14. By mitigating 5 kt AME, the methane removal increased from −2.34 kt CH_4 to −5.39 kt CH_4 compared to the no-mitigation scenario. This removal was less pronounced in the third scenario in the same year, amounting to −5.02 kt CH_4, due to the lower CME value in year 13. Applying mitigation measures only in year 14 or in both years 12 and 14 also proportionally reduced the CME in year 15. If there were no mitigation measures or only one in year 14, the CME was 10 kt CH_4 lower, and if both were applied, it was 1 kt CH_4 lower compared to the scenario with no mitigation. The parameter used to calculate this, compared to the first year (in this case, year 12), is the BME_F, which compares the CME with the fixed CME.

4. Discussion

Balance of cumulative non-fossil methane emissions (BME) presents a novel approach to assess methane burden or methane removal between any production periods on any livestock (sub)population or (sub) sector level. The BME method is based on AME data over two periods for the same livestock methane emitter. The approach considers the continuous removal of methane from the atmosphere, compares CME across different periods, and allows various modifications for end users: choice of methane lifetime, lengths of periods compared, and the interval between the two periods being compared. In this chapter, the practical value of the BME method is discussed in relation to a subpopulation-based balance structure, comparison of short- and long-term efficiency, practical application of mitigation measures, and possibilities for further development of tools for end users, such as farmers or breeding organisations. In addition, challenges in the application of different climate metrics are discussed, along with limitations and potential areas for future research.

4.1. BME calculations

4.1.1. Comparisons of periods

Applying BME_C and BME_F provides insight into short- and long-term production efficiency, respectively. BME uses a standardised 12-year period, aligned with the IPCC estimated methane lifetime (IPCC et al., 2021). This is particularly useful for animal populations when long-term (over 20 years) methane data are unavailable. In practice, BME_C can identify the actual amount of methane present in the atmosphere in a given year between two compared periods, for example, between 2022 and 2023 or 2023 and 2024. BME_F can compare emissions accumulated in, for example, 2024 with those accumulated in 2000 and assess the difference in emitted gases between these two time periods.

Using BME_F, attention can be focused on efficiency over a selected period. In the case study of Slovenian livestock-category calculations (Fig. 4), the focus was on the initial period (2001), with all subsequent periods compared to this base year. Since CME was calculated for the years 2001–2023, different years could be chosen as a fixed base: the first, the last, or any year in between. The value of CME of the chosen year is subtracted from the CME in year i. For example, if the fixed CME is in 2010, the BME_F would be calculated as follows: $BME_{2001} = CME_{2001} - CME_{2010}$, $BME_{2002} = CME_{2002} - CME_{2010}$, …, $BME_{2023} = CME_{2023} - CME_{2010}$. The fixed base can be adapted according to the user's needs.

4.1.2. Methane balance in subpopulations or subsectors

Calculating annual emissions or emission balances at the population level obscures the contribution of subpopulations that contribute to atmospheric methane removal or burden. For example, if the AMEs from subpopulations DECR and INCR are summed (Fig. 2(a)), the same result is obtained if the AMEs are reversed. A similar pattern was evident in published literature when calculations were performed using GWP*

(Cain et al., 2019; Smith et al., 2021) to assess sectoral contributions to increased or decreased warming. For example, Ridoutt (2021) used a time period of 28 years for assessment of CH_4, N_2O and CO_2 in Australian livestock production. It was found that methane from sheep for meat declined from 390 kt to 299 kt and which accounted to 19.3 mt CO_2-e and −2.85 mt CO_2-we in 2018. However, CH_4 emissions from chicken for meat sector increased in the same period from 1.08 kt to 3.02 Kt together with CO_2 and N_2O emissions accounted to 2.55 mt CO_2-e and 1.05 mt CO_2-we. Similarly was found for Slovenian cattle production; dairy cow sector expressed a decreased warming effect, while the non-dairy cattle sector had a warming effect (Pečnik and Verbič, 2024). To compare the results with the previous study (Pečnik and Verbič, 2024), five-year averages for 2018-2022 were calculated. Using GWP*, we found that the dairy cow sector exhibited a decreased warming effect (−279 kt CO_2-we), while the non-dairy cattle sector a warming effect (788 kt CO_2-we) (Pečnik and Verbič, 2024). Achieving negative CO_2-we in livestock production (e.g. Pečnik and Verbič, 2024) is also consistent with achieving sustainable agriculture and aligns with the Sustainable Development Goals (UNSD, 2015). Using BME, the average BME_F for Slovenian dairy cows and non-dairy cattle over the same period, compared to the fixed year 2001, was −46.45 kt CH_4 and 19.76 kt CH_4, respectively, indicating a long-term methane removal and burden, from these sectors. Between 2012 and 2022, most of the methane burden was contributed by other cows and non-dairy cattle, while other categories contributed mainly to methane removal (Fig. 4 (d)). These differences are not apparent when calculating total livestock-level emissions.

