

How much can combinations of measures reduce methane and nitrous oxide emissions from European livestock husbandry and feed cultivation?



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ABSTRACT

In the EU28, the meat and dairy supply chains emitted 360 Mt CO₂-eq or 80% of all agricultural CH₄ and N₂O emissions in 2016, which must be reduced to reach net-zero greenhouse gas emissions by 2050. Our research explores how far these emissions can be reduced by combining field tested mitigation measures for beef cattle, dairy cattle, swine, sheep, and synthetic fertilizers. Many mitigation measures targeting enteric fermentation, manure management, and fertilizer application have been experimentally tested; however, the impact of combining measures is relatively unexplored. To address this knowledge gap, we use graph theory to create combinations of measures for which we calculate the overall mitigation potential. From previous review studies, we identified 44 measures and formulated rules on impossible and mandatory combinations of measures. Based on the resulting sets of feasible cliques in the graphs and a simplified technological baseline, we estimate that the combinations with the highest reductions reduce CH₄ and N₂O emissions from beef cattle by 57%, dairy cattle by 47%, swine by 70%, sheep by 48%, and synthetic fertilizers by 44%. Together, they can reduce CH₄ and N₂O emissions in the EU28 from meat and dairy production by 54%, and for agriculture overall by 42%. This indicates that implementing more measures in the meat and dairy sectors can create room for further reduction than in the existing modelled pathways for the EU28. However, technical measures are incapable of fully eliminating agricultural CH₄ and N₂O, so there remains a need for CO₂ removal technologies.

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1. Introduction

The European Union (EU28) has outlined a strategy to reduce greenhouse gas (GHG) emissions to net-zero by 2050 in line in order to limiting the global temperature increase to 1.5 °C (European Commission, 2018a). Besides dramatically reducing CO₂ emissions, methane (CH₄) and nitrous oxide (N₂O) emissions from agriculture must also reduce from 461 Mt CO₂-eq in 2016 to 284 or even 237 Mt CO₂-eq in 2050 (European Commission, 2018b; European Environment Agency, 2018).

To achieve this, the EU28 needs to address the meat and dairy supply chains which emit 80% of the total agricultural CH₄ and N₂O through enteric fermentation, manure management, and fertilizer application. The EU28 has modelled two net-zero mitigation pathways that address these emission sources (European

Commission, 2018b): 1.5TECH and 1.5LIFE. Both pathways depend on implementing two CH₄ and three N₂O mitigation measures (Gambhir et al., 2017; Höglund-Isaksson, 2012): improve feed of cattle to reduce CH₄ from enteric fermentation; anaerobically digest cattle and swine manure to reduce CH₄ emissions from manure management; improve nitrogen (N) use efficiency; add nitrification inhibitors to fertilizers; and use precision nitrogen application to avoid direct and indirect N₂O from fertilizer application. In addition, 1.5LIFE assumes that diets will include less animal products. However, these measures do not result in zero CH₄ and N₂O emissions, so they require CO₂ removal technologies to achieve net-zero CO₂-eq emissions.

It may be possible to reduce the dependency on CO₂ removal technologies further by reducing CH₄ and N₂O with additional mitigation measures that have been studied in previous reviews for enteric fermentation (Broucek, 2018; Cottle et al., 2011; Knapp et al., 2014; Mirzaei-Ag and Maheri-Sis, 2011; Moumen et al., 2016; Patra et al., 2017; Patra, 2012; Pickering et al., 2015; Sejian et al., 2011; Yang et al., 2016), manure management (Dennehy

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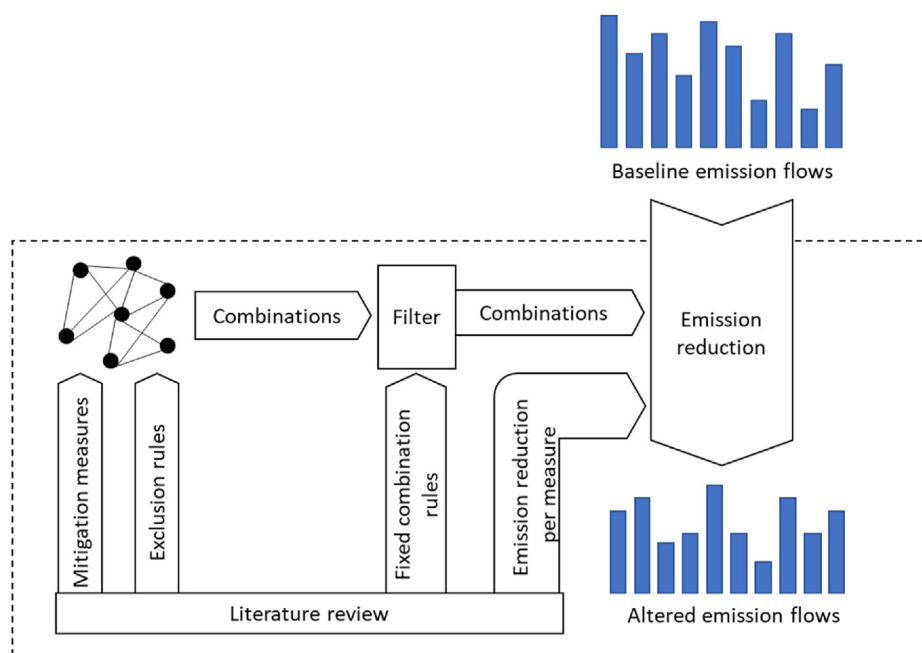


Fig. 1. Conceptual flowchart of the method where the baseline CH₄ and N₂O emission flows in CO₂-eq are modified by combinations of measures. The steps within the dotted lines were performed in this study and the baseline emission flows were based on Aan den Toorn et al. (2020).

et al., 2017; Hou et al., 2015; Montes et al., 2013; Sajeev et al., 2018; Wang et al., 2017), and fertilizer application (Akiyama et al., 2010; Vanderzaag and Jayasundara, 2011). The wide range of additional mitigation options includes measures such as feeding additives and further processing manure. Although many measures have been experimentally tested, the impact of combining measures is relatively unexplored. Only one study to our knowledge estimates the impact of combining measures by comparing how different manure management scenarios impact CH₄, N₂O, and ammonia (NH₃)

emissions (Hou et al., 2015). To assess the potential reduction of CH₄ and N₂O from the meat and dairy supply chains in the EU28, further research is needed that goes beyond manure management to include measures targeting other emissions.

In this research, we aim to address this knowledge gap by exploring the following research question: how much can CH₄ and N₂O emissions from meat and dairy supply chains in the EU28 roughly be reduced by combining mitigation measures? To answer the research question, we identify and evaluate the reduction

	Beef cattle	Dairy cattle	Swine	Sheep	Synthetic fertilizer	Other livestock
Enteric fermentation						
Direct CH ₄	█	█	█	█		
Manure management						
Direct CH ₄	█	█	█	█		
Direct N ₂ O	█	█	█	█		
Indirect N ₂ O from NH ₃	█	█	█	█		
Fertilizer for feed on arable land						
Direct N ₂ O	█	█	█	█	█	
Indirect N ₂ O from NH ₃	█	█	█	█	█	
Indirect N ₂ O from NO ₃	█	█	█	█	█	
Manure on pasture						
Direct N ₂ O	█	█		█		
Indirect N ₂ O from NH ₃	█	█		█		
Indirect N ₂ O from NO ₃	█	█		█		

Fig. 2. The green blocks show the included CH₄ and N₂O emission sources in the EU28 in 2016 for beef cattle, dairy cattle, swine, sheep, and synthetic fertilizer. For the four animal categories, the fertilizer for feed on arable land is limited to manure. All synthetic fertilizer use is included in its own category. The scope of this study excludes emission sources from production of imported feed and from other livestock including poultry.

Table 1

Measures with short descriptions and overall impact factors on the basis of CO₂-eq per category. Measures are grouped based on the identified exclusion rules, fixed combination rules, and the primary targeted CH₄ and N₂O emission source. Measures with multiple experimental measurements show both the average and the range (within brackets). See Appendix B for the impact factors per emission source per category. EF = enteric fermentation, MM = manure management, FA = fertilizer application.

