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Cattle population required for favorable conservation status of management-dependent semi-natural grasslands and forests, and associated increase in enteric methane emissions

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ABSTRACT

The state of biodiversity in the world is critical where natural grassland is one of the habitat types showing the strongest deteriorating trend of biodiversity loss. At European Union level, 75 % of all grassland habitats have poor or bad status, with cessation of farming and subsequent overgrowth posing the greatest threat. To achieve favorable conservation status of natural grasslands, the area given over to grazing livestock or hay mowing needs to increase in many regions. The aim of this study was to calculate the number of cattle required to manage various types of unfertilized grazing land, and associated enteric methane emissions from these cattle, using Sweden as the study area. Four different scenarios with various categories of grazing cattle were evaluated: beef suckler cows and their offspring or dairy and beef cows in the current ratio and their offspring, combined with all male calves being raised as grazing steers or with males being raised as grazing steers in the current ratio and other males being raised as indoor bulls. Potential important factors that could reduce the number of additional cattle required were considered. The scenario requiring the smallest number of animals, beef cows and their grazing offspring, gave the lowest methane emissions, 16 kg/ha/year for low-yielding grazing land, such as wooded pasture, and 117 kg/ha/year for high-yielding grazing land, such as wet meadows. Taking all cattle reducing factors into account (mowing parts of the area, lower predicted stocking rate, use of all existing male cattle) significantly reduced the required cattle stock to one-third, corresponding to methane emissions of 5 and 34 kg/ha/year for low and high-yielding grazing land, respectively. In Sweden, 2.2 million ha of grazing land need to be restored to favorable conservation status, which would require 150 000–510 000 new beef cows and their grazing offspring would be needed, producing 33 000 to 109 000 tonnes of methane, compared to the 105 000 tonnes emitted by the present cattle stock (around 300 000 dairy cows and 210 000 beef cows).

1. Introduction

Biodiversity loss is a critical issue world-wide, including in the European Union (EU) (Brondizio et al., 2019; European Environment Agency, 2020). To counteract loss of biodiversity, the EU Species and Habitats Directive requires member states to report regularly on the state of biodiversity nationally, e.g., by assessing the current area and the required area of a number of defined habitats in each of nine biogeographical regions in the EU (Directive 92/43/EEC; European Council, 1992). The most recent reports reveal that only 15 % of habitats have favorable conservation status, while most continue to have poor (45 %) or low (36 %) status. In response to the severity of biodiversity loss, the EU has introduced a nature restoration law requiring at least 20 % of EU land and sea areas to be treated with nature restoration measures by 2030 (European Commission, 2022; European Parliament, 2023).

At EU level, natural grassland is one of the habitat types showing the strongest deteriorating trend, with 75 % of all 126 recognized grassland habitats assessed as having poor or bad status and with cessation of agricultural management and subsequent overgrowth posing the greatest threat (European Environment Agency, 2020). There is an ongoing trend for abandonment of marginal grassland due to intensified livestock production world-wide, with extensive grassland-based husbandry often replaced by intense livestock production. Anthropogenic

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landscapes with traditionally managed semi-natural grasslands in low-intensity livestock systems harbor an exceptional richness of many taxa, such as plants, fungi, and insects (Bele et al., 2018; European Environment Agency, 2020; Eriksson, 2021). The species richness in these landscapes reflects a species pool from Pleistocene herbivore-structured environments, which, after the extinction of Pleistocene megafauna, was rescued by the introduction of domestic herbivores in pre-historic agriculture (Eriksson, 2021). Increasing the area of traditionally, extensively managed semi-natural grassland in the EU has been identified as the single most important measure to prevent species and habitat losses (European Environment Agency, 2020).

Extensive pasture-based animal husbandry is one of few agricultural production systems that can increase biodiversity in a landscape (Eriksson, 2022). The grazing process influences flora and fauna in the base layer and field layer through a combination of mechanisms. These include biting and trampling, affecting e.g., seed production; removal of biomass, affecting plant establishment possibilities and providing a microenvironment for invertebrates; and redistribution of nutrients, through patchy feces and urine deposition by grazing animals. Grazing also affects temperature and light levels in the vegetation cover and at the soil surface. Acting together, these mechanisms lead to grazing-tolerant species, low-growing (weakly competitive) species, and short-lived species (depending on frequent recruitment) of vascular plants becoming more common, and thus to greater total species numbers than in unmanaged grassland and other biotopes where succession is allowed to operate freely (Pykälä, 2005).

The proposed EU nature restoration law will influence the entire European continent. Sweden was selected as a case study in the present analysis, because its grasslands are in the worst condition of all Swedish habitat types (Toräng and Jacobsson, 2019). Today, only 1–3 % of historical semi-natural Swedish grasslands remain (Dahlström et al., 2008). This decline has led to more than 1300 species that depend on these habitats being red-listed (SLU Swedish Species Information Centre, 2020). Grazing in forests has received research attention more recently than grazing in open landscapes in terms of its significance for promoting biodiversity (Westin et al., 2022). About 75 % of the current forested area in south-central Sweden was formerly grazed, so the vast proportion of red-listed species found in forest habitats today is suggested to be a remnant of grazing management in the past (SLU Swedish Species Information Centre, 2020; Westin et al., 2022). Some Swedish grasslands was formerly pastureland and others were hay meadows, resulting in differences in vegetation composition between the types. Vascular plants on former meadows are adapted to late and indiscriminate cutting, often followed by grazing, so late mowing after flowering would be the optimal management for former meadows (Lennartsson and Westin, 2019). Traditional mowing, e.g., by scythe, is however usually not a practical option today, so grazing is often the best available management strategy not only for former grazing land but also for former meadows. Grazing favors biodiversity much more than free succession, which in Sweden ultimately results in dense coniferous forest (Lennartsson and Westin, 2019). Unfortunately, Swedish marginal grasslands and grazed forests are abandoned, especially small, scattered grazing areas in forest districts, which are largely dependent on small-scale farming in these districts. Livestock rearing, particularly at small scale, is decreasing due to shortage of a new generation of livestock farmers resulting from expected poor profitability compared with other occupations, combined with high workload and physical and economic risks (Kumm, 2003; Kumm and Hessle, 2020; Holmström et al., 2021; Holmström et al., 2023).

