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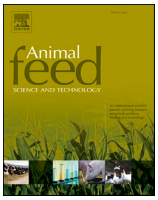

Review article

Effect size and land-requirements of plant-based feeding interventions to reduce methane emissions from cattle and sheep in European subalpine regions

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ABSTRACT

In the past decades, hundreds of scientific studies have aimed at identifying feeding interventions to reduce the production of enteric methane (CH_4) from ruminant livestock. However, mitigation measures for extensive grassland-based ruminant production systems are largely lacking, or are hardly transferred into practice. The aim of this study was to determine the effect size of plant-based feeding interventions in cattle and sheep, and to assess the feasibility of implementation by calculating the agricultural area required to grow these products. A literature research was carried out to identify plant-based feeding interventions, where the effect size was determined by at least three publications measuring CH_4 *in vivo* in cattle or sheep, and which could be grown in temperate Europe. Using Switzerland as an example for a country with low availability of arable land and representative for grass-based ruminant production systems, it was estimated how much agricultural land would be required to grow these plant products in sufficient quantities to achieve the effects in the entire population of Swiss cattle or sheep. The review revealed that the evident effect size of plant-based feeding interventions in cattle reached only in few cases an average reduction in CH_4 per unit dry matter intake (DMI) of 20%, and often stayed below 10%. For sheep, one intervention (*Lotus ssp.*) exceeded 30% reduction of methanogenesis, the others fitted into the results for cattle. The calculations revealed that for many products, the area required to supply them to the entire Swiss cattle population would exceed the current national area of arable land. For the effective plant-based products identified for sheep, much less agricultural land would be required, due to the small population size. Given the low efficacy of the interventions and the vast requirements for land resources to produce the respective plants, the cost of implementing them appears to exceed the benefit in greenhouse gas reduction. While feeding products of arable cultures appear hardly feasible for CH_4 mitigation, implementing effective pasture plants in existing grasslands may be more practicable. Despite their comparably low efficacy to reduce CH_4, including plants rich in plant secondary metabolites into multispecies swards would be a feasible approach with comparatively low risks and further benefits. Overall, the calculations reveal that the implementation of plant-based CH_4 mitigators may largely increase the competition for the use of agricultural land, which is the opposite of intentions with grassland-based dairy and meat production, and which affects climate change as well.

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1. Introduction

Due to its properties as a greenhouse gas, methane (CH_4) enterically produced by ruminant livestock has received increasing interest from the scientific community (Arndt et al., 2022; Beauchemin et al., 2008; Knapp et al., 2014), policy makers and agricultural professionals. With the current goals to reduce global warming, much effort has gone into investigating measures to reduce enteric CH_4 emission from ruminants. In the past 40 years, the number of publications on this topic has increased almost exponentially (Fig. 1), and the investigated options to reduce enteric CH_4 production include feeding strategies, breeding for low emitting animals, increasing animal longevity, or dietary supplementation of compounds inhibiting ruminal methanogenesis. Several comprehensive review articles have recently been published with the aim to collate viable mitigation methods and to assess their efficacy. One of the most recent articles (Arndt et al., 2022) identified several measures which have shown promising results in *in vivo* trials. Among them are strategies such as reducing the amount of fibre in the ruminant's diet (which is the main substrate for CH_4-formation) by decreasing the ratio of roughage to concentrates, or the supplementation with synthetic CH_4 inhibitors (e.g. 3-NOP), Ionophores (Monensin) or Nitrate. While the efficacy of these methods is promising, they are not suitable for all ruminant production systems. In particular, extensive grass-based systems with a high emphasis on low input of external nutrients, animal welfare and sustainability (e.g. organic farming) require different assessments and solutions (Eugène et al., 2021; Zeitz et al., 2012). Mitigation through reducing dietary roughage:concentrate proportions is contrary to targets of grassland-based production (Leiber, 2022). Feed additives or a change of the basal ration can be practicable for intensive husbandry systems, where the composition of the diet can be monitored and controlled, and where it is offered at a constant rate to each animal. However, implementing additives in pasture-based systems is a challenge, as the animals show a higher variability in intake and diet composition and a constant administration of feed additives is much more challenging. Furthermore, synthetic feed additives are not allowed in organic agriculture (Varga et al., 2022), and for reasons of feed-food competition the use of higher concentrate amounts is criticized for having only limited positive effects on larger scale system models (Schader et al., 2015). Herb-based approaches, which often rely on the modulating effects of plant secondary compounds in the rumen appear as interesting options, and are frequently assessed and reported (Beauchemin et al., 2008; Khiaosa-Ard and Zebeli, 2013; Min et al., 2020). However, some of these approaches may not be viable due to low availability, production costs, unsustainable production, or because they are also in competition with human food production due to limited arable land resources. Moreover, realistic figures of production conditions for such plants containing effective CH_4 mitigating substances have rarely been assessed or estimated. Most of the experimental studies available do not ask the question of feasibility of production, nor do large comprehensive reviews (Arndt et al., 2022; Min et al., 2020). Thus, proposed measures for mitigation of CH_4 on the basis of plant feed additives most often lack evidence of practical feasibility.

The aim of this review was therefore to collate mitigation options through plant-based feeding interventions and to assess their effectiveness and the feasibility of implementation, focusing on the area required to grow the product in question. The latter was assessed based on the example of Switzerland, where grassland-based animal production is predominant and crucial (Hofstetter et al., 2014; Leiber et al., 2017) due to the limited availability of arable land. At the same time, the limitations in arable land in Switzerland set limits for producing feed additives within the region. Therefore, Switzerland appears to be a model specific for subalpine and mountainous regions in Europe, but the basic challenge may be elucidated for other regions short in arable land and with a high prevalence of ruminant livestock. By reporting the potential effects together with the agricultural areas required to realize them, this approach aims at contributing to the discussion about the urgently needed implementation of decades-long research efforts on the topic.

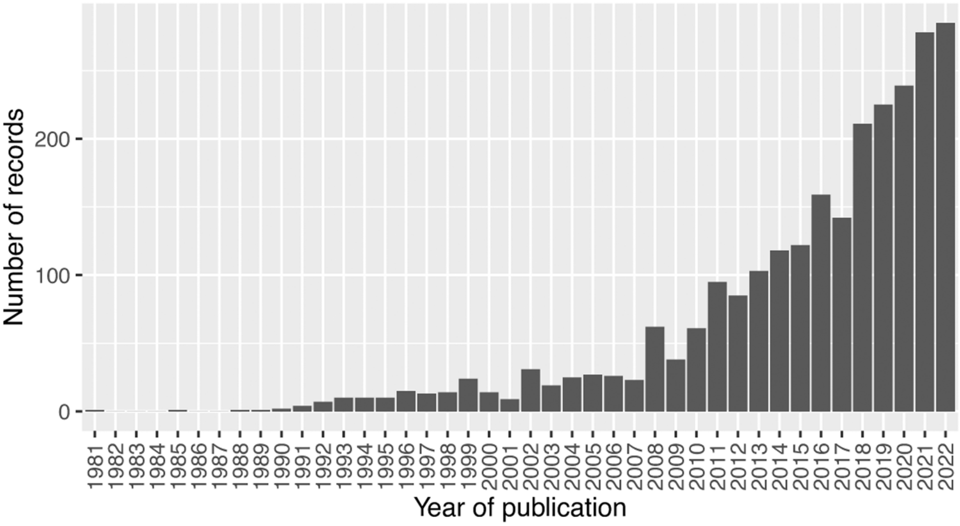

Fig. 1. Number of scientific publications on CH_4 production in ruminants from 1980 to 2022. The data are based on a Web of Science search including the search terms 'methane' and 'ruminant'.

Table 1
List of the plant species or process-based interventions, which were assessed in the publications selected for this literature review.

