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Mark Brady
Nils Malmström
Hampus Nylén

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Mark V. Brady[a,b], Nils Malmström[a] and Hampus Nylén[c]

Affiliations:
[a] AgriFood Economics Centre, Dept. of Economics, Swedish University of Agricultural Sciences (SLU), Box 730, 220 07 Lund, Sweden.
[b] Centre for Environmental and Climate Research (CEC), Biodiversity and Ecosystem services in a Changing Climate, Lund University, Sölvegatan 37, 223 62 Lund, Sweden.
[c] AgriFood Economics Centre, Lund University.

Corresponding Author email: Mark V. Brady, mark.brady@slu.se

Abstract
Reducing enteric methane emissions from agriculture is considered imperative in the short term to stabilise global warming below 1.5 degrees. However, policymakers are faced with multiple and potentially conflicting goals in this pursuit, particularly with food security and conservation of biodiversity. The aim of this paper is to investigate whether there exists a policy response that can ensure the preservation of nature areas, specifically semi-natural *pastures (naturbetesmarker)*, while simultaneously reducing enteric methane emissions from livestock cost-effectively. We perform the analysis with the spatial and dynamic, agent-based model AgriPoliS that is capable of simulating structural change in agriculture in response to radical policy reform, which we extended for methane abatement. Our simulations of the cost-effective solution for increasingly ambitious methane abatement targets, demonstrated that 25 % abatement could be reached with minimal impact on the area of pastures through re-structuring of livestock production and the use of a commercially available feed additive (3-NOP) that suppresses the generation of methane in the rumen. We conclude that technical measures to reduce emissions, such as feed additives, are a promising complementary measure for reducing emissions, but currently farmers have no economic incentive to invest in such low-cost abatement technologies. To avoid loss of nature areas dependent on ruminant grazing, targeted agri-environmental schemes were found to be necessary to preserve these areas in the event of climate action. In this respect agri-environmental payments play a crucial role in strengthening the resilience of agricultural biodiversity to policy measures targeting methane abatement.

1 Introduction

The EU and Sweden are committed to climate action and conserving biodiversity. The agricultural sector is pivotal in both respects. Agriculture accounts for 13.2% of the EU's territorial emissions of greenhouse gases (GHG), with almost half of these emissions coming from enteric fermentation (feed digestion) by ruminants (Trinomics, 2013). The EU's goal is to reduce GHG emissions from domestic transport (excluding aviation), buildings, agriculture, small industry and waste disposal by 40% by 2030 compared to 2005 levels (REGULATION (EU) 2023/857). The Swedish target is even more ambitious, a 50 % reduction by 2030. There are, though, no specific reduction targets for agricultural GHG emissions. Nevertheless, the scientific consensus holds that reducing methane emissions from agriculture is necessary in the short-term to stabilise global warming below 1.5 (Lynch and Garnett, 2021).

Concurrently, the EU's Habitats Directive has set ambitious goals for the preservation and restoration of nature areas for the conservation of biodiversity (European Commission, 1992). Ruminants are integral for conserving biodiversity in the EU through the perpetuation of High Nature Value (HNV) farming, which is conducted on around 25 % of the EU's agricultural area. In these systems extensive grazing by ruminant livestock such as cattle and sheep is crucial for preserving biodiversity-rich permanent grasslands such as Sweden's semi-natural pastures (Eriksson, 2021), Mountain Agriculture (MacDonald*, et al.*, 2000) and Upland Farming (O'Rourke*, et al.*, 2016). The positive impact on biodiversity is derived from the fact that traditionally managed grasslands, through extensive grazing, constitute vital habitats for a large number of species that beyond their intrinsic conservation value also provide important ecosystem services (Bengtsson, 2019, Habel*, et al.*, 2013, Regeringen, 2022). Accordingly, a goal conflict emerges in that ruminant livestock contribute to both GHG emissions and the conservation of biodiversity. It is therefore feared that interventions to reduce methane emissions could adversely affect grazing of permanent grasslands that are important for preserving biodiversity.

Currently, there is no *targeted* economic policy instrument in place within the EU to reduce agricultural GHG emissions, such as the EU Emissions Trading System (EU ETS) for other sectors. On the contrary, within the EU's Common Agricultural Policy (CAP), the Coupled Income Support (CIS)[1] totalling approximately €4.2 billion annually and most commonly designed as a payment for holding cattle (European Commission, 2022), increases cattle numbers and consequently GHG emissions (Jansson*, et al.*, 2021). In Sweden, an argument for coupling this support to cattle is that cattle can have a positive effect on biodiversity through grazing of semi-natural pastures (Regeringen, 2022). If the CIS indeed contributes to the preservation of semi-natural pastures, it is feared that removing it to combat GHG emissions would result in the loss of biodiversity. Moreover, the introduction of an economic incentive to reduce agricultural GHG emissions, for instance a tax on methane emissions, would likely also reduce livestock numbers. The underlying concern in both respects is that policy interventions to mitigate methane emissions from ruminants, could have a negative effect on the continuation of HNV farming in the EU in general, and preservation of biodiversity-rich grasslands in particular. However, to the best of our knowledge, no study has analysed the potential effects of mitigating enteric methane emissions on the conservation of biodiversity associated with grassland habitats in Europe.

Policymakers thus face a dilemma; to design a cost-effective policy instrument to reduce GHG emissions from agriculture, particularly enteric methane emissions, without substantial losses of valuable nature areas. **The aim of this paper** is to investigate whether there exists a policy response that can ensure the preservation of nature areas, specifically semi-natural pastures, while simultaneously reducing enteric methane emissions from livestock, cost effectively. That is, we ask

[1] Previously called Voluntary Coupled Support (VCS) in the 2015-22 CAP framework.

whether it is possible to achieve both climate and biodiversity goals simultaneously and determine which measures would constitute a cost-effective solution to methane abatement. Furthermore, given additional goals of agricultural policy, such as promoting food security and preserving agricultural landscapes, we also investigate the broader impacts on land use and livestock holdings for food.

The study is carried out in a Swedish context; however, the general conclusions should be applicable in a wider context, since Sweden's semi-natural pastures are a relevant example of HNV farming in the EU.

Including agricultural GHG emissions in the EU ETS or introducing an environmental tax on these emissions have been proposed as potential policy responses to reduce agricultural GHG emissions (e.g., Verschuuren, 2022, Weishaupt*, et al.*, 2020). Environmental taxes and their possible implementation have been analysed in numerous studies. According to economic theory, a tax on emissions at the source would ensure cost-effective methane abatement, as it incentivises producers to alter their practises or implement new technologies to reduce emissions in the least costly way possible and leads to higher consumer prices that reflect the full production cost including environmental costs. However, taxation of diffuse agricultural emissions implies measurement difficulties and potentially high transaction costs, counteracting the cost-effectiveness of the instrument. Therefore, other implementation strategies have been investigated such as, e.g., a consumption tax (Edjabou and Smed, 2013, Jansson and Säll, 2018, Säll and Gren, 2015, Springmann*, et al.*, 2017, Wirsenius*, et al.*, 2011), or a production tax based on average national GHG emissions per unit of commodity (Jansson*, et al.*, 2023, Key and Tallard, 2012). Here, we focus on production-orientated policy responses via the CAP, in particular simulating the cost-effective solution to abating enteric methane emissions and the associated impact on the area of semi-natural pastures. We also investigate the impacts of abolishing the CIS and levying a carbon-dioxide equivalent (CO2e) tax on enteric methane emissions.

We base the analysis on simulation experiments with the AgriPoliS model (Agricultural Policy Simulator), which is a spatial and dynamic, agent-based model of regional structural change in agriculture that has been empirically calibrated to multiple regions in Sweden and the EU (Balmann, 1997, Happe*, et al.*, 2006). A potentially important methane-abatement measure is the restructuring of livestock holdings and potentially farms. Further, the costs of managing pastures have a high spatial dependency, since livestock need to be moved intermittently between pastures and stables, as well as requiring daily monitoring. For these reasons, it is important that the analysis can consider structural change and spatial aspects, which is a feature of the AgriPoliS model. We use the model to simulate how changes in agricultural policy aimed at reducing GHG emissions cost-effectively, affect the composition of livestock and the adoption of technical measures to reduce emissions (a feed additive described below) in our study region, as well as the presence of semi-natural pastures and impacts on food production.

As AgriPoliS is a regional model, a comprehensive analysis of impacts on a national or international level is not possible. Instead, we analyse impacts in a relevant Swedish agricultural region and let it exemplify how agricultural structure and nature areas (semi-natural pastures) in such regions are likely to be affected by policy to mitigate methane emissions. We focus on Jönköping County for its large number of cattle and area of semi-natural pastures (25 % of the agricultural area) that are crucial for conservation of biodiversity and the cultural landscape in Sweden (Nilsson*, et al.*, 2013).

Furthermore, we focus on abatement of enteric methane because there is a potentially strong trade-off between reducing these emissions and preserving semi-natural pastures. On the other hand GHG emissions from manure management (including methane and nitrous oxide), depend heavily on management systems, while CO2 emissions from land use changes or N2O emissions from fertilizers, are not directly linked to livestock numbers.

We perform the analysis initially under the assumption that Sweden imposes climate policy unilaterally and hence with constant prices for livestock products such as milk and beef, and thereafter, using sensitivity analysis, evaluate the implications of EU-level policies that would have implications for product prices. Evaluations at the national level are, though, also relevant to study because climate goals for the agricultural sector are national and the implementation of the new CAP for 2023-28 has increased national flexibility for the implementation of environmental measures. For instance Denmark has decided to impose carbon pricing on their agricultural sector from 2027 (Ekspertgruppen, 2024). We even evaluate the implications of having agri-environmental payments in place or not, for preserving biodiversity, when pursuing methane abatement.

Next we determine whether any technical measures are currently feasible for abating enteric methane emissions based on a literature review we conducted in parallel with this study (Nylén and Brady, 2024).

2 Technical measures for abating enteric methane emissions

The climate impact of methane emissions in combination with rising demand for livestock products has led to an explosion in research to develop technical abatement measures (Nisbet*, et al.*, 2020). These can be divided in to four subcategories of measures, those orientated towards: i) management, ii) nutrition, iii) breeding and iv) rumen manipulation (Beauchemin*, et al.*, 2020, Temesgen*, et al.*, 2021). The subcategories differ fundamentally in how they abate emissions: the first two primarily affect relative emissions, i.e., methane yield (g CH4/dry matter intake) or intensity (g CH4/product), while the last two reduce absolute emissions per animal (g CH4/animal) (Roques*, et al.*, 2024). The distinction is essential because methane intensity can, for instance, be reduced by increasing animal productivity, which does not translate into less total emissions without reductions in herd sizes (Beauchemin*, et al.*, 2020).

Accordingly, technical measures resulting in absolute reductions are arguably more desirable from a climate perspective. Rumen-manipulation measures affect absolute emissions by impeding enzymes that are necessary for the methanogenic process (Roques*, et al.*, 2024). However, some measures with a clearly estimated effectiveness, such as feed supplementation with macroalgae or nitrate have been observed to have negative effects on production or animal health, or both (Fouts*, et al.*, 2022, Honan*, et al.*, 2021, Roque*, et al.*, 2019, Stefenoni*, et al.*, 2021), which has prevented widespread commercial implementation (Fouts*, et al.*, 2022). On the contrary, 3-nitrooxypropanol (3-NOP) supplementation has been approved as a safe substance with an established efficacy by the European Food Safety Association (Bampidis*, et al.*, 2021). Hence, 3-NOP is the technical front-runner and the first commercially approved feed additive with environmental benefits in the EU as of February 2022 (Palangi and Lackner, 2022). However, there is a need for more knowledge about the long-term effects of feed additives and external factors affecting their efficacy (Hristov, 2024).