Emission source	Groups	Measure	Description	Overall impact factor ^a				
				Beef cattle	Dairy cattle	Swine	Sheep	Synthetic fertilizer
EF	1. Methanogenesis disruption	1A Selectively breed	Selectively breeding livestock for low CH ₄ production by selecting for cattle with a low methane yield or low residual feed intake (difference between net energy intake and calculated energy requirements for maintenance) and by interbreeding with low CH ₄ producing breeds (Cottle et al., 2011; Pickering et al., 2015).	1.08 (0.89 –1.25)	0.93 (0.73 –1.00)		0.94 (0.81 –1.20)	
		1B Vaccinate	Vaccination of livestock against strains of microbes that cause methanogenesis (Broucek, 2018; Moumen et al., 2016).				1.01 (0.91 –1.14)	
		1C Feed 3NOP additive	Mixing 3-Nitrooxypropanol (3NOP) or ethyl-3NOP into diet which are synthetic compounds with anti-methanogenic properties (Patra et al., 2017).	0.57	0.70 (0.58 –0.79)		0.80	
		1D Feed 9,10-A additive	Mixing 9,10-Anthraquinone (9,10-A) into diet which is a synthetic compound that inhibits methane production in the rumen (Kung et al., 2003).				0.66	
		1E Infuse acetic acid into rumen	Infusion of acetic acid into the rumen which reduces methanogenesis, likely by reducing internal pH (Pampulha and Loureiro-Dias, 1989; Tyrrell et al., 1979).		0.95			
		1F Feed ACI additive	Mixing alpha-cyclodextrin-iodopropane (ACI) into diet. The compound includes iodopropane which has anti-methanogenic properties (Mohammed et al., 2004).		0.87			
		1G Feed essential oil additive	Mixing essential oils into diet which have anti-microbial properties inhibiting methanogenesis (Meale et al., 2012).	0.97 (0.86 –1.06)	0.88 (0.75 –1.00)		0.91 (0.87 –0.99)	
		1H Feed lipid additive	Mixing lipids except from coconut and linseed into diet which inhibits methanogens. The inclusion rate is limited to a maximum of 8% of dry matter to avoid negative impacts on livestock (Broucek, 2018; Meale et al., 2012; Moumen et al., 2016).	0.95 (0.73 –1.46)	0.94 (0.75 –1.18)		0.79 (0.52 –0.98)	
		1I Feed coconut lipid additive	Mixing lipids from coconut into diet which inhibits methanogens. The inclusion rate is limited to a maximum of 8% of dry matter to avoid negative impacts on livestock (Broucek, 2018; Meale et al., 2012; Moumen et al., 2016).	0.87 (0.75 –0.97)	0.81 (0.56 –1.01)		0.84 (0.50 –0.98)	
		1J Feed linseed lipid additive	Mixing lipids from linseed into diet which inhibits methanogens. The inclusion rate is limited to a maximum of 8% of dry matter to avoid negative impacts on livestock (Broucek, 2018; Meale et al., 2012; Moumen et al., 2016).	0.85 (0.72 –0.95)	0.80 (0.55 –1.00)		0.90 (0.77 –1.08)	
	1K Feed nisin additive	Mixing nisin into diet which is a small peptide produced by certain strains of microbes (Lactococcus lactis). It has anti-microbial properties similar to antibiotics (Santoso et al., 2004).				0.93		
	1L Feed organic sulfur additive	Mixing organic sulfur into diet which is a secondary metabolite exhibiting anti-microbial properties (Broucek, 2018).	0.96 (0.93 –0.99)	0.99 (0.99 –1.00)		0.99 (0.98 –0.99)		
	1M Feed saponin additive	Mixing saponins into diet which are compounds in plant extracts with anti-microbial properties (Holtshausen et al., 2009).	0.85 (0.78 –0.92)	0.98 (0.91 –1.04)		0.97 (0.81 –1.16)		
	1N Feed tannin additive	Mixing tannins into diet which are compounds in plants with anti-microbial properties (Piñeiro-Vázquez et al., 2015).	0.94 (0.75 –1.01)	0.87 (0.80 –0.93)		0.94 (0.80 –1.15)		
	2. Alternative H sink provision	2A Feed nitrate additive	Mixing nitrate into diet which reacts and removes free H, but it potentially leads to too much nitrite in the rumen which is toxic to livestock (Yang et al., 2016).	0.84 (0.80 –0.88)	0.89		0.73 (0.55 –0.86)	
		2B Feed sulfate additive	Mixing sulfate into diet which reacts and removes free H (Van Zijderveld et al., 2010).				0.87 (0.83 –0.90)	
		2C Feed propionate enhancer additive	Mixing propionate enhancers into diet which are compounds that can be metabolized with free H into propionate (Patra et al., 2017).	0.96 (0.83 –1.07)	0.96 (0.84 –1.03)		0.72 (0.48 –1.03)	
2D Feed probiotic additive		Mixing probiotics into diet which are microbe cultures that possibly stimulate the formation of acetogens. This competes for free H ₂ with methanogenesis (Broucek, 2018; Patra, 2012)	0.99 (0.99 –1.00)	0.99 (0.93 –1.06)		0.98 (0.88 –1.12)		
3. Propionate pathway stimulation		3A Improve feed quality	Improving feed by replacing roughages with higher quality fodder/concentrates which promotes the conversion of pyruvate into propionate instead of acetate which avoids methanogenesis (Gerber et al., 2013).	0.93 (0.57 –1.28)	1.05 (0.60 –1.07)		1.02 (0.7 –1.84)	
	3B Feed enzyme additive	Mixing enzymes into diet to potentially improve feed digestibility (Chung et al., 2012)		1.04 (0.99 –1.08)				
MM	4. Nitrogen intake reduction	4A Reduce crude protein intake	Reducing crude protein intake to reduce nitrogen content in manure resulting in less NH ₃ volatilization without influencing animal growth (Hayes et al., 2004).	0.99 (0.99 –0.99)	0.99 (0.98 –1.00)	0.98 (0.97 –1.00)		

(continued on next page)

Table 1 (continued)