Plant species	Material used for feeding experiments	N studies investigating product		References
		Cattle	Sheep	
Allium sativum	Leaves, bulb, extract	3	3	Kim et al. (2018);Ma et al. (2016);Meale et al. (2014);Panthee et al. (2017);Staerfl et al. (2012);van Zijderveld et al. (2011)
Astragalus cicer	Whole plant	1	0	Stewart et al. (2019)
Brassica campestris	Fodder	0	2	Sun et al. (2014);Sun et al. (2012)
Brassica napus	Seed, oil, expeller, fodder	8	4	Bayat et al. (2018);Beauchemin and McGinn (2006);Brask et al. (2013);Gidlund et al., (2015, 2017);Hellwing et al. (2012);Machmüller et al. (2000); Moate et al. (2011);Pinares-Patiño et al. (2016);Sun et al. (2015);Sun et al. (2014);Sun et al. (2012)
Brassica oleracea	Fodder	0	1	Sun et al. (2012)
Calluna vulgaris	Whole plant	0	1	Pérez-Barbería et al. (2020)
Carthamus tinctorius	Oil	1	0	Bayat et al. (2018)
Carum carvi	Oil	1	0	Lejonklev et al. (2016)
Castanea sativa	Extract	1	0	Aboagye et al. (2019)
Cichorium intybus	Whole plant	0	4	Niderkorn et al. (2019);Sun et al. (2011);Sun et al. (2012);Waghorn et al. (2002)
Corylus avellana	Leaves	1	1	Terranova et al. (2021); S.Wang et al. (2018)
Eutrema japonicum	Oil	1	0	Mohammed et al. (2004)
Glycine max	Beans, meal, oil	5	3	Beck et al. (2019);Boland et al. (2020);Fiorentini et al. (2014);Gidlund et al. (2015);Lima et al. (2019); V.Lind et al. (2020);Mao et al. (2010);Neto et al. (2015)
Hedysarum coronarium	Whole plant	1	1	Waghorn et al. (2002);Woodward et al. (2002)
Helianthus annuus	Oil, seeds	6	1	Bayat et al. (2017);Beauchemin et al. (2007);Chuntrakort et al. (2014);Machmüller et al. (2000);Mata e Silva et al. (2017);McGinn et al. (2004); Woodward et al. (2006)
Hordeum vulgare	Seeds	0	1	Moss and Givens (2002)
Juniperus sp.	Oil	1	0	Meale et al. (2014)
Linum usitatissimum	Seeds, oil, extrudate	14	1	Bayat et al. (2018);Benchaar et al. (2015);Boland et al. (2020);Fiorentini et al. (2014);Focant et al. (2019);Hammond et al. (2015);Hassanat and Benchaar (2021);Machmüller et al. (2000);Martin et al., (2008, 2016);Pinares-Patiño, Ulyatt et al. (2003);Poteko et al. (2020);van Gastelen et al. (2017);van Zijderveld et al. (2011);Veneman et al. (2015)
Lotus sp.	Whole plant	6	3	Dini et al. (2012);Hammond et al. (2014);Lagrange et al. (2020);Pinares-Patiño, Ulyatt et al. (2003);Stewart et al. (2019);Waghorn et al. (2002); Woodward et al., (2001, 2004)
Lupinus sp.	Beans	1	0	Staerfl et al. (2012)
Medicago sativa	Whole plant	6	2	Chaves et al. (2006);Doreau et al. (2014);Gere et al. (2021);Hassanat et al. (2014);McCaughey et al. (1999);Stewart et al. (2019);Waghorn et al. (2002);Woodward et al. (2001)
Morus sp.	Extract	0	2	Chen et al. (2015);Ma et al. (2017)
Onobrychis sp.	Whole plant	5	1	Bouchard et al. (2015);Chung et al. (2013);Huyen et al. (2016);Lagrange et al. (2020);Niderkorn et al. (2019);Stewart et al. (2019)
Origanum vulgare	Leaves, extract	7	2	Benchaar (2020);Hristov et al. (2013);Kolling et al. (2018);Lejonklev et al. (2016);Olijhoek et al. (2019);Stefenoni et al. (2021);Tekippe et al. (2011); C. J.Wang et al. (2009);Zhang et al. (2021)
Raphanus sativus	Whole plant	0	1	Sun et al. (2014)
Sanguisorba minor	Whole plant	1	0	Stewart et al. (2019)
Sorghum sp.	Whole plant	2	0	de Oliveira et al. (2007);Gere et al. (2021)
Tagetes erecta	Whole plant	1	0	Pineda et al. (2018)
Trifolium pratense	Whole plant	4	3	Gidlund et al. (2017);Hammond et al. (2014);Kasuya and Takahashi (2010);Niderkorn et al. (2015);Niderkorn et al. (2019);van Dorland et al. (2007);Waghorn et al. (2002)
Trifolium repens	Whole plant	4	4	Enriquez-Hidalgo et al. (2014);Hammond et al. (2013);Hammond et al. (2014);Lee et al. (2004); V.Lind et al. (2020);Niderkorn et al. (2017);Ulyatt et al. (1988);van Dorland et al. (2007)
Triticum sp.	Whole plant silage	1	0	McGeough et al. (2010)
Vaccinium myrtillus	Whole plant	0	1	Pérez-Barbería et al. (2020)
Vicia faba	Beans	1	0	Cherif et al. (2018)
Vitis vinifera	Grape marc	3	0	Caetano et al. (2019);Moate et al., (2014, 2020)

(*continued on next page*)

Table 1 (*continued*)

Plant species	Material used for feeding experiments	N studies investigating product		References
		Cattle	Sheep	
Zea mays	Whole plant, silage, seeds, oil	21	0	Benchaar et al., (2014, 2015);Brask et al. (2013);Dall-Orsoletta et al. (2019);Doreau et al. (2014);Hammond et al. (2015);Hart et al. (2014);Hassanat et al., (2013, 2017);Hatew et al. (2015);Hindrichsen et al. (2006);Judy et al. (2019);Lettat et al. (2013);Moate et al. (2011);Na et al. (2013); Schwarm et al. (2015);Staerfl et al. (2012);Uddin et al. (2020);van Dorland et al. (2007);van Gastelen et al. (2015)

Other plant-based products		N studies investigating product		References
		Cattle	Sheep	
Biochar		2	1	L.Lind et al. (2020);Terry et al. (2019);Winders et al. (2019)
Brewers grains		2	0	Duthie et al. (2015);Moate et al. (2011)
Carvacol		1	0	Benchaar (2020)
DDGS		6	0	Benchaar et al. (2013);Bernier et al. (2012);Garnsworthy et al. (2021);Hoffmann et al. (2021);Judy et al. (2019);McGinn et al. (2009)
Essential oil blends		5	0	Alemu et al. (2019);Beauchemin and McGinn (2006);Castro-Montoya et al. (2015);Hart et al. (2019);Tomkins et al. (2015)
High quality pasture or forage		2	5	Archimède et al. (2018);Boadi and Wittenberg (2002);Fraser et al. (2014);Jonker et al., (2014, 2018);Ulyatt et al. (2005);Zhao et al. (2017)
Industry byproducts		1	0	Pang et al. (2018)
Mixed concentrates supplementation or increase in ration		12	3	Aguerre et al. (2011);Barbero et al. (2015);Chong et al. (2014);Ferris et al. (2020);Hoffmann et al. (2021);Jiao et al. (2014);Liu et al. (2013);Lovett et al. (2005);Muñoz et al. (2015);Neto et al. (2015);Patel et al. (2011);Pedreira et al. (2013);Silvestre et al. (2021);van Wyngaard et al. (2018); C.Wang et al. (2007)
Mixed legume forages	Hay, pasture	2	0	Boadi and Wittenberg (2002);Dini et al. (2018)
Multispecies pasture containing clover, plantain, chicory and other species		4	0	Carmona-Flores et al. (2020);Jonker et al. (2019);Loza et al. (2021);Wilson et al. (2020)
Partial mixed ration		1	0	O'Neill et al. (2012)
Resveratrol		0	1	Chen et al. (2015)
Tannin pellets		1	0	Focant et al. (2019)