Another reason for focusing on Sweden in this study is that it is one of the largest EU countries, ranging over three of the nine European biogeographical regions and harboring almost 20 % of European grassland types. Baseline for original semi-natural grassland area reported to EU from Sweden has been set to the year 1850, when Sweden had 12.3 million hectare (ha) of various types of grazing land, with forest grazing being the most important feed resource during summer (Dahlström et al., 2008; Toräng and Jacobson, 2019). To meet the EU requirement for favorable conservation status of a grassland type, defined as at least 20 % of the original area, 2.6 million ha of semi-natural grasslands and forests in Sweden would need to be managed by annual grazing or mowing (Toräng and Jacobsson, 2019). The current managed area is 0.4 million ha, so the grassland area that would need to be restored through re-introduced grazing or mowing is 2.2 million ha. Transition from afforested to more open land would have to begin with manual clearing of undesirable brushwood and other overgrowth vegetation, before turning out grazing livestock. Depending on humidity and soil type, frequent recurrent manual clearance might be needed even when grazing has been re-established.

The Swedish cattle stock currently comprises around 300 000 dairy cows and 210 000 beef suckler cows, and their offspring (Swedish Board of Agriculture (2022a). Heifer calves are used for replacement and for beef production. Male offspring for beef are mostly reared as intact bulls (82 % of dairy breeds, 91 % of beef breeds), but some are castrated and reared as steers (18 % and 9 %, respectively) (Gård och djurhälsan, 2022). Swedish cattle are typically kept indoors during winter and fed feed rations based on grass-clover silage. During summer, all cattle except young calves and intact bulls graze a combination of semi-natural grassland (sometimes including forest), cultivated grassland, and ley aftermath (Ahlgren et al., 2022). Cattle are the most common livestock species on Swedish semi-natural grasslands and forests (Spörndly and Glimskär, 2018) and favor biodiversity in conservation grazing better than sheep (Öckinger et al., 2006; Karlsson, 2009). From an animal production point of view, beef cows, with relatively low nutritional requirements (Spörndly, 2003), are the most suitable type of cattle for grazing semi-natural grasslands and forests. Extensively reared heifers and steers of both dairy and beef breeds are also suitable, whereas intact bulls require higher feed intensity to utilize their growing potential (Spörndly, 2003). Dairy cows have even higher nutritional requirements during lactation, but can graze semi-natural grasslands during a few weeks of their dry period.

Apart from improving biodiversity on semi-natural grasslands and forests, grazing cattle provide nutrient-dense foods and generate other values to society. However, they also have negative impacts, which include greenhouse gas emissions, so increasing the number of cattle in order to restore semi-natural grasslands will also lead to elevated emissions. Methane produced via enteric fermentation by ruminants accounts for around 40 % of greenhouse gas emissions from beef and milk production, being the largest contributor to greenhouse gases from agriculture, and accounts for about 5 % of all anthropogenic emissions globally (Herrero et al., 2016). In Sweden, annual enteric emissions from ruminants are currently around 2.9 million metric tonnes (t) of carbon dioxide equivalents (CO2e) (Swedish Environmental Protection Agency, 2024), which represents 58 % of total methane emissions and 6.4 % of all Swedish anthropogenic greenhouse gas emissions.

The aim of this study was to estimate the number of cattle needed to graze various types of semi-natural grasslands and forests to achieve favorable conservation status, and associated enteric methane emissions from these cattle, using Sweden as an example.

2. Materials and methods

2.1. Experimental design

The additional number of cattle needed to obtain favorable conservation status of management-dependent, but unfertilized, semi-natural grasslands and forests was calculated for each of the 22 grassland types within the three biogeographical regions of Sweden (alpine, boreal, continental) (Supplementary Fig. S1; Supplementary Table S1). The area of each grazing land type needing re-introduction of grazing cattle was defined as the 2.2 million ha difference between the area with favorable conservation status and the current area reported by Toräng and Jacobson (2019). Hence, the study focused on the additional area of semi-natural grasslands and forests needing to be managed, excluding the current managed area of semi-natural grasslands and forests and the current livestock population. All grazing land management was assumed to occur by grazing cattle.

The extra number of cattle required was calculated in four alternative scenarios (Table 1). Scenario 1 investigated how many more beef suckler cows would be required if the current number of dairy cows remained constant and assuming the current ratio of grazing steers in calves from dairy and beef cows (18 % and 9 %, respectively; Gård och djurhälsan, 2022). Scenario 2 investigated the extra number of beef cows required if all male calves were castrated and raised as grazing steers. In scenarios 3 and 4, it was assumed that the additional dams comprised beef cows and dairy cows kept in the current ratio (59 % dairy cows, 41 % beef cows; Swedish Board of Agriculture, 2022a), and this cow alternative was combined with the two different alternative for rearing the male calves, i.e., as the current ratio of indoor intact bulls and grazing steers (scenario 3) or with all male calves castrated and raised as grazing steers (scenario 4) (Table 1). It was assumed that on average all cows give birth to 0.5 heifer calves and 0.5 bull calves per year.

2.2. Herbage mass yield of semi-natural grasslands and forests

Gross yield of herbage mass in open grasslands in the boreal region was set to 2500 kg dry matter (DM)/ha/year in dry/mesic areas and 5000 kg DM/ha/year in wet areas, based on literature values (Back, 2011; Hessle et al., 2011; Pelve et al., 2020). Lower herbage mass was set for alvar and rocky ground. Herbage mass in Wooded pasture can vary widely, but was set to 1000 kg DM/ha according to Rekdal and Angeloff (2021). All herbage mass yields were adapted for the alpine and continental regions of Sweden by modifying reported yields for the boreal region based on differing length of the growing season (Swedish Meterological and Hydrological Institute (SMHI), 2022), and set to 70 % and 110 %, respectively, of the herbage mass yield in the boreal region.

