What can we learn from the past? Tracking sustainability indicators for the Swedish dairy sector over 30 years

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What can we learn from the past? Tracking sustainability indicators for the Swedish dairy sector over 30 years

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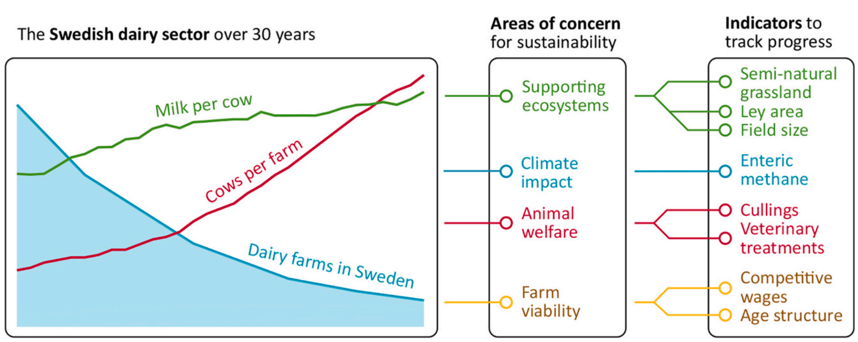
HIGHLIGHTS

- The transformation of the Swedish dairy sector has resulted in considerably fewer but larger and more high-yielding farms.
- We identified four areas of sustainability concern: supporting ecosystems, climate impact, animal welfare, farm viability.
- Over 30 years, climate impact was reduced, animal welfare improved, while results for farm viability varied.
- Contribution to supporting ecosystems through grazing semi-natural grassland has diminished while more farms are organic.
- Accounting for spillover effects is important due to the increased specialisation between dairy and beef production.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The dairy sector has undergone profound transformation over recent decades, resulting in considerably fewer but larger and more specialised farms, with unclear implications across sustainability dimensions.
OBJECTIVE: The objective was to develop and employ a framework for assessing sustainability in the Swedish dairy sector to shed light on how recent historical developments (1990–2020) have influenced sustainability outcomes.
METHODS: Using a data-driven, multidisciplinary approach, main areas of concern for sustainability in the primary production stages of the dairy sector were identified. These were then populated with indicators to track developments over time and highlight synergies and trade-offs.
RESULTS AND CONCLUSIONS: Four areas of concern were identified and populated with eight indicators (listed in brackets): 'supporting ecosystems' (semi-natural grassland area, ley area, mean field size), 'climate impact' (methane from enteric fermentation), 'animal welfare' (veterinary treatments, percentage of culled cows due to diseases) and 'farm viability' (competitive wages, farmer age structure). The results showed that area of semi-

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natural grassland per dairy cow decreased by 27% from 2003 to 2020. Area of ley per cow decreased slightly but the proportion of arable land on dairy farms devoted to ley cultivation increased, due to improved roughage quality enabling an increase in proportion of roughage in feed rations. In terms of climate impact, enteric methane emissions per kg milk decreased by 21%. Regarding animal welfare, veterinary treatments of diseases decreased from 45% to 21% over the 30 years, with declining trends for most recorded diseases except hoof disease. The indicators for farm viability showed that the average dairy farm was unable to pay a wage comparable to the national average throughout most of the period 2004–2020, but a slightly positive trend was observed, although with large year-on-year variability. A rapid change in age structure was seen between 2003 and 2020, with the proportion of land managed by older farmers (+60 years) increasing from 12% to 22%, indicating challenges with demographic viability.

SIGNIFICANCE: Tracking changes over time across sustainability dimensions gives important insights into improvements made and challenges that remain to be solved. Overall, developments in the Swedish dairy sector have diminished its capacity to support ecosystems, particularly related to semi-natural grasslands, while reducing its climate impacts and improving animal welfare. An increased specialisation has also resulted in spillover effects where services and impacts have shifted from dairy herds to specialised beef herds. These findings are important in navigating policy processes targeting developments in the dairy sector.