Processes	N studies investigating product		References
	Cattle	Sheep	
Decrease maturity of cut forage	7	1	Brask et al. (2013);Chung et al. (2013);Hironaka et al. (1996);Kasuya and Takahashi (2010);Machado et al. (2015);Pang et al. (2018);Warner et al. (2017)
Decrease pasture maturity	10	2	Barbero et al. (2015);Boland et al. (2013);Congio et al. (2018);Hart et al. (2009);Kidane et al. (2018);Molano and Clark (2008);Muñoz et al. (2016);Pinares-Patiño, Baumont et al. (2003);Ramírez-Restrepo et al. (2020);Warner et al., (2016, 2015);Wims et al. (2010)
Grazing vs conserved forage silage or TMR	2	5	Chong et al. (2014);Dall-Orsoletta et al. (2016);Liu et al. (2013);McDonnell et al. (2016);Pinares-Patiño, Ulyatt et al. (2003);Santoso et al. (2007);Zhao et al. (2016)
Increase feeding frequency	1	0	Jonker et al. (2016)
Increase grazing pressure	4	1	Chiavegato et al. (2015);de Souza Filho et al. (2019);DeRamus et al. (2003);McCaughey et al. (1997);Savian et al. (2014)
Increase intake	6	4	Boadi and Wittenberg (2002);Goopy et al. (2020);Hammond et al. (2014);Hironaka et al. (1996);Jonker et al., (2014, 2016);O'Neill et al. (2012);Sun et al. (2012); Warner et al. (2017);Yang et al. (2021)
Increase maize maturity	3	0	Hatew et al. (2016);McGeough et al. (2010);Nishida et al. (2007)
Milling or pelleting forage	1	2	Hironaka et al. (1996);Zhao et al., (2016, 2017)
Nitrogen fertilization of pasture	2	1	Amaral et al. (2016);Warner et al., (2015, 2016)
Rotational stocking	1	2	McCaughey et al. (1997);Savian et al., (2014, 2018)
Spatial separation of forages	1	0	Carmona-Flores et al. (2020)

2. Material & methods

2.1. Search strategy, selection of publications, calculation of effect size

In an in-depth literature research, data was collated on CH_4 reduction potential of plant-based feeding interventions and supplements. The initial search was carried out on Web of science, Pubmed and Google Scholar, using the terms “enteric”, “methane”, “ruminant” in different combinations. Once a certain feeding intervention was identified, a specific search for further publications was carried out by using the search terms “[feeding intervention]”, “methane”, “ruminant”. Furthermore, the references given in relevant recent reviews and studies on specific interventions were screened for additional publications. Publications to be included in the database were selected based on the following criteria: in vivo CH_4 measurements with established methods (respiration chamber, SF6, head hoods or boxes, e.g. Greenfeed ®); relevant ruminant grazer-type livestock species, i.e. cattle or sheep; information on diet composition and DMI available; investigation of an intervention and a control treatment to allow the calculation of the percentage in decrease or increase of CH_4 emissions; sound study design (e.g. randomized block, Latin square, cross-over); peer-reviewed publication. Due to the different study designs of the included publications, some investigated the effect of the potential mitigator in the same animals on different diets, while others assessed their effect in different groups of animals, where one would receive a control diet and the other the treatment diet. For each of the publications, the control treatment was considered the diet defined as control by the respective authors. For stabled animals, this was generally the basal diet without the plant-based additive. In studies where the effect of a certain type of concentrates was assessed, the control diet consisted of either the diet without concentrates or the diet with a different type of concentrates. In studies where the effect of a certain pasture composition was studied, the control was generally a pasture without the studied plants, e.g. pure ryegrass or grass-clover compared to multispecies swards. It has to be noted, that the control and basal diet often differed between studies assessing the same plant-based feeding intervention, which probably added to the variability in the results. It has previously been shown that absolute enteric CH_4 production is highly correlated with DMI (Hammond et al., 2013; Niu et al., 2018; van Lingen et al., 2019), therefore, publications which provided absolute emissions per animal without information on DMI were excluded. While DMI reported for experiments performed indoors or with animals fed individually is generally accurate, the assessment of DMI on pasture is more challenging and less precise (e.g. by using fecal markers or by measuring pre- and post-grazing herbage mass). Although all publications included in this review were peer-reviewed, it should be noted that the lack of methods to accurately quantify intake in grazing animals may have added some variability to the data.

Only plant-based interventions were included (exclusion of animal products, synthetic substances, ionophores, micro-organisms, or antibiotics). Measures were only included, if they could be implemented in temperate climatic regions, e.g. if there was evidence for successful cultivation of the crop or plant species in temperate climatic regions; products based on tropical plants (e.g. coconut, acacia, tea, tropical algae) were excluded. Furthermore, studies where animals received a diet with more than 40% concentrates were excluded, as this is the upper limit for concentrates in the EU Organic Regulations (European Commission, 2018) and this amount of concentrates is seldom exceeded in grass-based systems (Muñoz et al., 2018). Approximately 2000 publications were screened initially based on their title and abstract, 369 of which were downloaded for further screening and 183 of which met the inclusion criteria and were included in the database. The following information was gathered from all publications: type of intervention, composition of the control diet, animal species, number of animals per treatment, experimental design, inclusion rate of the tested feed components

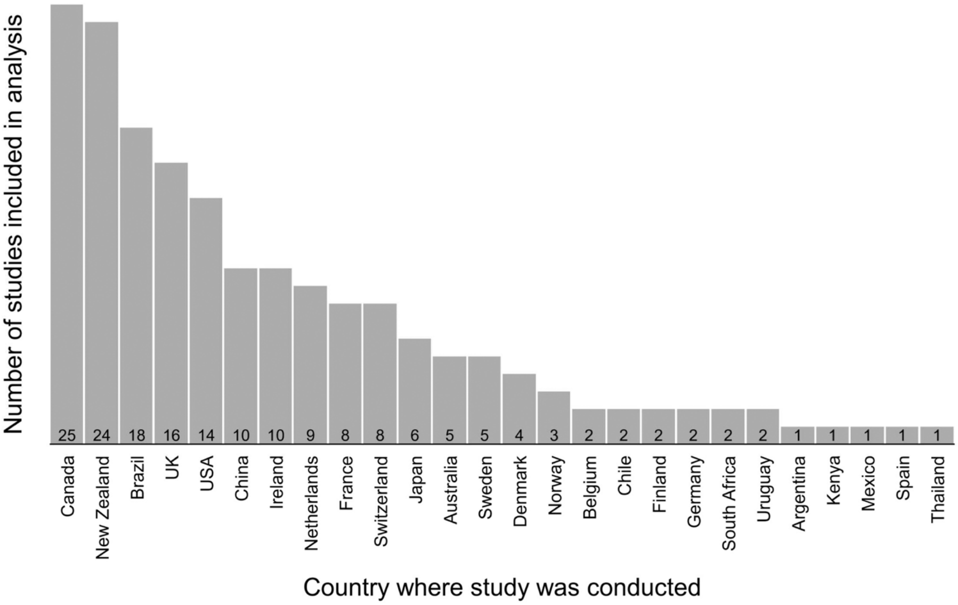

Fig. 2. Number of publications included in the analysis in this review divided by the country in which the experiments had been conducted.

Table 2

[a]Evaluation of the amount and area required to supply the entire Swiss sheep and cattle population with selected plant-based feed products previously assessed for their potential to reduce CH_4 emissions.