Emission source	Groups	Measure	Description	Overall impact factor ^a		
FA	5. Inhouse floors	5A Install deep litter floor	Maintaining a thick layer of bedding on a solid floor where manure can decompose (Gerber et al., 2013).	0.99 (0.99)	0.99 (0.99)	
		5B Install slatted floor	Having a floor with small openings that allow manure to pass through into a collection pit (Hou et al., 2015).	-1.00 (0.99)	-0.99 (0.93)	
	6. Livestock housing management	6A Frequent manure removal	Removing manure at a high frequency from livestock housing into manure storage using a scraper (Amon et al., 2007).			0.65 (0.60)
		6B Add straw bedding	Covering (parts of) the floor with straw bedding (Gilhespy et al., 2009).	0.99 (0.99)	1.00 (0.99)	-0.69 (-1.01)
	7. Slurry storage	7A Cover slurry with artificial film	Covering stored slurry with an artificial film (VanderZaag et al., 2010).	0.98 (0.98)	0.65 (0.56)	
		7B Cover slurry with granules	Covering stored slurry with small granules such as clay coated with waterproof material (Balsari et al., 2006).	0.99 (0.98)	0.98 (0.98)	0.96 (0.96)
		7C Cover slurry with straw	Covering stored slurry with straw (Petersen et al., 2013).	-0.99 (0.99)	-0.99 (0.94)	-0.97 (0.75)
		7D Cover slurry with surface crust	Covering stored slurry with naturally formed crust (Smith et al., 2007).	-1.00 (0.99)	-1.00 (0.98)	-17.84 (-0.99)
		7E Cover slurry with wooden lid	Covering stored slurry with a wooden lid (Clemens et al., 2006).	0.98 (0.96)	0.99 (0.98)	0.65 (0.55)
	8. Solid fraction storage	8A Compact solid fraction	Compressing solid manure during storage (Sommer and Dahl, 1999).	-0.99 (1.10)	-1.00 (-0.76)	
		8B Cover solid fraction	Covering solid manure with a plastic film (Jiang et al., 2013).			8.58 (5.69)
		8C Turn solid fraction	Regularly turning the solid manure during storage (Jiang et al., 2013).	1.22 (1.22)	1.34 (1.29)	0.44 (0.41)
	9. Acidification	9A Acidify slurry	Adding nitrate or sulfate to slurry to reduce the pH level (Petersen et al., 2014).	-1.23 (-1.40)	-1.40 (-0.49)	0.39 (0.37)
10. Anaerobic digestion	10A Produce biogas	Process manure with an anaerobic digester which degrades organic matter in manure to produce biogas through methanogenesis, composed of CH ₄ and other gases, and digestate (Sajeev et al., 2018).	0.98 (0.91)	0.96 (0.91)	0.83 (-1.01)	
	10B Fertilize with digestate	Fertilize soil with digestate from anaerobically digested slurry (Nyord et al., 2012).			0.98 (0.96)	
11. Separated slurry application	11A Fertilize with solid fraction	Fertilize soil with the solid fraction of mechanically separated manure (Balsari et al., 2008).	1.00 (0.99)	0.97 (0.95)	1.06 (1.04)	
	11B Fertilize with liquid fraction	Fertilize soil with the liquid fraction of mechanically separated manure (Balsari et al., 2008).	-1.01 (0.99)	-0.99 (0.95)	-1.08 (0.92)	
12. Manure application	12A Fertilize through band spreading	Fertilize soil by applying manure in narrow bands without cutting the grass (Huijsmans et al., 2001).	-1.00 (0.99)	-1.04 (0.99)	-1.16 (0.98)	
	12B Fertilize through incorporation	Fertilize soil by first spreading manure on the surface and then tilling it into the soil which incorporates the manure (Huijsmans, 2003).	-1.01 (1.13)	-1.01 (1.13)	-0.99 (1.12)	
	12C Fertilize through injection	Fertilize by burying manure in the soil with an injector (Huijsmans, 2003).	1.13 (0.94)	1.13 (0.97)	1.12 (0.91)	
13. N volatilization inhibition	13A Add nitrification inhibitor	Fertilize soil by applying manure in narrow bands without cutting the grass (Huijsmans et al., 2001).	-2.96 (0.98)	-2.87 (0.98)	-2.15 (0.97)	
	13B Apply polymer-coated fertilizer	Using slow-release fertilizers with a polymer-layer to slow the release of nitrogen so plants have more time to take up N resulting in less N converted to N ₂ O (Akiyama et al., 2010).	0.98 (0.96)	0.98 (0.98)	0.97 (0.97)	
	13C Add urease inhibitor	Add a urease inhibitor to fertilizer on soil to delay the conversion of urea to ammonia so plants have more time to take up N resulting in less N converted to N ₂ O (Akiyama et al., 2010).	-0.99 (-0.99)	-0.99 (-0.99)	-0.98 (-0.98)	

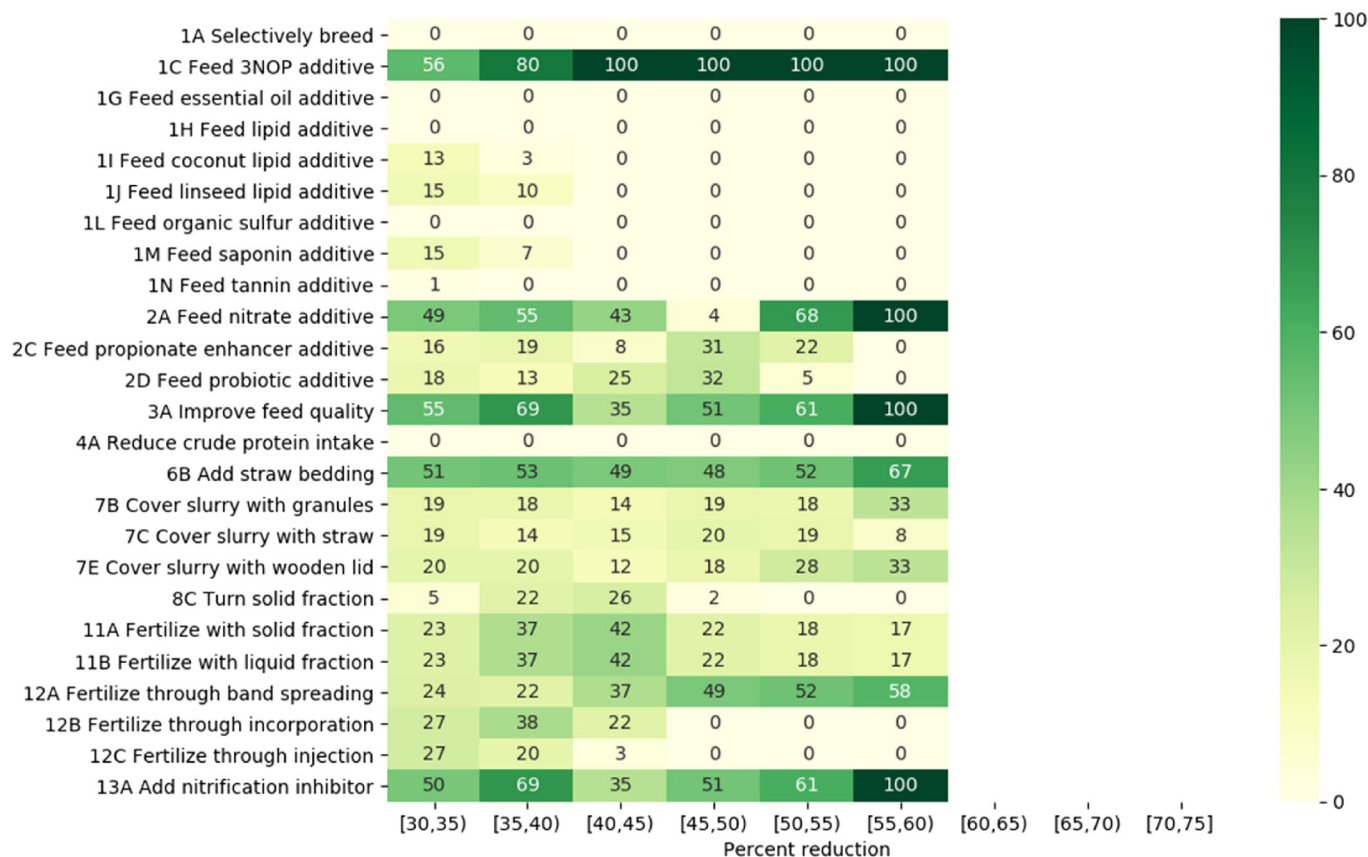


Fig. 3. Heatmap showing for each measure applicable for beef cattle the share of combinations in which it is included (color and value) with the combinations grouped by the percent reduction of the total combined CH₄ and N₂O emissions in CO₂-eq compared to the baseline.

potential of combinations of mitigation measures based on reviews of mitigation measures targeting enteric fermentation, manure management, and fertilizer application. We limit our scope to the CH₄ and N₂O emissions emitted in the EU28 from the feed production and husbandry of beef cattle, dairy cattle, swine, sheep, and the application of synthetic fertilizers for feed, because these are responsible for around 96% of the emissions in the meat and dairy supply chains (Aan den Toorn et al., 2020).

2. Methods

In this research, we developed a method that uses a baseline of emission flows contributing to climate change which can be reduced by a combination of mitigation measures (Fig. 1). To achieve this, we first selected the relevant emission flows for our baseline. Next, we used literature to list the available mitigation measures and their GHG reduction potential. Moreover, we derived rules from literature that exclude the combination of certain measures and used these rules to identify pairs of measures that cannot be combined. Next, we constructed mathematical graphs to find feasible combinations excluding the identified incompatible pairs. These combinations were filtered to take into account that some measures must be combined. Finally, we calculated the emission reduction of each combination and applied it to the baseline emission flows. Based on these results, we analyzed the highest mitigating combinations and assessed their reduction potential for the EU28.

2.1. Included GHG sources

The scope of our study is limited to three emissions sources: enteric fermentation, manure management, and fertilizer application. Additionally, we limit our scope to emissions from five categories: beef cattle, dairy cattle, swine, sheep, and synthetic fertilizer. Other livestock such as poultry and goats were excluded, because they together emit less than 5% of CH₄ and N₂O emissions in CO₂-eq from meat and dairy production in the EU28 (Aan den Toorn et al., 2020). The use of synthetic fertilizers for feed was separated from the use of manure and grouped into a single category because mitigation measures for applying fertilizers cannot always be used for both manure and synthetic fertilizers. As a result, emissions from fertilizer application are limited to manure for the individual animal categories.

