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RESEARCH ARTICLE

Modelling the effect of context-specific greenhouse gas and nitrogen emission mitigation options in key European dairy farming systems

Xabier Díaz de Otálora [1,2,3] · Agustín del Prado[2,4] · Federico Dragoni[1] · Lorraine Balaine[5] · Guillermo Pardo[2] · Wilfried Winiwarter[6,7] · Anna Sandrucci[8] · Giorgio Ragaglini[8] · Tina Kabelitz[1] · Marek Kieronczyk[7,9] · Grete Jørgensen[10] · Fernando Estellés[3] · Barbara Amon[1,7]

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Abstract

Understanding the environmental consequences associated with dairy cattle production systems is crucial for the implementation of targeted strategies for emission reduction. However, few studies have modelled the effect of tailored emission mitigation options across key European dairy production systems. Here, we assess the single and combined effect of six emission mitigation practises on selected case studies across Europe through the Sustainable and Integrated Management System for Dairy Production model. This semi-mechanistic model accounts for the interacting flows from a whole-farm perspective simulating the environmental losses in response to different management strategies and site-specific conditions. The results show how reducing the crude protein content of the purchased fraction of the diet was an adequate strategy to reduce the greenhouse gas and nitrogen emission intensity in all systems. Furthermore, implementing an anaerobic digestion plant reduced the greenhouse gas emissions in all tested case studies while increasing the nitrogen emissions intensity, particularly when slurry was applied using broadcast. Regarding the productivity increase, contrasting effects were observed amongst the case studies modelled. Moreover, shallow slurry injection effectively mitigated the intensity of nitrogen losses from the fields due to strong reductions in ammonia volatilisation. When substituting urea with ammonium nitrate as mineral fertiliser, site-specific conditions affected the mitigation potential observed, discouraging its application on sandy-loam soils. Rigid slurry covers effectively reduced the storage-related nitrogen emissions intensity while showing a minor effect on total greenhouse gas emission intensity. In addition, our results provide novel evidence regarding the advantages of cumulative implementation of adapted mitigation options to offset the negative trade-offs of single-option applications (i.e. slurry covers or anaerobic digestion and slurry injection). Through this study, we contribute to a better understanding of the effect of emission mitigation options across dairy production systems in Europe, thus facilitating the adoption of tailored and context-specific emission reduction strategies.

Keywords Sustainability · Mitigation · Modelling · Emissions · Dairy

✉ Xabier Díaz de Otálora
xdiaz@atb-potsdam.de

[1] Leibniz-Institute for Agricultural Engineering and Bioeconomy (ATB), 14469 Potsdam, Germany

[2] Basque Centre for Climate Change (BC3), 48940 Leioa, Spain

[3] Institute of Animal Science and Technology (ICTA), Universitat Politècnica de València, 46022 Valencia, Spain

[4] Basque Foundation for Science (Ikerbasque), 48940 Leioa, Spain

[5] Teagasc, Agricultural Economics and Farm Surveys Department, Mellows Campus, H65 R718 Athenry, Co. Galway, Ireland

[6] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

[7] Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, 65-417 Zielona Góra, Poland

[8] Department of Agricultural and Environmental Sciences, University of Milan, 20133 Milan, Italy

[9] Institute of Technology and Life Sciences – National Research Institute, Falenty, 3 Hrabska Ave, 05-090 Raszyn, Poland

[10] NIBIO, Norwegian Institute of Bioeconomy Research, P.O. Box 34, N-8860 Tjøtta, Norway

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1 Introduction

Dairy cattle production systems (DPS) are a strategic food production sector for the socioeconomic development of Europe (Bórawski et al. 2020). Some of them provide strong identity and cultural heritage elements by preserving traditions, landscapes, and biodiversity (Sturaro et al. 2013). In addition, unlike other animal categories, ruminants transform fibrous biomass, inedible for humans or monogastric animals, into high-quality nutritionally concentrated products, thereby contributing to global food security (Ertl et al. 2015; Feil et al. 2020). Likewise, in addition to providing feed for the DPS, the maintenance of grasslands is presented as a way to increase carbon stocks, thus contributing to the mitigation of agricultural greenhouse gas (GHG) emissions (Smith et al. 2016; Whitehead 2020). However, the increasing demand for milk and dairy products, together with a shift towards production intensification, heavily affects the environmental impact, social perception, and economic performance of the sector (Salou et al. 2017; Styles et al. 2018). In this complex and challenging scenario, adapted approaches must be taken to ensure the future viability and sustainability of DPS (Díaz de Otálora et al. 2021).

GHG emissions and nitrogen (N) losses from livestock production threaten the environmental quality and human health. At the global scale, 14.5% of anthropogenic GHG emissions come from the livestock sector (Gerber et al. 2013), of which 20% are directly associated with DPS (Tricarico et al. 2020). On-farm methane (CH_4) and nitrous oxide (N_2O) contribute the most to non-carbon dioxide emissions from DPS (UNFCCC 2023). For the year 2020, enteric fermentation and manure management CH_4 emissions in the European Union of the 27 accounted for 74 Mt of CO_2-eq, whereas those associated with N_2O emissions (fields and manure management) reached a value of 16 Mt of CO_2-eq (FAO 2023). Furthermore, N losses in the form of ammonia (NH_3), nitrogen oxides (NO_x), and N_2O associated with manure management (fields and storage) and fertilisers are key drivers of the environmental impact of DPS (Leip et al. 2015). In this sense, at the European level, NH_3 and NO_x emissions contribute significantly to the total particulate matter ($PM_{2.5}$) (Wyer et al. 2022). Furthermore, nitrate leaching (NO_3^-) into waterways could potentially increase the toxicity of water meant for animal and human consumption (Doole 2012). However, the sources and magnitude of these losses are highly dependent on management practises. Differences in feed compositions, manure management practises, or fertilisation schemes determine the emissions associated with DPS (Christie et al. 2011; Wattiaux et al. 2019). Similarly, GHG emissions and N losses are sensible to the existing pedoclimatic conditions (i.e. air temperature, soil texture, precipitation). Clear examples of this effect are the direct correlation between CH_4 emission from manure and air temperature (Baldé et al. 2016) or the link between some soil texture and GHG and N emission from fertiliser application (Shakoor et al. 2021). In this context, improved animal efficiency, better slurry storage, and application practises, or the use of alternative mineral fertilisers, have been described as effective measures to reduce GHG and N emissions of DPS (Aguirre-Villegas et al. 2019; Nartey et al. 2021; Arndt et al. 2022).

To date, the individual effect of mitigation measures on single farms and specific emission sources has been widely explored in the literature. Previous studies have highlighted the positive impact of diet-oriented mitigation options on CH_4 and NH_3 emissions (Ouatahar et al. 2021). Substantial reductions in enteric CH_4 have been reported by increasing the level of concentrates in the diet and modulating the forage-to-concentrate (F:C) ratio (Martin et al. 2010; Congio et al. 2021). In addition, modulating dietary protein content has been shown to limit N losses from DPS (Sajeev et al. 2018a). As for emissions derived from manure management, DPS represent an important source of GHG and N losses (Vangeli et al. 2022). To this end, improved manure management and slurry application techniques contribute to reducing these emissions (Owen and Silver 2015; Petersen 2018). Moreover, high-efficiency covers and anaerobic digestion (AD) plants significantly reduce NH_3, CO_2, and CH_4 emissions, and for the latter, generate energy from alternative sources (Clemens et al. 2006; Burg et al. 2018; Kupper et al. 2020). However, scale and contextual limitations in existing studies do not allow for a comprehensive assessment of different mitigation measures on case study farms from key European regions for dairy production (Fig. 1). Thus, there is a need to better assess the individual and combined effects of adapted mitigation measures on key European DPS, facilitating the application of context-specific policies. In this

Fig. 1 Examples of different European farming systems for dairy cattle production. Photographs by Federico Dragoni, 2022

context, previous works have highlighted the positive effect that the combination of mitigation options from different fields has on the reduction of the adverse effects of their individual application by promoting synergies and positive interactions (Prudhomme et al. 2020).

Amongst the wide range of methods and models available (Schils et al. 2007a; Rotz 2018; Ahmed et al. 2020; Díaz de Otálora et al. 2021), whole-farm models are presented as valuable tools to analyse the effects of mitigation options on DPS sustainability (Crosson et al. 2011). These models consider individual farm processes in a systemic manner, capturing the trade-offs between farm components (i.e. soil, crops, feed, animals, and manure) and assessing the interactions with GHG and air pollutants (Schils et al. 2007b). In this context, selecting the most appropriate modelling tool is essential to obtain meaningful results to promote the sustainability of DPS (Díaz de Otálora et al. 2021). The Sustainable and Integrated Management Systems for Dairy Production ($SIMS_{DAIRY}$) integrates the major components of a dairy farm into a modelling framework with a system-based approach (Del Prado et al. 2011). In this way, interactions between farm management, climatic conditions, and environmental characteristics are assessed, and their effects on GHG and N emissions are simulated (Del Prado and Scholefield 2008; Del Prado et al. 2010, 2013b).

Given the diversity of DPS across Europe, the effectiveness and applicability of mitigation options are subject to major uncertainty (Sommer et al. 2009). Different levels of specialisation, structural characteristics, and production contexts can classify DPS into multiple typologies and largely determine their emission performances and mitigation potentials (Gonzalez-Mejia et al. 2018; Díaz de Otálora et al. 2022). In this context, there is a lack of knowledge about the effect of different emission reduction options on diverse DPS and in various pedoclimatic conditions. Since the adoption of approaches considering the particular attributes of the different farms is a much-needed prerequisite for the successful reduction of the emission on DPS, this study aims to assess the effects of selected and context-specific mitigation options on a wide range of GHG emissions and N losses of six key DPS across Europe through the $SIMS_{DAIRY}$ model on a 1-year period. Furthermore, the combined effects of GHG and N mitigation measures at the whole-farm level are assessed, thus paving the way for better and more adapted decision-making.