In a range of applications, BME can be applied at different levels of livestock subpopulations or subsectors such as animal species (e. g. cattle, buffalo, pig, sheep, horse, goat), breed (e. g. Holstein, Brown Swiss or Simmental cattle), or category (e. g. dairy cows, other cows or non-dairy cattle), geographical regions (e. g. town or municipality), individual farms within regions or farms with common feed rations structures. The decision depends on the user's attempt for which population they want to gain better insight into the methane emissions balance or on the financial and practical possibilities of application of methane mitigation measures. For example, measures could be applied within breeding programs among breeding organisations (for breed level), regional advisory services (for regional level), and farms within regions (for farm level). However, some precautions should be taken when interpreting the results at different levels. For example, on species-breed level, Drežnica goat breed is a unique genetic resource (Pogorevc et al., 2021) found in Slovenian hilly and mountain areas, but because of a very small population with less then thousand animals in today's population, it is very endangered. Therefore, it is urgent to increase this population which would show an increase of emissions if mitigation measures not applied. In those scenarios emission increases should be tolerated with trade-offs on other sources.

4.1.3. *Assessment of mitigation measures in AME, CME and BME calculations*

Methane mitigation measures can be assessed in BME calculations. Globally, various methane mitigation measures are studied, implemented and interpreted for their mitigation success on different levels: within seasons and livestock systems, species, categories, breeds, regions or farms. In the last decades one of the most promising mitigation measures were feed additives in enteric fermentation (Beauchemin et al., 2020), which are usually studied on category level within species (Kinley et al., 2020; Narvaez-Izquiedo et al., 2024). Examples include adding feed additive red seaweed *Asparagopsis taxiformis* to mitigate enteric methane in beef steers (Roque et al., 2021) or in dairy cows (Eikanger et al., 2024), combining with genetic selection (De Haas et al., 2021) and technical measures as acidification of stored slurry (Ambrose et al., 2023). These mitigation measures can be assessed in BME equations as subtraction of mitigated AME. For example, if 5 kt were mitigated in subpopulation CONST in year 50 (Fig. 2(a)), 37.33 kt would be used for the calculation of CME, BME_C, and BME_F instead of 42.33 kt (Supplementary Table 1).

Table 5
Demonstrating the effect of incorporating methane mitigation measures on CME in BME (AME remains as shown in Fig. 5). CME values from 12-year periods are compared, with the first calculation of CME occurring in year 12.

Scenario	Mitigating methane emissions	Year	CME (kt CH_4)	BME_F (kt CH_4)	BME_C (kt CH_4)
1	No mitigation	12	321.42	/	/
		13	318.56	−2.86	−2.86
		14	316.17	−5.25	−2.39
		15	316.36	−5.06	0.19
2	5 kt in year 14	12	321.42	/	/
		13	318.56	−2.86	−2.86
		14	313.17	−8.25	−5.39
		15	311.75	−9.67	−1.42
3	5 kt in years 12 and 14	12	316.42	/	/
		13	313.96	−2.46	−2.46
		14	308.94	−7.48	−5.02
		15	307.86	−8.56	−1.08

CME – cumulative methane emissions over 12-year periods; BME_F – balance of cumulative non-fossil methane emission with fixed base; BME_C - balance of cumulative non-fossil methane emission with chain base.