Gross yield of herbage mass was corrected according to Spörndly and Glimskär (2018), as grassland and forest areas consist not only of edible vegetation, but also of stones, outcrops, small streams, roads, settlements, etc., reducing the productive area (−3%), while shading trees and bushes also lower the yield (−20 % of yield on 20 % of the area, or −4%). In order to have a margin for year-to-year variation, a further 5 % of the initial gross yield was subtracted. Hence, experimentally measured gross yields reported above were multiplied by a correction factor of 0.88 to represent gross yield on actual grasslands.

It was estimated that grazing cattle normally utilize 45 % of the gross yield of herbage mass on semi-natural grasslands, based on Steen et al. (1972). The proportion of herbage mass utilized was set lower for alvar and wooded pasture (30 %). The amount of grazed herbage utilized was denoted 'net yield'.

Gross yield of herbage mass, utilization, and net yield for the various grassland types, listed by EU habitat code and abbreviated scientific name, can be found in Supplementary Table S2.

Table 1
Types of additional animals required to graze Swedish semi-natural grasslands and forests in order to obtain favorable conservation status in the four different scenarios compared in this study. Grazing capacity was achieved through additional beef suckler cows only (scenarios 1 and 2) or through a combination of additional dairy and beef cows in proportions corresponding to the ratio in the current Swedish population (59% and 41%, respectively) (scenarios 3 and 4), plus their offspring in all cases. In scenarios 2 and 4, all male offspring were assumed to be castrated and raised as grazing steers. In scenarios 1 and 3, the proportion of grazing steers corresponded to the current Swedish ratio, i.e., 9% of beef breed males and 18% of dairy males were assumed to be castrated and reared on grazing, while the remaining intact bulls were reared indoors.

Scenario	Additional dams	Male offspring
1	Beef cows only	Present proportion of steers and bulls
2	Beef cows only	All males are raised as steers
3	Present proportion of dairy and beef cows	Present proportion of steers and bulls
4	Present proportion of dairy and beef cows	All males are raised as steers

2.3. Cattle rearing and feed consumption

Cattle rearing in the four scenarios was intended to reflect typical Swedish cattle production, but using semi-natural grasslands and forests for grazing to a greater extent. Descriptions of typical cattle rearing systems, including estimates of pasture herbage and indoor feed consumption, were retrieved from previous studies (Bertilsson, 2016; Ahlgren et al., 2022), and adjusted to fit the biogeographical regions considered in the present study.

The length of the grazing period was assumed to be shortest in the alpine region and longest in the continental region, with 120–190 grazing days for beef cows and 110–170 days for young cattle. Spring-calving beef cows were assumed to graze semi-natural grasslands and forests only, while grazing young cattle were assumed to receive 80 % of their DM intake from semi-natural grasslands and forests, complemented with 20 % from ley aftermath in late summer. Beef heifers were assumed to graze one period after weaning, whereas beef steers grazed two periods between weaning and slaughter. Except for beef bull calves, which grazed as sucklers, intact bull calves were assumed to be reared indoors. Dairy heifers and steers grazed two periods before calving and slaughter, respectively. Dairy cows were assumed to calve all year round, with cows that were dry during summer grazing semi-natural grasslands and forests for four weeks, resulting in on average 8–13 days/year of grazing across all dairy cows.

The basis for all indoor feed rations was assumed to be grass-clover silage cut at different times. Weaned heifers and steers of beef breeds were assumed to be fed grass-clover silage only, whereas the feed ration of beef cows also consisted of whole-crop barley silage. The grass-clover silage was assumed to be complemented with commercial complete feed for dairy cows, dried peas/beans and commercial complete feed for young dairy calves, and rolled barley for dairy young stock and beef bulls.

The various categories of young cattle considered were aged 15–30 months at slaughter, with each yielding 315–385 kg carcass weight and 214–263 kg of bone-free meat. Mean annual milk production per cow was set at 10,162 kg energy-corrected milk. Detailed descriptions of the feeds, cattle numbers, and cattle rearing can be found in Supplementary Tables S3–S8.

2.4. Meat, milk, and methane production

Meat and milk production from the additional cattle stock were calculated for scenarios 1–4 based on official statistics (Gård och djurhälsan, 2022; Swedish Board of Agriculture 2022b; Swedish Board of Agriculture, 2023).

Enteric methane emissions from the additional cattle were calculated using two different equations (Nielsen, 2012; Nielsen et al., 2013). For dairy cows and beef cows, methane emissions were calculated as:

$$CH_4 \quad (MJ/cow/day) = 1.23 \times DMI - 0.145 \times FA + 0.012 \times NDF \qquad (1)$$

where CH_4 is methane production in megajoules per cow and day, DMI is DM intake in kg per cow and day, FA is fatty acid content in the feed ration, expressed as g/kg DM, and NDF is neutral detergent fiber in the feed ration, expressed as g/kg DM.

For growing cattle, methane emissions were calculated as:

$$CH_4, MJ \quad (\% \ of \ GE) = \frac{-0.046 \times ConcP + 7.1379}{100} \qquad (2)$$

Table 2
Sensitivity analysis on factors possibly reducing the estimated number of cattle required in order to manage semi-natural grasslands and forests to obtain favorable conservation status of these land types.

Factor	Reduction
Smaller grazing area:	
Former high-yielding meadows are mown instead of grazed where possible	−30 %
Lower stocking rate:	
Grazing lands with re-introduced grazing have lower herbage yields than present grazing lands	−25 %
Reduced grazing pressure with increased inter-annual variation	−10 %
Grazing of game animals	−5%
Use of existing cattle:	
Letting all male offspring graze, including those currently raised indoors	−16 %

where GE is gross energy and ConcP is average proportion of concentrate in the diet across the rearing period, expressed as a percentage of total DM.

To calculate gross energy in the feed ration, 20.0 MJ per kg DM of roughage and 18.4 MJ per kg DM of concentrate feed were assumed (Bertilsson, 2016). The values were weighed according to proportions of roughage and concentrate in the total feed ration.

Emissions from the cattle stock required to achieve favorable conservation status per ha of each grassland type and biogeographical region were calculated for the different scenarios.

2.5. Sensitivity analysis

As uncertainties arose in estimating the number of grazers needed, especially downwards, a sensitivity analysis was conducted on the most potent factors for diminished grazing land area, decreased stocking rate, and use of existing cattle (Table 2). The factors considered are explained in detail in the Discussion section.