2 Material and methods

2.1 DPS description

Data for the 2020 accounting year from six case study DPS across Europe (Germany, Poland, Italy, Norway, and Ireland) was used for this study. All the DPS studied were specialised in milk production, with more than two-thirds of their economic output coming from the dairy enterprise (EUROSTAT 2015). The selected case studies represented different typologies of DPS based on their production systems, intensity, productivity, management practises, structural characteristics, and socioeconomic attributes (Díaz de Otálora et al. 2022). The required information for the modelling exercise and characterisation (i.e. herd management and production, manure and fertilisation management, production) was collected through interviews with the farmers. The monthly meteorological information was extracted from nearby weather stations to the farms for the assessed period (2020). Key attributes of the different DPS analysed are presented in Table 1.

As for the pedoclimatic characteristics, the Western European conventional intensive DPS (WC_i) featured a sandy soil and a temperate humid climate, while the Western European organic semi-extensive DPS (WO_s) presented a sandy loam soil with a temperate humid climate. Likewise, the Central-Eastern European conventional semi-extensive DPS (EC_s) exhibited a cold humid climate with a clay loam soil texture. The Atlantic conventional semi-extensive (AC_s) had the same climate as WC_i but presented a loam soil texture. As for the Mediterranean European conventional intensive DPS (MC_i), a temperate humid climate and sandy loam soil were noted. Lastly, the Northern European conventional semi-extensive DPS (NC_s) presented a cold, humid climate, and a clay soil texture.

The size of the farms in terms of the number of animals varied from large farms in Southern Europe (MC_i) to small farms in Central-Eastern Europe (EC_s). However, the number of animals was not directly correlated with the size of the farm in terms of utilised agricultural area (UAA), resulting in a lower stocking rate on farms with a larger area (i.e. WO_s). In addition, diet played a fundamental role in determining the productivity of the analysed DPS. Higher productivity was associated with intensive systems characterised by a more significant presence of concentrates (lower forage-to-concentrate ratio), whole plant maize in the diet, and the absence of grazing. This was the case for WC_i, with 30.6 kg milk cow^{-1} day^{-1}, and MC_i, with 26.2 kg milk cow^{-1} day^{-1}. In contrast, semi-extensive systems with greater forage in the diet (mainly grass, grass silage, or maize silage) and more grazing days present lower milk yields. This is especially notable in AC_s, where production was 15.1 kg milk cow^{-1} day^{-1}, or in WO_s and NC_s, where productivity reached 21.1 and 21.5 kg milk cow^{-1} day^{-1}.

As for manure management (production, storage, and application), the evaluated farms showed significant differences in the systems present and technologies applied. All DPS, except for EC_s and MC_i, were characterised by the predominance of liquid slurry as a manure management system (on average, 70% slurry compared to 30% solid manure).

Table 1 Key features of the dairy production systems modelled. *WC_i* Western European conventional intensive system, *WO_s* Western European organic semi-extensive system, *EC_i* Central-Eastern European conventional semi-extensive system, *MC_i* Mediterranean conventional intensive system, *NC_s* Northern European conventional semi-extensive system, *AC_s* Atlantic conventional semi-extensive system, *°C* degrees centigrade, *mm* millimetres, *LU* livestock units, *FPCM* fat and protein corrected milk, *UAA* utilised agricultural area, *CAN* calcium ammonium nitrate, *U* urea, *AN* ammonium nitrate. [a]standardised to 4% fat and 3.3% protein per kilogram of milk (IDF 2015); [b]Holstein, Montbéliarde, and Polish red; [c]Holstein and Jersey; [d]20% of the diet composed by self-produced cereal mix (no concentrates bought); [e]more than one typology of mineral fertiliser is applied

	Units	WC_i	WO_s	EC_s	MC_i	NC_s	AC_s
Location	-	Germany	Germany	Poland	Italy	Norway	Ireland
Production system	-	Conventional	Organic	Conventional	Conventional	Conventional	Conventional
Degree of intensification	-	Intensive	Semi-extensive	Semi-extensive	Intensive	Semi-extensive	Semi-extensive
Average monthly temperature	°C	12	11	9	14	7	10
Average monthly precipitation	mm	72	50	57	87	84	84
Soil texture	-	Sand	Sandy loam	Clay loam	Sandy loam	Clay	Loam
Dairy animals	Animals	138	240	50	565	55	185
Total dairy livestock units	LU	184	304	83	956	91	236
Main cow breed	Name	Holstein	Holstein	Crossbreed[b]	Holstein	Norwegian red	Crossbreed[c]
Milk production	kg FPCM[a] animal^{-1} year^{-1}	11,194	7724	8898	9547	7865	5522
Milk yield	kg animal^{-1} day^{-1}	30.6	21.1	24.3	26.2	21.5	15.1
Forage-to-concentrate	Ratio	60:40	80:20[d]	80:20	50:50	60:40	90:10
Crude protein in purchased feed	%	27	15	23	20	18	14
Silage type	-	Grass/maize	Grass/maize	Grass/maize	Grass/maize	Grass	Grass
Farm area (UAA)	ha	71	495	80	270	87	87
Surface grassland	%	55	44	71	46	86	100
Grazing time (adult)	Days	0	215	164	0	139	259
Slurry storage cover	Type	Crusted	Crusted	Rigid	Crusted	Rigid	Crusted
Slurry application technique	Type	Shallow injection	Band spreading	Broadcast	Broadcast	Broadcast	Shallow injection
Main mineral fertiliser	Type	CAN[e]	-	U[e]	U	AN[e]	U

Regarding slurry storage, a great diversity of technologies was observed. Crusted slurry tanks were the predominant typology (WC_i, WO_s, MC_i, and AC_s), followed by rigid covers (NC_s and EC_s). The slurry was applied as organic fertiliser using a shallow injection (WC_i and AC_s), band spreading (WO_s), or broadcast (EC_s, MC_i, and NC_s).

Regarding the utilised agricultural area (UAA) distribution for each case study analysed, grasslands (temporary and permanent) accounted for 100 and 86% of the area in the AC_s and NC_s, respectively. In the case of EC_s, grasslands occupied 71% of the farm, while lower values were observed in WC_i, MC_i, and WO_s, with 55, 46, and 44% of the UAA. As for mineral fertilisation, three were the predominant typologies observed: calcium ammonium nitrate (CAN), ammonium nitrate (AN), and urea. Mineral fertiliser was applied in all the DPS analysed, except in the system with organic production (WO_s). In the case of MC_i and AC_s, only urea was applied as mineral fertiliser in doses of 124 and 43 kg N ha^{-1} of total UAA. In EC_s and NC_s, a combination of AN and urea was applied, reaching a total dose of mineral N of 43 and 128 kg N ha^{-1} of total UAA. Finally, in WC_i, CAN and urea were applied with a total mineral fertiliser dose at the farm level of 85 kg N ha^{-1} of UAA.

2.2 Modelling environmental impacts

$SIMS_{DAIRY}$ is one of the existing whole-farm models specifically developed to simulate within a year the monthly interactions between farm management, climate, soil type, and the GHG emissions and N losses from DPS (Schils et al. 2007c; Del Prado et al. 2011, 2013a). A detailed description of the main characteristics and underlying principles of the model used in this manuscript (including the original and modified version used in this study) is described in Del Prado et al. (2011) and in Supplementary Material 4. $SIMS_{DAIRY}$ has proved its appropriateness for assessing synergies and trade-offs associated with different farming management options since it showcases the effect of various management strategies on N losses and GHG emissions from different sources (Del Prado et al. 2010).

$SIMS_{DAIRY}$ integrates the significant components of a dairy farm (i.e. animals, manure, fields, off-farm emissions) into a modelling framework using a system-based approach. Furthermore, the modular construction of $SIMS_{DAIRY}$ allows to perform calculations at different farm levels or subsystems either using already existing models (i.e. MANNER (Chambers et al. 1999) and NGAUGE (Brown et al. 2005)) or specific module developments. In this way, N flows and GHG emissions are simulated for a given combination of management strategies, soil textures, and farm characteristics (i.e. manure storage and application).

The model calculations are presented in the following sequence (Figure 9 of Supplementary Material 4). First, the dry matter (DM) yield, N per ha, and the crude protein (CP) content of forage crops in the fields are calculated based on the monthly-based NGAUGE model results that include all N inputs to the fields except for those coming from stored manure (stored manure is calculated as an internal flow in subsequent steps). Second, animal energy requirements are estimated using as input the herd management characteristics and the previously estimated nutritional values (i.e. CP) from on-farm forage. Additionally, manure emissions and a first estimation of manure characteristics (i.e. total N and ammonium N) and total volume applied to the field are also calculated based on the first animal and field calculations. At this stage, the on-farm forage surface is estimated (requirements of initial on-farm forage DM are met with DM per ha yields from the different field types). Therefore, as the third step, there is a subsequent update of DM and N yield per ha, and CP content of forage considering the fertilising effect of applied manure. Fourth, another model iteration updates the previously estimated animal energy requirements using the updated on-farm forage characteristics. In this step, CH_4 from enteric fermentation, manure volatile solids, and manure CH_4 and N losses are calculated. $SIMS_{DAIRY}$ repeats these iterations until a steady state is reached (i.e. until the forage hectares of each field type do not change significantly from one iteration to the next).