We included 10 types of emission flows of CH₄ and N₂O, although not all flows are relevant for each category (Fig. 2). The first emission flow is CH₄ from enteric fermentation which is mostly a by-product from ruminants at the start of their digestive tract (Broucek, 2018; Patra, 2012). However, swine and other non-ruminants also emit limited amounts of CH₄ in their digestive tracts. The next 3 emission flows originate from manure management, as during manure storage, the organic matter decomposes into CH₄, N₂O and NH₃. The latter is not a GHG but can undergo nitrification resulting in additional N₂O emissions (Broucek, 2017). The final 6 flows relate to N₂O emissions from fertilizer application. During fertilizer application, the nitrogen in the fertilizer that is not completely absorbed in plants can undergo nitrification and denitrification resulting in direct N₂O emissions (Broucek, 2017; Eckard et al., 2010). In addition, the unabsorbed nitrogen can volatilize into

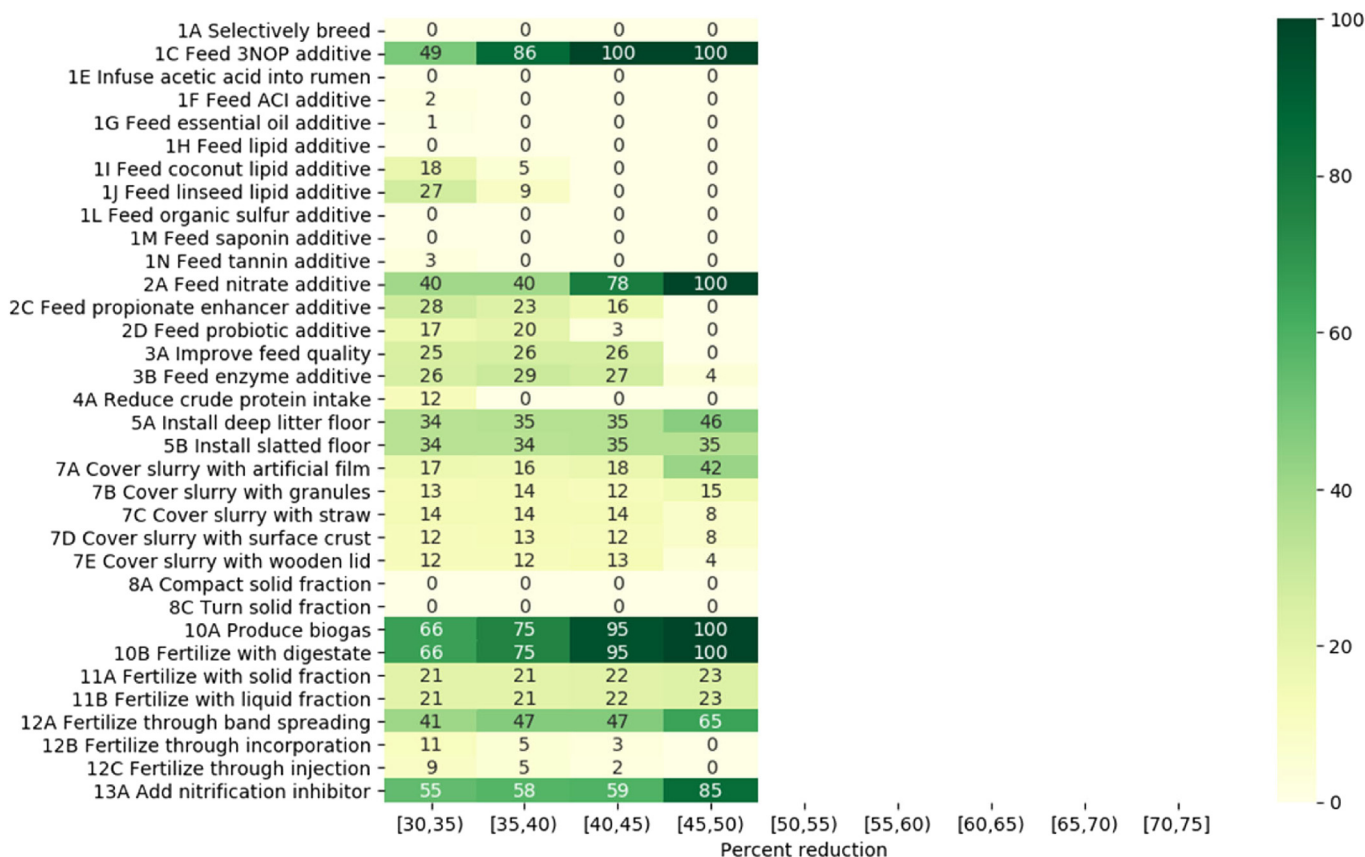


Fig. 4. Heatmap showing for each measure applicable for dairy cattle the share of combinations in which it is included (color and value) with the combinations grouped by the percent reduction of the total combined CH₄ and N₂O emissions in CO₂-eq compared to the baseline.

the air as NH₃ or leach into groundwater as NO₃. Both these substances can also undergo nitrification and denitrification resulting in indirect N₂O emission flows. These 3 types of N₂O emissions are distinguished for fertilizer application on arable land and pasture resulting in 6 separate N₂O emission flows.

For the CH₄ and N₂O emission flows in the baseline scenario, we used the emissions from Aan den Toorn et al. (2020). The data is from 2016 and is derived from FAOSTAT which uses IPCC tier 1 methods to estimate agricultural CH₄ and N₂O emissions (Aan den Toorn et al., 2020; IPCC, 2006). We limit our scope to the CH₄ and N₂O emissions emitted in the EU28. These emissions do not distinguish between sub-processes in each emission source such as manure in stables and manure in long-term storage in the case of manure management. The baseline scenario consists of 261.2 Mt CO₂-eq of CH₄ and 96.4 Mt CO₂-eq of N₂O resulting in a total of 357.6 CO₂-eq. The largest emission flow is CH₄ from enteric fermentation which emits 59% of the total emissions. The next largest emission flow is CH₄ from manure management emitting 14%, followed by direct N₂O from fertilizer application on arable land emitting 11%. The remaining N₂O emission sources each emit 5% or less but their combined contribution is 15% of the total.

2.2. Finding measures and individual GHG reduction potential

We identified 44 mitigation measures and classified them into 13 groups (Table 1). To identify the available reduction measures and their theoretical potential, we conducted a literature review targeting articles reviewing one or more measures. To search for literature, we used targeted search terms in Web of Science for review articles in the period 2010–2018. We then used references

in these reviews to find other relevant articles and case study databases. Of the available measures, we only included those that met the following three criteria: the impact on emissions was measured by *in vivo* studies, the reduction was not transient, and the measure was not banned in the EU28. If multiple variations exist for a measure, we grouped them together except for particular variations with significantly different reduction potentials. The result was a dataset with reduction measurements from 367 experimental studies (see Appendix B for all datapoints and Appendix A3 for the full reference list of the sources).

2.3. Identifying feasible combinations of measures

To identify possible combinations, we created a graph in which vertexes (or nodes) represent the measures and edges (or lines) between the vertexes represent the possibility of combining the two adjoined measures. Next, we searched for compatible measure combinations by finding in the graph all cliques, which are subsets of vertexes with an edge between each vertex (Weisstein, 2019a). Thus, we found viable combinations as each pair of measures in these combinations is feasible.