On the other hand, distribution is a challenge when frequent dosing of livestock is necessary, which is the case for 3-NOP, nitrate, macroalgae and nutritional measures. Currently, they cannot be effectively distributed in grazing systems (Smith*, et al.*, 2022), but orally installed, slow-release technologies are under development to make it feasible to dose livestock while on pasture (Roques*, et al.*, 2024).

Breeding strategies and vaccination are also promising solutions with potential for absolute emission reductions for grazing cattle (Beauchemin*, et al.*, 2020). This is because breeding mitigates methane emissions with a permanent and cumulative effect by actively breeding for animals with naturally lower emission rates (de Haas*, et al.*, 2021), while vaccination subdues microorganisms necessary for methanogenesis. The latter is categorised as rumen manipulation and would ideally only require rare supplementation. Both breeding and vaccination are under development, but more research is needed to establish potential side effects and effectiveness (Roques*, et al.*, 2024).

We conclude from the literature that there are currently limited technical measures available to reduce enteric methane emissions without negatively affecting production or endangering animal health. However, 3-NOP has proven to be effective and approved as safe for use, hence we model it as a potential abatement measure in this study. On a final note, adopting technical measures will be costly for farmers, and hence will not be extensively adopted without appropriate economic incentives, which implies a need for policy interventions (Roques*, et al.*, 2024).

3 Methodology

3.1 Theory: Cost-effective abatement of enteric methane emissions

The cost-effective solution for achieving an environmental goal defines the changes to production or adoption of technical abatement measures that guarantee the lowest possible cost to society for achieving a particular goal, in this case a particular level of methane abatement within the studied agricultural region. According to economic theory the cost-effective solution is defined by the equalization of marginal abatement costs across all farms and potential abatement measures available to the farms (e.g., reducing livestock numbers or dosing livestock with a methane inhibiting feed additive). This problem is solved in our model (AgriPoliS) using mathematical programming (i.e., an optimization algorithm) that finds the minimum loss in total farm profits to achieve a particular level of abatement for the region and time frame given the available abatement measures.

3.2 The Study Region

Jönköping County in Sweden is typical of agriculture conducted in marginal areas in the south of Sweden (and other HNV farming regions in the EU), where 75 % of the country's total area of around 450 thousand ha of semi-natural pastures exist (SCB, 2020, Tabell 3.1). The area of semi-natural pastures has declined from around 3 million ha in Sweden over the past century due to the intensification of agriculture (Eriksson, 2021), but remains a rich source of biodiversity and other cultural values (Lennartsson and Westin, 2019). Topographic characteristics and the distance to farm centres explain most of the ongoing loss of semi-natural pastures (Aune*, et al.*, 2018). In general, relatively small and isolated pastures are most likely to be abandoned (afforested), because these are more costly to manage than a large pasture lying close to livestock stables (Larsson*, et al.*, 2020).

Due to climate and topographic conditions crop yields are low, while conditions are relatively favourable for grasses (**Table 1**). Consequently, farming in the region is focused on raising ruminant livestock, principally cattle and sheep for milk and meat production. Roughly 25% of the agricultural area is semi-natural pasture and 80% of the arable area is used for grass fodder production. Arable pastures are however relatively low in biodiversity compared to semi-natural pastures, because these are typically fertilized, ploughed and frequently broken with a grain crop to boost yields; for this reason, arable pastures are not eligible for agri-environmental payments that target semi-natural pastures. Agricultural land is otherwise interspersed among forest, which dominates the overall landscape, accounting for almost 80 % of land use. The wide dispersal of agricultural land implies that the potential to rationalize production through amalgamation of farms and fields is relatively low. Most farms in the region are joint agricultural and silvicultural enterprises (**Table 1**), with forestry providing diversification of income, which we consider in the modelling. The main threat to agricultural land and hence biodiversity in the region is that it will be converted to forest if it is not sufficiently profitable to maintain as agricultural land. Due to the marginal conditions for agriculture in the region it is highly dependent on support provided by the CAP (Brady*, et al.*, 2024).

Table 1. Agricultural characteristics of Jönköping County

	Unit	Area/Head	Product	Normal Yield[#] *kg unit^{-1} yr^{-1}*
Arable land	ha	87,546		
- grains	ha	17,934	Spring barley	3,800
- grasses	ha	65,591	Grass silage	5,340
- set-aside	ha	2,016	Green fallow	nil
Semi-natural pasture	ha	40,526	Grass forage	1,500
Forest area on farms	ha	199,298		
Dairy cows	head	28,926	Milk	8,424
Suckler cows for beef	head	16,110	Beef from suckler calf	350
Other cattle (> 1 year)	head	43,037	Beef from dairy calf	300
Sheep (ewes for lamb)	head	13,487	Lamb	35

Notes: Grass yields are weight dm, milk is raw milk, beef slaughter weight and sheep two lambs slaughter weight for each ewe. Source: (SCB, 2017)

3.3 AgriPoliS Model

The AgriPoliS model is based on a population of individual farms representative of the typical farms and regional structure of agriculture in the study region. It is primarily used to evaluate the effects of changes in agricultural policy on agricultural structure, production and farm incomes, but has been extended over time to evaluate concomitant effects on the landscape, biodiversity, and the provision of ecosystem services (Brady*, et al.*, 2009, Hristov*, et al.*, 2020, Sahrbacher*, et al.*, 2017). The conceptual design of AgriPoliS and its mathematical structure is documented in Kellermann*, et al.* (2008). We, therefore, only describe here how the model is modified in order to model livestock methane emissions, cost-effective abatement of enteric methane emissions and the chosen policy scenarios.

3.4 Data on enteric methane emissions and grass forage needs

Annualised enteric methane emission rates for cattle are modelled in AgriPoliS based on the method used by the Swedish EPA (2023) for their GHG emission reporting, which in turn is developed in Bertilsson (2016). As for emissions from sheep production (ewes for lamb) there is no specifically Swedish data available. Instead, these emission rates are based on IPCC methodology (Gavrilova*, et al.*, 2019, Table 10.10) after transforming the rates to account for the heavier normal live weight of a Swedish ewe.

Data on feed rations, animal weights and, meat and milk production needed to calculate methane emissions by animal type (see Appendix A for details of our calculations) were obtained from AgriWise (2020), which is a farm planning tool developed and maintained by the Swedish Board of Agriculture and Swedish University of Agricultural Sciences for supporting farm management in Sweden. All methane emissions are subsequently expressed as carbon dioxide equivalents (CO2e) and Global Warming Potential over 100 years (GWP_{100}), by multiplying kg methane emitted by the conversion factor of 28 (Masson-Delmotte*, et al.*, 2021, Table 7.15).

Table 2 summarizes the key input data for calculating enteric methane emissions and grass forage needs that could potentially be satisfied from semi-natural pasture, for modelled types of Swedish ruminant livestock. Note that the assumed forage need for a dairy cow is nil, because dairy cows normally utilize only arable pasture in Swedish systems due to the logistics of high intensity milk production. Most of the other livestock can utilize pastures for their forage needs, but not necessarily, because forage needs can be fully satisfied from arable grass pastures, as is often the case (Larsson*, et al.*, 2020).

To provide an indication of the relative environmental effectiveness of each type of livestock for grazing pastures relative to their methane emissions, we include the column Forage/Methane in **Table 2**. From this simple calculation it can be seen that *Sheep* are relatively effective in this sense for maintaining pastures, consuming 1.25 kg grass per kg emitted methane (in CO2e), while a *Replacement heifer for a Dairy cow* only consumes 0.64 kg grass and a dairy cow doesn't make a contribution according to our assumptions based on the current production system in Sweden. This simple calculation demonstrates that there exist substantial substitution possibilities between livestock categories for optimizing the preserved area of semi-natural pastures and attendant methane emissions. Furthermore, the opportunity costs of running different livestock on pastures can vary among livestock types, which is considered implicitly in the modelling and hence difficult to represent as a single number in a table. This potential is further demonstrated by the implied GHG tax based on the methane emissions and priced to match the average EU-ETS permit price of 80 € per tonne CO2e in 2022 (Swedish EPA, 2023) and converted to SEK using an exchange rate of 12 SEK/EURO, resulting in a tax rate of 0.96 SEK per kg CO2e. In this respect, a dairy cow would attract the highest tax and sheep the lowest.

Table 2. Input data used for modelling livestock methane gas emissions and grass forage needs per animal type based on average annual emissions and forage needs over the animal's life.

Livestock category	**Enteric Methane** *kg CO2e/yr*	**Grass forage need** *kg/head/yr*	**Forage/Methane** *kg grass/kg CO2e*	**CO2e Tax[4]** *SEK/head/year*	**3-NOP Feed additive** *Max. Reduction kg CO2e/yr (%)*
Cows for milk and breeding					
Dairy cow	3943	0	0	3785	-1227 (31)
Suckler cow[1]	2467	2297	0.93	2368	-435 (18)
Recruitment heifers[2]					
for Dairy cow	1223	787	0.64	1174	-216 (18)
for Suckler cow	960	1200	1.25	922	-169 (18)
Beef cattle					
Bullock, dairy breed	1111	1080	0.97	1066	-189 (17)
Young bull, dairy breed	989	773	0.78	950	-297 (30)
Young bull, beef breed	802	0	0	770	-241 (30)
Heifer, for slaughter[3]	960	1100	1.15	922	-169 (18)
Sheep					
Ewe, lamb production	441	550	1.25	423	-75 (17)

Notes: 1) For production of beef cattle, 2) For replacement of dairy and suckler cows at end of their life, 3) Includes heifers from both dairy and suckler cows not needed for recruitment and hence are slaughtered for beef. 4) Calculated based on the SEK equivalent tax rate of 0.96 SEK per kg CO2e, e.g., for dairy cow 3943 x 0.96 = 3785 SEK/head/year.

Our approach implies that all livestock of a particular type emit methane to the same extent, i.e., genetic variation in individuals is not considered. However, it is possible for farmers to reduce emissions per livestock type using a commercially available technological measure, in the form of the feed additive *Nitrooxypropanol* (3-NOP), as identified in our earlier literature review. The assumed maximum annual reduction in emissions per animal type that is achievable through this measure are given in the column *3-NOP Feed Additive*. The maximum reduction rate of 30 % is achievable for livestock that are continually fed mineral supplements, such as dairy cows. Currently there is however no technology available to regularly dose 3-NOP, i.e., at least every three hours, when livestock are on pasture, hence the assumed maximum reduction rate is adjusted for the standard pasture period for the different livestock types. The cost of dosing 3-NOP is assumed to be 1000 SEK per animal per year according to consultation with a sales representative for the commercially available 3-NOP additive, Bovaer (Ohlsson, 2024). This cost was quoted to us as a maximum price and could be reduced in practice depending on the volume of purchases. However, with the view of adopting a conservative approach to our modelling of the effects of this feed additive, we use this cost and scientifically verified reduction rates in our modelling. Higher reduction rates could be achieved through higher dosage rates, but this would risk negative side effects on animal health and productivity according to the company manufacturing Bovaer. Consequently, the assumed reduction rates are also within approved dosage rates for animal welfare.

Although approval has not yet been sought for giving 3-NOP to sheep, it has in practice the same abatement potential as for cattle. Hence in the interest of not unnecessarily distorting the emissions abatement potential among different livestock types, we also assume that 3-NOP can be given to sheep. Overall, the inclusion of the 3-NOP feed additive as a potential methane abatement measure, has a broader importance in this study, as it will illustrate the potential implications of technical measures for the costs of methane abatement and the area of pastures, since other novel technologies such as CH_4 inhibitors, vaccines, low-emissions breeding and the use of certain types of seaweed as feed additives could be available in the future (Reisinger*, et al.*, 2021).

We assume standard feed requirements for each animal type (i.e., mix of silage, pasture and grain/protein fodder), since Swedish livestock production is highly developed and rationalised. Dietary changes are, off course, possible in reality. However, this is problematic to account for in the computations of emissions. In addition, dietary differences between animal types can, to a large extent, be explained by biological characteristics of the different animal types and conditions given by the production systems. In genera,l we assume that livestock feeding is efficiently managed in Sweden, i.e., there is relatively little wastage that could potentially be improved upon.