Product	Number of studies included	Mean reduction CH_4 per g/kg DMI	±SD	Mean inclusion rate in ration reported in these studies	Daily required amount per head	Annual amount required for entire Swiss population	Estimated annual yield of product in CH	Area required to grow product for entire Swiss population	Swiss arable or grassland* area required to grow product for entire population	References for yield estimate
		%	%	DM %	DM kg/day	DM t/year	DM t/ha	ha	%	
Cattle										
Brassica napus (expeller)	3	1.7	8.1	13.7	2.1	1134613	1.8	620007	157	Agristat (2022)
Brassica napus (oil)	3	14.8	3.0	5.7	0.9	472832	1.2	404130	102	Agristat (2022)
Helianthus annuus (oil)	5	19.6	5.4	4.0	0.6	330724	1.2	285107	72	Agristat (2022)
Linum usitatissimum (extruded)	6	10.2	9.6	10.5	1.6	874186	1.2	728488	184	Diepenbrock and Pörksen (1992); Mirzaie et al. (2020);Swiss granum (2022)
Linum usitatissimum (oil)	8	17.7	16.0	4.1	0.6	338918	0.8	423647	107	Diepenbrock and Pörksen (1992); Mirzaie et al. (2020);Swiss granum (2022)
Lotus sp.	6	7.9	13.4	97.5	14.6	8087916	10.0	808792	133 *	Bullard and Crawford (1995); Elgersma et al. (2015);Hunt et al. (2015);MacAdam and Griggs (2013);Minneé et al. (2007);Özpınar et al. (2019)
Medicago sativa	6	0.0	21.3	78.5	11.8	6509044	13.0	500696	83 *	Bundesamt für Landwirtschaft (2016);LfL Institut für Pflanzenbau und Pflanzenzüchtung (2016);Suter and Frick (2022)
Multispecies pastures containing tannin rich species	4	2	18.3	93.3	14.0	7739513	10.0	773951	128 *	Grace et al. (2019);Jonker et al. (2019);Moloney et al. (2020)
Onobrychis sp.	5	7.8	6.6	86.0	12.9	7133957	9.0	792662	131 *	Agridea (2012);Malisch et al. (2017)
Origanum vulgare (leaves)	5	11.4	19.0	1.6	0.2	134161	3.0	44720	11	Baranauskiene et al. (2013); Dordas (2009);Rey et al. (2002); Sotiropoulou and Karamanos (2010)
Trifolium pratense	4	2.5	7.4	75.5	11.3	6259096	11.5	544269	90 *	Bundesamt für Landwirtschaft (2016)
Trifolium repens	4	2.0	12.8	75.9	11.4	6298971	8.0	787371	130 *	Bundesamt für Landwirtschaft (2016)
Vitis vinifera (grape marc)	3	14.4	6.4	26.9	4.0	2229858	1.0	2322768	587	Spinei and Oroian (2021);Taylor et al. (2005)
Zea mays (silage)	14	6.0	5.9	53.4	8.0	4430760	20.0	221538	56	Baux (2013)
Sheep										

(*continued on next page*)

Table 2 (*continued*)

Product	Number of studies included	Mean reduction CH_4 per g/kg DMI	±SD	Mean inclusion rate in ration reported in these studies	Daily required amount per head	Annual amount required for entire Swiss population	Estimated annual yield of product in CH	Area required to grow product for entire Swiss population	Swiss arable or grassland* area required to grow product for entire population	References for yield estimate
		%	%	DM %	DM kg/day	DM t/year	DM t/ha	ha	%	
Brassica napus (forage)	3	20.6	8.0	100.0	1.5	188082	5.0	37616	10	Keogh et al. (2012);Sala et al. (2008)
Cichorium intybus	4	5.5	4.4	89.6	1.3	168490	8.0	21061	3 *	Lee et al. (2015);Li and Kemp (2005)
Lotus sp.	3	41.0	18.6	100.0	1.5	188082	10.0	18808	3 *	Bullard and Crawford (1995); Elgersma et al. (2015);Hunt et al. (2015);MacAdam and Griggs (2013);Minneé et al. (2007);Özpınar et al. (2019)
Trifolium pratense	3	3.2	14.2	70.8	1.1	133224	11.5	11585	2 *	Bundesamt für Landwirtschaft (2016)
Trifolium repens	4	-10.4	12.4	80.4	1.2	151171	8.0	18896	3 *	Bundesamt für Landwirtschaft (2016)
							Estimated current amount imported into CH (t DM / y)		**Increase required in import (factor)**	
DDGS (in cattle)	6	0.5	12.9	18.3	2.7	1516283	32850		46	Furrer and Grüter (2020)

[a] The table only includes products identified during the literature research, for which at least three independent publications were available. The inclusion rate of the product in the animal's diet is based on an average from the publications on which the average reduction in CH_4 is based. Required amounts on a population level are calculated based on 1.52 mio head of cattle and 0.34 mio sheep kept in Switzerland (CH) in 2020 (Bundesamt für Statistik, 2021). The average yields of the products and the current production in CH were estimated based on references given in the last column. The percentage of agricultural area required to grow sufficient product for the entire cattle and sheep population was based on the total arable area in CH for arable cultures (0.39 mio ha), or for pasture plants for the current area of pastures and meadows (0.61 mio ha, indicated with *) (Bundesamt für Statistik, 2021). Cells, where no information was available are denoted with NA.

(where applicable), CH_4 emission in g/kg DMI, and where available in g/kg milk, or in g/kg average daily gain (ADG). In most studies, these variables were extracted directly from the results section but in certain cases they were calculated based on the information given as CH_4 emission in g/d and daily DMI, milk yield or ADG. The data from all publications were checked twice for correctness. 96% of the included studies listed in Table 1 were published after the year 2000. Fig. 2 illustrates in which countries the experiments included in further analyses where conducted.

Interventions were assigned to one of two concepts: 1) Product based interventions aimed at changing the composition of the animal's diet by introducing other feedstuffs or changing their ratio, 2) Process based interventions, relying on different management processes, such as grazing management, harvest date, or conservation of feedstuffs.

In order to assess the variability of the effect size of certain interventions, publications evaluating the same intervention were grouped. For process-based interventions, publications were grouped based on the nutritional strategy proposed to reduce CH_4 production (e.g. decreasing forage maturity or increasing grazing pressure). If several experiments were carried out evaluating the same intervention within one publication, the effect size was averaged over all trials to create one value per publication. If different treatments were investigated within the same publication, effect size was averaged within treatment.

As the impact of feeding interventions was found to differ between ruminant species (van Gastelen et al., 2019) their effectiveness was calculated separately for cattle and sheep. For determination of effectiveness of individual feeding interventions, products or processes that had been investigated in the same species in at least three independent publications were considered. The effect size of these interventions was expressed in percent reduction (or increase) in CH_4 in g/kg DMI, milk or ADG using the following formula:

$$([CH_4 \text{ in g/kg on control diet}] - [CH_4 \text{ in g/kg on intervention}]) / [CH_4 \text{ in g/kg on control diet}] * 100$$

Data were plotted in R Studio (version 3.6.1) using the packages *ggplot* and *beeswarm*.

2.2. *Assessing the land-requirements of selected product-based feeding interventions*

For the selected products where three independent publications were available to calculate a mean reduction in CH_4 g/kg DMI, the area required to grow the product was assessed. Products were not included in this analysis if they were an extract (e.g. an essential oil or a specific plant component, where no information was given on the amount of crude plant material required to produce it) or if they were unspecific (e.g. increase in feeding mixed concentrates). For the selected products, the average required daily intake (in % DMI) was calculated based on the publications assessing their effectiveness as a CH_4 inhibitor. In order to assess if these product-based interventions could be implemented for the entire population of cattle or sheep kept in Switzerland, the required daily percentage in DMI of each product was extrapolated based on an average feed intake per head (15 kg DM/d in cattle, 1.5 kg DM/d in sheep, estimated based on Agroscope, 2021; Bundesanstalt für Agrarwirtschaft und Bergbauernfragen, 2023; Steinwidder et al., 2007) and animal numbers in 2020: 1.52 Mio head of cattle and 0.34 Mio head of sheep (Bundesamt für Statistik, 2021). Based on these assumptions, it was calculated how much product would be required nationally on an annual basis (t DM per year). To evaluate, if the required amount could be met by the current Swiss production, a literature research was carried out to establish a potential average annual yield of the crop. All plants included in this research are currently grown in Switzerland, but the number of publications reporting national yields of the plants of interest was limited. Therefore, publications reporting yields from other temperate countries were also considered. Where several publications on the yield were available, we chose an average value within the range reported in these studies. Based on these yield estimates, we calculated how much area would be required to grow this amount of produce. For