Although we could have created a list of all pairs of measures that can be combined, the number of pairs of measures that cannot be combined is much lower. To take advantage of this, we created a graph where the vertexes still represent measures but the edges represent pairs of incompatible measures. For this purpose, we derived from literature 11 exclusion rules for combining measures and used these to list incompatible combinations of measures (see Appendix A2 for details on the 11 exclusion rules). Next, we converted this graph to the desired graph with the same vertexes and

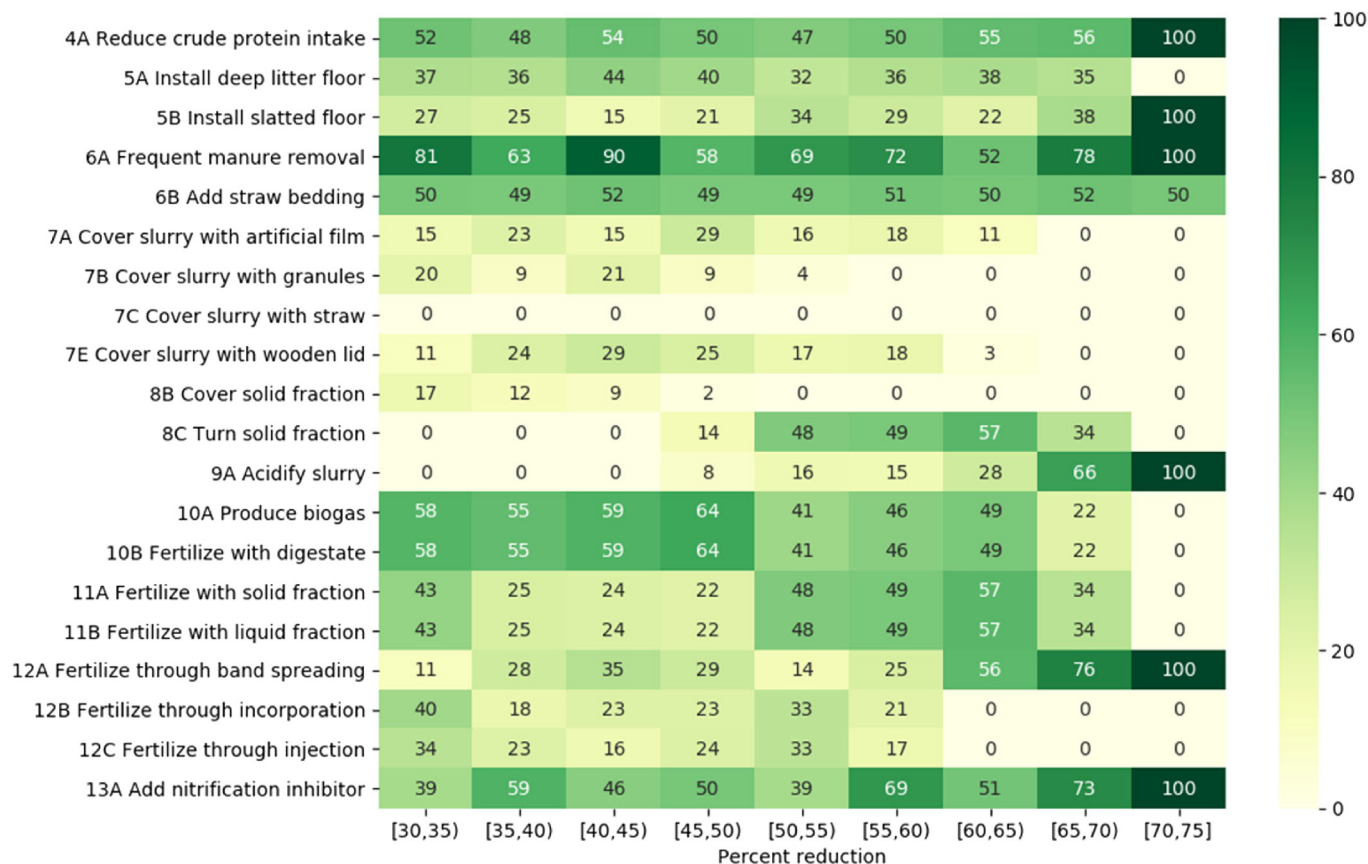


Fig. 5. Heatmap showing for each measure applicable for swine the share of combinations in which it is included (color and value) with the combinations grouped by the percent reduction of the total combined CH₄ and N₂O emissions in CO₂-eq compared to the baseline.

edge representing compatible pairs of measures by taking the ‘complement’ of the graph (Weisstein, 2019b).

The cliques in the graphs now represent combinations of measures that are mutually compatible, but do not account for measures that must be combined together. For example, the measure to use manure for biogas production also produces digestate as a by-product which is used as a fertilizer. Therefore, the biogas production measure must be combined with the digestate use measure. One way to ensure that such measures are always combined is to aggregate them into a single measure. However, the underlying data points for each separate mitigation measure come from different studies. Rather than calculating the range of impact factors for each aggregated measure, we left the measures disaggregated. We implemented this by defining which measures must be combined according to 5 fixed combination rules and filtered out cliques with measures that must be combined with another measure that is not in the same clique (see Appendix A2 for details on the fixed combination rules).

2.4. Estimating total GHG reduction for combinations

To estimate the emission reduction of combinations, we determined impact factors of each measure on the 10 emission flows per category. The impact factor is < 1 if the measure reduces the emission flow, >1 if it increases the flow, 1 if it has no impact. If the impact on this flow was not measured, the value is left blank but defaults to 1 for the calculations. For example, if a measure for manure management reduces CH₄ by 70% and increases the direct N₂O emissions by 10%, the impact factors are 0.7 and 1.1,

respectively.

As the impacts of measures are expressed relative to a baseline technology or the lack of the measure, we simplified the technological assumptions for our baseline. We assumed that farms use the following measures: solid floors for the animal housing; no cover during manure storage; static piling for the storage of the solid fraction if manure was separated into solid and liquid fractions; surface spreading to fertilize arable land with manure. With respect to animal feed, we assumed that measures changing the feed would affect the emission flows as if our baseline had the same feed composition as the baselines in the experimental studies. For other measures, we assumed that they were not in use in the baseline. The impact factors of several competing measures were relative to different baselines, so we harmonized their baselines to make them comparable (see Appendix A1 for details).

To calculate the new emissions after implementing a clique of measures, we use the following equation:

$$EN_{ck} = \sum_{s \in S_c} \left\{ \prod_{m \in M_{ck}} I_{ms} \times EO_{sc} \right\} \forall c \in C, k \in K_c$$

EN = emissions new (in t CO₂-eq.)

EO = emissions old (in t CO₂-eq.)

I = impact factor

C = set of categories



Fig. 6. Heatmap showing for each measure applicable for sheep (y-axis) the share of combinations in which it is included (color and value) with the combinations grouped by the percent reduction (x-axis) of the total combined CH₄ and N₂O emissions in CO₂-eq compared to the baseline.

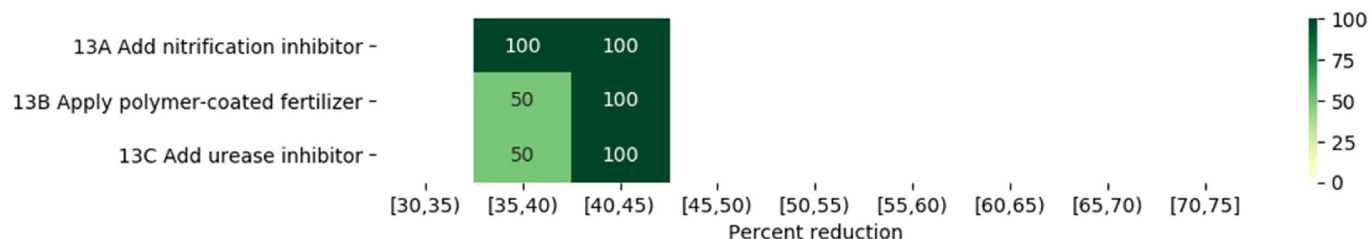


Fig. 7. Heatmap showing for each measure applicable for synthetic fertilizers the share of combinations in which it is included (color and value) with the combinations grouped by the percent reduction of the total combined CH₄ and N₂O emissions in CO₂-eq compared to the baseline.

c = category

K = set of cliques

k = clique of measures

M = set of measures

m = measure

S = set of emission sources

s = emission source

3. Results

Through our method, we uncovered a large range of feasible combinations from over 90,000 for dairy cattle to only three for synthetic fertilizers (see Appendix C for all combinations per category). In the following sections, we explore if there are characteristics for combinations with particularly high mitigation potentials. Following this, we estimate what the potential CH₄ and N₂O mitigation could be when the highest mitigating combinations for each category are implemented.