3. Results

3.1. National and biogeographical region level

The additional 2.2 million ha of managed semi-natural grassland and forest needed to achieve favorable conservation status had an estimated herbage net yield of 1.85 million t DM for all of Sweden. Most of the required increase was in the boreal region (86 %), which contains the majority of Swedish semi-natural grasslands and forest, with only small increases in the continental (12 %) and alpine (2 %) regions (Table 3).

The amount of pasture herbage ingested per year by the additional cattle depended on whether the stock consisted solely of beef cows and their offspring, or a mixture of beef cows and dairy cows and their offspring (Table 4). The amount of pasture herbage ingested by the additional cows also depended on whether their male offspring were raised as a mixture of intact indoor bulls and grazing steers, or solely as grazing steers (Table 4). In addition, grass consumption by a cow and her offspring was influenced by the length of the grazing period, and thus by the biogeographical region in which the cow was located. The highest pasture herbage consumption per cow and her offspring was in scenario 2, where all dams were beef cows and where all male offspring were raised as grazing steers (Table 4). The lowest pasture herbage consumption per cow and her offspring was in scenario 3 (Table 4). From a grazing point of view, scenario 3 was only half as effective as scenario 2. Intermediate amounts of pasture herbage were consumed per cow and her offspring in the remaining two scenarios (1 and 4).

The scenario requiring the lowest number of cattle was that in which each animal ingested as much herbage from semi-natural grassland and forest as possible, i.e., where the entire additional cattle stock consisted of beef cows and grazing steers (scenario 2) (Table 4). In that scenario, the number of beef cows needed to increase by approximately 510 000, which represented an increase of more than 240 % on the 210 000 Swedish beef cows in the current population (Swedish Board of Agriculture, 2022a). In the scenario requiring most animals, where the additional cattle stock was obtained by increasing the numbers of both dairy cows and beef cows while raising most of their male offspring as indoor bulls (scenario 3), the number of dams needed to increase by just under 1 100 000. That increase corresponded to a tripling of the current beef and dairy cow populations (Swedish Board of Agriculture, 2022a). Increasing only the number of beef cows and raising most of their male offspring as indoor bulls (scenario 1) required roughly 650 000 new dams, while increasing the numbers of both dairy cows and beef cows and raising all male offspring as grazing steers (scenario 4) required 775 000 new dams. The numbers of cattle required in all animal groups and scenarios are listed in Supplementary Table S3.

An increase in the number of cattle in the different scenarios resulted in a proportional increase in enteric methane emissions. Hence, scenario

Table 3
Area (ha) of Swedish semi-natural grassland and forests grazed today, total grazed area required to obtain favorable conservation status of these grazing land, and additional grazed area required (difference between these two figures), and herbage mass (net yield, tonnes of DM) in all cases, in the three biogeographical regions of Sweden (alpine, ALP; boreal, BOR; continental, CON) and total.

Grazing land	ALP	BOR	CON	Total
Area grazed today	17 670	275 981	64 066	357 717
Area needing to be grazed	84 200	2 244 163	237 030	2 565 393
Additional grazed area	66 530	1 968 182	172 964	2 207 676
Net yield of area grazed today	1 629	244 551	65 291	311 417
Net yield of area needing to be grazed	31 832	1 848 225	286 304	2 166 360
Net yield of additional grazed area	30 203	1 603 673	221 013	1 854 889

Table 4
Herbage mass (kg DM) from Swedish semi-natural grassland and forest required annually to feed a cow and her offspring, and number of cows with offspring needed to resume grazing management of Swedish grazing land areas to obtain favorable conservation status of these habitats in the three biogeographical regions of Sweden (alpine, ALP; boreal, BOR; continental, CON) in four different scenarios (1–4) with either beef suckler cows only (1, 2) or both dairy and beef cows (3, 4), combined with their male offspring reared as grazing steers only (2, 4) or as both grazing steers and indoor bulls in the current ratio (1, 3).

Scenario	Dams	Males	Herbage mass/dam			Numbers of dams		
			ALP	BOR	CON	ALP	BOR	CON
1	Beef	Bulls + steers	1 971	2 814	3 129	15 321	569 934	70 629
2	Beef	Steers	2 566	3 625	4 048	11 771	442 441	54 596
3	Dairy + beef	Bulls + steers	1 234	1 690	1 882	24 471	948 875	117 415
4	Dairy + beef	Steers	1 736	2 375	2 661	17 394	675 256	83 055

Table 5
Additional amount of bone-free meat, milk, and enteric methane emissions (1000 tonnes/year) from additional Swedish cattle in four different scenarios (1–4) with either beef suckler cows only (1, 2) or both dairy and beef cows (3, 4), combined with their male offspring reared as grazing steers only (2, 4) or as both grazing steers and indoor bulls in the current ratio (1, 3).

Scenario	Dams	Males	Meat	Milk	Methane
1	Beef	Bulls + steers	157	–	114
2	Beef	Steers	125	–	109
3	Dairy + beef	Bulls + steers	223	6 310	227
4	Dairy + beef	Steers	153	4 489	179

2 gave the lowest increase in methane emissions (109 000 t/year) and scenario 3 gave the greatest increase (227 000 t/year) (Table 4; Supplementary Table S3).

In scenarios 1 and 2, only the amount of beef produced increased, as the dairy cow population was assumed to be unchanged compared with today, while scenarios 3 and 4 gave increased amounts of both beef and milk (Table 5). Scenario 2, the option with the lowest number of animals, also resulted in the smallest increase in amount of meat produced (125 000 t/year).

3.2. Grazing land type level

The extra animals required were unevenly distributed among the various grassland types in a restoration situation, as the herbage net yield varied (Supplementary Table S2). Appropriate stocking rate for the lowest-yielding grazing land types, dry Nordic alvar (EU habitat code 6280) and shady Wooded pasture (code 9070), was estimated to be 0.07 beef cow and her offspring per ha and year. The highest-yielding wet grasslands, Atlantic salt meadow (code 1330), Atlantic wet heath (code 4010), *Molinia* meadow (code 6410), and Alluvial meadow (not alpine region) (code 6450), were estimated to be capable of supporting 0.55 beef cow and her offspring per ha and year. Stocking rate within grazing land type was similar among the different biogeographical regions. Stocking rates in scenario 2 (beef cows and grazing offspring) for all grazing land types in the basic calculation are shown in Supplementary Table S9, where they are denoted ‘maximum stocking rate’.