As for emission calculations, enteric CH_4 is estimated following a Tier 2 approach from the latest Intergovernmental Panel on Climate Change (IPCC) refinement to the Guidelines (Gavrilova et al. 2019). These emissions are calculated from the gross energy (GE) intake and the methane emission factor (Y_m) as a function of feed quality and level of feed intensification. Animal performance and diet data are used to estimate feed intake according to animal needs. Likewise, CH_4 emissions from manure are calculated using the approach from the IPCC 2019 Guidelines refinement (Gavrilova et al. 2019). In this case, volatile solid content is calculated on a monthly basis using emission factors (EF) or, in the case of slurry storage, following the approach provided in the spreadsheet model for slurry emissions from the IPCC (MCF Calculations Example Spreadsheet) (Gavrilova et al. 2019). Furthermore, excreted N by the animals is estimated by subtracting N in milk and net body change from the N ingested by each type of animal (i.e. grazing or housed). In this case, urine and dung losses are divided following the equations derived from existing trials where urine and dung N are expressed as a function of N and DM intake (Reed et al. 2015). With regard to carbon dioxide (CO_2) and as described in Supplementary Material 4, $SIMS_{DAIRY}$ uses (DEFRA 2010) EF to estimate CO_2 emissions from electricity and fuel usage. Furthermore, pre-farm emissions from purchased concentrates and inorganic fertilisers were estimated following the approach by Casey and Holden (2005). $SIMS_{DAIRY}$ does not consider the C balance related to the respiration/fixation and the addition of C through the concentrate.

Nitrogen losses (NH_3, N_2O, NO_3^-, and NO_x) are divided into two groups: (i) manure (housing, yards, and storage) and (ii) fields and crops (fields and silage). The manure N losses and fluxes are simulated following the principles of a mass-balance approach (Webb and Misselbrook 2004). N losses are calculated from the pool of total ammoniacal nitrogen (TAN) in manure according to different EF for different manure management stages. As for housing emissions, $SIMS_{DAIRY}$ follows the approach and EF reported by the European Monitoring and Evaluation Programme (EMEP) (European Environmental Agency 2019). For this, two initial separate housing phases (yards and housing) are considered. After subtracting N losses generated during housing from the initial TAN content in manure, N losses from storage are predicted as a percentage of the remaining TAN content using EF for different storage systems (Del Prado et al. 2011).

Field and crop N losses are modelled using a semi-mechanistic approach where pedoclimatic characteristics determine the amount of inorganic N in the soil denitrified, nitrified, or lost by leaching. In this case, the NGAUGE model was applied following the iterations described above. Parameters

sensitive to soil moisture and air temperature were adjusted for European diversity. Furthermore, $SIMS_{DAIRY}$ estimates the amount of nitrogen lost (NH_3 and NO_x) during silage conservation. The model considers five qualitative classes of silage management (from very good to very poor) associated with a fixed N loss (Bastiman and Altman 1985). Furthermore, $SIMS_{DAIRY}$ estimates the proportion of the NH_3/NO_x that is volatilised or NO_3^- that is leached based on Chapter 11 of the IPCC 2019 refinement to the guidelines as a way of estimating indirect N_2O emissions.

$SIMS_{DAIRY}$'s suitability for the analysis of the effect of different mitigation measures has been demonstrated in previous works (Del Prado et al. 2010). In this sense, $SIMS_{DAIRY}$ has demonstrated its ability to capture the system's response towards different emission mitigation options and production optimization strategies according to a series of context-specific characteristics. Furthermore, the modular construction of $SIMS_{DAIRY}$ allows for the incorporation of additional models that evaluate mitigation measures not implemented in the original version (i.e. $SIMS_{WASTE}$ (Pardo et al. 2017)). In addition, $SIMS_{DAIRY}$ has also been continuously updated by incorporating updated emission factors and calculation approaches (i.e. IPCC 2019 refined Guidelines and EMEP/EAA 2019). The wide acceptance of the calculation methods included in the $SIMS_{DAIRY}$, its modular construction, and the contrasted capabilities of the model allow for its application to a wide variety of systems.

Furthermore, Supplementary Material 4 provides a sensitivity analysis of the original version of the $SIMS_{DAIRY}$ modelling framework. In this analysis, the influence of selected numerical and categorical input variable values (i.e. days in housing, herd size, milk production, protein/fat content, dietary neutral detergent fibre content, manure application, soil texture, slurry application method) on output variables (i.e. N losses, surface area) was tested. According to the results, $SIMS_{DAIRY}$ was sensitive to relevant numerical and categorical variable changes.

Total GHG and N emission intensities (GHG_{int} and N_{int}) were calculated with the following equation (Eq. 1):

$$Em_{int} = \sum Em_{individual} \quad (1)$$

where Em_{int} represents the GHG_{int} (expressed in kg CO_2-eq kg $milk^{-1}$) or N_{int} (expressed in g N kg $milk^{-1}$).

In the case of the GHG_{int}, $\sum Em_{individual}$ considers all the GHG emission intensities under study (CO_2, CH_4, and N_2O). CH_4 and N_2O emissions were converted to CO_2-eq using the 100-year Global Warming Potential (GWP-100) values of 27.2 (non-fossil fuel CH_4) and 273 (N_2O) according to the latest Sixth Assessment Report (AR6) from the IPCC (Forster et al. 2021). As for the N_{in}, $\sum Em_{individual}$ represents the sum of all the emission intensities from the reactive N losses assessed (NH_3, NO_3^-, N_2O, and NO_x). These losses were normalised based on their nitrogen content (NO_x-N, N_2O-N, NH_3-N, and NO_3^--N).

2.3 Mitigation measures

The modelled emission reduction options were selected by the researchers and existing literature (i.e. United Nations Economic Commission for Europe (2015)) based on three criteria: (i) the mitigation strategies had to be implemented by modifying the user inputs required by $SIMS_{DAIRY}$, (ii) the mitigation options should cover different management aspects of DPS (fields, manure, diet, animals), and (iii) the mitigation options should be tailored to the baseline characteristics of the case studies analysed. As a result, six mitigation options were identified and classified into two categories according to their scope: (i) diet management and (ii) slurry management and fertiliser application.

2.3.1 Diet management

An increase in the productive performance associated with a greater fraction of purchased feed (e.g. concentrates) (PI) was simulated. This measure has previously proven effective in reducing enteric CH_4 emissions (Arndt et al. 2022) and was especially relevant in DPS typologies with high forage supply and low productivity. However, the optimal ratio of forage to concentrate in lactating dairy cows is commonly discussed in the literature. A forage-to-concentrate ratio (F:C) of 70:30 is considered a high-forage formulation, while a ratio of 30:70 is considered a low-forage diet (Jaakamo et al. 2019). In this sense, an F:C ratio of 60:40 is generally considered a good compromise regarding milk yield and emissions (Mertens 2009; Aguerre et al. 2011). To this end, in conventional dairy production systems with a ratio above 70:30, their forage ratio in the diet was reduced to 60:40. As an organic DPS that initially did not present any purchased feed, WO_s was excluded from this mitigation strategy. Furthermore, reducing the forage supply has been related to increased productivity due to lower fibre content and higher diet digestibility (Ben Meir et al. 2021). In a previous study, an increase in production of close to 15% was observed when concentrates were increased in the diet (Mckay et al. 2019). As an approximation to the previously observed results, a 15% increase was applied in both DPS.

Secondly, the crude protein (CP) content of the purchased feed was reduced to minimise N excretion in the farms. This measure was proven to have a mitigating effect on NH_3 emissions (Hristov et al. 2011) and was particularly suitable for DPS where the CP content of the purchased fraction of the diet was exceptionally high. While AC_s presented a CP content of 14%, higher values were observed in WC_i (27%), EC_s (23%), MC_i (20%), and NC_s (18%). In the case of WO_s,

although the CP content was 15%, as an organic DPS that originally did not present any purchased concentrates, this DPS was excluded from this mitigation strategy. In this line, previous studies have demonstrated that reducing CP levels to around 14% in dairy cow concentrates increases the efficiency and reduces N excretion while not affecting the productive performance of the animals (Hynes et al. 2016). Consequently, the CP content of the purchased fraction of the diet was reduced to 14% in WC_i, EC_s, MC_i, and NC_s.

2.3.2 Slurry management and fertiliser application

Regarding slurry management and fertiliser application, four mitigation measures were modelled. First, the effect of high-efficiency covers on slurry storage (HES_c) was evaluated as a mitigation option for reducing N losses during the storage phase (Oenema et al. 2007). The impact of rigid covers was modelled in DPS that initially presented with open or slatted storage (without a crust). This was the case of WC_i, WO_s, MC_i, and AC_s. Second, concerning the slurry application, several authors highlighted the mitigation potential of high-efficiency shallow injection (HES_a) techniques compared to broadcast to reduce NH_3 emissions (Duncan et al. 2017). To this end, shallow injection was implemented in DPS where slurry was applied using broadcast or band spreading (i.e. WO_s, EC_s, MC_i, and NC_s).

Urea is one of the most widely used nitrogen sources, but at the same time, it is associated with higher NH_3 emissions than other mineral fertilisers (i.e. ammonium nitrate (AN)) (Del Moro et al. 2017). Therefore, substituting urea with alternative fertilisers has been reported as an effective mitigation measure to reduce NH_3 emissions (Ti et al. 2019). In this case, the substitution of urea by AN was evaluated in those DPS where only urea was applied (maintaining the originally reported application rate). Likewise, it was ensured that none of the DPS where this mitigation option was applied had sandy soil texture, commonly associated with higher nitrate leaching (Witheetrirong et al. 2011). Consequently, MC_i and AC_s were selected for this mitigation strategy.