3.1. Characteristics of combinations with high mitigation potential

To explore the combinations with high mitigation potential, we analyzed which measures were used in combinations reaching specific reduction ranges of 5 percentage points wide, e.g., 30–35% or 65–70% reduction. In Figs. 3–7 we show for each measure, the

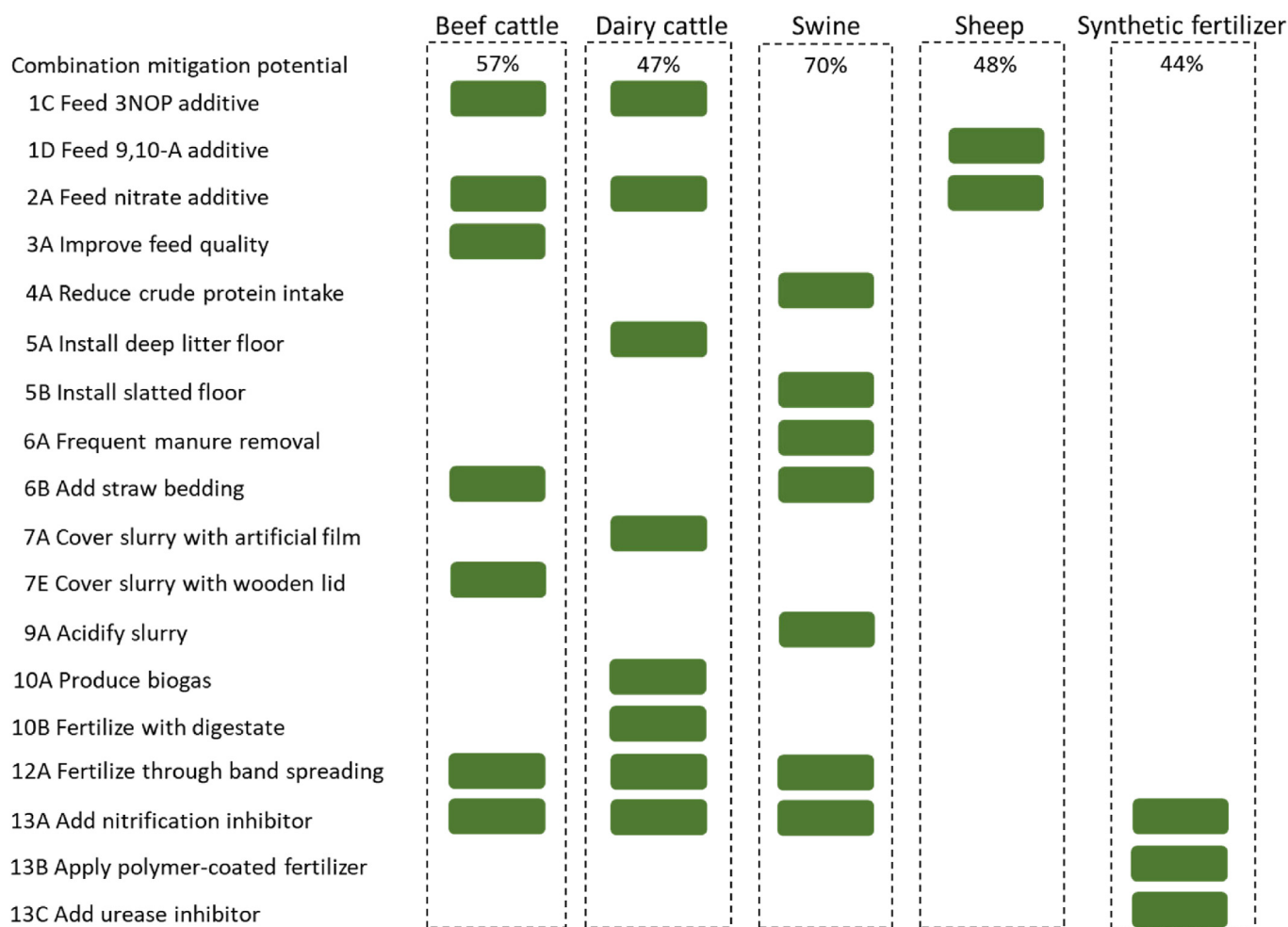


Fig. 8. Overview of measures in the highest mitigating combination for each category as indicated by green rectangles and the respective combined mitigation potentials.

share of combinations in which the measure is included to reach the different reduction ranges. For example, Fig. 3 shows for beef cattle combinations that '1C Feed 3NOP additive' is used in 56% of the combinations reducing emission by 30–35% and 100% of the combinations reducing by 40–45% or more.

For beef cattle (Fig. 3), dairy cattle (Fig. 4), and swine (Fig. 5), the combinations with a high mitigation potential show a pattern of a few core mitigation measures that can be combined with a wider set of other measures. The core measures are either measures with particularly low impact factors compared to competing measures or measures that do not compete with others. Good examples for the former are '1C Feed 3NOP additive' for beef and dairy cattle and '9A Acidify slurry' for swine. The measure '13A Add nitrification inhibitor' is an example for all three animals of a measure that is compatible with all others although it does not have a strong impact. Moreover, the core measures in part depend on which emission flows are relatively large for the particular livestock such as CH₄ from enteric fermentation for beef and dairy cattle, and CH₄ from manure management for swine.

For sheep (Fig. 6) and synthetic fertilizers (Fig. 7), the number of measures in each combination is very small. In the case of synthetic fertilizers, only three measures are included in our dataset. The reason is different for sheep which does include more measures, but the measures are limited to the three mitigation groups targeting enteric fermentation. Each of these groups has an exclusion rule that forbids combining measures within the same group

together. This limits the number of measures in a feasible combination for sheep to a maximum of three. Despite the limited number of measures, two are more critical for a high reduction, namely, '1D Feed 9,10-A additive' for sheep, and '13A Add nitrification inhibitor' for synthetic fertilizers. Both of these measures have low impact factors and the latter does not compete with other measures.

When comparing the combinations with the highest mitigation potential for each category, the number of measures in a combination appears to also influence the maximum mitigation potential (Fig. 8). The highest mitigating combinations of beef cattle and swine include relatively many measures and a mitigation potential up to 57% and 70%, respectively. In contrast, the combinations for sheep and synthetic fertilizers include few measures with a maximum reduction limited to 48% and 44%, respectively. Only dairy cattle, which has combination sizes similar to beef cattle and swine, does not fit in this description with a maximum reduction of 47%. This likely results from the lower impact factor of '1C Feed 3NOP additive' and to a lesser extent '2A Feed nitrate additive' for dairy cattle than for beef cattle.

3.2. Impact of highest mitigating combinations on total baseline emission flows

By applying the best combination of each of the five categories (Fig. 8) to the baseline emissions, the total CH₄ and N₂O of all

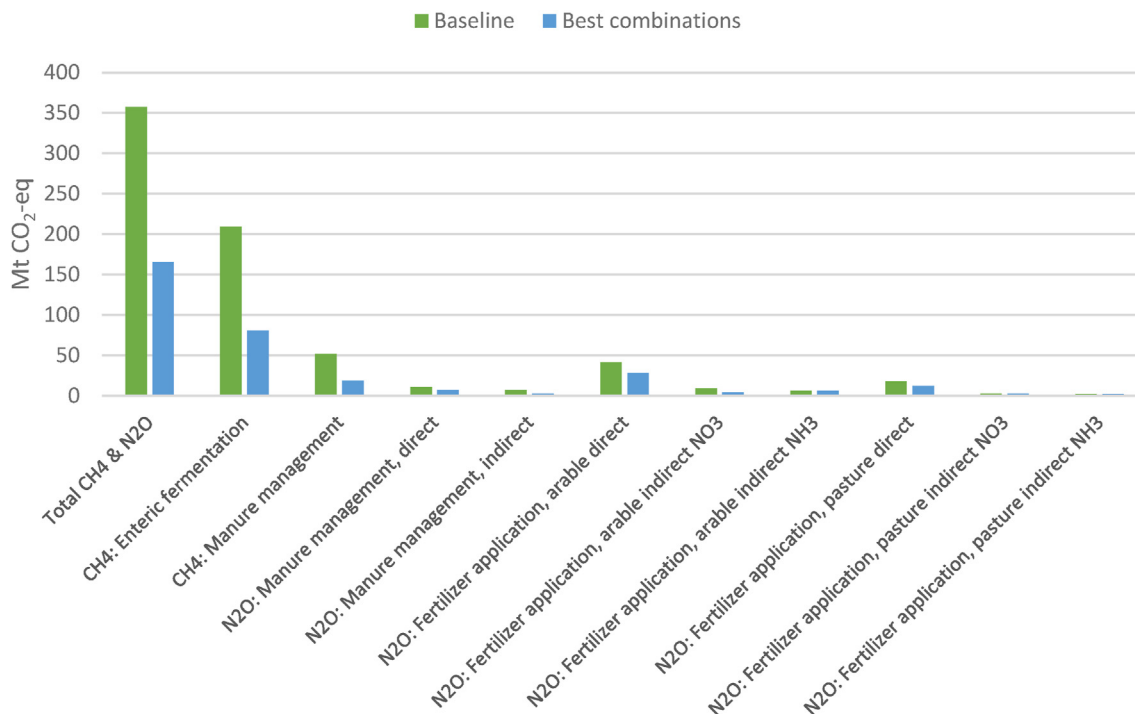


Fig. 9. Bar chart comparing the 10 emission flows and the total CH₄ and N₂O of the baseline scenario with the scenario applying the highest mitigating combinations for each category.