Yearly enteric methane emissions per unit grassland area were linearly correlated with the stocking rate needed. In scenario 2, the emissions ranged from 16 kg/ha for low-yielding grazing land to 117 kg/ha for the most high-yielding land types, with a national average of 50 kg/ha (Fig. 1; Supplementary Table S9). In scenario 3, the emissions ranged from 32 to 243 kg/ha for grazing land types with varying herbage yield. The amount of methane produced from the increased cattle stock in the Swedish case was dependent not only on the herbage yield, but also on the extra area on which grazing was re-introduced. The grazing land type with the largest area requiring restoration was Wooded pasture (1 089 200 ha), whereas the area of six grassland types was already sufficiently large to be regarded as favorable (Supplementary Table S2).

Taken together, the methane emissions from re-introducing cattle grazing to the extent needed to achieve favorable conservation status were highest for *Molinia* meadow (EU habitat code 6410), due to a combination of high herbage yield and large area. The extra emissions from this grassland type represented almost half (47 %) of the additional methane load for all grassland types (Table 6). Re-introduced grazing of Fennoscandian grassland (code 6270) and Wooded pasture (code 9070) generated 24 % and 16 % of the extra enteric methane emissions, respectively, whereas the remaining 19 grassland types were of minor importance for methane emissions (13 % of emissions).

Table 6
Yearly enteric methane emissions (tonnes) from beef suckler cows and their offspring in production systems where all animals graze different types of semi-natural grasslands and forests (code is EU habitat code) with an area within type and region large enough to ensure favorable conservation status, in the three biogeographical regions of Sweden (alpine, ALP; boreal, BOR; continental, CON) and total.

Code	Name	ALP	BOR	CON	Total
6270	Fennoscandian grassland	620	20 442	5 363	26 425
6410	*Molinia* meadow	994	45 557	4 547	51 097
9070	Wooded pasture	606	16 120	210	16 936
Other	All other 19 grassland types	154	8 724	1 178	16 057
Total		2 433	94 610	11 831	108 874

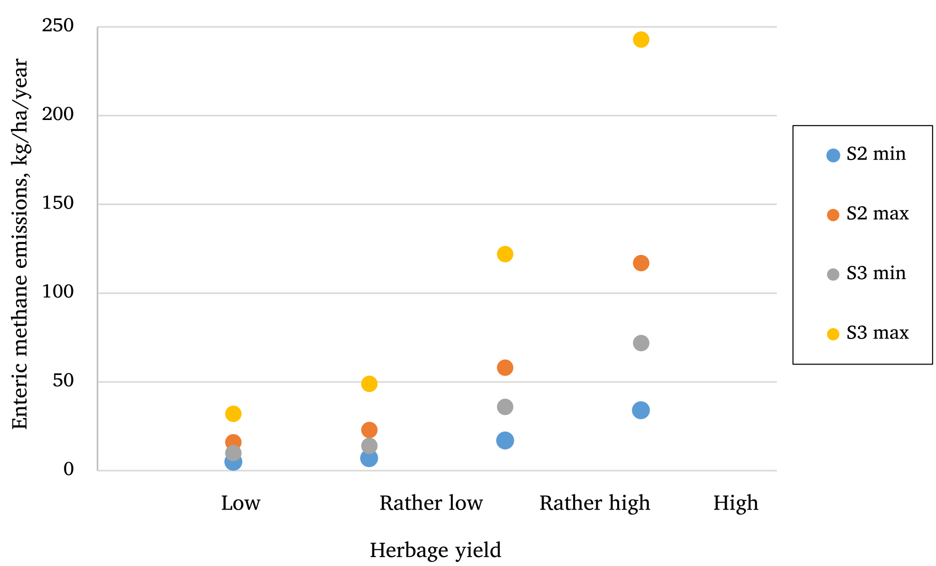

Fig. 1. Enteric methane emissions (kg/ha/year) from cattle grazing on restored management-dependent grazing land types with various herbage yield (Low: EU habitat codes 6280, 9070; Rather low: codes 8230, 8240; Rather high: codes 2320, 2330, 4030, 5130, 6110, 6120, 6210, 6230, 6270, 6510, 6520, 6530; High: codes 1330, 1630, 4010, 6410, 6430, 6450) in two different scenarios with either beef suckler cows combined with their male offspring reared as grazing steers only (S2) or both dairy and beef cows combined with their male offspring reared as both grazing steers and indoor bulls in the current ratio (S3). Maximum values (max) represent emissions from basic calculations and minimum values (min) are emissions on applying all factors reducing the required number of additional cattle in sensitivity analysis.

3.3. Sensitivity analysis

The sensitivity analysis revealed that a considerable reduction in the required additional cattle stock, to 29 % of the original estimates in the basic calculations, was possible due to: (a) smaller grazing area when high-yielding former hay meadows are mown instead of grazed (−30 % of herbage); (b) reduced general expected stocking rate due to lower herbage yield through new grazing areas being less fertile than present grazing land (−25 %), lower grazing pressure officially required for conservation than today (−10 %), and game animal grazing (−5%); and (c) use of male offspring currently raised indoors (−16 %). When all these factors were taken into account, the additional cattle stock, as a proportion of the basic calculation value, was ((1 − 0.3) × (0.75 × 0.9 × 0.95) − 0.16), or 29 % of the original estimate. In all four scenarios, there was an associated reduction in enteric methane production to around 29 % of the original estimate. Stocking rates in scenario 2 (beef cows and grazing offspring) for all grazing land types from the sensitivity analysis are shown in Supplementary Table S9, where they are denoted 'minimum stocking rate'. The decrease in methane production expressed per ha and year for various types of grazing land followed the same principle. The values from the sensitivity analysis are shown in Fig. 1, where they are denoted 'minimum stocking rate'.