Nonetheless, we do allow for the possibility for farmers to switch between intensive and extensive beef production (i.e., lesser or greater utilization of pasture), as well as switching from intensive to more extensive forms of livestock production, e.g., from milk production to suckler-cow beef production). In regard to milk production, we assume that production is to a certain extent limited by national demand from local dairies, hence we assume it cannot exceed the highest historical levels by more than 10%, in which case the price of milk is reduced in the model until market balance is restored. Furthermore, forage requirements in the model can be satisfied from either using semi-natural pastures or improved arable pastures. Similarly, grain fodder (barley/oats) can be purchased or produced on the farm. Consequently, the model offers farm-agents substantial opportunities to substitute between livestock and fodder sources, hence abating methane emissions while simultaneously preserving semi-natural pastures as indicated by **Table 2**.

3.5 Modelling cost-effective enteric methane abatement

Farm-agents can reduce methane emissions through changing agricultural structure, in particular the type and number of livestock, or dosing ruminant livestock with a 3-NOP feed additive. Rather than simply having the option to reduce livestock numbers and thereby emissions, farm agents have the possibility to change production orientation through investment in alternative livestock stables, as well as grow their farm through renting more land. This ability increases the flexibility available to farmers for achieving abatement goals in the region and reducing abatement costs compared to a static analysis.

The complex structure of the model does not allow us to simply impose an abatement target at the regional level to determine the cost-effective solution. Imposing targets at the farm level while possible, would however not guarantee the cost effective-solution for the region, since with such a solution the marginal costs of abatement will likely vary among farm-agents. However, a standard result from economic theory is that any abatement target can be achieved cost-effectively by levying a sufficiently high tax on emissions (i.e., equal to the marginal cost or shadow price associated with a particular abatement goal). In other words, a tax on emissions will generate cost-effective reductions in emissions given the tax rate and an increasing tax rate will result in higher abatement. Consequently, we implement an incrementally increasing methane tax to derive the cost-effective solution for increasing abatement levels.

This is achieved by levying a tax per kg CO_2e methane emissions by animal type, thus ensuring that the abatement cost is minimized within and among all farms in the region, as each farm has an incentive to reduce their emissions while their abatement cost is lower than the tax rate. The Total Abatement Cost (TAC) curve for abating methane emissions is derived by incrementally increasing the methane tax rate beginning at 0.2 SEK per kg CO_2e to a maximum rate of 1 SEK per kg CO_2e (SEK/EURO ~ 12). This is considered the maximum rate interesting to study, because it is roughly the level of the Swedish Carbon tax levied on fossil fuels. It's important to recall that the tax relates solely to methane emissions from enteric fermentation as motivated by the scope of this study.

The cost of the tax for farmers is reflected in farm profits. However, to correctly calculate abatement costs for society, we treat the implied tax expense of farm-agents as a transfer and hence eliminate it from the cost of methane abatement in accordance with proper Welfare Economic practice.

In the next section we describe the policy scenarios that are simulated to achieve the broader aims of this study, noting that the TAX scenario is equivalent to the cost-effective solution for a particular level of abatement.

3.6 Evaluated policy scenarios

In order to examine how a policy instrument aimed at reducing enteric methane emissions impacts the preservation of pastures, we conduct simulations for five alternative policy scenarios to the prevailing framework (**Table 3**). Initially, we model these policy changes assuming that product prices in the study region remain unaffected by the policy shift, since Sweden is a small agricultural country and thus will not affect world market prices in any significant way. However, this assumption may not hold true if the policy changes extend to the entire EU or if markets are geographically segmented, e.g., due to strong preferences for Swedish meat from consumers in Sweden implying that higher production costs in Sweden would increase prices in Sweden even with unchanged world market prices. To address the potential influence of market price shifts on our findings, we conduct thereafter a sensitivity analysis, evaluating the implications of adjustments in market prices.

Table 3. Evaluated policy scenarios to assess the impacts of alternative methane abatement instruments on methane emissions and the area of semi-natural pastures compared to the Reference scenario in 2028

ID	Scenario name	Description
SC0	**REF**	Continuation of the 2015-22 CAP framework.
SC1	**CIS**	Remove Coupled Income Support (CIS) for cattle.
SC2	**TAX**	Levy tax on enteric methane emissions at 80 EUR per ton CO2e.
SC3	**CIS+TAX**	Implement scenarios SC1 and SC2 simultaneously.
SC4	**AECM**	Implement SC3 in the absence of Agri-Environmental-Climate-Measure payments to semi-natural pastures (AECM).
SC5	**AECM+BIS**	Implement SC3 in the absence of both AECM and Basic Income Support (BIS) to pastures.

Notes: All scenarios are simulated over the period 2016 to 2028, where policy changes (SC1-5) are implemented in 2023 and results compared to the Reference scenario (SC0) in 2028.

3.6.1 Reference scenario

The Reference scenario is used to simulate the development of agriculture, methane emissions and the area of pastures in the region given the continuation of the 2015-22 policy framework and validate the simulated development with observed trends. The AgriPoliS model is calibrated and validated within the context of the CAP framework spanning from 2015 to 2021, aligning with the available agricultural data for that period. The model demonstrates an ability to replicate observed trends in the structural evolution of the region during this timeframe. Subsequently, the model simulates structural changes in the region into the future, from 2022 to 2028, assuming a continuation of the 2015-22 policy framework. This period is considered adequate for capturing major structural adjustments of the simulated policy scenarios. Although a new CAP reform was implemented in 2023, we anticipate minimal impact on the outcomes of this study, given that the CIS remains a crucial and unaltered component of the new CAP.

3.6.2 Tax on enteric methane emissions

The **TAX** scenario involves levying an environmental tax on estimated enteric methane emissions from specific livestock and will ensure a cost-effective reduction in emissions given the modelled abatement measures (we return to the issue of dynamic efficiency, i.e., incentive to develop new abatement technologies, in the Discussion). We set the tax at 0.96 SEK per kg CO2e, aligning with the average price of emission allowances in the EU ETS in 2022 (Swedish EPA, 2023).

Such an instrument would though signify a major shift in the CAP's trajectory, by embracing the Polluter Pays Principle for environmentally detrimental emissions. In the present context of political ambitions to raise domestic food production and protect farmers' incomes (Boezeman*, et al.*, 2023), a tax might appear to be an infeasible and hence uninteresting instrument to study. However, our implemented tax aligns with the prevailing price of emission allowances in the EU ETS, suggesting that policymakers could feasibly consider a similar policy intervention for the agricultural sector, given the intensifying impacts of climate change. Furthermore, Denmark has concrete plans to impose just such a tax on their agricultural sector by 2027 (Ekspertgruppen, 2024). Nevertheless, the focus here is not primarily on the feasibility of taxing agricultural emissions, but rather on the simulated tax's potential for generating cost-effective methane emissions abatement. This scenario therefore forms a crucial foundation for policy discussions, providing insights into possible strategies.

The tax is imposed on estimated annual methane gas emissions converted into carbon dioxide equivalents (CO2e) according to the livestock types reported in **Table 2**. This implementation means that farmers can mitigate their tax liability by either reducing animal numbers or altering livestock composition to types that produce lower enteric methane emissions. Furthermore, they will be provided with an incentive to dose their livestock with the modelled 3-NOP feed additive that suppresses methane production in the rumen. A similar approach is adopted by Key and Tallard (2012) in their analysis of a tax based on national methane emissions per unit of commodity output. They argue that policies targeting agricultural methane emissions specifically (as opposed to agricultural GHG emissions generally) are more feasible due to the relative ease of quantifying these emissions compared to others.

3.6.3 Abolition of CIS scenario

In the **CIS** scenario, the coupled support to cattle is eliminated, which is the only CIS in Sweden. Although this policy scenario doesn't directly target methane emissions reduction, it has been found that the CIS results in a higher cattle population, and hence increased GHG. Furthermore, as a first step towards reducing GHG emissions the OECD recommends removing inefficient subsidies that exacerbate emissions. Conversely, proponents argue that the CIS plays a crucial role in preserving semi-natural pastures, suggesting that its elimination might jeopardize biodiversity conservation. Eliminating the CIS could potentially represent a relatively straightforward measure achievable within the current CAP structure, requiring minimal policy design groundwork. Hence, the CIS scenario is highly relevant for the objectives of our research, particularly how policymakers should design policy instruments when considering potentially conflicting goals.

3.6.4 Combine TAX on methane emissions and abolition of CIS scenarios

Our third policy scenario combines the previous two, by simultaneously abolishing the CIS and implementing the methane tax. This scenario has additional value because it will highlight the potential for interactions between the two policy instruments, particularly whether the combined effect is larger than the sum of the individual effects in terms of emissions and area of pastures.

3.6.5 Absence of policy payments to semi-natural pastures

The area of semi-natural pastures in Sweden has remained relatively stable over recent decades, thereby breaking the dramatic historical decline described above. This success is largely attributable to the introduction of agri-environmental payments for grazing of these pastures in the early 1990s (now referred to as Agri-Environmental Climate Measures or AECM) and the eligibility of these pastures since 2005 for decoupled area payments, now called Basic Income Support for Sustainability (BISS)[2]. Both payments are interesting to study because they require a minimum grazing pressure (measured in sward length) for their collection. The question we answer in this scenario is to what extent do the AECM and BIS payments protect the area of semi-natural pastures from the potential negative impacts of a methane-abatement policy instrument? To do this we first simulate the TAX+CIS scenario in the absence of the AECM payment and then in the absence of both the AECM and BIS payments. Consequently, this analysis should provide an indication of the resilience value of the BIS and AECM payments for preserving semi-natural grasslands in the face of policy (or similar) shocks.

3.7 Sensitivity analysis

As AgriPoliS is a regional model, it does not model endogenously the potential market effects of policy changes on product prices. In reality, policy changes would most likely affect product prices, particularly if implemented at the EU level, but potentially also if the demand for “Swedish produced” products is sufficiently strong to cause price changes in geographically segmented markets. In either case the resultant increase in production costs of a tax could feed through to higher prices, and hence, dampen the impacts of the simulated policy scenarios. For example, large reductions in beef cattle numbers in the EU would reduce the global supply of beef and hence put upward pressure on beef prices within the EU. Such price increases could furthermore cause

[2] Previously named the Basic Payment Scheme (BPS) in the 2015-22 CAP.

substitution effects in consumption (e.g., consumers switching more to pork or chicken that are not affected by a tax on enteric methane), thereby magnifying the impact of the tax on reducing emissions but is not considered here.

To examine how price changes influence our results, we perform a sensitivity analysis whereby exogenously derived changes in market prices for meat and milk are imposed on the relevant methane policy scenarios. The modelled market price changes are based on assumptions derived from the literature. In the case of the CIS scenario, Jansson*, et al.* (2021) use the CAPRI model to analyse effects of abolishing the CIS for ruminants, and find it would lead to a 2.4% increase in the producer price of beef in the EU. However, in their scenario, the funds freed from removing the CIS are transferred to the BISS, which would mitigate the reduction in beef output and hence potential price increase. In our CIS scenario the freed funds are not returned to farmers, implying the price effects of our CIS scenario will be stronger. We also know that prices could not increase beyond the rate that would perfectly neutralize the revenue effect of eliminating the CIS, which corresponds to a price increase of 5.4% for beef and 4.8% for milk. Therefore, we test a potential price increase of 2.7% for meat and 2.4 % for milk in the CIS scenario, which are equivalent to 50% of the maximum possible price increases.