Table 2 Results of the sensitivity analysis showing the impact (as percentage change) of excluding individual measures on the maximum reduction per category and overall.

	Beef	Dairy	Swine	Sheep	Synthetic fertilizer	Total
Exclude 3NOP	-8.2%	-2.4%				-10.6%
Exclude nitrate	-1.6%	-1.2%				-2.8%
Exclude nitrification inhibitor	-0.8%		-0.4%			-1.2%
Exclude roughage feeds reduction	-0.8%					-0.8%
Exclude biogas production & digestate fertilizer		-1.5%				-1.5%
Exclude acidification			-0.2%			-0.2%
Exclude band spreading			-0.2%			-0.2%
Exclude crude protein reduction			0.0%			0.0%
Exclude frequent manure removal			-0.4%			-0.4%
Exclude slatted floor			-0.1%			-0.1%
Exclude 9,10-anthraquinone				-0.7%		-0.7%

emission flows decreases by 54% (Fig. 9). To reach this level, the reduction of CH₄ plays a more important role than that of N₂O: CH₄ from enteric fermentation contributed 36 percent point (ppt) and CH₄ from manure management 9 ppt compared to 4 ppt from N₂O emitted from fertilizer application on arable land and the remaining 5 ppt from the other N₂O sources. As enteric fermentation has an outsized role in the total baseline emissions and beef and dairy cattle emit most of these emissions, the measures reducing beef and dairy cattle enteric fermentation have a particularly large impact of 21 ppt and 11 ppt, respectively. Next, is the CH₄ from manure management from swine with which is 7 ppt of the decrease. The final emission flow is N₂O from applying synthetic fertilizer on arable land which contributes 3 ppt. In conclusion, the overall achievable reduction depends largely on the mitigation of the largest emission flows.

The importance of mitigating large emission flows might imply that a limited number of measures within the combinations mitigate the majority of N₂O and CH₄ emissions. To verify whether this is the case, we performed a sensitivity analysis checking the extent that excluding specific measures would affect the overall maximum

reduction (Table 2). In this analysis, we only included measures that appear essential for high mitigation combinations based on Figs. 3–7. We found that excluding 3NOP had the largest impact with the maximum reduction lowered by 10.6 ppt, followed by excluding nitrate with a reduction of 2.8 ppt. Excluding other measures had almost negligible impact as they at most lowered the maximum reduction by 1 ppt. This shows that achieving high reductions does not depend on only a few measures, but requires combining multiple mitigation measures.

4. Discussion

4.1. Implication for EU28 target

Assuming our simplified technological baseline, our results estimate that the best combinations for the five categories can reduce CH₄ and N₂O emissions by 62% and 32%, respectively, resulting in a combined CO₂-eq reduction of 54%. Assuming that emissions from non-feed, non-livestock, and livestock are not reduced at all, this leads to the total agricultural CH₄ and N₂O emissions reduction of

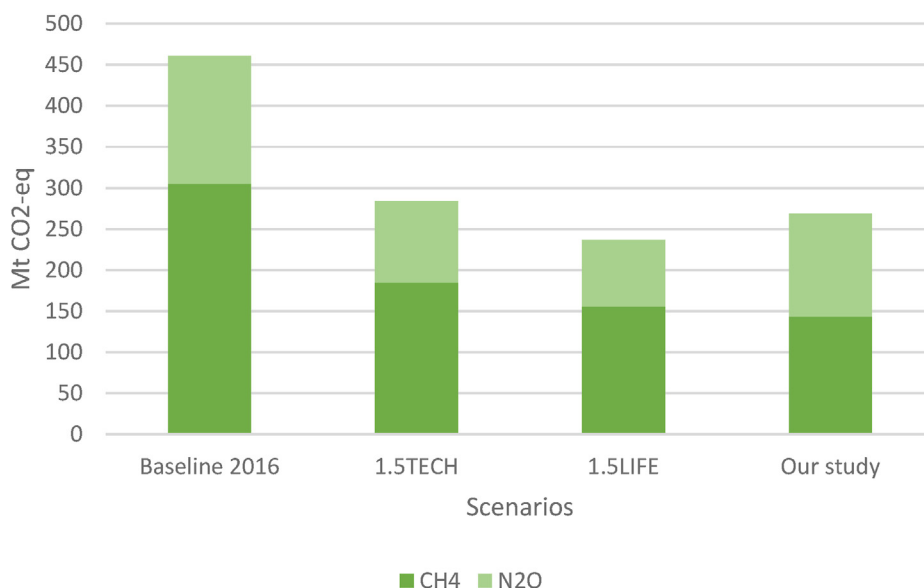


Fig. 10. The total agricultural CH₄ and N₂O emissions in 2050 of two EU28 decarbonization pathways, 1.5TECH and 1.5LIFE (European Commission, 2018b), and our study compared to the emissions in 2016. Our study pathway is based on the combinations with the highest emission reduction for each category under baseline impact factor (IF) values.

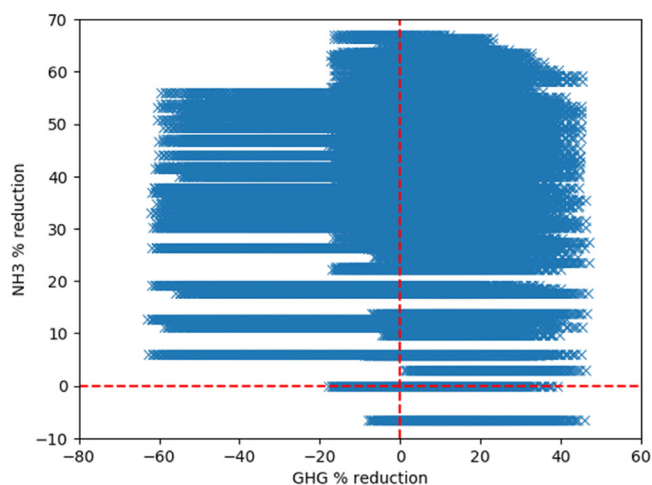


Fig. 11. Scatterplot showing the reduction of the combined CH₄ and N₂O in CO₂-eq compared to NH₃ reduction for each dairy cattle measure combination represented by a marker (×). The graph is divided into four sections: the top right with combinations reducing both GHG and NH₃ emissions; the bottom right rectangle with combinations reducing GHG but increasing NH₃ emissions; the top left rectangle with combinations reducing NH₃ but increasing GHG emissions; the bottom left rectangle with combinations increasing both GHG and NH₃ emissions.

53% and 20%, respectively. Overall, this reduces agricultural and CH₄ and N₂O emissions by 42% from 461 Mt CO₂-eq in 2016 to 269 Mt CO₂-eq (Fig. 10). To put these results into perspective, we compared our results to the mitigation pathways 1.5TECH and 1.5LIFE modelled by the EU28. Compared to these pathways, the mitigation potential from our study falls between 1.5TECH (38%) and 1.5LIFE (49%); thus, our study suggests that with decarbonization in the production of beef cattle, dairy cattle, swine, sheep, and the use of synthetic fertilizer, the agricultural sector could potentially reach a similar reduction potential in 2050.