4. Discussion

4.1. Methane emissions

4.1.1. Comparison of scenarios

Calculations made for different types of cattle stock grazing the required 2.2 million ha of restored semi-natural grasslands and forests in Sweden revealed that the number of extra animals needed was the factor with the greatest impact on enteric methane emissions. Thus scenario 2, with only beef cows and only grazing steers in the additional cattle stock (total cattle stock increase 1 018 000) had the lowest methane emissions, less than 45 % of those in the scenario with the most animals, a combination of dairy and beef cows and indoor bulls and grazing steers (scenario 3, total increase in cattle stock 2 180 000). The smaller number of additional animals more than compensated for the fact that the extensively reared beef cows and grazing young cattle in scenario 2 had a fiber-rich and less concentrated feed ration than the dairy cows and indoor bulls in scenario 3 (Hristov et al., 2018). In the present analysis, we calculated emissions of enteric methane as an effect of grazing a certain grazing land area. Since each individual beef cow and grazing steer ingested more pasture herbage than a dairy cow or an indoor bull, methane emissions per hectare grazing area were lower in the scenarios with more beef cows and/or grazing steers (scenarios 1 and 2) than in the scenarios with more dairy cows and/or indoor bulls (scenarios 3 and 4). However, if we had allocated the methane emissions to different animal products (meat and milk) instead of total methane production, the scenarios involving dairy cows would have performed relatively better (Bertilsson, 2016; Ahlgren et al., 2022). This is because dairy cows produce much more products (milk, beef) and because the proportion of energy intake used for maintenance is much lower than for beef cows (Volden, 2011).

4.1.2. Economic allocation

Pasture-based beef production is multifunctional, delivering food, biodiversity, and cultural values (Eriksson, 2022). Economic allocation of the methane emissions on both private goods (milk, beef) and public goods (biodiversity, cultural values) might have altered the ranking of the scenarios in terms of methane load. For example, von Greyerz et al. (2023) allocated climate impact on Swedish cattle farms according the proportions of revenues from sales of milk and beef versus agri-environmental payments and support, with up to half of the climate impact of beef and up to one-third of the climate impact of milk allocated to various types of public goods, e.g., management of semi-natural grasslands and forests. Scenario 4 in the present study, with a combination of dairy and beef cows and with all male calves raised as grazing steers, produced large amounts of milk (5800 kg), beef (200 kg), and management of grazing land (1.2–9.0 ha) per cow and year. There are therefore reasons to believe that scenario 4 would have been the most methane-efficient scenario in an economic allocation approach. However, the study by von Greyerz et al. (2023) did not include any farm with steers grazing large areas of semi-natural grassland.

4.1.3. Alternative livestock

The focus in our analysis was on cattle as the grazing livestock species, because cattle currently graze 80 % of Swedish semi-natural grasslands and forests (Spörndly and Glimskär, 2018). Furthermore, there is anecdotal evidence that cattle grazing is better than sheep grazing in preserving grassland biodiversity. There is also some scientific support for this claim, e.g., Öckinger et al. (2006) and Karlsson (2009) found that sheep grazing is less favorable for herbaceous plants and butterflies than cattle grazing, primarily due to sheep having a preference for grazing low herbs, driving the pasture towards more grass-dominated vegetation. Nevertheless, if the additional grazing livestock were to be wholly or partly sheep instead of cattle, the amount of enteric methane emissions would be approximately the same, based on the current production models used (Ahlgren et al., 2022). As found for cattle, there is also variation in both methane production and grazing land area for sheep, depending on production model. A typical extensively reared lamb has 20–25 % higher lifetime enteric methane production than a typical intensively reared lamb, but on the other hand the extensively reared lamb can manage a 50 % larger area of semi-natural grassland (Ahlgren et al., 2022).

Replacing grazing livestock with horses would reduce methane emissions, since methane emissions per unit feed from horses are only 30 % of those from ruminants (Franz et al., 2010). There are more than 350 000 horses in Sweden, most of which are leisure horses with low nutritional requirements and therefore suitable for rearing on semi-natural grasslands and forests (Official Statistics of Sweden, 2017; Ringmark et al., 2019). Horses are not as selective as sheep, but are fond of foraging overgrown grass. Nutritional heterogeneity of pasture is on a larger scale with grazing horses than with cattle and sheep, as horses mainly defecate in specific parts of their enclosure, whereas cattle and sheep feces are more evenly deposited resulting in a small-scaled heterogeneity (Pelve et al., 2020). Browsing by horses can occasionally damage trees, but in general their foraging promotes grassland biodiversity (Palmgren Karlsson, 2007). However, most horse owners want to keep their animals close to their home, for frequent riding and other types of togetherness, which is a limiting factor for keeping horses on semi-natural grasslands and forests (Karlsson, 2009).

4.1.4. Indirect effects on methane production

Methane from feed digestion is not the only greenhouse gas emitted from cattle farming, but it accounts for a significant proportion of the total (45–55 %) (Hessle et al., 2017; Ahlgren et al., 2022). Other emissions come mainly from manure storage, peat soils, energy use, and transport, and were not covered in this study. Due to methanotroph (microbial) activity (Yu et al., 2017), the soil in grasslands and forests can act as an important sink for atmospheric methane, representing approximately 10 % of total methane sinks (Saunois et al., 2020), but the effects of grazing land type and treatment on methanotrophs and the effect of conversion of various land types to grassland are uncertain, and were not considered in this study. Nevertheless, the conversion to grassland will likely offset some of the additional methane production due to reduction of moisture in soil (Rafalska et al., 2023). However, deforestation diminish the carbon sequestration. According to the Swedish Environmental Protection Agency (2024), in 2022 methane emissions from land use, land-use change and forestry (LULUCF) in Sweden corresponded to 0.5 million t CO_2e. An increase in the cattle stock according to scenario 2 would increase methane production by

109 000 t. Converting that figure to CO2e (conversion factor of 28 for GWP100), total methane production from enteric fermentation by the current cattle population and the additional cattle required to restore semi-natural grasslands would be 5.9 million t CO2e.