For the TAX scenario implemented at the EU level, the potential price effects will depend on to what extent producers can pass on their increase in costs due to the tax to consumers, the so-called tax incidence. This, in turn, depends on a number of factors, but essentially, consumers' elasticity of demand for beef and milk, and farmers' elasticity of supply for these products. Jansson*, et al.* (2023) find a tax incidence of 0.5 for beef producers when a similar tax is implemented in the EU (this tax is, however, applied to all agricultural goods and to all emissions of methane and nitrous oxide), indicating that the cost of the tax is more or less evenly distributed among producers and consumers. The implied tax effects on producers of our TAX scenario are 12.2 % for beef and 16.3 % for milk according to our modelling. Assuming a tax incidence of 0.5, implementation of the methane tax in our TAX scenario would imply a concomitant producer price increase of 6.1 % for beef and 8.1 % for milk.

For the CIS+TAX scenario we assume a concomitant price increase of 8.8 % for beef and 10.5 % for milk by applying the tax incidence of 0.5 to the implied tax effects of 17.6 % for beef and 21 % for milk. The reasonableness of this assumption is debatable, but the purpose of the sensitivity analysis is to gauge the potential significance of price effects on our results for the main scenarios, and not to predict these price effects per se.

To implement the assumed price changes, summarized in **Table 4**, we phase them in over the same time period as we phase in the different policy scenarios. The formula applied is $r = \sqrt[T]{\Delta P} - 1$, where r is the rate of change over the time period *T* in years and Δ*P* is the desired total price change over T years.

Table 4. Summary of assumed product price increases for sensitivity analysis of methane policy scenarios

ID	Scenario name	Beef Price *(% increase)*	Milk Price *(% increase)*
SA1	**CISp**	2.7	2.4
SA2	**TAXp**	6.1	8.1
SA3	**(CIS+TAX)p**	8.8	10.5

Finally, we do not consider price effects in the absence of AECM and BIS payments to semi-natural pastures, because these scenarios are designed to evaluate the significance of these payments for preserving pastures on the introduction of methane policy. Overall, it is important to keep in mind that these price-effect assumptions are adequate for our purposes: to test the sensitivity of our results to potential changes in prices, rather than the realism of the assumed price changes per se.

4 Results

We begin by presenting results for the cost-effectiveness analysis followed by the described policy scenarios and sensitivity analysis.

4.1 Impacts of Cost-effective Methane Abatement

4.1.1 Costs of methane abatement and area of semi-natural pastures

A tax on methane emissions results in cost-effective methane abatement, and measures to reduce methane emissions are taken as long as their marginal cost is lower or equal to the tax. That is the marginal abatement cost is equal to the tax rate in the cost-effective solution. To derive the cost-effective solution, we run a set of simulations where we vary the tax rate without altering other policies within the reference scenario. Both the marginal cost of methane abatement and impact in terms of diminished area of semi-natural pastures are initially steeply increasing in the level of abatement (**Figure 1**). However, a substantial increase in abatement is achieved from 10 to 45 kilotonnes CO2e at relatively small additional cost, because it becomes profitable for farmers to purchase the 3-NOP feed additive instead of paying the tax. The substantial jump in abatement is explained by the assumed pricing of dosing 3-NOP at 1000 SEK per animal, rather than per unit 3-NOP. The black curve (points marked with X) shows the impact on marginal cost and abatement if the 3-NOP additive is excluded from the analysis, thus demonstrating the potential of technical measures to increase the effectiveness and reduce the costs of enteric methane abatement.

The impact of methane abatement on the area of pastures is on the other hand relatively small, only losses of a few hundred ha compared to the total area of 40526 ha in the county. This demonstrates that the abatement of enteric methane emissions is not a substantial threat to the conservation of biodiversity, which is thanks to the ability of farm-agents to optimize their livestock holdings and purchase the 3-NOP additive to achieve an almost 25 % reduction in emissions for a less than 1.5 % loss in pastures. Interestingly, the availability of 3-NOP does not adversely affect the area of pastures, rather substantially more abatement is achieved for an equivalent loss in area.

To understand these results better we next delve into the effects of cost-effective abatement on farm structure, land use and livestock holdings.

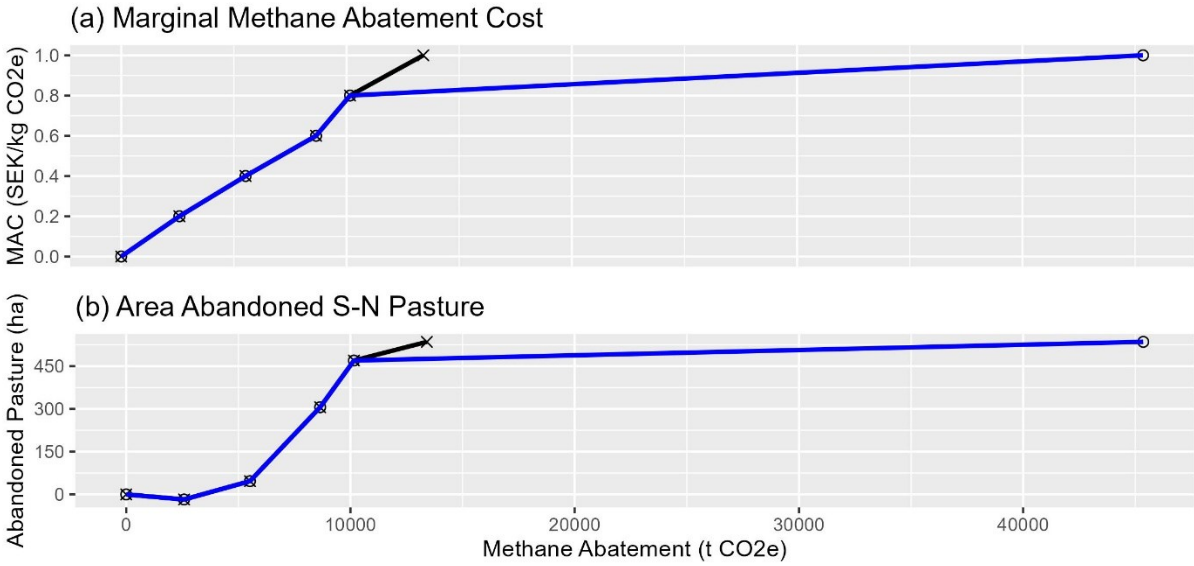

Figure 1. Marginal costs of abating enteric methane emissions (a) and area of abandoned semi-natural pastures (b) for increasing levels of abatement.

4.1.2 Impacts on farm structure and incomes

Increasingly ambitious abatement of methane emissions, as indicated by increasing MAC, was found to have a consistent impact on farm structure, with the number of farms in the region declining and the average farm size increasing compared to the reference scenario in response to increasing abatement (**Figure 2**). In this sense cost-effective methane abatement calls for accelerated structural change with less efficient producers leaving the sector at a faster rate. This allows other farms to grow and invest in larger stables, thereby lowering their production costs and allowing them to continue farming despite the higher costs attributable to methane abatement.

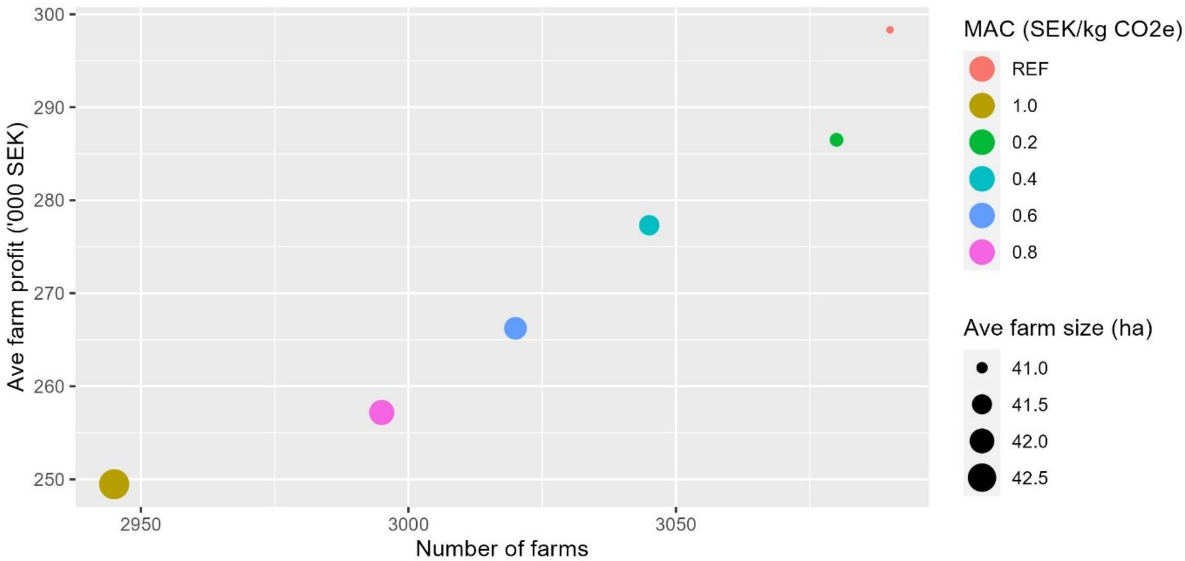

Figure 2. Effects of cost-effective methane abatement on agricultural structure in terms of i) Marginal Abatement Cost (MAC), ii) number of farms and iii) average farm size in the study region.

A further explanation for the minimal effects of methane abatement on the area of pastures (and arable land not being abandoned at all) is that the costs of methane abatement for farmers are countered, to some extent, by reductions in the rental prices of arable land and pastures (**Figure 3**), the reasons for which we evaluate in the sensitivity analysis to the policy scenarios below.

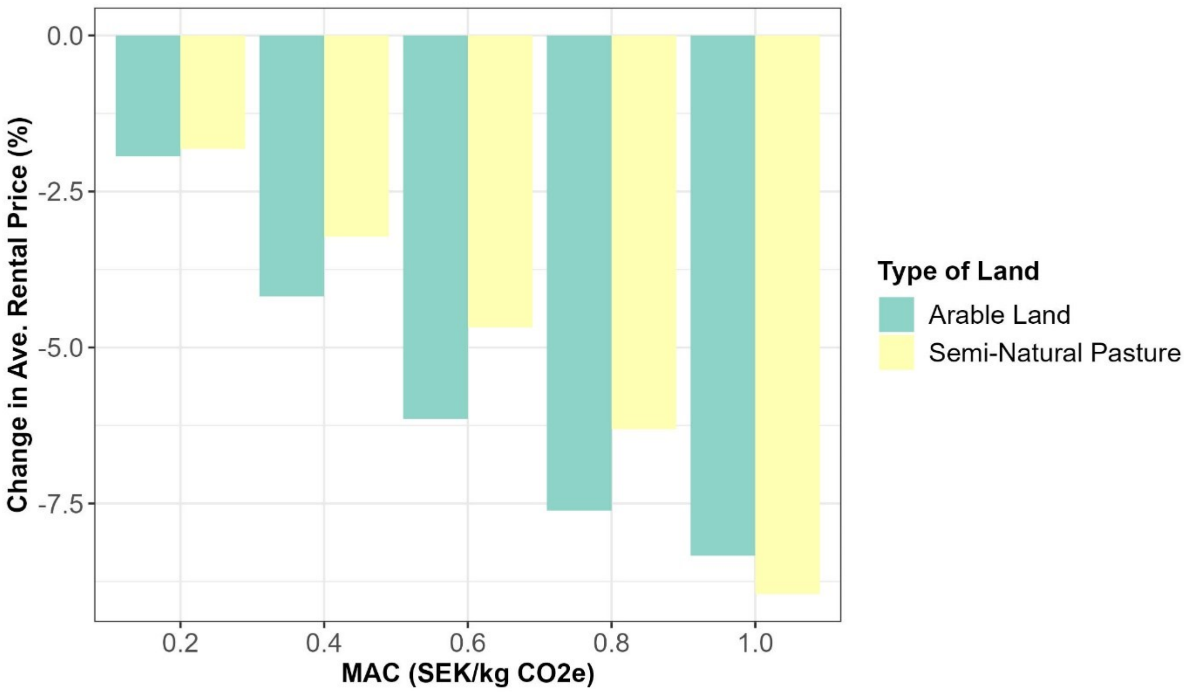

Figure 3. Impact of cost-effective abatement on land rental prices.