Past emission trends affect real-time BME outcomes. For example, the BME_F values are higher in the last three years in the third scenario than in the second scenario (Table 5) because the base from which they are calculated is smaller. This effect is also seen in BME_C, where the values in each year in the third scenario are higher than in the second. Specifically, the base for calculating BME_F and BME_C in the second scenario is 321.42 kt, while in the third scenario it is 316.42 kt (Table 5). Therefore, in the third scenario, the smaller base results in smaller differences in subsequent periods. A similar effect would be observed if GWP* is applied, for example, using the Smith et al. (2021) equation: $E(t)^* = 128 \times E(t) - 120 \times E(t\text{-}20)$, where E(t) represents methane emissions in year t and E(t-20) represents methane emissions in year t-20. If E(t) is 10 kt CH_4 and E(t-20) is 12 kt CH_4, the result would be very different from the case where E(t-20) is 8 kt CH_4: in the first case, there would be a decreased warming effect, and in the second case, a warming effect relative to the past temperature. The latter scenarios indicate that, to maintain the balance at zero after implementing mitigation measures, these measures must be sustained over the long term and not applied only in a single year; otherwise, with increased methane emissions, there will be a significant (short-term) impact on the methane burden and, consequently, on warming until the methane is removed from the atmosphere.

4.2. *Practical applications*

4.2.1. *Possibilities for development of tools for stakeholders*

For practical use, BME can be applied on farms within tools or indicators to provide additional information to already established environmental indicators. Some farms use Life-Cycle Assessment (LCA) approaches to gain insights into their production's environmental impact and to identify which part of their system boundary presents the greatest environmental burden. A remaining AME and BME calculation (as shown in Fig. 3 and Table 5) could provide an additional information. Based on the results of the methane burden (if obtained), the farm would receive information on how much methane it needed to mitigate to achieve net zero methane emissions.

As a practical tool, BME can be applied for stakeholders developing methane mitigation strategies in livestock systems. Its standardised approach facilitates comparisons across farms or regions, supporting targeted interventions. By providing a standardised, decay-informed metric for livestock methane emissions, the BME method advances our ability to quantify and manage the climate impacts of agriculture. Its adoption could support more accurate GHG interventions and inform strategies to achieve net-zero emissions in the livestock sector. Furthermore, the method emphasizes computational simplicity: the CME equation and BME derivation for relative or absolute values allow for straightforward implementation in spreadsheets or simple scripts, reducing barriers for farmers or policymakers. Moreover, visualizations (as in Fig. 5) enhance interpretability, allowing users to distinguish between burdens (BME >0) and removals (BME <0).

4.2.2. Evaluating climate metrics: opportunities, challenges, and practical applications

Each climate metric has advantages and disadvantages, which are also linked to the intended purpose of the metric. For example, compared to GWP* (Cain et al., 2019; Lynch et al., 2020; Smith et al., 2021), which is becoming the gold-standard approach for assessing the impact of a methane emitter on increased or decreased warming, an advantage of the BME is that it requires a shorter period of AME data (12 ± 2 years for BME and 20 years for GWP*, respectively). This is beneficial when calculations are performed on farms, for instance, where data on emissions over longer periods (>20 years) may not be available. It also takes into account a period of years instead of 20 years difference. Other BME opportunities include simplicity, adaptability, and reliance on established scientific principles, such as the methane decay function and the IPCC approach. The use of a 12-year period in BME method, based on the IPCC's methane lifetime estimate (IPCC et al., 2021), provides a practical and standardised framework.

As discussed by del Prado et al. (2023), methane emissions as CO_2 equivalents are typically calculated by animal scientists or experts, who often face challenges in the correct application of methods to calculate greenhouse gas emissions, and most critically, the accurate interpretation of results obtained using these methods. A BME advantage is that it avoids the need for converting methane emissions into CO_2 equivalents. Therefore, it does not require climatological knowledge to calculate CO_2 (warming) equivalents and could be more easily understood and applied by non-climatologists working in the livestock sector, such as animal scientists, advisory service, technicians working directly with farms, regional development institutions or farmers themselves to assess and monitor short- and long-term BME.