4.1.5. Comparison of grazing land types

Methane emissions linked to re-introduction of grazing to achieve favorable conservation status will differ between different types of grazing land. First, these emissions are dependent on biomass yield, and hence stocking rate, where grazing of high-yielding grassland (wet historical meadows) will generate up to seven-fold higher methane emissions per ha than grazing dry land. Second, methane emissions will depend on the area that needs to be restored to achieve favorable conservation status. For *Molina* meadows (code 6410), both the yield and the area requiring restoration are large, resulting in this grassland type producing almost half of the additional estimated methane emissions in this study. Restoration of Fennoscandian grassland (code 6270) accounted for the second highest methane emissions in this study, due to a combination of medium yield and rather large area. The third largest methane load was from restoration of Wooded pasture (code 9070), which requires few grazing cattle per unit area but covers a very large area of Sweden.

4.2. Modification of the size of additional cattle stock

4.2.1. Comparison of past and present stocking rate

To evaluate the plausibility of the required increases in the Swedish cattle population and to assess the effects of factors potentially reducing the number of cattle required, the estimated stocking rates in the basic calculations were compared with historical data. The stocking rate in scenario 2 corresponded to 0.21 beef cow with offspring per ha of semi-natural grassland and forest per year, assuming that the young cattle graze 20 % ley aftermath. Re-calculated based on their nutritional requirements, the total number of cattle, small ruminants, and horses in Sweden in the year 1850 (Rekdal and Angeloff, 2021; Official Statistics of Sweden, 2022) corresponded to roughly 1.4 million beef cows and their offspring. The managed grasslands and forests present in Sweden in 1850 consisted of 2.9 million ha meadow and 9.4 million ha pasture. Excluding the meadow area, the stocking rate per ha and year in 1850 was, on average, equivalent to 0.19 beef cow and her offspring, which is similar to the stocking rate estimated in the present study. It should be noted, however, that the larger body weight (BW) and higher nutritional requirements of modern livestock breeds compared with animals in the past was not taken into account in the calculations. For example, the energy requirement of a cow in 1850 (BW 300 kg, 5 L milk/day) was only 70 % of the energy requirement of a modern beef cow (BW 750 kg, 8 L milk/day; Volden, 2011), meaning that the modern animal needs to eat an extra ~4 kg DM pasture herbage per day. Grazing livestock in 1850 also grazed aftermath on meadows and stubble fields (Lennartsson and Westin, 2019). Taken together, the stocking rate expressed in number of animals per ha could have been expected to be lower in a restoration scenario than in 1850, but in fact it was somewhat higher. This discrepancy might be due to uncertainties in the historical figures. For example, there is reason to believe that the amount of pasture herbage consumed in the past was higher than stated above. First, the number of grazing livestock during summer might have been higher than the reported annual average because many animals on traditional farms were born in spring and slaughtered in autumn. Second, livestock were not evenly fed across the year but often underfed during winter, followed by compensatory herbage intake and regained body condition on pasture (Lennartsson and Westin, 2019). Pasture herbage yield may also have been lower in the 1850s than today, due to nutrient depletion of soil in the past and/or atmospheric deposition of nitrogen increasing yield in modern farming (Spörndly and Glimskär, 2018). Pasture herbage yields measured in the mid-1900s by Steen et al. (1972) represented only 50–70 % of the more recent yield values used in this study. A hundred years earlier, the nutritional state of grasslands was probably even lower. Taken together, our estimated stocking rates in the scenarios seem to be relevant.

4.2.2. Factors reducing the need for additional cattle

While national statistics on pasture herbage yield and stocking rate are lacking, there are several reasons why the calculated number of extra cattle required for conservation of semi-natural grassland and forest in Sweden may be lower than estimated.

Most managed historical meadows are grazed today, because traditional late hay mowing is often not a practical option. If only historical pasture and meadows that cannot be rationally mown were to be grazed today, the need for grazing livestock would be about 30 % lower (Supplementary Table S2). In this study, it was assumed that 20 % of the pasture herbage ingested by young cattle is ley aftermath. If all grazing cattle, including young cattle, only grazed semi-natural grassland and forest, the number of extra cattle required could be further reduced. The consequence of such a strategy would be rather low grazing pressure during early summer, high grazing pressure during late summer, and lower weight gain of the animals. In a conceivable scenario where former meadows are mown, young cattle could graze the aftermath on these meadows, which is the ideal management approach for this land type (Lennartsson and Westin, 2019). However, very large areas of meadow would be required to avoid weight loss in the animals.

Furthermore, the semi-natural grasslands and forests grazed today for which biomass yield levels are known are not a random sample of the diverse range of lands grazed in the past. Grazing lands within, or close to, former fertile infield (fenced agricultural land closest to the village) are still grazed much more often than former barren distant outland (wide-spread multifunctional areas with free-ranging, herded livestock), which have largely been abandoned. In Norway, the appropriate stocking rate in barren outland is reported to be only 8 % of that in fertile infield (Rekdal and Angeloff, 2021). It is likely that measured values of pasture herbage yield, i.e., those used in this study (Pelve, 2010; Back, 2011; Hessle et al., 2011), most closely correspond to the pasture yield within and close to infields, since these have been grazed more often in modern times and have been investigated. Within a certain grassland type, it is therefore reasonable to assume that restored land with resumed grazing would be lower-yielding than the land grazed today, and that a lower stocking rate would be needed.

A general modification of grazing pressure can have occurred over time, where the large inter-annual variation in the past needs to be considered in nature conservation today. In the past, the grazing pressure within individual villages often deviated by ±30 % in an average year, but by up to ±90 % in individual years (Dahlström, 2006). The average grazing pressure over many years was therefore probably lower in the past than today, since the feed in years with high grazing pressure would simply not have been sufficient otherwise. With predicted climate change bringing increased frequency and degree of extreme weather events, a sufficient feed supply needs to be assured even in years of extreme drought or flooding. Lower grazing pressure is sometimes desirable, because the grazing pressure in some areas of Sweden and of Europe as a whole is currently too high for several groups of organisms (European Environment Agency, 2020; SLU Swedish Species Information Centre, 2020). In the event of a possible reduction in officially recommended grazing pressure, coupled e.g., to agri-environmental payments and support, the need for grazing livestock would decrease further.