4.1.3 Impacts on land use and livestock holdings

It is the flexibility of land use and livestock holdings in response to increasing methane abatement (**Figure 4**) that allowed farm-agents to abate methane emissions while preserving nearly the entire area of pastures. Primarily suckler cows, beef cattle and sheep numbers are reduced to abate methane emissions, but these reductions have negligible impacts on the area of pastures. That is other land uses are changed instead; primarily the areas of arable-grass pasture and silage are reduced to compensate for the reduced demand for livestock fodder, and the associated arable land is converted to set-aside. However, as the abatement goal is increased, even some area of pastures and field crops are lost. Further, even the otherwise stable dairy-cow herd (the most profitable production activity) is reduced in the extreme case (MAC = 1.0). However, the large jump in abatement is principally achieved by purchasing the 3-NOP feed additive for all dairy cows, which becomes a cost-effective measure when MAC reaches 1.0 SEK/kg CO2e, but only for dairy cows.

Overall, the potential negative impact of the reduction in cattle and sheep on the area of pastures is, mitigated to a large extent, by farmers choosing to reduce arable fodder production instead and purchase the NOP-3 feed additive when MAC exceeds 0.8 SEK/kg CO2e. As we show next, the choice to continue preserving pastures is owing to the existing agri-environmental payments to pastures.

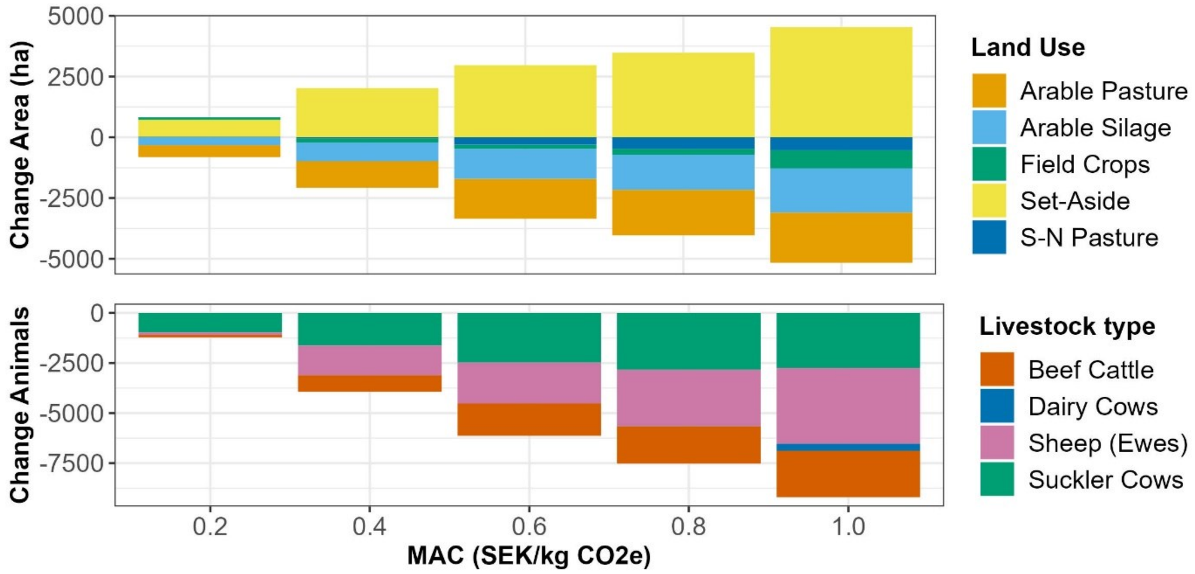

Figure 4. Impacts of cost-effective methane abatement on agricultural land use (a) and livestock numbers (b) in the study region.

4.2 Impacts of climate policy scenarios

We begin the policy analysis by overviewing the impacts of the different policy scenarios (**Table 3**, SC1–5) and sensitivity analyses (**Table 4**, SA1–3) on methane emissions and area of semi-natural pastures (**Table 5**). We include results of the subsequent sensitivity analysis in **Table 5** to aid comparisons later in the text. To begin with, note that methane emissions in the region decline over the simulation period (2016–27) by ~2,800 tonnes according to the Reference scenario, i.e., if we continue with the current policy framework emissions decline over time due to declining agricultural production. The area of pastures on the other hand remains roughly the same. Each of the targeted methane abatement policy scenarios (SC1–3) reduced emissions compared to the reference scenario, and with relatively small negative impacts on the area of pastures. Thus, the relative reduction in methane emissions were much higher than the relative loss of pastures. To understand this result we turn to the two scenarios considering the impacts of agri-environmental payments on semi-natural pastures.

According to scenario SC4, the AECM payment has a substantial impact on maintaining the area of pastures in the methane policy scenarios (SC1–3). In the absence of the AECM the area of pastures would decline dramatically with the removal of the CIS and implementation of a methane tax (**Table 5**, SC4). Furthermore, the reduction in pasture would be even more dramatic if the BIS also did not exist (SC5). These results vindicate, to some extent, the concern of policymakers that reducing ruminants would be negative for biodiversity. However, in the presence of payments for the preservation of pastures, i.e., the AECM and BISS, farmers are provided with a strong incentive to optimize their livestock herds for methane abatement and preservation of pastures. That is to say, the presence of these payments strengthens the resilience of pastures to policy (or similar) shocks that impact the profitability of livestock farming. The technical explanation for this resilience is attributable to the partial capitalization of payments in rental prices, i.e., positive rental prices (**Figure 3**). In the presence of the AECM and BISS, the methane tax results in a comparatively large reduction in rental prices for pastures rather than the area of pastures per se in the methane scenarios (SC1–3).

Table 5. Impacts of policy scenarios on methane emissions and area of semi-natural pastures and percentage changes compared to the reference scenario in 2027.

			Methane Emissions	**S-N Pasture Area**
Scenario No.	**Policy Scenario Description**	**ID**	% Change on Ref in 2027 *[t CO2e]*	% Change on Ref in 2027 *[ha]*
SC0	Reference scenario	REF	[39,013]	[39,028]
SC1	Eliminate CIS	CIS	-3 %	0 %
SC2	Tax on enteric CH4 emissions	TAX	-23 %	-1 %
SC3	Combine SC1+SC2	CIS+TAX	-26 %	-2 %
SC4	Combine SC3 with absence of AECM payment	CIS+TAX-AECM	-37 %	-23 %
SC5	Combine SC3 with absence of both AECM and BIS	CIS+TAX-AECM-BIS	-62 %	-77 %
Sensitivity Analysis				
SA1	Product price increase for SC1#	CISp	-3 %	0 %
SA2	Product price increase for SC2	TAXp	-22 %	-1 %
SA3	Product price increase for SC3	CISp+TAXp	-23 %	-1 %

Notes: # Price changes according to Table 4.

4.2.1 Sensitivity analysis of potential increases in product prices

The sensitivity analysis indicates that potential price increases resulting from, e.g., implementation of methane abatement policy at the EU level, would all but eliminate the potential negative impacts of methane policy on the area of pastures (SA1–3). Interestingly, the price increases only cause minor increases in methane emissions in the TAXp and CISp+TAXp, because the tax maintains the incentive for farmers to purchase the 3-NOP feed additive, thereby achieving considerable emissions abatement without losing semi-natural pastures.

4.2.2 Impacts on farm structure and incomes

We overview the structural impacts on farm incomes, number of farms and average farm size in **Figure 5**. Important results regarding farm structure are that potential product price increases, would greatly ameliorate the potential loss of farms and reduction in farm incomes in the region (indicated by arrows). Furthermore, the AECM and BIS payments have a substantial impact on preserving farms as well as the area of pastures. Thereby indicating that a synergy exists between these two variables, because the cost of preserving pastures are lowered if livestock stables and hence livestock are more evenly distributed in the landscape. In contrast, declining numbers of farms and concentration of livestock holdings implies increasing distance costs for managing pastures (i.e., transport of livestock between pastures and stables, as well as monitoring of livestock), because these area-based payments incentivise extensive farming (i.e., using more land relative to other inputs) and with that a greater spatial spread of farms.

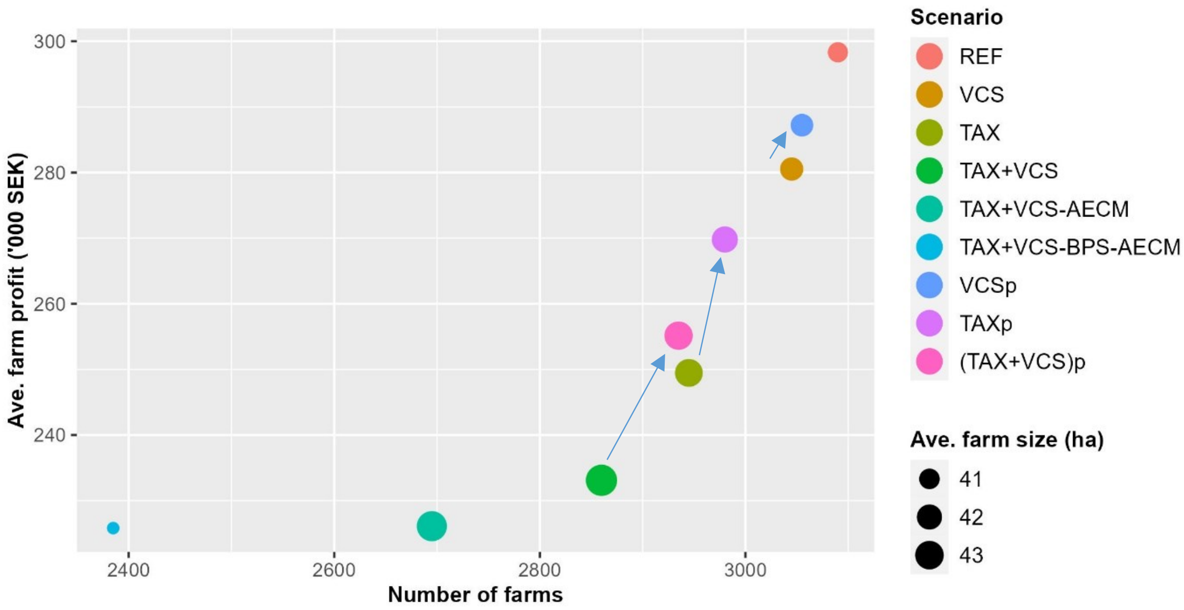

Figure 5. Effects of methane abatement policy instruments and payments to semi-natural pastures on agricultural structure in terms of i) average farm profit, ii) number of farms and iii) average farm size in the study region. Arrows indicate the direction of effect of the assumed price increases in the sensitivity analysis for relevant methane policy scenarios.

4.2.3 Impacts on land use

Finally, we evaluate the impacts of the different scenarios on land use **Figure 6**. Without payments to semi-natural pastures (scenarios TAX+VCS-AECM and TAX+VCS-BPS-AECM), substantial areas of pastures would be afforested (i.e., abandoned) and arable land put in set-aside. This scenario confirms the perceived complementary relationship between ruminants and preservation of pastures, but since society already has payments for maintaining pastures, the impacts of methane policy on pastures is minimized. Furthermore, these payments also indirectly incentivise farmers to keep arable land in agricultural production through the need for additional fodder production, as pastures are only a source of fodder for a few months of the year in Sweden (i.e., over the spring and summer months). Finally, the assumed price increases that would occur if the modelled methane policy scenarios were implemented at the EU level, would moderate the reductions in active land use, and associated livestock numbers (not shown).