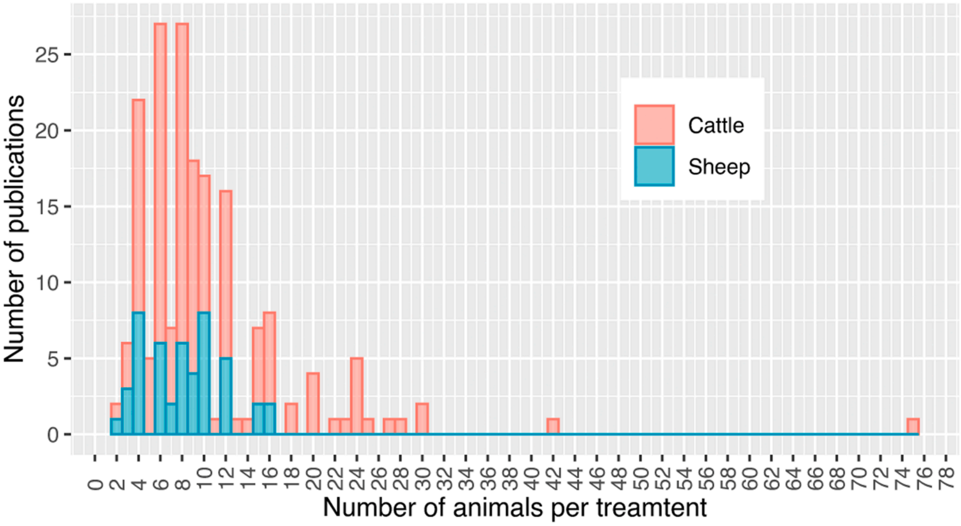

Fig. 3. Histogram of the number of animals used per treatment group in the selected publications.

arable cultures, the required area was then set into relation to the current arable area of Switzerland (0.4 mio ha). For cultures, which could be established on pasture and which made up the entire ration of the ruminants in the assessed studies, the area was set into relation with the current Swiss area consisting of pastures and meadows (0.6 mio ha). All references referring to effectiveness and yields of the selected feeding interventions are cited in Table 2.

3. Results

3.1. Dataset and effectiveness of feeding interventions

The literature search resulted in a cattle dataset of 137 publications providing data on CH_4 in g/kg DMI (Table 1). Of these publications, 79 further provided data on CH_4 in g/kg milk, and 24 on CH_4 in g/kg ADG. The sheep dataset was based on 47 publications for CH4 in g/ kg DMI, 2 of which further provided data on CH_4 in g/kg ADG (none provided CH_4 in g/kg milk). On average, the number of animals used within a treatment group to test the effect of an intervention was (mean ± standard deviation) 10 ± 8 individuals for cattle and 8 ± 4 individuals for sheep (Fig. 3).

On the control diets, which varied considerably between studies (e.g. TMR with 40% concentrates vs completely grass-based diet), the mean CH_4 emission (averaged within publications) was 22.6 ± 5.6 g/kg DMI, 17.6 ± 5.6 g/kg milk and 223 ± 138 g/kg ADG for cattle. For sheep, the average CH_4 emission on the control diet was 21.6 ± 5.2 g/kg DMI and 317 ± 233 g/kg ADG (note that ADG in sheep was only available from 2 publications). For cattle, the average reduction in CH_4 emissions (over all interventions and publications) achieved by the intervention treatments compared to the control treatment was 7.4 ± 11.5% for g/kg DMI, 8.5 ± 11.0% for g/kg milk and 13.3 ± 27.1% for g/kg ADG. In sheep, the average reduction in CH_4 was 8.2 ± 16.6% in g/kg DMI and 6.4 ± 51.1% in g/kg ADG. The range of the data is illustrated in Fig. 4 A-C.

Table 1 lists the plant species, products and processes investigated in publications included in the overall database. The most common product-based interventions tested in cattle were the replacement of grass-based roughage with legume forages or tannin-containing plants, an increase in content of concentrate or maize silage in the ration, supplementation of oilseeds (linseed, rapeseed, sunflower), plant-based oils, essential oils, or other extracts. In sheep, similar approaches were investigated, although most studies focused on forage-based interventions. The most frequently investigated processes were related to pasture and forage management, such as decreasing forage maturity, or increasing the animals' intake. For a large proportion of the studies included in the literature review, only one or two publications were found to investigate the same feeding intervention in the same ruminant species.

Effect sizes of selected individual product-based interventions to reduce CH_4 in g/kg DMI are shown in Figs. 5 and 6. These figures include interventions which had been studied in at least three independent publications in the respective species. In numerous interventions, the effect of the product differed drastically between studies using different or even the same control diets. For eleven out of the 17 selected feedstuffs assessed in cattle, there was a discrepancy in the effect, i.e. at least one study reported an increase in CH_4 in g/kg DMI while at least one other publication reported a decrease. The same was the case for three out of the seven selected feedstuffs in sheep. These interventions are those that have datapoints below 0 in Figs. 5 and 6. The effect averaged over the selected studies showed a reduction in CH_4 in g/kg DMI for 15 of the 17 product-based interventions in cattle and five out of six in sheep. The highest

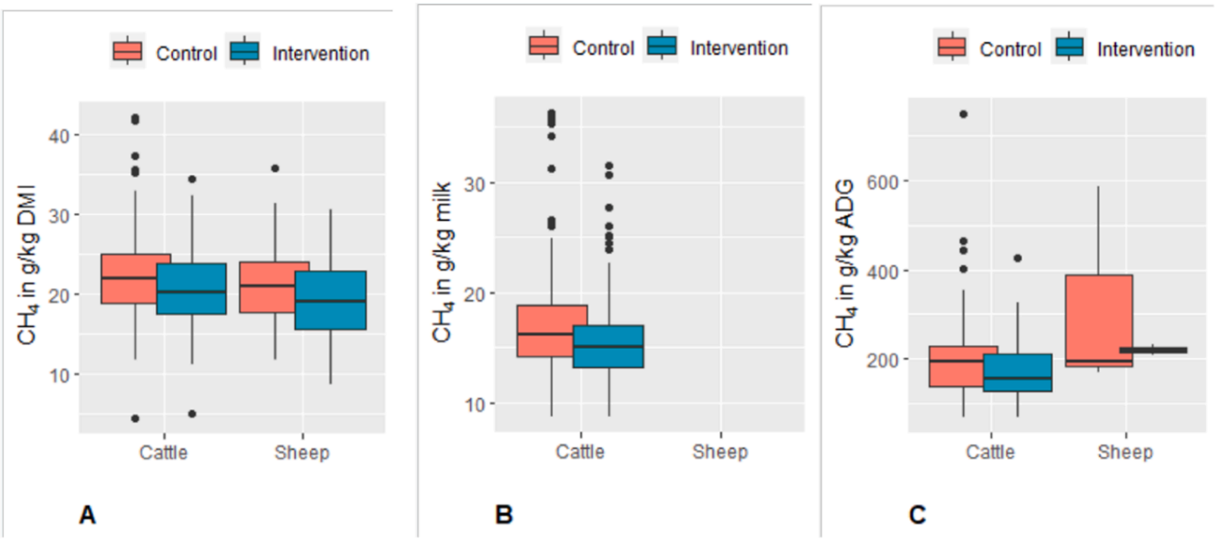

Fig. 4. Illustration of the range of all included literature data on CH_4 emission by cattle and sheep in g/kg DMI (A), g/kg milk (B) and g/kg ADG (C). In each of the selected publications, the emission of the animals was quantified in a control treatment (red) and at least one intervention (blue). Note that none of the included publications reported data on milk yield for sheep, and that sheep data in Fig. C are based on two publications only. Boxplots indicate median, as well as 25% and 75% quartiles.