Using different climate metrics for specific purposes in livestock production can lead to confusing interpretations. For example, one of the most commonly used phenotypes in dairy production for international comparisons is methane intensity, calculated as (kilo)grams of methane per kilogram of milk, (kilo)grams of methane per kilogram of energy-corrected milk, (kilo)grams of methane per kilogram of fat- and protein-corrected milk, or as (kilo)grams of CO_2 equivalent per kilogram of milk (e.g. Dehareng et al., 2012; Manzanilla-Pech et al., 2022). Methane intensity enables various comparisons, such as improvements in efficiency in livestock production and differences between herds, breeds, or regions (Rotz et al., 2024). Using GWP*, McAuliffe et al. (2023) demonstrated the application of GWP* at the product level. They calculated GWP* intensity using emission intensity instead of emissions in the GWP* equations (e.g. eq. (6)). Negative CO_2-we emission intensity can be obtained, because the historic emission intensity (in year t-20) are larger to current emission intensity (in year t) (e.g. McAuliffe et al., 2023). Calculating GWP* intensity, Ridoutt (2021) described the results for example as "1.75 kg CO_2 removal per kg live weight, or 4.80 kg CO_2 removal per kg edible meat". Following the same principles as in the derivation of GWP* intensity (McAuliffe et al., 2023), the intensity of CME and BME is derived. A schematic, step-by-step approach with interpretation is shown in Supplementary Fig. 1. The equations use the emission intensity of the current year instead of annual emissions. Considering the decay function, the intensity of CME and BME is calculated. The value of intensity of BME can be either positive or negative (negative if historic emissions are greater than current emissions). For example, the negative result of −2.01 g/kg milk indicates that, when comparing the two livestock production periods, 2.01 g of methane per kg of milk more was removed from the atmosphere than was emitted. If the result were positive (+2.01 g/kg milk), they indicate that, when comparing the two livestock production periods, 2.01 g of methane per kg of milk more was emitted to the atmosphere than was removed.

When comparing emissions from different sectors or sources, we usually present the relative structure (e.g. Lauk et al., 2024). Calculating relative structure becomes more challenging if negative values are obtained using GWP* or BME. This can be addressed by calculating two separate relative structures within subpopulations or subsectors: one for those contributing to the burden and another for those contributing to removal. For example, according to the BME_C data for Slovenian sectors (Table 4) for the period 2018–2022, 77% of the burden was contributed by the non-dairy cattle category and 23% by other cattle. In contrast, 49% of the removal was contributed by dairy cows, 34% by swine, and 12%, 5%, 2%, and less than 1% by poultry, sheep, horses, and goats, respectively. The highest percentages of removal in dairy cows and swine are understandable due to the significant reduction in their annual emissions (Fig. 4(a)).

4.3. Limitations and future research

4.3.1. Uncertainties of calculations

Potential sources of BME uncertainty include variability in AME data quality and differences between methods used to obtain AME. If data on the uncertainty of AME are available, either from emission measurements, calculations, or other sources, these can be used as the uncertainty of AME in the calculation of CME (equation (2) or 3), and subsequently as the varied CME in the BME equation (4) or 5. Uncertainties also result from the assumption of a decay rate, which may not account for feedback loops such as hydroxyl radical variability. This can be resolved if data on the specific mean atmospheric lifetime and its uncertainty at the regional level are available, and this lifetime is further included in the CME calculation as the modified τ in equation (1).

4.3.2. Robustness of calculations

The limitations of static emission metrics (e.g. AME) are addressed by the BME method, which accounts for the continuous removal of methane from the atmosphere. It is flexible, allowing the use of either calculated (IPCC Tier methods) or measured (sniffer, laser detector) AME data, which broadens its applicability. By incorporating the methane decay function, $P(t) = \exp(-t/\tau)$, the BME method captures the temporal dynamics of methane persistence, offering a more nuanced assessment of livestock emissions compared to static inventories. Its compatibility with both modelled and measured AME data enhances its utility across diverse research and policy contexts.