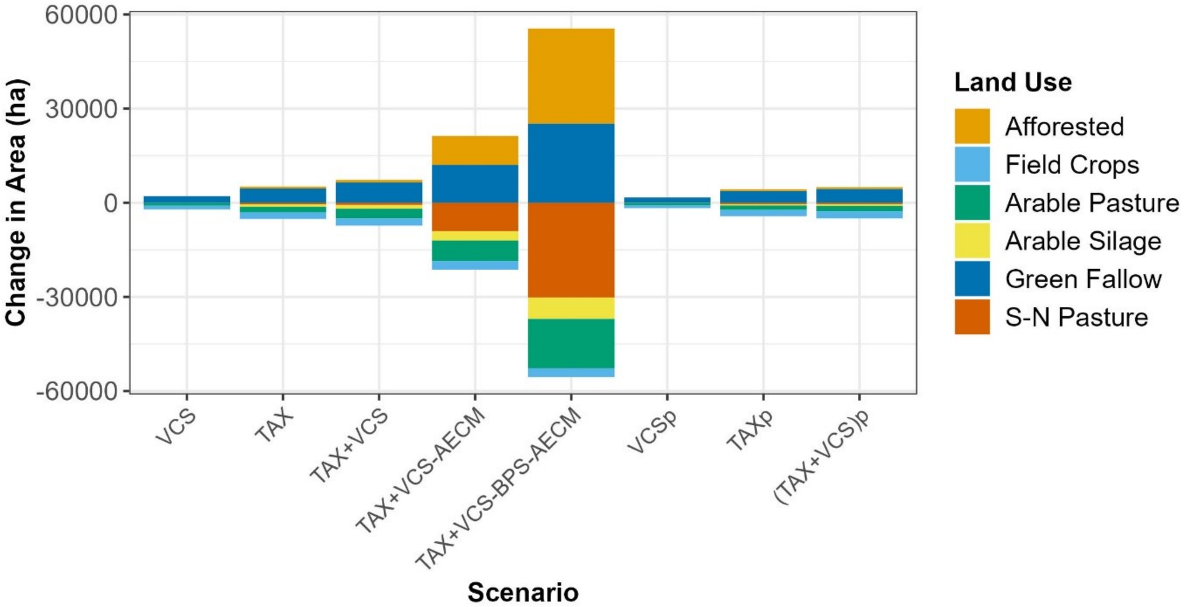

Figure 6. Impacts of policy scenarios and sensitivity analysis scenarios on land use.

5 Discussion

Enteric methane abatement poses a complex dilemma for policymakers. While milk and beef production account for around 50 % of agriculture's GHG emissions, cattle and other ruminants such as sheep also contribute to the conservation of biodiversity in the EU (and the cultural landscape and other ecosystem services) through the preservation of extensively grazed grasslands, such as Sweden's semi-natural pastures. The aim of this study has been to explore how policy instruments aimed at reducing agricultural GHG emissions, specifically enteric methane, would affect preservation of semi-natural pastures particularly, and agriculture generally, in a study region characterized by large numbers of ruminant livestock and a relatively large area of biodiversity-rich pastures. Given that methane-abatement policy is likely to have profound impacts on the structure of agriculture we carry out the analysis with the spatial and dynamic, agent-based model AgriPoliS that is capable of simulating structural change in agriculture in response to policy reform.

The cost-effective solution for increasing methane abatement demonstrated that abatement targets could be reached with minimal impact on the area of pastures through re-structuring of livestock production and use of a commercially available feed additive. In general, suckler-cow beef production and sheep are increasingly reduced for all abatement levels, and for the highest level of abatement even the dairy herd is reduced somewhat, but substantial reductions are achieved through use of the modelled feed additive (3-NOP). The cost-effective solution even calls for fewer but larger farms, which ameliorates costs of methane abetment through economies of scale.

We thereafter evaluated three methane abatement policy scenarios (SC1–3) and their sensitivity to potential increases in output prices (SA1–3). We demonstrated that it is quite possible to radically reduce methane emissions with relatively small losses in the area of pastures through removing the Coupled Income Support to cattle (CIS) and implementing an environmental tax on enteric methane emissions. This is because of the considerable flexibility available to farmers to reduce emissions through restructuring livestock holdings and purchasing the modelled feed additive (3-NOP); and the strong incentive provided by existing policy payments to preserve pastures for biodiversity (i.e., the BIS and AECM).

A key result from the deeper policy analysis (SC4–5) is that existing agricultural and environmental payments proved crucial for preserving the area of pastures in the presence of methane abatement policy. Without these payments the area of pastures was shown to decline severely, but also methane emissions would be substantially lower (Table 5, SC5). Thus agri-environmental payments are not only important for compensating farmers for the extra costs of maintaining pastures today, but also for strengthening the resilience of pastures to potential policy (and market) shocks. Consequently, implementing a carbon tax in the presence of AECM payments results in an optimal area of pastures and methane emissions, assuming these payments reflect the societal benefits of preserving pastures and the methane tax the social cost of methane emissions. That is, the resultant higher level of methane emissions is motivated, from a Welfare Economic perspective, by the conservation of biodiversity associated with pastures.

A further insight gained from the results was that, rather than the area of pastures declining in the presence of the methane tax and abolition of the CIS, as modelled here, it was primarily the rental price of agricultural land that declined. This value can be likened with the option value of preserving arable land to safeguard food security, by raising its value in agriculture through policy payments, despite it not being used in production today; but maintained in good agricultural and environmental condition for the future (Di Corato and Brady, 2019).

5.1 Contrasting results

According to our simulations, removing the CIS to cattle would reduce methane emissions without a significant impact on the area of semi-natural pastures. This result stands in stark contrast to the 20 % or more loss in area of pastures predicted in simulations using another model, the Swedish Agricultural Sector Model (SASM) (Regeringskansliet, 2018). It is difficult for us to explain why SASM predicts such a strong effect, as this requires detailed understanding of the modelling assumptions. Nevertheless, we can describe the reasons for AgriPoliS predicting such a limited impact. First, the fact that SASM does not account for the potential for structural change, provides AgriPoliS farm-agents with greater flexibility to adapt to a new policy environment. In particular, when some farms are closed down in AgriPoliS, causing a potentially strong reduction in availability of livestock to graze pastures, remaining farms can grow by renting the land released by closed farms, and investing in larger stable and machinery capacities; thereby taking advantage of economies of scale to reduce costs and continue the maintenance of pastures. As we demonstrate the methane policy scenarios also exert strong downward pressure on land rental prices, thereby partially compensating active farmers for tax expenses.

In the same vein, AgriPoliS farm-agents can change the orientation of their livestock production by switching from, e.g., dairy production which is high in methane emissions and relatively low in contribution to preservation of pastures, to suckler beef production that has the opposite characteristics. Similarly, they can switch from suckler beef to lamb production. All made possible by the potential to invest in new stables and grow the farm in AgriPoliS, in response to more land entering the rental market. Finally, given the relatively low level of CIS payments compared to the combined value of the BIS and AECM directed to pastures, farmers maintain a strong incentive to maintain pastures despite elimination of the CIS in our simulations; thus reducing arable grass fodder production rather than semi-natural pastures. In essence, the relative profitability of environmental management increases compared to that of commodity production in the presence of agri-environmental payments (i.e., as the BIS and AECM function for pastures). In this sense introduction of a methane tax in the presence of the BIS and AECM provides farmers with a strong incentive to optimize farm structure to minimize methane emissions and maximize the area of pastures in AgriPoliS. Consequently, our simulations indicate a greater flexibility in the agricultural system over time to adapt to new conditions than is predicted by a static model such as SASM.

Furthermore, the validity of the CIS as a conservation measure is undermined by the fact that the levels of CIS payments to cattle do not depend on the extent to which the cattle graze on semi-natural pastures (Regeringen, 2022). Cattle in different production systems differ greatly regarding their grazing needs, because fodder can not only be sourced from semi-natural pastures, but also from intensively farmed arable grasslands (recall **Table 2**). Therefore, it is not the number of cattle per se that is vital for the preservation of semi-natural pastures, but the availability of livestock types that can feasibly (i.e., economically and biologically) utilize semi-natural pastures. Finally, it has been shown that the number of cattle in Sweden can be reduced without negatively impacting the preservation of semi-natural pastures when considering the overall grazing need compared to supply of potential grazers (Larsson*, et al.*, 2020).

Today's design of the CIS therefore raises questions about its cost-effectiveness for preserving semi-natural pastures in addition to its climate cost. Furthermore, farmers can apply for voluntary environmental support, as compensation for the additional costs of maintaining pastures. Hence, an instrument targeting the preservation of semi-natural pastures already exists, thereby making the CIS all but redundant in this respect. The more reliable response for an increasing risk of pastures being abandoned is therefore to strengthen these payments through reduction of the CIS.

5.2 Technical measures for methane abatement

In our simulations, we only consider a single technical measure to reduce enteric methane emissions, a 3-NOP feed additive, but other promising measures are in development, though not currently viable as described in Section 2. Nevertheless, including the feed additive as an abatement measure has provided interesting insights into the implications of such measures for abatement costs generally, and the area of semi-natural pastures specifically. Namely, that they offer the promise of achieving deep reductions in methane emissions while not conflicting with the goal to preserve grasslands or food production.

Another aspect to consider in light of the dual policy challenge in focus here is that research on additives is concentrated on intensive production systems, such as milk production and those utilizing feedlots to fatten cattle. In cases where fodder type and intake is strictly controlled, dosing additives can be feasible, but would be a challenge for grazing systems (Rivera and Chará, 2021). Consequently, technical fixes are more likely to be a partial solution for intensive livestock systems, rather than extensive grazing systems that are crucial for the preservation of pastures. Nevertheless, continuous dosing through, e.g., implants are under development, and with the right incentives could be available in the near future even for livestock on pastures.

For these reasons, we conclude that an instrument targeting expected emissions by livestock-type is, currently, the only feasible policy option to promote cost-effective methane abatement (assuming the emissions relations are sufficiently well known, which seems to be the case), as measuring actual emissions from individual animals though possible, is prohibitively costly. Nonetheless, if this instrument is closely linked to predicted emissions abatement, then it will provide a strong incentive for development of innovations in breeding, fodder and feed additives to reduce benchmark emissions for different livestock types, if the system allows for revising predicted emissions by animal type, once the abatement effect is confirmed of a new measure, a so-called system based on modelled results (Bartkowski*, et al.*, 2021).

5.2.1 Reducing livestock numbers and regulated reductions generally

A policy instrument currently being adopted in a number of EU member states (Netherlands, Belgium and Denmark), is a scheme whereby farmers receive a compensatory payment to reduce livestock populations. These are potentially more attractive to farmers than say a tax on emissions for obvious reasons. The main reason for implementing these buyouts is to solve environmental problems associated with nutrient emissions at national and local scales (Boezeman*, et al.*, 2023). These schemes are also cited as having co-benefits in the form of reducing GHG emissions, and indeed could be conceived to reduce methane and other GHG emissions associated with ruminants. As the damage caused by nutrient emissions is usually highly place dependent, a buyout scheme can make economic sense, since it is crucial which livestock and where they are reduced. However, in the case of methane emissions, the damage caused by their contribution to warming is a global problem and hence it is not important where or from which livestock emissions are reduced. The overriding policy challenge is to reduce these emissions cost-effectively, wherever that might be.

According to environmental economic theory, the most cost-effective way to mitigate emissions of greenhouse gases is for farmers to be able to choose mitigation measures themselves. In that way, they can choose the measures that are cheapest for them. Admittedly, the cost-effective solutions derived in our study require restructuring of livestock holdings or purchasing the NOP-3 feed additive, but still there is great freedom in the region to choose which livestock and on what farms to reduce emissions. This indicates a limitation of our study, in that we do not consider the full range of potential abatement measures. Thus in reality, methane abatement is likely to be less costly than found here, if all potential abatement measures are considered. However, as found above, there is great uncertainty regarding the universal impacts of currently available technologies for mitigating per animal methane emissions from enteric fermentation. Nevertheless, the policy options investigated here are likely to be more cost-effective than a livestock buyout scheme and provide incentives for the faster development and adoption of technical measures.