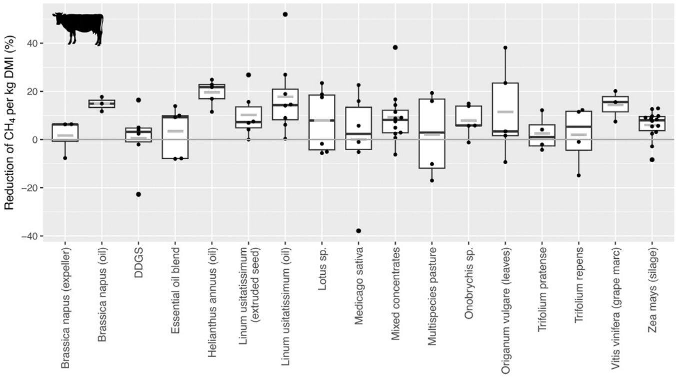

Fig. 5. Effectiveness of product-based feeding interventions in cattle expressed as percentage reduction in CH_4 in g/kg DMI. Individual dots represent the average effect of an intervention within one study. Boxplots indicate median, as well as 25% and 75% quartiles. The grey dash indicates the mean.

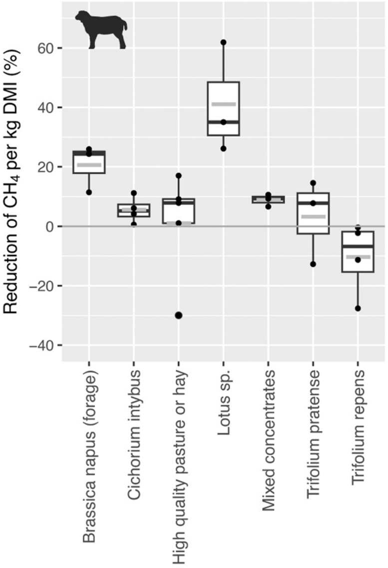

Fig. 6. Effectiveness of product-based feeding interventions in sheep expressed as percentage reduction in CH_4 in g/kg DMI. Individual dots represent the average effect of an intervention within one study. Boxplots indicate median, as well as 25% and 75% quartiles. The grey dash indicates the mean.

average effects with a consistent reduction in CH_4 in g/kg DMI in cattle were found for the feeding of rape oil (15%), sunflower oil (20%), linseed oil (18%) and grape marc (14%). The feeding of linseed and oregano leaves showed an average reduction in CH_4 in g/kg DMI above 10%, but for both products, there were studies reporting no effect or an increase in CH_4 in g/kg DMI. In sheep, the feeding of *Brassisa napus* fodder and *Lotus sp.* resulted in the highest average reductions in CH_4 in g/kg DMI of 21% and 41% respectively. Several interventions were investigated in both species: the supplementation or increase in concentrates, the feeding of *Lotus sp.*, *Trifolium pratense* and *Trifolium repens*. The supplementation of concentrates and the feeding of *Trifolium pratense* show a similar reduction in CH_4 in g/kg DMI in both species of approximately 10% and 3%, respectively. The reduction in CH_4 in g/kg DMI when feeding *Lotus sp.* was considerably higher in sheep than in cattle (41% vs 8%). The effect of feeding *T. repens* was low in cattle and even adverse in sheep (2% vs −10%).

For eleven of the selected products for cattle, there were at least three publications available to assess the efficacy with regard to CH_4 in g/kg milk (Fig. 7A). With regard to the effect on in CH_4 in g/kg ADG there were three publications assessing the effect of supplementing or increasing the amount of concentrates in the diet (Fig. 7B). The plots indicate that products, which show a reduction in CH_4 in g/kg DMI in cattle also show a reduction in CH_4 in g/kg milk or ADG, except for multispecies pastures, where on average CH_4 in g/kg milk was increased.

With regard to the selected process-based interventions in cattle (Fig. 8A), two of them showed a reduction of CH_4 in g/kg DMI in all studies: an increase in grazing pressure and an increase in maize maturity. For sheep (Fig. 8B), an increase in intake was associated with a reduction in CH_4 in g/kg DMI in all assessed studies. The effect of the remaining processes showed a discrepancy between

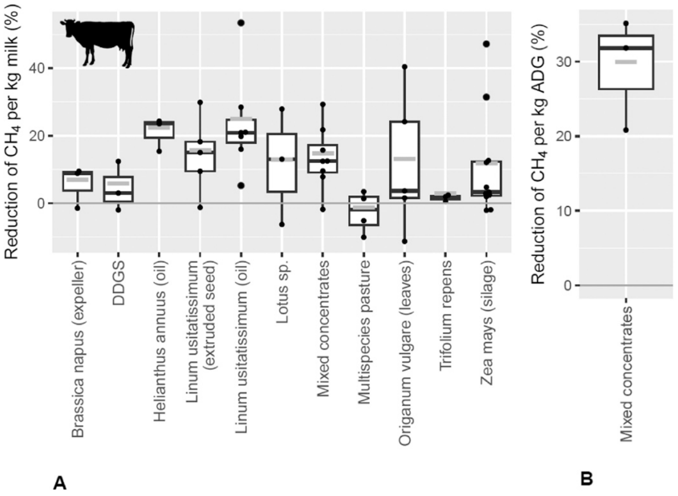

Fig. 7. Effectiveness of product-based feeding interventions in cattle, where at least three studies were available to assess the effect on CH_4 in g/kg milk (A) and CH_4 in g/kg ADG (B). For sheep neither variable was assessed at least three times for the same product. Individual dots represent the average effect of an intervention within one study. Boxplots indicate median, as well as 25% and 75% quartiles. The grey dash indicates the mean.

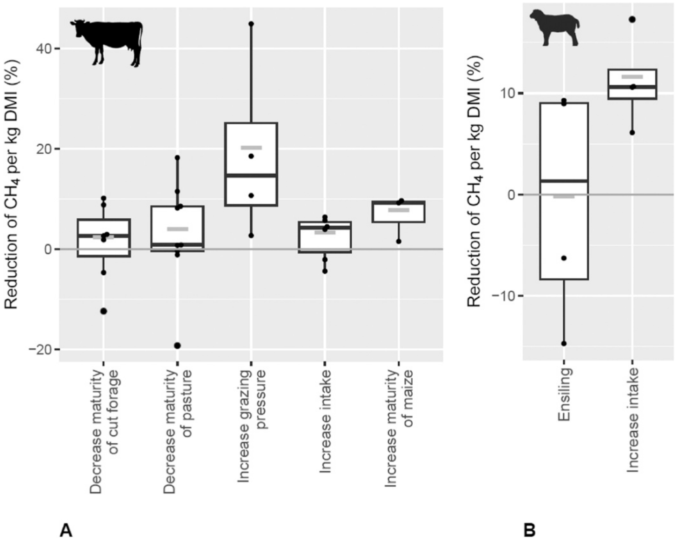

Fig. 8. Effectiveness of process-based feeding interventions in cattle (A) and sheep (B) expressed as percentage reduction in CH_4 in g/kg DMI (note the difference in scale). Individual dots represent the average effect of an intervention within one study. Boxplots indicate median, as well as 25% and 75% quartiles. The grey dash indicates the mean.

studies. The average effect of an increase in intake was higher and consistent in sheep when compared to cattle (11% vs 2%). In cattle, decreasing the maturity of cut forage or pasture showed a reduction in CH_4 in g/kg milk (Fig. 9A). Increasing grazing pressure was associated with an increase in CH_4 in g/kg ADG (Fig. 9B).