Finally, the effect of anaerobic digestion (AD) was modelled. The proposed AD plant only considers the slurry produced in the different DPS as substrate. Although AD plants commonly rely on crop residues, energy crops (e.g. maize), and other organic residues as substrates, this manuscript modelled the theoretical effect of slurry-based AD on the GHG and N losses. AD implementation is limited mainly by the slurry availability (Scott and Blanchard 2021). Therefore, we assumed that DPS with at least 100 livestock units (LU) and cattle staying less than two-thirds of the year at pasture qualified for this mitigation option (i.e. WC_i, WO_s, and MC_i), as an appropriate flow of slurry is necessary to ensure the economic and technical viability of the digester (Pellerin et al. 2013; Höglund-Isaksson et al. 2016). In order to simulate the C and N transformations associated with manure processed through AD, the $SIMS_{WASTE}$ model was applied (Pardo et al. 2017). Flow (on a yearly basis) and basic chemical composition of manure (i.e. volatile solids, N, and TAN) were detailed as primary inputs. In addition, parameters describing operational conditions were modelled. A mesophilic temperature regime was assumed in the digester, in a covered digestion tank with residual biogas collection. The amount and composition of biogas and digestate (i.e. TAN content) were estimated as outputs of the model, as well as energy produced and gaseous emissions associated with digester leakages and biogas combustion. Avoided emissions of manure processed through AD were calculated according to IPCC guidelines (Gavrilova et al. 2019), considering covered digestate storage. Avoided emissions of biogas energy production were calculated assuming that biogas displaces electricity production from natural gas, according to an emission factor of 0.47 tCO_2-eq $megawatts^{-1}$ (Swiss Center for Life Cycle Inventories 2016). In addition, slurry derived from AD (digestate) was subsequently applied as organic fertiliser in a similar manner to the baseline scenario with untreated manure but considering the new characteristics regarding total and inorganic N content.

3 Results and discussion

3.1 Baseline GHG and N emission intensity

An average GHG_{int} of 1.1 ± 0.27 kg CO_2-eq kg $milk^{-1}$ was obtained. As shown in Table 2, the highest values were observed in the Northern conventional semi-extensive DPS (NC_s) with a GHG_{int} of 1.6 kg CO_2-eq kg $milk^{-1}$, followed by the Mediterranean conventional intensive DPS (MC_i) with 1.4 kg CO_2-eq kg $milk^{-1}$. The Atlantic conventional semi-extensive (AC_s) and the Eastern-Central European conventional semi-extensive DPS (EC_s) DPS accounted for 1.1 kg CO_2-eq kg $milk^{-1}$ each. Lastly, the Western European organic semi-extensive (WO_s) and the Western European conventional intensive DPS (WC_i) obtained a GHG_{int} of 0.9 kg CO_2-eq kg $milk^{-1}$ each.

When comparing the results obtained with those reported in the literature, baseline GHG_{int} for both German DPS aligns with previously obtained results (0.8–1.8 kg CO_2-eq kg $milk^{-1}$) (Zehetmeier et al. 2020). As for MC_i, previous studies for Italian DPS with similar milk production showed values between 1.3 and 1.6 kg CO_2-eq per unit of product (Lovarelli et al. 2019). In this context, the obtained results are consistent with the previous author's findings. The results obtained in the NC_s were similar to those observed by previous authors who, in comparable productive and geographical contexts, observed GHG emissions ranging between 1.2

Table 2 Greenhouse gas (GHG) and nitrogen (N) emission intensity for the modelled baseline dairy production systems. *WC_i* Western European conventional intensive system, *WO_s* Western European organic semi-extensive system, *EC_s* Central-Eastern European conventional semi-extensive system, *MC_i* Mediterranean conventional intensive system, *NC_s* Northern European conventional semi-extensive system, *AC_s* Atlantic conventional semi-extensive system, *CH_4* methane, *N_2O* nitrous oxide, *CO_2* carbon dioxide, *NH_3* ammonia, *NO_x* nitrogen oxide, *NO_3^-* nitrate

		WC_i	WO_s	EC_s	MC_i	NC_s	AC_s
GHG emission intensity							
Enteric CH_4	kg CO_2-eq kg milk^{-1}	0.320	0.429	0.421	0.410	0.454	0.542
Manure CH_4		0.177	0.094	0.131	0.262	0.091	0.103
Direct manure N_2O		0.015	0.007	0.007	0.023	0.001	0.009
Indirect manure N_2O		0.021	0.011	0.012	0.023	0.019	0.013
Direct field N_2O		0.006	0.036	0.137	0.048	0.256	0.130
Indirect field N_2O		0.020	0.035	0.046	0.049	0.066	0.084
Feed purchase (CO_2)		0.216	0	0.115	0.339	0.276	0.152
Energy use (CO_2)		0.103	0.272	0.174	0.194	0.351	0.054
Fertilizer purchase (CO_2)		0.006	0	0.012	0.010	0.041	0.006
Total GHG emission intensity		0.884	0.884	1.055	1.359	1.554	1.092
N emission intensity							
Ammonia (NH_3)	g N kg milk^{-1}	5.754	5.012	5.876	11.362	8.100	5.442
Nitrate (NO_3^-)		2.219	3.891	5.182	1.609	8.461	14.181
Nitrous oxide (N_2O)		0.048	0.101	0.335	0.167	0.599	0.323
Nitrogen oxide (NO_x)		0.476	0.383	0.352	0.547	0.531	0.349
Total nitrogen emission intensity		8.497	9.387	11.745	13.685	17.691	20.294
N emission sources							
Yards	g N kg milk^{-1}	0.837	0.811	0.770	0.843	1.178	1.096
Housing		2.009	0.632	0.781	2.023	1.616	0.664
Storage		0.740	0.367	0.359	1.003	0.290	0.437
Fields		3.756	6.749	8.977	8.501	13.262	17.260
Silage		1.155	0.827	0.858	1.314	1.344	0.837

and 1.6 kg CO_2-eq kg milk^{-1} (Mittenzwei 2020). Lastly, concerning AC_s, farms with comparable productions (5500 kg FPCM animal^{-1} year^{-1}) obtained a value of total GHG emissions close to 1 kg CO_2-eq kg milk^{-1} (O'Brien et al. 2015), in line with the results obtained for this study.

On average, enteric and manure CH_4 and CO_2 from feed purchases constituted 67% of the GHG_{int}. Enteric CH_4 emissions were the largest source of GHG in all DPS, representing 39% of the average GHG_{int}. However, differences were observed across the analysed DPS. For instance, the percentage of GHG_{int} associated with enteric CH_4 in intensive DPS (WC_i and MC_i) was lower than that obtained for semi-extensive systems (WO_s, EC_s, NC_s, and AC_s) 33 ± 4.3% *vs* 42 ± 9.5%. These lower values were associated with the feeding strategy, predominantly based on concentrates and forage such as green maize, whose higher digestibility reduces fermentation time and enteric CH_4 emissions (Hassanat et al. 2013; Lettat et al. 2013). Conversely, intensive systems showed a higher share of manure CH_4 emissions over the total GHG_{int} than those observed for semi-extensive DPS (20 ± 0.5% *vs* 10 ± 2.8%). As acknowledged by previous authors, intensification (i.e. animal numbers and housing time) is associated with larger direct manure-related emissions (Petersen et al. 2013). Additionally, while emissions related to feed purchase represented 11 ± 7.6% of GHG_{int} in semi-extensive DPS, higher values were reached in the intensive systems (25 ± 0.4%). This could be due to the fact that intensive DPS are characterised by a higher reliance on off-farm feed inputs (Reinsch et al. 2021), which are commonly associated with significant off-farm GHG emissions (Battini et al. 2016). Lastly, as noted by previous authors, excretion during grazing substantially contributes to N_2O emissions (Soares et al. 2023). This is confirmed by our results that showed higher N_2O emissions (direct and indirect) from the fields in semi-extensive (16 ± 5.8%) than intensive (5 ± 3.0%) DPS.

Concerning the N_{int}, an average value of 13.5 ± 4.66 g N kg milk^{-1} was obtained. In this context, previously published modelling results at the European scale indicated that total N emissions per unit of dairy product ranged from 10 to 50 g N kg^{-1} (Leip et al. 2014). As for the individual assessment, the highest values were observed in the Atlantic and Northern European conventional semi-extensive systems (AC_s and NC_s) with 20.3 and 17.7 g N kg milk^{-1}, respectively. These

DPS were followed by the Mediterranean intensive conventional (MC_i) (13.7 g N kg milk^{-1}) and the Eastern-Central European conventional semi-extensive system (EC_s) (11.7 g N kg milk^{-1}). Lastly, the Western European semi-extensive organic (WO_s) and Western European intensive conventional (WC_i) accounted for 9.4 and 8.5 g N kg milk^{-1}, respectively.