In the same sense as a buyout scheme, prescribing abatement measures through regulations would also be unnecessarily costly for achieving methane reductions. It is key to cost-effective methane abatement that a policy instrument targets the rate of emissions by animal type, as for instance our tax on methane emissions, or eliminate market-distorting subsidies that drive higher emissions, such as the CIS in our study region.

5.3 Limitations

Our study has some important limitations. First, it is a regional analysis and not a comprehensive analysis for Sweden - therefore, the results should not be viewed as answers to what happens with emissions and semi-natural pastures on a national level, but as being indicative of the effects in regions with similar conditions, such as mixed silvicultural-agricultural regions (i.e., skogsbyggder). Second, it does not account for potential carbon leakage, i.e., domestic production being replaced by imports, which could lead to increased methane emissions in other locations. Such leakage is expected to be substantial if Sweden enacts methane policy unilaterally. Third, we have had no ambition to find optimal levels of semi-natural pasture area for biodiversity conservation, rather we assume the current area is desirable and hence any losses are negative for societal welfare. While we assume that the modelled losses are negligible (i.e., several hundred ha of ~41K ha), in practice it would matter exactly which pastures are abandoned. Overall, it is important to recall that our aim has been to quantify the potential trade-offs between methane abatement and conservation of biodiversity, and not the efficacy of Swedish abatement from a global perspective, nor the biological value of preserving a certain area of pastures.

Finally, the 3-NOP feed additive modelled here is currently produced by a single company with a patent on the substance, suggesting they have monopoly power. The cost of dosing it used in this study is also based on a "rough" estimate by a company representative. Consequently, the costing in this study is uncertain and could be higher or lower in an actual commercial situation depending on factors that normally impact commercial contracts, i.e., availability of alternative products, volume of purchase, etc. Nevertheless, this consideration does not change the overall conclusions of this study about the potential cost-effectiveness of feed additives for mitigating methane emissions and the implications for semi-natural grasslands.

6 Conclusions

Our overriding conclusion is that it is eminently possible to reduce enteric methane emissions without substantial losses of nature areas such as Sweden's semi-natural pastures. However, this conclusion is contingent upon the existence of sufficiently high agri-environmental payments to reward farmers for continuing to preserve these areas and the efficacy of the 3-NOP feed additive modelled here. In the absence of the feed additive, only small reductions in methane emissions were shown to be achievable at a marginal cost of around the same value as the Swedish CO2 tax and EU ETS pricing of CO2e emissions.

The capacity to reduce methane emissions in the absence of technical measures rests on the ability of farmers to restructure livestock holdings; either reducing numbers of animals per se or substituting between different types of ruminant livestock, which we found to be very costly for achieved emissions reductions. We found that technical measures, such as the 3-NOP feed additive modelled here to reduce generation of methane in animal rumens, i.e., at source, are likely crucial for achieving deep cuts in enteric methane emissions. Despite showing promise for reducing methane emissions according to our literature review (Section 2), other additives such as those based on algae, have also generated severe side effects for animal health and productivity, while measures such as breeding and vaccination are in their early development. Consequently, we conclude that a broader pallet of technical measures is not currently available, but could be in the future, if the necessary incentives for research and development, and adoption by farmers are put in place. Currently, there exists little or no incentive for farmers to abate enteric methane emissions.

To avoid simultaneous loss of nature areas dependent on ruminant grazing, such as semi-natural grasslands, we also demonstrated that it is imperative that targeted agri-environmental schemes are in place to reward farmers for continuing to preserve these areas.

In view of the immense challenge to EU policymakers (and farmers) in dealing with multiple policy goals, such as climate action and biodiversity conservation, it is important to realise that trade-offs are inevitable, as shown here. In this case the rational policy goal is to find an optimal balance between conflicting goals and to achieve this balance cost-effectively (i.e., without wasting resources). To achieve this balance, it will usually be necessary to have at least one instrument in place for steering towards achievement of specific goals, unless goals are highly correlated. In the current study, we examined a tax on methane emissions for climate action and agri-environmental payments to grasslands for biodiversity conservation. In this respect, we demonstrated the crucial role of agri-environmental payments to strengthen the resilience of agricultural biodiversity to policy shocks targeting other goals. On the other hand, Coupled Income Support (CIS) such as the payments to cattle evaluated here, used as a single instrument to achieve multiple goals was shown to be a poor alternative.

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8 References

AgriWise (2020). Agriwise: Data Book for Production Planning and Regional Enterprise Budgets. Jordruksverket.

Aune, S., Bryn, A., Hovstad, K. A. (2018). Loss of semi-natural grassland in a boreal landscape: impacts of agricultural intensification and abandonment. *Journal of Land Use Science* 13: 375-390.

Balmann, A. (1997). Farm-based modelling of regional structural change: a cellular automata approach. *European Review of Agricultural Economics* 24: 85-108.

Bampidis, V., Azimonti, G., Bastos, M. d. L., Christensen, H., Dusemund, B., Fašmon Durjava, M., Kouba, M., López-Alonso, M., López Puente, S. (2021). Safety and efficacy of a feed additive consisting of 3-nitrooxypropanol (Bovaer® 10) for ruminants for milk production and reproduction (DSM Nutritional Products Ltd). *Efsa Journal* 19: e06905.

Bartkowski, B., Droste, N., Ließ, M., Sidemo-Holm, W., Weller, U., Brady, M. V. (2021). Payments by modelled results: A novel design for agri-environmental schemes. *Land Use Policy* 102: 105230.

Beauchemin, K. A., Ungerfeld, E. M., Eckard, R. J., Wang, M. (2020). Fifty years of research on rumen methanogenesis: Lessons learned and future challenges for mitigation. *animal* 14: s2-s16.

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H. G., & Lindborg, R. (2019). Grasslands—more important for ecosystem services than you might think. *Ecosphere BECC: Biodiversity and Ecosystem Services in a Changing Climate* 10(2).

Bertilsson, J. (2016). Updating Swedish emission factors for cattle to be used for calculations of greenhouse gases.

Boezeman, D., de Pue, D., Graversgaard, M., Möckel, S. (2023). Less Livestock in North-western Europe? Discourses and Drivers Behind Livestock Buyout Policies. *EuroChoices* n/a.

Brady, M., Kellermann, K., Sahrbacher, C., Jelinek, L. (2009). Impacts of Decoupled Agricultural Support on Farm Structure, Biodiversity and Landscape Mosaic: Some EU Results. *Journal of Agricultural Economics* 60: 563-585.

Brady, M. V., Boke Olén, N., Malmström, N., Roger, F., Clough, Y. (2024). Potential for Optimizing Common Agricultural Policy Payment Instruments for Sustaining High Nature Value Farming Areas. AgriFood Working Paper. Lund: AgriFood Economics Centre, SLU and Lund University.

de Haas, Y., Veerkamp, R., De Jong, G., Aldridge, M. (2021). Selective breeding as a mitigation tool for methane emissions from dairy cattle. *animal* 15: 100294.

Di Corato, L. and Brady, M. V. (2019). Passive farming and land development: A real options approach. *Land Use Policy* 80: 32-46.

Edjabou, L. D. and Smed, S. (2013). The effect of using consumption taxes on foods to promote climate friendly diets–The case of Denmark. *Food Policy* 39: 84-96.

Ekspertgruppen (2024). Green tax reform. Report February 2024. Copenhagen: Ekspertgruppen for en grön skattereform [https://skm.dk/media/tngh1b4r/green-tax-reform-final-report.pdf].

Eriksson, O. (2021). The importance of traditional agricultural landscapes for preventing species extinctions. *Biodiversity and Conservation* 30: 1341-1357.

European Commission (1992). COUNCIL DIRECTIVE 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

European Commission (2022). Voluntary coupled support
Member States' support decisions applicable for claim year 2022.

Fouts, J. Q., Honan, M. C., Roque, B. M., Tricarico, J. M., Kebreab, E. (2022). Enteric methane mitigation interventions. *Translational Animal Science* 6: txac041.

Gavrilova, O., Leip, A., Dong, H., MacDonald, J. D., Gomez Bravo, C., Amon, B., Barahona Rosales, R., PRADO, A. d., de Lima, M. A., Oyhantcabal, W. (2019). Emmisions from livestock and manure management.

Gavrilova, O., Leip, A., Dong, H., MacDonald, J. D., Gomez Bravo, C., Amon, B., Barahona Rosales, R., Del Prado, A., de Lima, M. A., Oyhantcabal, W. (2019). Chapter 10. Emissions from livestock and manure management. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

Habel, J. C., Dengler, J., Janišová, M., Török, P., Wellstein, C., Wiezik, M. (2013). European grassland ecosystems: threatened hotspots of biodiversity. *Biodiversity and Conservation* 22: 2131-2138.

Happe, K., Kellermann, K., Balmann, A. (2006). Agent-based Analysis of Agricultural Policies: an Illustration of the Agricultural Policy Simulator AgriPoliS, its Adaptation and Behavior. *Ecology and Society* 11: 49 [http://www.ecologyandsociety.org/vol11/iss41/art49/].

Honan, M., Feng, X., Tricarico, J., Kebreab, E. (2021). Feed additives as a strategic approach to reduce enteric methane production in cattle: Modes of action, effectiveness and safety. *Animal Production Science*.

Hristov, A. N. (2024). Invited review: Advances in nutrition and feed additives to mitigate enteric methane emissions. *Journal of Dairy Science* 107: 4129-4146.

Hristov, J., Clough, Y., Sahlin, U., Smith, H. G., Stjernman, M., Olsson, O., Sahrbacher, A., Brady, M. V. (2020). Impacts of the EU's Common Agricultural Policy "Greening" Reform on Agricultural Development, Biodiversity, and Ecosystem Services. *Applied Economic Perspectives and Policy* 42: 716-738.

Jansson, T. and Säll, S. (2018). Environmental consumption taxes on animal food products to mitigate Greenhouse gas emissions from the European Union. *Climate Change Economics* 9: 1850009.

Jansson, T., Nordin, I., Wilhelmsson, F., Witzke, P., Manevska-Tasevska, G., Weiss, F., Gocht, A. (2021). Coupled agricultural subsidies in the EU undermine climate efforts. *Applied Economic Perspectives and Policy* 43: 1503-1519.

Jansson, T., Malmström, N., Johansson, H., Choi, H. (2023). Carbon taxes and agriculture: the benefit of a multilateral agreement. *Climate Policy*: 1-13.

Kellermann, K., Happe, K., Sahrbacher, C., Balmann, A., Brady, M., Schnicke, H., Osuch, A. (2008). AgriPoliS 2.1-Model documentation. *Leibniz Institute of Agricultural Development in Central and Eastern Europe*.

Key, N. and Tallard, G. (2012). Mitigating methane emissions from livestock: a global analysis of sectoral policies. *Climatic change* 112: 387-414.

Larsson, C., Boke Olén, N., Brady, M. (2020). Naturbetesmarkens framtid - en fråga om lönsamhet. Rapport 2020:1. Lund: AgriFood Economics Centre.

Larsson, C., Olen, N. B., Brady, M. (2020). Naturbetesmarkens framtid-en fråga om lönsamhet. *Rapport/AgriFood Economics Centre*.

Lennartsson, T. and Westin, A. (2019). *Ängar och slåtter. Historia, ekologi, natur- och kulturmiljövård*. Stockholm: Riksantikvarieämbetet.

Lynch, J. and Garnett, T. (2021). Policy to Reduce Greenhouse Gas Emissions: Is Agricultural Methane a Special Case? *EuroChoices* 20: 11-17.

MacDonald, D., Crabtree, J. R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez Lazpita, J., Gibon, A. (2000). Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *Journal of Environmental Management* 59: 47-69.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. (2021). Climate change 2021: the physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*.

Nilsson, S. G., Franzén, M., Pettersson, L. (2013). Land-use changes, farm management and the decline of butterflies associated with semi-natural grasslands in southern Sweden. *Nature Conservation* 6: 31-48.