In terms of magnitude, some processes are comparable with the reduction found for certain product-based interventions: with an average reduction in CH_4 in g/kg DMI of 19%, an increase in grazing pressure shows a similar efficacy in cattle as the supplementation with sunflower oil or linseed oil. A 7% reduction achieved by the increase in maize maturity in cattle is comparable to the supplementation with *Lotus sp.*, *Onobrychis sp.* or maize silage. In sheep, the reduction achieved by an increased intake is lower than the effect of the supplementation of *Lotus sp.* or *Brassica napus* fodder, but higher than the effect of feeding *Cichorium intybius* (6%).

3.2. Land requirements of selected product-based feeding interventions

The product-based feeding interventions selected for this analysis are listed in Table 2. The required areas in order to supply the entire Swiss populations of cattle (dairy and beef) and sheep with amounts sufficient to realize the average effect size in CH_4 mitigation

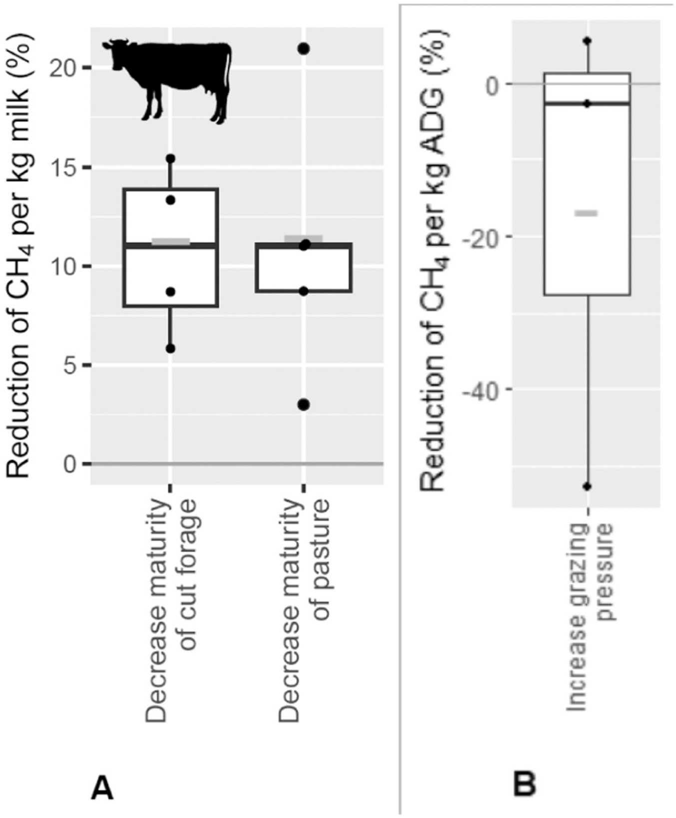

Fig. 9. Effectiveness of process-based feeding interventions in cattle, where at least three studies were available to assess the effect on CH_4 in g/kg milk (A) and CH_4 in g/kg ADG (B). For sheep neither variable was assessed at least three times for the same product. Individual dots represent the average effect of an intervention within one study. Boxplots indicate median, as well as 25% and 75% quartiles. The grey dash indicates the mean.

are presented in Table 2. Yields and area estimates should be interpreted with care, as they are (realistic) estimates. For nine interventions, the entire Swiss arable land or grassland would have to be used to grow the product in question, in order to reduce CH_4 emissions by a few percent. For cattle, the product which would require the least area is *Origanum* (11% of arable land). For sheep, the required areas are much smaller (below 10% of the land) than those for cattle, which can be explained by the smaller population and the lower DMI.

4. Discussion

During the past three decades, a broad spectrum of dietary interventions with various feed plants, often based on effects of specific plant metabolites like tannins or essential oils (Khiaosa-Ard and Zebeli, 2013; Vasta et al., 2019) was investigated for their ruminal CH_4 mitigation potential. These plant additives have repeatedly shown the potential to mitigate CH_4 production *in vitro*, but fewer studies have investigated their effect *in vivo,* where their impact on enteric CH_4 production is often more variable and less pronounced (Jayanegara et al., 2012). However, some options of mitigating enteric CH_4 production with forage plants and herbs were identified after *in vivo* investigations, and are referred to in recent reviews (Arndt et al., 2022; Min et al., 2020; Varga et al., 2022). Often, such products are claimed to be more natural, since they are not synthetic, and sustainable, since they are (erroneously) considered to be no arable crops. Additionally, in the case of herbs or leaves, several potentially beneficial effects on animal welfare and ecosystems are attributed to the production and dietary inclusion of such herbal feedstuffs (Gregorini et al., 2017; Leiber et al., 2020).

However, what has rarely been assessed and defined, are the resources and efforts required to produce the necessary amounts of such plants or their extracts in order to realize the desired effects in large (e.g. national) populations of ruminant livestock. Discussion about the size of arable surfaces to produce these plant materials is widely lacking, and the gap between experimental evidence and practical implementation is still wide. Therefore, proposals based on experimental findings often lack realistic in-practice potential. Since land-use is one of the most critical issues of global food production - and the feed-food competition is part of that problem (Schader et al., 2015) – it is of particular importance to deliver estimates for the land resources needed for proposed plant-based CH_4 mitigation measures. The land requirements in connection with estimated mitigation effects of proposed dietary interventions would provide a basis to assessing their overall suitability and sustainability.

The present study, based on the example of ruminant production systems in Switzerland, aims at opening the discussion on this important aspect of CH_4 mitigation through feeding interventions. The area of agricultural land in Switzerland and the size of national cattle and sheep populations were used to estimate the potential effects and necessary land resources of scientifically proposed dietary interventions. With its specificity of a small arable to grassland proportion (38:62) (Bundesamt für Statistik, 2021), Switzerland is not representative for intensive agricultural countries in Europe, but it well represents grassland-based ruminant production systems (Hofstetter et al., 2014). In any case, the estimates developed in this study highlight that required resources for plant-based CH_4 mitigators are not negligible.

4.1. Effect sizes of plant-based methane mitigation interventions

With regard to the large body of literature considering plant-based feed additives with CH_4 mitigation potential (Durmic et al., 2014; Jayanegara et al., 2012; Min et al., 2020; Ugbogu et al., 2019; Varga et al., 2022; Vasta et al., 2019), the number of interventions investigated with at least three *in vivo* studies was rather small. One considerable reason was, that we restricted selection to plants with potential to grow in temperate climatic regions, while experimental research also includes various tropical plants (Durmic et al., 2022; Soliva et al., 2008; Varga et al., 2022), Furthermore, large parts of the literature evaluating and discussing the topic still rely on *in vitro* data (Durmic et al., 2022; Jayanegara et al., 2012; Varga et al., 2022).

Of the interventions covered by our selection criteria the averaged effects for CH_4 mitigation (related to DM intake) in cattle and sheep were around 7–8%, with large standard deviations and a considerable number of studies, where the intervention resulted in an increase in CH_4. This overall picture is congruent with the review of Vargas et al. (2022) who also found high numbers of studies on CH_4 mitigators in grassland-based systems with no effect or even increases. The only additives for cattle achieving aspired effects in all studies were oils (rapeseed, sunflower, linseed) and grape marc. In sheep, it was fodder rape, trefoil (*Lotus sp.*), *Cichorium intybus*, as well as the supplementation with mixed concentrates. Notably, with few of these additives the effects were not just consistent but even at around 20% (cattle) or 40% (sheep) reduction of CH_4 emissions per unit of DMI. However, for most products the effect on CH_4 mitigation varied considerably between studies. This variation may be caused by differences in study design, animal breed, control diets or measurement methods between publications. Therefore, the average effect size calculated in this study is a somewhat theoretical value, which does not reflect a specific production system. However, this problem reflects the very small basis of available *in vivo* study data.