1. Introduction

Dairy production plays a key role in the economy of many European Union (EU) countries, as it is the second largest agricultural sector in the EU and accounts for 12% of agricultural economic output (Augère-Granier, 2018). Dairy production in the EU has gradually transformed over time. Milk yield per dairy cow has increased by on average 2% year-on-year in recent decades (FAO, 2022) and consolidation has resulted in fewer, but larger and more specialised, dairy farms (Augère-Granier, 2018). Similar trends have been seen in Sweden, where the average milk yield per cow delivered to dairies increased from 6.1 t in 1990 to 9.1 t in 2020 (FAO, 2022). Almost 20% of Swedish agricultural land is managed by dairy farms (Swedish Board of Agriculture, 2022), and dairy products account for up to 18% of all protein in Swedish diets (Amcoff et al., 2012). Therefore sustainability in the dairy sector is important for sustainability in the Swedish food system at large.

Globally, dairy cattle are estimated to account for around 3% of anthropogenic greenhouse gas emissions (Gerber et al., 2013) and 28% of reactive nitrogen emissions from livestock supply chains (Uwizeye et al., 2020). In Sweden, dairy production accounted for almost half of livestock sector GHG emissions in 2005 (Cederberg et al., 2013). Higher milk yield per cow and increased efficiency in feed production and use has however reduced greenhouse gas emissions per kg milk by 20% between 1990 and 2005 (Cederberg et al., 2013). But, there may be trade-offs with other aspects of sustainability such as biodiversity conservation (Lomba et al., 2014) and animal welfare (Arnott et al., 2017; Barkema et al., 2015). Moreover, while dairy intensification has given economic benefits at national level, there are likely trade-offs with economic and social outcomes at local scale, with e.g. smaller farms going out of business and loss of rural livelihoods (Clay et al., 2020). In order to identify and manage trade-offs and potential synergies across sustainability dimensions, comprehensive assessments that track and support progress in sustainable development are essential (Clay et al., 2020; Hebinck et al., 2021).

Approaches available for sustainability assessment range from farm or single product level (de Olde et al., 2017; Schader et al., 2014) to the level of complete diets in a region, country or globally (Eme et al., 2019). Approaches may also be either prospective (studying scenarios of alternative futures) or retrospective (looking backwards based on compiled data from the past) (Lebacq et al., 2013). While several scenario studies applied to the dairy sector have been conducted recently (e.g. Aubert et al., 2021; Gaudino et al., 2018; Kok et al., 2020; Verduna et al., 2020), retrospective assessments studying developments over time are scarcer (exceptions being e.g. Gonzalez-Mejia et al., 2018; Kelly et al., 2020). Considering the tremendous changes that have occurred in the dairy sector and the potential lessons to be learned by studying recent history, retrospective assessments across sustainability dimensions can provide important insights to guide future policy decisions.

A key component in sustainability assessment frameworks is selection of indicators, with use of multiple indicators being crucial for a comprehensive assessment (Fanzo et al., 2021). However, several sustainability aspects, such as social welfare, animal welfare and economics, are commonly underrepresented in existing frameworks (Hebinck et al., 2021). Many studies on food systems and diets focus exclusively on only one or a few aspects, in particular greenhouse gas emissions, while indicators for e.g. biodiversity are less frequently used (Jones et al., 2016). Since profound structural changes have occurred in the Swedish dairy sector in conjunction with changes in legislation, standards and agri-environmental support schemes (Lundmark et al., 2016), synergies and trade-offs between different sustainability outcomes are likely.

In this paper, we apply a retrospective approach to study changes over time in the Swedish dairy sector using a set of indicators of performance across sustainability dimensions. The focus is on primary production (i.e. dairy farming), leaving the dairy industry post-farm-gate largely outside the study scope. Thus the term 'dairy sector' is used to describe the system of actors and processes up to farm-gate and the term 'dairy industry' to include actors and processes farther along the supply chain. We start with a brief introduction to the Swedish dairy sector and changes since 1990 (Section 2). We then identify principal areas of concern for sustainability in the sector and develop indicators to track progress (Section 3). Section 4 presents and analyses results for each area of concern, while synergies and trade-offs across areas of sustainability concern are discussed in Section 5. The overall aim of the work was to improve understanding of developments in the Swedish dairy sector and their implications across sustainability dimensions. This was done by studying the past 30 years, an important period when Sweden became a member of the EU, new technologies were implemented at large scale and organic milk production gained a large market share.