The calculation of cumulative emissions should account for the continuous oxidation of methane, as simply summing the emissions results in an overestimation of CME. This is because most methane is removed from the atmosphere in the first years after release through reaction with OH^- (Ehhalt, 1974). For example, summing the AME data from Fig. 2 without accounting for continuous methane removal between years 2 and 15 yields a total of 580.3 kt of methane. When methane removal is considered (using $\tau = 12$), the sum is 377 kt (Fig. 2). Therefore, calculating CME as a simple sum of AME in this case represents approximately a 54% overestimation of CME compared to when the decay function is applied. Depending on new findings regarding methane's atmospheric lifetime, its value can be adjusted in Eq. (1).

The long-term and short-term methane balance is calculated from AME data and its continuous chemical decay in the atmosphere. However, when calculating BME and comparing periods of 12 years in length, a small proportion of older emissions from 12 years remains in the observed year. Nevertheless, for assessing short- and long-term efficiency, the difference between emissions are practically negligible due to their small proportions and, compared to CO_2, the methane emissions are after a decade mostly gone.

4.3.3. Comparisons of pollutants

Comparing different pollutants, BME focuses exclusively on methane and its implications at the farm level or other levels of livestock production, such as animal breed, category, or region. The results cannot be directly compared with other emissions, namely annual nitrous oxide (N_2O) emissions. Since N_2O is a long-lived climate pollutant and remains in the atmosphere for 109 ± 10 years (IPCC et al., 2021), the comparison could be made by calculating cumulative N_2O emissions for the same period as CME, where the decay function accounts for an atmospheric N_2O lifetime of 109 ± 10 years (lifetime based on IPCC et al., 2021). As this is beyond the scope of this study, it should be investigated in further research.

The BME could potentially be applied to other methane sources, as described by Saunois et al. (2024), to expand its practical value; for example, fossil fuel production, rice cultivation, waste, anthropogenic biomass burning, and other anthropogenic sources. The suitability and added value of the BME approach in non-livestock sectors should be the subject of further studies.

5. Conclusions

A novel method was developed to calculate the balance of cumulative non-fossil methane emissions in the form of methane burden or methane removal over livestock production periods. The method accounts for the short lifetime of methane and continuous methane decay within the livestock production period. The proposed balance equations allow updates based on new findings regarding atmospheric methane lifetime. Short- and long-term methane balances can be calculated using BME_C and BME_F, respectively, to compare real-time balance and methane amounts over periods of livestock production that are close together or further apart. A negative balance value indicates that between studied periods more methane is reduced than emitted, resulting in a methane removal and a decreased warming effect on temperature; a positive value indicates a methane burden and net warming. The average BME_F for Slovenian dairy cows and non-dairy cattle between 2018 and 2022, compared to the fixed year 2001, was -46.45 kt CH_4 and 19.76 kt CH_4, indicating a long-term methane removal and burden, respectively, from these sectors. Between 2012 and 2022, most of the methane burden was contributed by other cows and non-dairy cattle, while other categories contributed mainly to methane removal. Additional novelties include various possible modifications: choice of methane lifetime, lengths of periods compared, interval between the two periods compared, and possible assessment of methane mitigation measures in BME calculations. By simulating the mitigation of annual methane emissions, the partitioner can determine the extent of mitigation required to avoid the emission burden. Finally, the BME method can be applied to any livestock (sub)population or (sub)sector, assisting livestock scientists, specialists, technologists, advisory services, technicians working directly with farms, regional development institutions, or farmers themselves in assessing and monitoring the short- and long-term methane balance.

Funding

This work was supported by Slovenian Research and Innovation Agency (Programme P4-0133).

Declaration of competing interest

The author declares no competing interest.

Acknowledgements

This work was supported by Slovenian Research and Innovation Agency (Programme P4-0133).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148971.

Data availability

All data is available in the supplementary files.

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