4.2. Land requirements of plant-based methane mitigation interventions

The subsequent objective of this study was to assess, if the daily supplementation of the entire national population of cattle and sheep would be feasible based on the area of arable land or, in the case of pasture plants, grassland in Switzerland, considering the country as a model for grassland-based production regions (Huber et al., 2022). The calculations shown in Table 2 allow a basic assessment of the land which would be required for the growth of the selected plant products intended for methane mitigation. Although the yields and areas are based on realistic estimates from literature, the numbers should be interpreted with care. Furthermore, climate change is likely to affect the future yields and demand for these products. On one hand, plants thriving under warm conditions (e.g. trefoil or sainfoin), may become more suitable for cultivation in Switzerland. On the other hand, increasing temperatures and drought may make it increasingly difficult to keep ruminant livestock on lowland pastures, resulting in a reduction in animal numbers and consequently the required amounts of plant material. As the effect of climate change on Swiss agriculture is hard to predict, making assumptions on yields, required amounts and animal numbers is somewhat speculative. However, the calculations shown in Table 2 help to put the efforts which would have to go into methane mitigation through these feeding interventions into perspective. They indicate, that several plant-based products assessed in cattle would require an area larger than the total of current Swiss arable land or grassland, in order to be available at the amounts necessary to achieve the methane mitigation effects from experimental literature. For example, if the most effective product – sunflower oil – would be produced at the required amount within the country, its production would require over 2/3rd of the area currently used for the production of arable crops. Other effective plant-based oils would require an area even larger and the production of grape marc for all Swiss cattle (which is notably a by-product and thus a desirable feed stuff) would require an area almost six times larger than the current national arable area. Even the comparably small area required to grow *Origanum sp.* (10% of arable area) still exceeds the areas currently used to grow e.g. potatoes and vegetables (3% of arable land each), sugar beets (4%), or barley (7%) (Bundesamt für Statistik, 2021) – cultures which are of importance for the supply of local food and feed. This example illustrates a conflict in land use, in particular if CH_4 mitigation is given priority over national food security. Even for the comparatively simple example of maize silage, which is already a standard component in most dairy rations, the increase in land use would be 5-fold: from 11% of arable land at the moment (Bundesamt für Statistik, 2021) to 56% if the inclusion rate of 534 g/kg DM is to be met.

For sheep, the implementation of the assessed feedstuffs for the national population appears somewhat more feasible, as growing them would only require 10% percent of the arable land (for *Brassica napus* fodder) or 2–3% of grassland. However, considering the areas of arable land currently used for food production, these proportions are still substantial.

The integration of effective pasture plants into the seed mixtures for forage production could be more practical than the supplementation of specific additives or concentrates. The integration of these plants into existing pastures requires no change in land use, does thus not create a conflict between CH_4 mitigation and food security, and the pasture plants are directly consumed by the animals. In contrast to other feed supplements, their administration is less labor intensive. Species like chicory, sainfoin, red clover or trefoil can be integrated in existing pastures and meadows to create multispecies swards, which have also been linked with a wide array of ecological and agricultural benefits (Bryant et al., 2017; Isbell et al., 2015; Lüscher et al., 2022). However, the dietary inclusion rate of most pasture plants assessed in the studies included in this review was very high (up to 100%). Due to their reduced yield, establishing monocultures of the pasture plants in question, e.g. red clover (*Trifolium repens* or *T. pratense*), sainfoin (*Onobrychis sp.*), alfalfa (*Medicago sativa*) or trefoil (*Lotus sp.*) would require an area exceeding the current Swiss grassland area. Furthermore, seasonal availability of the plants would make year-round administration challenging and pure legume pastures would be an unbalanced diet for grazer-type ruminant species like cattle and sheep. While the integration of effective pasture plants into existing pastures requires comparably little effort, it remains unclear if a small inclusion rate would have any notable effect on CH_4 emission. This is reflected by the comparatively low efficacy (and its variability) of multispecies swards reported in the studies included in this review. Furthermore, when compared to a control diet, feeding on multispecies swards resulted in an average increase in CH_4 per kg milk in the studies included in this review (Fig. 7A), indicating that a lower feed efficiency of these diets may result in increased emissions to achieve the same milk yield. This example illustrates that – beyond efficacy of a mitigator and the land required to produce it – a multitude of aspects have to be considered when assessing if a feeding intervention can be realized on farm.

The proportional land distribution of Switzerland makes the examples discussed above rather drastic, but it generally shows that plant-based feed additives for CH_4 mitigation would require agricultural areas large enough to evoke debates around land-use, such as the challenge of feed-food competition (Schader et al., 2015; Wilkinson, 2011). Since land-use change relates to carbon sequestration and release (Yumashev et al., 2022), such measures need to undergo thorough climate impact analyses for the production side, before they can be reasonably proposed as measures to mitigate ruminal methanogenesis. Furthermore, the target of grassland-based ruminant production, which is particularly tailored for regions with small resources of arable land (Leiber, 2022) becomes obsolete if the inhibition of CH_4 requires additional agricultural area.

The effect size of the assessed process-based interventions was highly variable and it was not assessed, which additional efforts would be required to realize them in terms of labour, costs, or land-use. However, the results highlight, that certain processes related to pasture management and feed production may be as efficient as product-based interventions. For example, an increase in maize maturity is as efficient in reducing CH_4 per unit DMI as an increase in maize proportions in the ration of cattle (7% vs. 6%). An increase in grazing pressure in cattle appears as effective as the supplementation with linseed oil. Both examples highlight, that the improvement of management practices in existing systems may be a more sensible way to achieve CH_4 mitigation than the implementation of certain feedstuffs.

4.3. Methodological aspects

Besides the effect size and feasibility, the existing data also have to be critically discussed with regard to methodology of the research done until now. The results of our literature review illustrate the sheer amount of combinations of feeding interventions and control treatments which have been investigated to date. Few studies have replicated previously investigated combinations of product and control treatment and if so, the results often vary considerably between such studies. For example, the comparison between alfalfa and grass was investigated in at least five studies in cattle, but the results vary from a 40% increase in emissions to a 20% decrease. In the case of concentrate supplementation, a reduction in CH_4 in kg/DMI ranges from 0% to almost 40%. These examples and the variability of effects as displayed in Figs. 5 to 7 illustrate, that the investigation of product-control-combinations require manifold independent replications to acquire certainty about the effectiveness of the intervention and knowledge about the variability of the effects under real practice conditions. Rather than investigating ever new feed additives and components, research projects verifying existing studies would be just as valuable. In particular, because it is rarely possible to investigate more than ten individual animals in one study.

The data further demonstrate, that defining the control diet is as important as the intervention itself. Sainfoin compared to alfalfa resulted in hardly any reduction in CH_4 in kg/DMI, while sainfoin compared to grass showed a considerable reduction of approx. 15%. This should also be considered when suggesting interventions on farm level: compared to a low-quality pasture, feeding white clover may decrease emissions, but compared to a nutritious rye-grass pasture, the effect may be negligible. Due to the very low number of studies repeating the same intervention under different conditions, it is almost impossible to generalize effects or to allocate them systematically to different production conditions.

The dataset may further be skewed by a positive-results bias, where studies showing the desired effect of the intervention, i.e. a reduction in CH_4, may be more frequently submitted or published than studies finding no effect or even an increase in CH_4. Given the variability of the results in the literature dataset, it is likely that the inclusion of each new publication may completely change the average effect size of an intervention.

5. Conclusion

The present review aimed to relate potential effects of plant-based CH_4 inhibitors with the land requirements for implementation. Based on the criterion, that for a certain plant-based intervention at least three published *in vivo* studies were available, the number of options was surprisingly small. On average, effect-sizes are below 10% reduction of CH_4 per unit of DM intake, with high variation between studies, including adverse results. Production of the necessary amounts of such feed additives would require considerable amounts of agricultural area, a fact which has been widely neglected, so far. Since land requirements imply climate change threats as well, our study results in an urgent call for assessing carbon-cycle effects by production of the debated plant-based CH_4 inhibitors. In terms of feeding interventions, the integration of plants with inhibitory effects into artificial or natural swards appears to be the most practicable solution, which requires no change in land use, bears little risks and has other beneficial effects.

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CRediT authorship contribution statement

Marie Dittmann: Investigation, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Florian Leiber:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare no competing interests.

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