Apart from domestic livestock, game ruminants forage on grasslands and to some extent ingest the same plants. In Norway, Rekdal and Angeloff (2021) estimated that game animals consume 15 % of the pasture resource in outland. The grazing pressure from game animals is likely to be slightly lower in Sweden than in Norway because, unlike in the Norwegian system, Swedish livestock are usually kept within fenced areas and game animals avoid both fences and domestic cattle.

There would be less need to increase the number of cattle above the current level if all existing indoor-reared bulls of dairy and beef breeds (107 000 and 72 000 head, respectively) (Gård och djurhälsan, 2022) were instead castrated and raised as grazing steers. Their pasture herbage consumption would be equivalent to that of 80 000 beef cows and their offspring.

Hence, it is probably possible to reduce the calculated number of animals required for favorable conservation status to be achieved for Swedish semi-natural grasslands and forests. The possible reductions in extra cattle stock (Table 2), as discussed above, can be quantified as follows: (a) former meadows are mown instead of grazed where possible (−30 %); (b) grasslands with re-introduced grazing have lower herbage yields than grasslands grazed at present (−25 %), grazing pressure is reduced with associated increased inter-annual variation (−10 %), and game animals contribute to grazing (−5%), giving in total 36 % lower yield ($1 - 0.75 \times 0.90 \times 0.95$); and (c) 80 000 fewer beef cows are needed through the use of all existing male offspring for grazing (−16 %).

Taking into account all these major factors, in i.e. scenario 1, only 150 000 extra beef cows and their offspring, corresponding to 30 % of the current beef cow population, would be needed to manage the desirable semi-natural grassland area in Sweden. With an increase of only 150 000 beef cows, methane emissions from Swedish cattle would only increase by 30 % above today's level.

There are some uncertainties in the calculations, which could both increase and decrease the number of cattle needed and associated methane emissions. These relate in particular to feed intake, feed NDF concentration, and herbage yield due to variations in grazing systems. The uncertainty in the data is particularly large for the most widespread grazing land type (Wooded pasture, code 9070), but has not been taken into account in this study.

4.2.3. Decreased ambition for restored area

An obvious way of decreasing the additional enteric methane production is to decrease the level of ambition regarding restored grazing land area. Although 20 % of the original area of a habitat is the scientifically defined threshold for favorable conservation status of vertebrates (Andrén, 1994; Hanski, 2011), plants and invertebrates could most likely keep persistent populations in smaller areas and therefore less ambitious restoration plans would still promote biodiversity. Linked to the European Commission's proposal for a legal act on the nature restoration law, member states must draw up national restoration plans. For Sweden, this work was done by the Swedish Board of Agriculture (Swedish Board of Agriculture, 2022c), using a 20 % threshold as in the EU report (Toräng and Jacobsson, 2019), but based on the grazing land area in 1950, when large areas of historical grassland had already been converted to ungrazed forest or arable land. This approach led to the conclusion that only 0.9 million ha of managed grazing land, including the 0.4 million ha of existing land, are required to achieve favorable conservation status of Swedish grasslands (Swedish Board of Agriculture, 2022c). Taking this as the level of ambition in conservation work would reduce enteric methane production in all our scenarios to 23 % of the original estimates. In contrast, choosing a baseline some hundred years earlier (around 1750, before the 'agricultural revolution') would most likely have resulted in a greater land area requiring conservation management through grazing. However, maps and statistics from the 1700s are scarce and comparative analysis is therefore impossible.

4.3. Policy implications

Climate policy and nature conservation policy need to achieve science-based trade-offs between the benefits of grazing cattle for biodiversity and their impact in terms of greenhouse gas emissions. For favorable conservation status of semi-natural grasslands to be achieved in accordance with the EU Habitats Directive, significant methane emissions from conservation pasture-based animal production would have to be tolerated. Replacing beef from other types of systems with beef from conservation grazing would not increase the methane emissions very much. In addition, through using known existing technology and good work practices, primary producers and the livestock industry could reduce greenhouse gas emissions by up to 70 % (Hessle et al., 2017; Ahlgren et al., 2022). Such measures could be stimulated by policy means.

There probably also needs to be a balance in terms of the grazing land types that should be prioritized, where the amount of methane emissions generated may influence the decision. As the problems facing grazing land vary across Europe and globally, the solutions will differ between regions. Locally, large animal stocks, with associated overgrazing and over-application of manure and mineral fertilizer, are a problem in some regions, while grassland biodiversity in other regions is suffering from cessation of grazing. Redistribution of the existing livestock population in terms of production system, livestock species, and location could make it easier to achieve several environmental goals simultaneously.

5. Conclusions

The basic calculations show an estimated 510 000 additional beef cows and their offspring would be required to manage the area of restored grazing land needed in Sweden to obtain favorable conservation status of grassland habitats. If this additional cattle stock instead consisted of the present combination of dairy cows and beef cows, with their male offspring raised as the present combination of indoor bulls and grazing steers, 1 100 000 new cows and their offspring would be required. In total, 109 000 and 227 000 t of enteric methane would be produced annually in these two scenarios, with intermediate methane emissions in the other two scenarios investigated (current ratio of beef and dairy cows, with current ratio of indoor bull calves and steers or with all grazing steers). Sensitivity analysis showed if parts of the semi-natural grasslands were mown instead of grazed combined with a decreased predicted stocking rate on restored grazing land and assuming all existing male cattle were used for grazing, the methane production could be reduced to less than a third (29 %) for all scenarios compared to the basic calculations. Enteric methane emissions per ha restored grazing land varied due to herbage yield of the grassland type, type of cattle used, and possible reductions in the number of grazers (as in sensitivity analysis). When the cattle stock was assumed to consist of beef cows and their grazing offspring only, methane emissions were 5–16 kg/ha/year for low-yielding grazing land and 34–117 kg/ha/year for high-yielding grazing lands, with the range depending on possibilities to reduce the number of grazing cattle. When the cattle stock was a combination of dairy cows and beef cows, with their male offspring raised as a combination of indoor bulls and grazing steers, methane emissions per ha more than doubled.

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CRediT authorship contribution statement

A. Hessle: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **R. Danielsson:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

All data used in the manuscript are available in tables in manuscript and supplementary file and are generated mainly from statistics or other references that are the referred to in the manuscript.

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