The breakdown of the N losses showed that, on average, 54% of the N_{int} was associated with NH_3 emissions. To a lesser extent, NO_3^- losses represented 40% of the N_{int}, while NO_x and N_2O emissions accounted for 4 and 2%, respectively. The fields were the largest source of N losses, averaging 69% of the N_{int}. Higher values were shown in semi-extensive systems (WO_s, EC_s, NC_s, and AC_s) than in intensive DPS (WC_i and MC_i), with values ranging between 77 ± 5.6 and 53 ± 12.7%. Although fertilisers were applied in semi-extensive and intensive DPS, a higher deposition of excreted N in fields was noted in semi-extensive DPS. According to the literature, this is one of the key factors causing higher N emissions for this DPS typology (Gourley et al. 2012). As for the combined N losses during housing and yards, our results showed higher emissions for intensive DPS than in semi-extensive DPS (27 ± 8.9% *vs* 13 ± 3.3%). Similarly, N emissions from storage were higher in intensive systems (8 ± 1.0%) than in semi-extensive (3 ± 1.0%) DPS. Due to their location and production system, emissions regarding silage-making could be a concern for particular DPS. In this context, as described by previous authors, intensive farms are more inclined to use silage in addition to concentrate (Gallo et al. 2022), which results in higher emissions from this system for this N source.

3.2 Mitigated modelling

Main variations concerning the baseline modelling for each gas (i.e. CH_4, N_2O, CO_2, NH_3, NO_3^-, and NO_x) were detailed. Complete results can be found in Supplementary Material 1 (in %) and Supplementary Material 2 (in absolute values).

3.2.1 Diet management

The productive performance (PI) increase showed contrasting effects depending on the DPS. This mitigation option decreased the N_{int} in AC_s by 3.0 (−15%) and 2.0 (−17%) g N kg milk^{-1} in EC. However, contrasting effects were found for the GHG_{int}. In this case, a reduction of 0.03 kg CO_2-eq kg milk^{-1} (−3%) in EC_s and an increase of 0.01 kg CO_2-eq kg milk^{-1} (1%) in AC_s were noted. Both enteric and manure CH_4 emissions intensity were substantially mitigated in both DPS, showing reductions of 0.05 (−12%) and 0.03 (−19%) kg CO_2-eq kg milk^{-1} in the EC_s, and 0.06 (−11%) and 0.02 (−18%) in the AC_s, while increasing the emission intensity from feed purchases by 107% (0.12 kg CO_2-eq kg milk^{-1}) in EC_s and by 95% (0.15 kg CO_2-eq kg milk^{-1}) in the AC_s. As for the N losses, it is essential to highlight the baseline characteristics of the purchased fraction of the diet in each DPS. While in the AC_s the CP content was 14%, in the EC_s this value was notably higher (23%). As demonstrated by previous authors, dairy cows fed with high protein content concentrates (EC_s) lead to a higher N excretion (Mulligan et al. 2004). Our results confirm previous findings showing an increase in NH_3 losses of 0.004 g N kg milk^{-1} from EC_s, while in the AC_s these emissions were reduced by 1.07 g N kg milk^{-1} (−20%). This increase in NH_3 emissions directly affects indirect N_2O emissions associated with manure management and fields. As indicated by previous authors, higher NH_3 increases indirect N_2O emissions (Nevison 2000; Martins et al. 2015). The obtained modelling outputs are consistent with these findings, showing an increase of 0.001 kg CO_2-eq kg milk^{-1} in the indirect N_2O emission from manure only in the case of EC_s. As for the rest of the N losses (NO_3^-, N_2O, and NO_x), reductions were observed in both DPS. According to the obtained results, the overall effectiveness of the tested mitigation options must be assessed from a holistic perspective. As mentioned by previous authors and further demonstrated by our results, the increase in concentrate supply can lead to undesirable negative trade-offs at the whole-farm scale (Wilkinson et al. 2019). Moreover, an increased supplementation of a concentrate rich in grains could lead to rumen acidosis and affect herd health (Kleefisch et al. 2018; Petri et al. 2021). This would result in higher economic costs in the long term, making this measure inadvisable if attention is not paid to concentrate composition and dosage. As an alternative, diversified, and integrated forage systems with high-quality silages have proven to be a feasible alternative to concentrates as they allow for better productivity without compromising the environmental performance of the farms, at the same time that they promote circularity and reduce food-feed competition (Gislon et al. 2020; Gaudaré et al. 2021; Díaz de Otálora et al. 2022).

Reducing the CP content of the purchased diet fraction decreased the total N_{int} from WC_i, EC_s, MC_i, and NC_s. The observed mitigation potential for N losses was more significant in the WC_i, EC_s, and MC_i than in the NC_s, with reductions of 2.2 (−26%), 0.7 (−6%), 2.1 (−15%), and 0.4 (−2%) g N kg milk^{-1}. As for the GHG_{int}, emissions were mitigated from 0.02 kg CO_2-eq kg milk^{-1} in MC_i to 0.0001 kg CO_2-eq kg milk^{-1} in NC_s. N_2O emissions from manure management (direct and indirect) and the fields (indirect and direct) were reduced in all DPS. In the case of the MC_i, these emissions were mitigated by 0.02 kg CO_2-eq kg milk^{-1}, followed by the WC_i (0.017 kg CO_2-eq kg milk^{-1}), the EC_s (0.004 kg CO_2-eq kg milk^{-1}), and the NC_s, (0.0001 kg CO_2-eq kg milk^{-1}). As for the N_{int}, the observed reduction was primarily due to the effect of CP reduction on NH_3 emissions. Such values were mitigated by 1.9 (−34%), 0.8 (−14%), 1.9 (−16%), and

0.7 (−8%) g N kg milk^{-1} in the WC_i, EC_s, MC_i, and NC_s, respectively. Regarding other N sources, both DPS showed lower values from the yards, housing, storage, and fields. Moreover, the N_2O reduction observed has been previously described as a positive synergy derived from a better N-use efficiency and lower NH_3 excretion (Powell and Rotz 2015). In this sense, as described by previous authors (Niu et al. 2016; Schrade et al. 2023) and confirmed by our results, lowering the CP content mitigates NH_3 emissions early in the manure management chain by reducing the amount of N supplied (Sajeev et al. 2018a). In addition to the amount of N excreted, a reduced ratio between urinary and dung N is favoured, which lowers the ratio between TAN and organic N, thus decreasing NH_3 losses (Kebreab et al. 2001; Sajeev et al. 2018a, b). Furthermore, positive long-term effects of this measure include reduced lameness (Sinclair et al. 2014). However, attention should be paid to an excessive reduction of CP, as this could result in undesirable reductions in protein yields and animal productivity (Mutsvangwa et al. 2016). This requires carefully considering this measure to ensure that nutritional needs are met, and unintended consequences on production levels are avoided (Del Prado et al. 2013a). As for the suitability of this mitigation option, DPS with a higher CP content (WC_i, EC_s, and MC_i) have a higher mitigation potential than those with a lower baseline CP content (NC_s). In this sense, a comprehensive diet composition analysis is crucial to identify which DPS the reduction of CP content leads to the most significant emission reduction.

3.2.2 Slurry management and fertiliser application

Implementing high-efficiency rigid slurry storage covers (HES_c) in WC_i, WO_s, MC_i, and AC_s was associated with a decrease in the N losses from storage from all DPS due to the favourable effect of rigid covers when reducing NH_3 and N_2O from this source (Berg et al. 2006). In this sense, our results confirm previous authors' findings by showing reductions of N losses from storage ranging from 0.4 (−48%) in the WC_i to 0.2 (−45%) g N kg milk^{-1} in the AC_s. However, a negative trade-off was observed with field emissions, which were increased in all DPS ranging from 0.9 g N kg milk^{-1} in AC_s to 0.1 g N kg milk^{-1} in the WC_i and WO_s. As mentioned by previous authors, covered slurry tanks are associated with lower TAN losses (Baldé et al. 2018). Therefore, higher TAN content in the slurry after storage could increase N losses in the following steps of the manure management chain (e.g. field application) (Pedersen et al. 2021). However, rigid covers are a good mitigation option for direct and indirect manure N_2O emissions. These reductions ranged from 0.01 to 0.005 kg CO_2-eq kg milk^{-1} for the direct emissions and from 0.002 to 0.001 kg CO_2-eq kg milk^{-1} for the indirect N_2O. These findings were associated with the relative environmental advantage of rigid covers over other options (i.e. open with crust), which is expressed in the $SIMS_{DAIRY}$ model by a lower EF (Del Prado et al. 2011). Lastly, no emission reductions were observed in CH_4 emissions from manure. Overall, HES_c is an effective option for reducing GHG and N emissions, especially during manure storage (Viguria et al. 2015; Kupper et al. 2020). Compared to permeable or semi-permeable membranes, completely sealed covers significantly reduce N losses and GHG emissions (Montes et al. 2013). Although there is no variation in CH_4 emissions, several studies have attributed promising results in reducing this gas after applying this type of cover (Reis et al. 2015; Zhang et al. 2021). Furthermore, the negative trade-offs observed after the application of this measure (i.e. higher field emissions) could be mitigated by the combination with additional measures during storage (e.g. acidification) by improving application techniques (e.g. injection) or by reducing the N application rate (Fangueiro et al. 2018; Pedersen et al. 2022). This would be especially advisable in those intensive systems where the production and application of slurry as organic fertiliser are more prominent (i.e. MC_i) or systems with high-emitting slurry application technologies.