Nisbet, E., Fisher, R., Lowry, D., France, J., Allen, G., Bakkaloglu, S., Broderick, T., Cain, M., Coleman, M., Fernandez, J. (2020). Methane mitigation: methods to reduce emissions, on the path to the Paris agreement. *Reviews of Geophysics* 58: e2019RG000675.

Nylén, H. and Brady, M. (2024). Potential for mitigation of enteric methane emissions from agriculture through technical measures: a literature review. Working Paper 2024:4. Lund: AgriFood Economics Centre.

O'Rourke, E., Charbonneau, M., Poinsot, Y. (2016). High nature value mountain farming systems in Europe: Case studies from the Atlantic Pyrenees, France and the Kerry Uplands, Ireland. *Journal of Rural Studies* 46: 47-59.

Ohlsson, C. (2024). Meeting with the Business Development Manager for Bovaer from DSM Scandinavia AB at AgriFood Economics Centre, Lund on 10 April 2024. Lund: DSM Scandinavia AB

Palangi, V. and Lackner, M. (2022). Management of enteric methane emissions in ruminants using feed additives: A review. *Animals* 12: 3452.

Regeringen (2022). Rapport om den strategiska GJP-planen 2021

Regeringskansliet (2018). EU:s framtida jordbrukspolitik. Ds 2018:10. Stockholm: Regeringskansliet, Näringsdepartementet.

REGULATION (EU) 2023/857 amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement, and Regulation (EU) 2018/1999.

Reisinger, A., Clark, H., Cowie, A. L., Emmet-Booth, J., Gonzalez Fischer, C., Herrero, M., Howden, M., Leahy, S. (2021). How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379: 20200452.

Rivera, J. E. and Chará, J. (2021). CH4 and N2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. *Frontiers in Sustainable Food Systems* 5.

Roque, B. M., Salwen, J. K., Kinley, R., Kebreab, E. (2019). Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *Journal of Cleaner Production* 234: 132-138.

Roques, S., Martinez-Fernandez, G., Ramayo-Caldas, Y., Popova, M., Denman, S., Meale, S. J., Morgavi, D. P. (2024). Recent Advances in Enteric Methane Mitigation and the Long Road to Sustainable Ruminant Production. *Annual Review of Animal Biosciences* 12: 321-343.

Sahrbacher, A., Hristov, J., Brady, M. V. (2017). A combined approach to assess the impacts of Ecological Focus Areas on regional structural development and agricultural land use. *Review of Agricultural, Food and Environmental Studies* 98: 111-144.

Säll, S. and Gren, M. (2015). Effects of an environmental tax on meat and dairy consumption in Sweden. *Food Policy* 55: 41-53.

SCB (2017). Jordbrukstatistik sammanställning 2017 (Agricultural statistics 2017). Örebro: Statistics Sweden.

SCB (2020). Jordbrukstatistik sammanställning 2020 (Agricultural statistics 2020). Örebro: Statistics Sweden.

Smith, P. E., Kelly, A. K., Kenny, D. A., Waters, S. M. (2022). Enteric methane research and mitigation strategies for pastoral-based beef cattle production systems. *Frontiers in Veterinary Science* 9: 958340.

Springmann, M., Mason-D'Croz, D., Robinson, S., Wiebe, K., Godfray, H. C. J., Rayner, M., Scarborough, P. (2017). Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Climate Change* 7: 69-74.

Stefenoni, H., Räisänen, S., Cueva, S., Wasson, D. E., Lage, C., Melgar, A., Fetter, M., Smith, P., Hennessy, M., Vecchiarelli, B. (2021). Effects of the macroalga Asparagopsis taxiformis and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows. *Journal of Dairy Science* 104: 4157-4173.

Swedish EPA (2023). National Inventory Report Sweden 2023. Greenhouse Gas Emission Inventories 1990-2021. Stockholm, Sweden.

Swedish EPA (2023). Utsläppsminskning på 4,4 procent för svenska anläggningar i EU:s utsläppshandel.

Temesgen, T., Ayeneshet, B., Aman, Y. (2021). Nutritional mitigation of enteric methane gas emission from livestock sector: A Review. *Forage Res* 47: 139-146.

Trinomics (2013). Pricing agricultural emissions and rewarding climate action in the agri-food value chain. CLIMA/2022/OP/0006. Brussels: European Commission, Directorate-General for Climate Action.

Verschuuren, J. (2022). Achieving agricultural greenhouse gas emission reductions in the EU post-2030: What options do we have? *Review of European, Comparative & International Environmental Law* 31: 246-257.

Weishaupt, A., Ekardt, F., Garske, B., Stubenrauch, J., Wieding, J. (2020). Land use, livestock, quantity governance, and economic instruments—Sustainability beyond big livestock herds and fossil fuels. *Sustainability* 12: 2053.

Wirsenius, S., Hedenus, F., Mohlin, K. (2011). Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. *Climatic change* 108: 159-184.

Appendix A. Methane emission calculations

Emission calculations for all animal types except sheep is based on method developed in (Bertilsson, 2016). The method is used by the Swedish Environmental Protection Agency in their greenhouse gas emission inventory (Swedish EPA, 2023).

Table A 1. Basic production data relating to livestock activities.

AgriWise name	AgriPoliS type	Slaughter weight	Milk	
		kg	*kg ECM*	**Description**
Stut, mjölkras	BEEF_BULLOCK	310		Mjölkras, 25 månader, 630 kg levande vikt, Nybyggnad, spaltgolv, flytgödsel,
Ungtjur, mjölkras	BEEF_DAIRY	300		Mjölkras, 18 månader, 620 kg levande vikt, En betessäsong,
Gödtjur, köttras	BEEF_SUCKLER	350		Tung köttras, Slutuppfödning av dikalvar (ca 6 mån), 50 producerade djur per år,
Slaktkviga, kötttras	BEEF_HEIFER	290		Köttras, 18 månader.
Diko - rekryteringskviga	HEIFER_SUCKLER	na		Tung köttras, uppfödning från 6 till 18 månader, egen rekrytering,
Mjölkko - rekryteringskviga	HEIFER_DAIRY	na		Mjölkras, 520 levande vikt vid inkalvning,
Diko	SUCKLER_COWS	390		Moderdjurens ras: Tung köttras, 185 dagars betesperiod
Mjölkko	DAIRY_COWS	310	10,200	SLB/SRB-kor, 600 kg levande vikt, 130 dagars betesperiod,
Tacka, vårlamm	SHEEP *	39		Slaktvikt för tacken efter 5 år är ca. 30 kg
Slaktgris	FATTENING_PIGS	298		Föds upp 3.29 stycken per stallplats per år
Sugga	SOWS	164		Föder 27 smågrisar om året. BIS plus-smågrisar, 5 veckors digivning, säljs vid 30 kg

8.1 Dairy cows

Energy corrected milk per day (ECM/day):
ECM/day = 10200/365=28
Metabolic energy required per day (ME):
ME = ((0.507* 650^0.75) + ECM/day * 5 + (1/12 * (8.5+13+19.5)) = 205
Metabolic energy corrected for actual feeding levels (ME_Corr):
ME_Corr = 1.11 * ME - 13.6 = 214
Metabolic energy corrected for actual feeding levels (ME_Feed):
ME_Feed = FracConc * Conc + (1- FracConc) * Silage = 0.55*13.4+(1-0.55)*10.1 = 12
Fatty acids content in the feed (FA)
FA = FracConc * Conc_F + (1- FracConc) * Silage_F = 0.55*43+(1-0.55)*12 = 29
Dry matter intake per animal and day (DMI)
DMI = ME_Corr / ME_Feed = 214/12 = 18
Energy content of methane (CH4_MJ):
CH4_MJ = 1.39 * DMI - 0.091 * FA = 22

Total emissions from enteric fermentation per animal (kg CH4/cow and year):
CH4_MJ / 55.65) * 365 = 146

8.2 Suckler cows

Energy corrected milk per day (ECM/day):
5.5
Metabolic energy required per day (ME) :
ME = (0.507*750^0.75)+ECM/day*5+(1/12*(10+16+29)) = 104.7
Metabolic energy corrected for actual feeding levels (ME_Corr):
ME_Corr = 1.11 * ME - 13.6 = 102.7
Metabolic energy corrected for actual feeding levels (ME_Feed):
ME_Feed = Silage = 9.5
Fatty acids content in the feed (FA)
FA = 0*43 + (1)*12 =12
Dry matter intake per animal and day (DMI):
DMI = ME_Corr / ME_Feed = 214/12 = 10.8
Energy content of methane (CH4_MJ):
CH4_MJ = 1.39 * DMI - 0.091 * FA = 13.9
Total emissions from enteric fermentation per animal (kg CH4/cow and year):
kg CH4/cow and year = CH4_MJ / 55.65) * 365 = 91.4

8.3 Dairy cow, replacement heifer; Suckler cow, replacement heifer; Slaughter heifer

Table A2. Activity data

	Heifers			Bulls and steers		
	<1 year	1-2 years	>2 years	<1 year	1-2 years	>2 years
Live weight	200.0	385.0	580.0	250.0	500.0	625.0
Energy requirements (MJ)	45.5	70.5	93.5	67.5	101.2	102.1
Metabolisable energy in feed (MJ/kg DM)	11.5	10.1	10.1	12.3	11.7	10.4
Fracconc	0.5	0.2	0.2	0.7	0.5	0.1
Gross energy in feed (MJ/kg DM)	19.2	19.8	19.8	18.9	19.2	19.8

Source: Bertilsson (2016)

$$\text{Kg CH4/year and cow} = \frac{(-0.046 \times \text{FracConc} + 0.071379) * \text{Gross energy intake} * 365}{\text{energy content of methane } (55.56 \frac{\text{MJ}}{\text{kg}} \text{CH}_4)}$$

Table A 3. Activity data

		Kg CH4/year and cow		
	Slaughter age	<1 year	1-2 years	>2 years
Heifer dairy	27	24.1	58.4	77.5
Heifer suckler	18	24.1	58.4	77.5
Beef heifer	18	24.1	58.4	77.5
Beef bullock	24	26.7	52.7	85.1
Beef dairy	18	26.7	52.7	85.1
Beef suckler	13	26.7	52.7	85.1

Mean emissions/year:

8.3.1 Heifer dairy

$$\frac{12}{Slaughter\ age} * 24.1 + \frac{12}{Slaughter\ age} * 58.4 + \frac{3}{Slaughter\ age} * 77.5 = 45.3$$

8.3.2 Heifer suckler/Beef heifer

$$\frac{12}{Slaughter\ age} * 24.1 + \frac{6}{Slaughter\ age} * 58.4 = 35.6$$

8.3.3 Beef bullock

$$\frac{12}{Slaughter\ age} * 26.7 + \frac{12}{Slaughter\ age} * 52.7 = 39.7$$

8.3.4 Beef dairy

$$\frac{12}{Slaughter\ age} * 26.7 + \frac{6}{Slaughter\ age} * 52.7 = 35.3$$

8.3.5 Beef suckler

$$\frac{12}{Slaughter\ age} * 26.7 + \frac{1}{Slaughter\ age} * 52.7 = 28.7$$

8.3.6 Sheep (Ewes)

According to IPCC methodology a sheep emits 9 kg CH4 per head per year assuming a live weight of 40 kg (Gavrilova*, et al.*, 2019, Table 10.10). Given that a normal Swedish ewe weighs 70 kg and assuming enteric methane emissions to be a linear function of weight we use the following emissions rate in our modelling :

9/40 * 70 = 15.75

which we consider to be a conservative rate, since the linear assumption is most likely to result in a slight overestimation of the true rate.

kg CH4 per head per year	15.75
kg CO2-eq per head sheep per year = kg CH4 * 28	441

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AgriFood Economics Centre
PO Box 730
SE-220 07 Lund
SWEDEN

www.agrifood.se
mail: info@agrifood.se

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