Comparing specific emission reductions in the EU28 decarbonization pathways with our results shows that the 53% reduction of CH₄ in our study is higher compared to 39–49% in the EU28 pathways; whereas, the 20% N₂O reduction in our study is lower

compared to 37–38% in the EU28 pathways. This difference can be explained by our study excluding non-feed arable crops, which emit N₂O from fertilizer use, and by our study including more measures reducing enteric fermentation which accounts for most agricultural CH₄. Consequently, the overall reduction can be even greater if additional measures are implemented for emissions unrelated to animal production, as our study only covers around 80% of agricultural CH₄ and N₂O.

4.2. Limitations and future research

This study has the following four main limitations which will be addressed in this section resulting in the identification of knowledge gaps for further research. First, the data from experimental studies on which our results are based face some uncertainty. Second, our baseline is based on simplified technological and process assumptions. Third, the reduction potential for each combination is hypothetical and assumes that combining measures is multiplicative. Fourth, factors beyond CH₄ and N₂O emission reduction have been excluded.

Our study faces uncertainty in the data used from experimental studies. First, our study has an incomplete coverage of measures which ultimately results from extensively depending on review studies that we identified in literature. These review studies may not cover all measures that have been tested, because certain measures may not have been reviewed and our literature search strategy may not have found all relevant review studies. For example, our included measures lack grazing mitigation measures and changes to fertilizer management to better balance N fertilization. Second, Table 1 shows that included measures have not always been experimentally tested for all relevant categories. For example, sheep lacks measures that target emission flows other than enteric fermentation, while swine lacks measures that do target enteric fermentation. Third, the experimental studies do not always cover all affected emission flows. For example, studies that experimentally tested ‘1C Feed 3NOP additive’ only measured the impact on CH₄ from enteric fermentation but did not consider the impacts on emission flows during manure management; as a result, our study implicitly assumed that there is no impact on other

emission flows. Fourth, we used the average impact factors of the experimental studies which may not properly represent the impact of a measure. This especially affects measures that have different impact factors when applied at different rates, such as '1H Feed lipid additive' (Patra, 2013), or when experimental measurements include outliers. Future studies can further improve on our results by increasing the number mitigation measures and providing more robust impact factors.

The CH₄ and N₂O emission reductions are likely overestimated, because of simplified assumptions. First, the technological assumptions for the baseline do not represent the actual share in practice in the EU28. This is mostly problematic for measures assuming a change in management practices such as the method for spreading manure fertilizer, the type of floor and bedding for housing, the type of storage for slurry, and the type of feed. Creating a more representative baseline could be done with further research by altering the impact factors to account for the relative share of current practices and their relation to the total CH₄ and N₂O emissions. Second, our method to calculate emission reduction did not account for an increase in emissions caused by reductions in earlier emissions flows, i.e., pollution swapping. This is particularly an issue for N in manure which can be turned into N₂O directly or indirectly during manure management and fertilizer use. In contrast, carbon in manure can only be converted to CH₄ during anaerobic conditions which can occur during manure management but are minimal when manure is applied to arable land (Rotz, 2018). Furthermore, the emission flows for manure management that were used in our study are an aggregation of the actual emissions at different stages of manure handling such as at the animal housing and in long-term storage. Measures usually only directly affect emission flows at one of these stages, but the retained N and C in manure then move on into the next stage. If the emissions in this next stage are increased, the emissions were swapped rather than reduced. In total, 14% of the baseline emissions are from CH₄ in manure management and 12% are from N₂O related to manure excluding manure excreted on pasture. This is a significant source of uncertainty for the emission reduction potential of combinations. Further research can address this limitation by using a more fine-grained baseline of emission flows suitable for accounting pollution swapping.

Furthermore, the hypothetical reduction potentials of combinations of measures resulting from our analysis require experimental verification. We assume that the impact factors of combined measures are multiplicative for each emission source. This diminishes the effect of each additional measure for the same emission source. In principle, this can both under- and overestimate the actual impact of measures. Negative interactions between measures have been limited in this study by the applied exclusion rules. However, additive interactions were not accounted for in our method which may be relevant for some measures, particularly those targeting enteric fermentation (Patra et al., 2017). If true, this would increase the reduction potential. Addressing this limitation requires experimental studies verifying reduction potential of promising combinations, as well as expanding the method to include additive impact factors and experimental research to identify additive measure combinations.

Our analysis is limited to the reduction of direct CH₄ and N₂O emissions and does not comprehensively assess the sustainability of the mitigation measure combinations. First, we did not take into account the life cycle GHG emissions of the mitigation options which may reduce the overall mitigation potential. Second, some measures may negatively affect the health of livestock. For example, feeding nitrate to animals can result in nitrite poisoning because nitrate is reduced to nitrite faster in the rumen than nitrate to NH₃ (Sar et al., 2005). Third, feed cultivation and livestock

husbandry contribute to other environmental issues such as eutrophication and biodiversity (Groenestein et al., 2019; Knudsen et al., 2019). Thus, reducing CH₄ and N₂O may lead to environmental burden shifting, but measures may also result in reductions of other emissions. For example, Fig. 11 shows that, based on our results, most combinations for dairy cattle lead to NH₃ reductions. Finally, we did not take into account how the measures would influence the profitability of farmers. This issue may be critical for uptake by farmers considering the expected decline in real income for agriculture in the EU28 (European Commission, 2017). The measures influence profitability through their costs and the potential impact on livestock output. An example of the latter is increasing the fat content of feed to more than 6% through lipid additives which reduces feed digestion and in turn reduces milk production (Patra et al., 2017). Including the costs would also allow the combinations to be ranked based on the estimated cost per unit of reduced greenhouse gas emissions. In future research, cost and other impacts can be included in the method presented in this study, although this may require additional research to provide the relevant data input.

5. Conclusion

In this research, we assessed the potential of CH₄ and N₂O emission reduction in the meat and dairy supply chains in the EU28. We identified 44 combinations of measures taking into account rules for measures that are mutual exclusive or have to be combined. Based on our simplified technological baseline, the combinations with the highest mitigation reduce the CH₄ and N₂O emissions of beef cattle by 57%, dairy cattle by 47%, swine by 70%, sheep by 48%, and applying synthetic fertilizers to feed production by 44%. In general, the combinations with a high mitigation potential show a pattern of a few core mitigation measures targeting the largest emission flows combined with a wider set of other measures. For beef and dairy cattle in particular, the measure '1C Feed 3NOP additive' is critical for high reductions as it strongly reduces enteric fermentation. The number of measures in a combination also appear to influence how much can be mitigated.

Our study pathway estimates that implementing the highest mitigating combination for each category can potentially reduce meat and dairy related CH₄ by 62% and N₂O by 32%, resulting in an overall 54% reduction in CO₂-eq. Assuming that no additional measures are implemented, these combinations can potentially reduce total agricultural CH₄ and N₂O emissions by 42% which lies between the 1.5TECH (38%) and 1.5LIFE (49%) pathways modelled for the EU28 to reach net-zero emissions. Although this is based on a simplified technological baseline, this indicates that implementing more measures in the meat and dairy sectors could create room for further reduction than in the modelled pathways. However, technical measures are incapable of fully eliminating agricultural CH₄ and N₂O, so there remains a need for CO₂ removal technologies.

Besides the direct results, our research uncovers knowledge gaps that future studies can address. First, the impacts of the different combinations require experimental research to verify the combined emission reduction potential. In particular, this experimental research could focus on potential high impact combinations as highlighted in this study. Second, experimental research should focus on applying measures to categories where they have not been tested yet and on assessing all relevant CH₄ and N₂O emission flows for each measure. Third, more research should focus on the potential additive measure combinations which could significantly change the potential mitigation within the livestock sector. Finally, future research can also improve the method by including a more representative technological baseline for the EU28, using a more detailed baseline for the emission flows to better account for

pollution swapping, including cost and other impacts, and by increasing the number mitigation measures and providing more statistically robust impact factors.

CRedit authorship contribution statement

S.I. aan den Toorn: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Data curation. **E. Worrell:** Conceptualization, Writing – review & editing, Project administration. **M.A. van den Broek:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.127138>.

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