Shallow slurry injection (HES_a), implemented in WO_s, EC_s, MC_i, and NC_s, reduced the GHG_{int} of WO_s, EC_s, and MC_i while marginally increasing the one from the NC_s. Furthermore, the increase of direct N_2O emissions ranged from 8% (0.02 kg CO_2-eq kg milk^{-1}) of NC_s to 0.5% (0.001 kg CO_2-eq kg milk^{-1}) in the EC_s. In contrast, indirect N_2O emissions from fields were reduced in all DPS, ranging from 0.01 to 0.006 kg CO_2-eq kg milk^{-1}, presenting a greater mitigation potential in the MC_i (−31%). No variations were observed for the rest of the GHG. As for N_{int}, reductions ranged from 2.4 (−17%) g N kg milk^{-1} in the MC_i to 0.9 (−10%) in the WO_s. The breakdown of N emissions showed mitigation of NH_3 emissions in all DPS, being especially relevant in MC_i with 2.9 g N kg milk^{-1} (−25%). In addition, this measure led to an overall increase in NO_3^- leaching and N_2O emissions in the MC_i. In contrast, all DPS reduced their N emission from the fields reaching a reduction of 2.4 g N kg milk^{-1} (−28%) in the case of the MC_i. As described by previous studies and demonstrated by our results, HES_a could be associated with lower NH_3 and indirect N_2O emissions but higher direct N_2O emissions (Rodhe et al. 2006; Bessou et al. 2010; Langevin et al. 2015). Our results align with those described by previous authors (Herr et al. 2019), as indirect N_2O emission reductions may derive from less NH_3 volatilisation (Räbiger et al. 2020). Further mitigation of the field emission could be achieved through the use of nitrification inhibitors as a way to reduce both NH_3 and N_2O losses (Fan et al. 2022). Overall, our results indicate that it is advisable to adjust the fertiliser dose to avoid possible leaching and N_2O emission in those DPS with high N input (MC_i) (Min et al. 2012).

Urea substitution increased the GHG_{int} of the MC_i by 0.003 kg CO_2-eq kg $milk^{-1}$ (0.2%) while reducing by 0.003 kg CO_2-eq kg $milk^{-1}$ (−0.3%) the one in AC_s. Furthermore, direct N_2O emission intensity from the fields increased by 0.01 kg CO_2-eq kg $milk^{-1}$ in MC_i. In contrast, indirect N_2O emissions from the fields were reduced by −3% (0.003 kg CO_2-eq kg $milk^{-1}$) in AC_s and by −7% in MC_i (0.004 kg CO_2-eq kg $milk^{-1}$). Regarding N_{int}, a positive effect was observed in both DPS, with a reduction of 0.6 g N kg $milk^{-1}$ (−4%) in MC_i and 0.5 g N kg $milk^{-1}$ (−2%) in AC_s. This mitigation option was associated with lower NH_3 emissions, which were reduced by 0.6 (−6%) g N kg $milk^{-1}$ in the MC_i and 0.4 (−8%) g N kg $milk^{-1}$ in the AC_s. In contrast, N_2O emission and NO_3^- leaching were increased more significantly in the MC_i. This may be associated with the soil texture of the MC_i (sandy loam) and the higher doses of N applied, thus potentially leading to higher leaching values (Zhou et al. 2006). In this context, attention should be paid to the N source used for substitution, as the effectiveness of the mitigation option could vary (Rahman and Forrestal 2021). As demonstrated by our results, nitrate-based fertilisers increased the N_2O emissions compared to urea (Harty et al. 2016). This is mainly due to the higher nitrification and denitrification potential of AN (Wrage et al. 2004) and higher TAN per ha applied to the fields considering a much lower N volatilisation loss just after application. Therefore, incorporating N stabilisers or nitrification inhibitors (not considered by the current version of the model) and the optimization of fertiliser application could further decrease NH_3 and N_2O emissions (Wang et al. 2020, 2021; Rahman et al. 2021). Overall, the increase in field NO_3^- losses and N_2O emissions could advise against the change to AN from a whole-farm perspective in farms with high N input and soils with a higher proportion of sand (MC_i).

Lastly, implementing AD in WC_i, WO_s, and MC_i reduced the GHG_{int} in all DPS, with a greater mitigation potential in WC_i than in MC_i or WO_s. In this line, the WC_i showed a GHG_{int} reduction of 0.17 kg CO_2-eq kg $milk^{-1}$ (−19%), while MC_i and WO_s accounted for reductions of 0.17 (−12%) and 0.09 (−10%) kg CO_2-eq kg $milk^{-1}$. Notable reductions were observed in manure (CH_4 and N_2O) and energy-related (CO_2) emissions. For instance, CH_4 from manure was reduced by 0.14 kg CO_2-eq kg $milk^{-1}$ (−55%) in MC_i, 0.14 (−80%), and 0.07 kg CO_2-eq kg $milk^{-1}$ (−79%) in WC_i and WO_s, respectively. Furthermore, CO_2 emission intensity related to energy use was mitigated in a range of 0.03 to 0.01 kg CO_2-eq kg $milk^{-1}$. As for N_{int}, differences in mitigation potential were observed across DPS with reductions of 0.3 g N kg $milk^{-1}$ (−3%) in WC_i and an increase of 0.01 (0.1%) and 0.6 g N kg $milk^{-1}$ (5%) in WO_s and MC_i, respectively. Furthermore, an increase in field N losses was observed in all the DPS evaluated when AD was applied. In the same line as the results obtained for the HES_c and the HES_a, the higher content of TAN in the digestate, combined with a higher and more frequent organic fertiliser application, could derive in a N supply above crop demand (Perego et al. 2012). Likewise, the baseline technology applied (i.e. broadcast, band spreading, or injection) conditions the observed values. Nevertheless, storage N losses were lowered in all DPS due to the advantage of AD in reducing NH_3 emissions, ranging from 0.6 g N kg $milk^{-1}$ in WC_i to 0.3 g N kg $milk^{-1}$ in WO_s. Overall, implementing AD plants was a valuable way of reducing manure storage emissions through biogas recovery systems, especially when covered digestion tanks are adopted, as considered in this study (Harrison and Ndegwa 2020; Kim and Karthikeyan 2021). Previous studies highlighted the potential of this technology in reducing GHG emissions from manure (Clemens et al. 2006; Scott and Blanchard 2021). Our results align with these findings and confirm AD effectiveness in various DPS. Moreover, the potential of this measure goes beyond emission reduction, as it can play an essential role in the circularity of farming systems through the generation of renewable energy (Holly et al. 2017; Stanchev et al. 2020). Nevertheless, special attention should be paid to using digestate as fertiliser as it could lead to higher N losses after application (Baldé et al. 2018; Aguirre-Villegas et al. 2019) unless rates from other N fertiliser forms (especially mineral fertiliser) are reduced accordingly. This was demonstrated as an especially relevant trade-off in those intensive systems with higher fertilisation rates (MC_i). Therefore, it is necessary to analyse the emissions from a holistic perspective, assessing the possible negative interactions (i.e. pollutant swapping) associated with the single application of AD as a mitigation option.

3.2.3 Combined application

In contrast to previous studies that described the effect of individual options, the applied modelling framework considered the interactions between different measures. In this way, a particular measure's negative or positive effects could be influenced by the combined effect of two or more mitigation options (Del Prado et al. 2010; Beukes et al. 2011). This approach enabled the assessment of the suitability of a wide range of measures in different production contexts and as supported by our results, achieved positive emission reduction results (Vellinga et al. 2011). In addition to the full application of the selected mitigation options for each case study, in those DPS where more than two mitigation options were applied, the effect of an alternative combination of mitigation options has been modelled based on their single impact on the GHG_{int} and N_{int}.

Figures 2 and 3 show the single and combined effect of the selected mitigation options on each modelled DPS. For the GHG sources, enteric (CH_4), manure (CH_4 and direct/indirect N_2O), field-related (direct/indirect N_2O), and

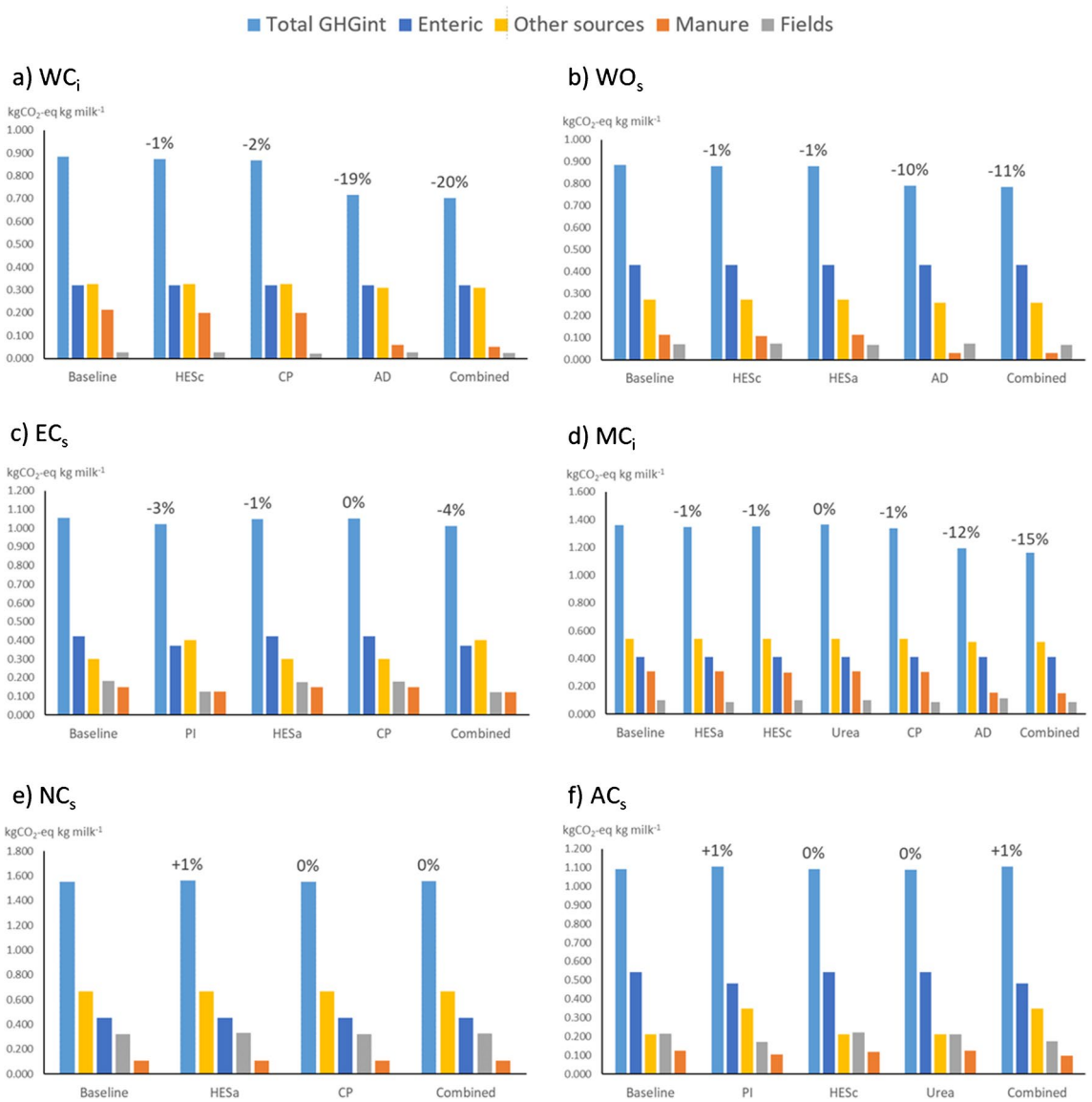

Fig. 2 Variation of greenhouse gas (GHG) emission sources for the different dairy production systems and mitigation options evaluated. GHG_{int} greenhouse gas emission intensity, WC_i Western European conventional intensive system, WO_s Western European organic semi-extensive system, EC_s Central-Eastern European conventional semi-extensive system, MC_i Mediterranean conventional intensive system, NC_s Northern European conventional semi-extensive system, AC_s Atlantic conventional semi-extensive system, HES_c high-efficiency slurry cover, HES_a high-efficiency slurry application, *Urea* urea substitution, *CP* low crude protein, *PI* increased productivity, *AD* anaerobic digestion.

emissions from other sources (CO_2 from feed purchases, energy use, and fertiliser purchases) were considered. As for the N emission sources, yards, housing, storage, fields, and silage were evaluated. Mitigation results for the entire sample (in % and absolute values) are presented in Supplementary Material 3.

The combined application of HES_c, CP, and AD resulted in positive synergies that reduced the N_{int} by 2.3 g N kg milk^{-1} (−27%) and the GHG_{int} by 0.2 kg CO_2-eq kg milk^{-1} (−20%) in the WC_i. Figure 2 shows that a reduction of 0.16 kg CO_2-eq kg milk^{-1} (−76%) in the manure-related GHG emission (CH_4 and direct and indirect N_2O) was observed. Less prominent reductions were achieved for the emission intensity from other GHG sources (feed purchase, energy use, and fertiliser purchase), which were mitigated by 0.01 kg CO_2-eq kg milk^{-1} (−5%). For this DPS, no variations were observed in the enteric GHG emissions. As for the N losses, those related to manure storage were reduced by 0.6 g N kg milk^{-1} (−83%) (due to strong reductions of N_2O and NH_3). In addition, emission intensity from the housing and the yards was mitigated by 0.8 (−40%) and 0.3 (−40%) g N kg milk^{-1}. As demonstrated by our results, the joint

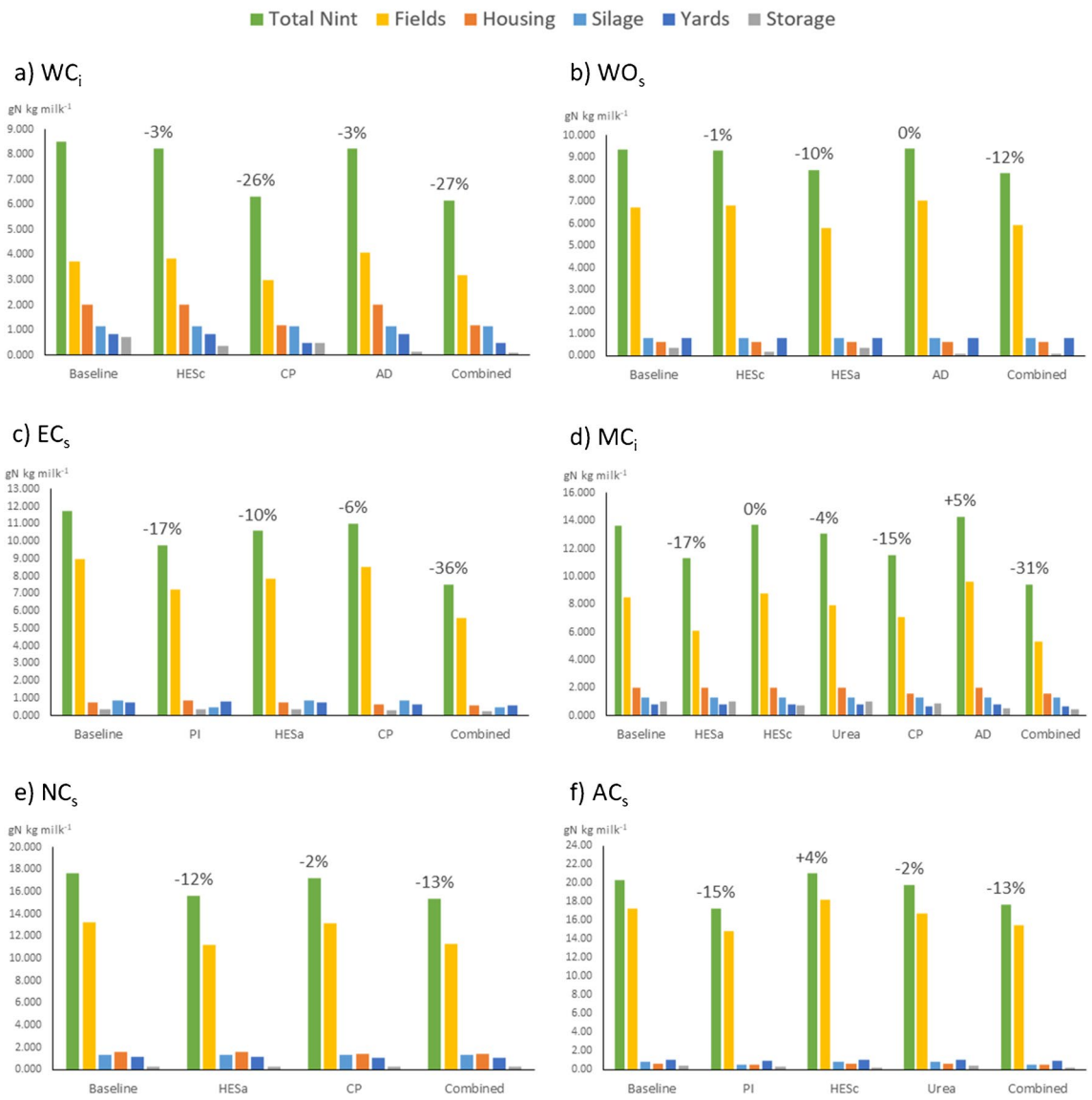

Fig. 3 Variation of nitrogen (N) loss sources for the different dairy production systems evaluated and mitigation options applied. N_{int} total nitrogen emission intensity, WC_i Western European conventional intensive system, WO_s Western European organic semi-extensive system, EC_s Central-Eastern European conventional semi-extensive system, MC_i Mediterranean conventional intensive system, NC_s Northern European conventional semi-extensive system, AC_s Atlantic conventional semi-extensive system, HES_c high-efficiency slurry cover, HES_a high-efficiency slurry application, *Urea* urea substitution, *CP* low crude protein, *PI* increased productivity, *AD* anaerobic digestion.

application of the abovementioned mitigation options in Western European conventional intensive DPS resulted in significant reductions of GHG_{int} and N_{int} creating positive synergies that reduced the negative effect of measures acting separately. In addition, the combined application of CP reduction and the HES_C reduced by 0.02 kg CO_2-eq kg $milk^{-1}$ GHG_{int} (−3%). This value was significantly lower than the one observed from the application of the three options together (i.e. reduction of CP, HES_c, and AD). However, this alternative combination showed better results for the N_{int} from the fields, which were reduced by 0.75 g N kg $milk^{-1}$ (−20%) due to the avoidance of the negative effect of AD on N losses from this source. Overall, the modelled mitigation options for this DPS were adequate as no major negative trade-offs were identified, and positive synergies were enhanced (i.e. NH_3 manure storage emissions).

Regarding WO_s, the joint implementation of HES_a, HES_c, and AD decreased the GHG_{int} by 0.1 kg CO_2-eq kg $milk^{-1}$ (−11%) and 1.1 g N kg $milk^{-1}$ (−12%) the N_{int}. The reduction in GHG_{int} was mainly associated with emissions from

manure (CH_4 and N_2O) which were mitigated by 0.08 kg CO_2-eq kg milk^{-1} (−72%) and the fields (N_2O) with a reduction of 0.004 kg CO_2-eq kg milk^{-1} (−6%). To a lesser extent, the combined action of the mitigation measures resulted in a reduction in other GHG sources, mostly associated with emissions intensity from energy use of 0.01 kg CO_2-eq kg milk^{-1} (−5%). Regarding the breakdown of N emission sources, emissions from the storage were mitigated by 0.29 (−78%) g N kg milk^{-1}. This result was expected because both mitigation measures significantly reduced N_2O and NH_3 emissions during the manure storage period. In addition, the combined application of HES_a and HES_c in the absence of AD reduced GHG_{int} less prominently compared to the full implantation of mitigation measures (−1% or 0.01 kg $CO_{2\text{-}eq}$ kg milk^{-1}) while obtaining similar results for the reduction of the N_{int} (−11% or 1.1 g N kg milk^{-1}). In addition, this combination obtained better results in mitigating N losses from the fields (−13% or 0.9 g N kg milk^{-1}). Due to the nature of organic systems, the applicability of diet-oriented measures is limited. Likewise, this same production system limits the number of improvements made at the field scale (i.e. mineral fertilisers). For this reason, the joint implementation of the proposed mitigation options is effective and feasible for semi-extensive organic systems. At the same time, future modelling exercises should explore the possibility of increasing the forage quality to enhance the milk yields.

The combined application of PI, CP, and HES_a resulted in a −4% (0.04 kg CO_2-eq kg milk^{-1}) reduction of the GHG_{int} and a −36% mitigation (4.2 g N kg milk^{-1}) of the N_{int} for EC_s. While enteric (CH_4), manure (CH_4 and N_2O), and field (N_2O) emissions were reduced by 0.05 (−12%), 0.03 (−20%), and 0.06 (−34%) kg CO_2-eq kg milk^{-1}, an increase in emissions from other sources (0.1 kg CO_2-eq kg milk^{-1}), mainly associated with CO_2 emissions from feed purchases, was observed. Regarding the N emission sources assessed, the combined application of measures significantly reduced emissions in all sources evaluated. The results showed how the negative trade-offs associated with the single application of PI (i.e. NH_3, losses from the yards and housing) were reversed by implementing, at the same time, a reduction of CP in the purchased fraction of the diet. Compared to implementing all the suggested options, increasing the share of the purchased feed and decreasing its CP content produced similar outcomes concerning the GHG_{int}. However, a lower potential for N_{int} mitigation was observed in this alternative combination. This lower performance relates to the N_{int} from the fields, which were reduced to a lower extent by this alternative approach. Consequently, fully adopting the mitigation options demonstrates better performance (−36% or 4.2 g N kg milk^{-1}) in reducing N_{int} compared to applying just two mitigation techniques (−29% or 3.4 g N kg milk^{-1}). In the case of EC_S, our results demonstrate the effectiveness of the proposed combined tailored application of mitigation measures preventing unwanted pollutant swapping and improving the mitigation potential. In addition, to further reduce the negative impacts of the concentrate increase, future work should address the effect of improved dietary forages to increase productivity.

Applying HES_a, HES_c, CP, the substitution of urea, and the AD plant resulted in reductions of the GHG_{int} (−15%) and N_{int} (−31%) of MC_i, accounting for 0.2 kg CO_2-eq kg milk^{-1} and 4.3 g N kg milk^{-1}, respectively. Manure-related and external input GHG emissions (i.e. energy use) were mitigated by 0.2 (−52%) and 0.03 (−5%) kg CO_2-eq kg milk^{-1}. However, proposed mitigation options increased the direct field N_2O emissions by 0.01 (15%) kg CO_2-eq kg milk^{-1}. Concerning the N_{int}, remarkable reductions were observed in manure storage (0.5 g N kg milk^{-1} (−51%)) mainly derived from the lower NH_3 emissions, which were reduced by 41% (4.7 g N kg milk^{-1}). Furthermore, the proposed mitigation measures reduced the previously noted negative trade-offs associated with the field emissions. In contrast, the applied mitigation scheme further enhanced the losses of NO_3^-, which were increased by 0.4 (26%) g N g milk^{-1}, respectively. While implementing the AD plant has a significant positive effect on the GHG_{int}, this was not accompanied by a reduction of the N_{int}. While the proposed combination of mitigation strategies effectively reduced the GHG_{int} and N_{int} emissions, mainly from manure storage, the combined application of the proposed options resulted in a higher TAN content in the slurry and higher N_2O emissions and NO_3^- losses, thus increasing the field N losses. Therefore, the future combination of the proposed measures with better fertilisation strategies should be explored, adjusting the N input to the crop needs. As an alternative, the application of HES_a, HES_c in combination with urea substitution by AN, and the reduction of the CP content of the purchased fraction of the diet was able to reduce by 4.5 g N kg milk^{-1} (−33%) the N_{int} while reducing the GHG_{int}, by 3% and lowering the negative trade-offs in the N_2O emissions and losses of NO_3^-.

As for NC_s, the effect of HES_a and CP acting in combination showed an increase in the GHG_{int} of 0.003 kg CO_2-eq kg milk^{-1} (0.2%) while reducing the N_{int} by −13% (2.3 g N kg milk^{-1}). In terms of GHG emission sources, the manure emissions were reduced by −2% reduction (0.002 kg CO_2-eq kg milk^{-1}) while increasing the fields by 2% (0.005 kg CO_2-eq kg milk^{-1}), with no variation in the GHG emission from enteric fermentation. Concerning the N_{int}, emissions associated with the fields (−15%), housing (−12%), yards (−11%), and storage (−10%) were mitigated by 2.0, 0.2, 0.1, and 0.03 g N kg milk^{-1}, respectively. In all, the adopted combination of mitigation measures proved to be effective in reducing GHG and N emissions in conventional semi-extensive Northern European DPS. According to the

characteristics of the farm (significant supply of concentrate), it would be advantageous to implement quality forages (legumes) that partially replace these external inputs, thus reducing the off-farm emissions.

Lastly, as for the AC_s, the combined application of PI, HES_c, and urea substitution resulted in a 1% increase in GHG_{int} (0.01 kg CO_2-eq kg $milk^{-1}$) and a −13% (2.6 g N kg $milk^{-1}$) reduction in N_{int}. As for the GHG sources, significant reductions were observed in emissions intensity from enteric fermentation (−11%), the manure (−22%), and fields (−18%) with 0.06, 0.03, and 0.04 kg CO_2-eq kg $milk^{-1}$, respectively. However, the increased supply of concentrate in the diet led to a higher emission intensity from other sources (0.14 kg CO_2-eq kg $milk^{-1}$), mostly derived from CO_2 emission from feed purchases. Regarding the sources of N emissions, the full adoption of the proposed mitigation measures mitigated the N emissions from the storage (−53%), the silage (37%), the housing (−14%), the yards (−13%), and the fields (−10%) by 0.2, 0.3, 0.1, 0.1, and 1.8 g N kg $milk^{-1}$, respectively. Alternatively, the combination of urea substitution and the use of HES_c results in a 1% increase in N_{int} (0.3 g N kg $milk^{-1}$) with no effect on the GHG_{int}, which was reduced by 0.3% (−0.003 kg CO_2-eq kg $milk^{-1}$). This is due to no increase in CO_2 emissions derived from the purchased feed and no increase in N_{int} derived from the yards, which increases as a result of a greater share of the purchased fraction of the diet. Our results demonstrate that the increase in the concentrates supply hinders the positive effect and the synergies between the different applied measures. Therefore, the application of this mitigation measure should be subject to further consideration to evaluate to what extent this option does not negatively affect the overall emissions of the farm. In addition, using slow-release fertilisers (i.e. protected urea) could be a solution for further mitigating emissions associated with applying mineral fertilisers.

4 Conclusions

As an essential prerequisite for effectively reducing emissions on DPS, this study contributes to a better understanding of the emission reduction potentials in European farming systems for dairy production, setting the base for applying adapted concepts, strategies, and policies. The diversity of the selected farms, representing certain agronomic practises considered typical for specific parts of Europe, make the results applicable to relevant European dairy systems. Furthermore, the applied process-based modelling approach evaluated the single and combined effect of adapted emission mitigation options on intensive, semi-extensive, conventional, and organic DPS across Europe, showing the model's capabilities to obtain meaningful results regarding emission abatement measures. In this way, our results allow the identification of the most appropriate options according to the particularities of the systems.

Reducing the CP content of the purchased fraction of the diet was an advisable option to reduce both GHG and N emissions independently of the production system. However, AD reduced GHG emissions in all cases (especially from manure storage), with undesirable trade-offs in the field N emissions due to higher TAN content on the slurry. Similarly, opting for rigid slurry covers reduced storage NH_3 volatilisation while increasing N losses from the fields. Therefore, considering the whole manure management chain when implementing this option is crucial. In this sense, shallow slurry injection notably reduced N losses associated with fields, showing higher mitigation potential in intensive DPS. Regarding the substitution of urea, overall N losses were reduced while discouraging this option for systems with sandy-loam soils due to higher N_2O emissions and NO_3^- losses. Finally, while lowering the F:C ratio can lead to an overall reduction of GHG emissions, attention should be paid to N losses associated with excreta as these may increase due to a high CP content in the concentrate. Furthermore, when combined mitigation measures are applied, our results represent a novel contribution to analysing emission mitigation potential across European DPS. Positive synergies were promoted, and negative trade-offs were eliminated by combining CP and F:C ratio reductions. In addition, the joint application of slurry covers or AD and shallow injection was a suitable combination for reducing emissions from both intensive and semi-extensive systems.

As demonstrated by our results, the future sustainability of DPS largely relies on optimising farm processes by adopting tailored combinations of mitigation measures. In this sense, emphasis is made on reducing emissions and improving efficiency by avoiding reliance on external inputs and optimising farm practises. In this context, future research and model developments should incorporate options to reflect the quality of the forages and adapted fertilisation plans. This would help reduce emissions by promoting the circularity and sustainability of dairy cattle farming systems.

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Declarations

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