2. The Swedish dairy sector

Since 1990, the European dairy sector has experienced several periods of economic turmoil. Multiple changes in the EU Common Agricultural Policy (CAP) support payments, the abolition of production quotas and price crises accompanied by aid packages are just a few of the challenges faced by the sector (for overviews see e.g. Augère-Granier, 2018; Eurostat, 2018). Due to the integration of markets, the Swedish dairy sector is highly affected by events on EU level, in particular since it became a member state in 1995 (Fig. 1). The years prior to EU accession were also turbulent, with drastic changes in market conditions for Swedish farmers due to a radical policy reform in 1990 whereby internal market regulation and export subsidies were removed (OECD, 2018).

There has been a global tendency for sector concentration and intensification of dairy production for several decades (Clay et al., 2020). There are economic reasons for this. For example, increasing farm size and scale of production can increase profits by diminishing marginal costs of production, i.e. to achieve economies of scale (Hansson, 2008). In Sweden, the number of dairy farms has decreased by almost 90%, from around 26,000 in 1990 to 3000 dairy farms in 2020, and the average number of dairy cows per farm has increased from 22 to 98 (Fig. 1a). Farms keeping less than 50 dairy cows have decreased drastically in number, while the number of farms with more than 100 cows has increased. In terms of the total dairy herd, there has been a decline from 576,000 to 304,000 dairy cows in Sweden during the period 1990–2020, whereas milk production has decreased proportionally less, from 3.4 to 2.8 million tonnes per year (Fig. 1a). The remaining Swedish dairy farms can be summarised as large-scale and intensive, as the average farm is now four times larger and the average dairy cow produces 53% more than 30 years ago.

Increased milk production per farm and per dairy cow brings efficiency gains from use or allocation of inputs or technological improvements. However, it is important to consider the high levels of investment and accompanying risks associated with this development. In previous studies, dairy farms with less than around 50 cows in the EU and the United States have been associated with high production costs per litre of milk and low economic viability (Wilczyński and Kołoszycz, 2021; MacDonald et al., 2020). However, the relationship between farm size and efficient use of production factors seems to be non-linear and evidence from Swedish dairy farms suggests that efficiency decreases with farm size in the short term, but increases with farm size in the long term (Hansson, 2008). The rapid structural changes in the dairy sector have also sparked societal concerns and discussions about risks with further depopulation of the vast, already sparsely populated countryside and loss of cultural landscapes with rich biodiversity. More recently, concerns are also raised about the self-sufficiency in dairy products that has rapidly turned from over- to underproduction.

The structural changes in the Swedish dairy sector have been accompanied by changes in technology and management. Dairy production has moved from tie-stall barns to loose-housing systems (Fig. 1c). In 1981, loose-housing farms were almost non-existent in Sweden (3% of farms). In 2007, neck-tied systems were prohibited in new-build barns and in 2020 almost 80% of all cows were loose-housed (54% of Swedish farms). The expansion of loose-housing systems was supported by mechanisation of feeding and of milking, with the introduction of new milking parlour designs such as rotaries and automatic milking systems (AMS). AMS were introduced in the late 1990s and the proportion of Swedish farms with AMS has grown fast since then, reaching 44% in 2020 (Fig. 1d).

Temporary grass/clover leys (preserved as hay) were traditionally the dominant roughage for indoor feeding during the 7–9 month winter housing period in Sweden. Since the early 1980s, haymaking has gradually been replaced by ensiling as the main preservation method. The move to silage entailed harvesting at earlier stages of plant growth and increasing the cutting frequency from the traditional two cuts a year to up to four cuts in southern Sweden, which resulted in higher concentrations of energy and protein in the roughage (Nilsdotter-Linde et al., 2019). This increase in roughage quality, in combination with changes in market prices for cereal grain and protein feeds, led to an increasing share of roughage in lactating dairy cow diets from around 35–40% in the 1990s to 50–55% in 2010, despite a simultaneous increase in milk yield per cow (Nilsdotter-Linde et al., 2019).

Organic dairy farming has increased in importance across the EU in recent decades. In Sweden, the proportion of organic dairy production has steadily increased since its introduction in 1990, to reach 19% of delivered milk in 2020 (Fig. 1b). Organic dairy production is promoted by environmental subsidies, policies and public procurement (Lindström, 2022). Characteristics of organic dairy production under current regulations include no use of synthetic fertiliser and pesticides, a high share of roughage in cow diets, more than 60% home-grown feeds,

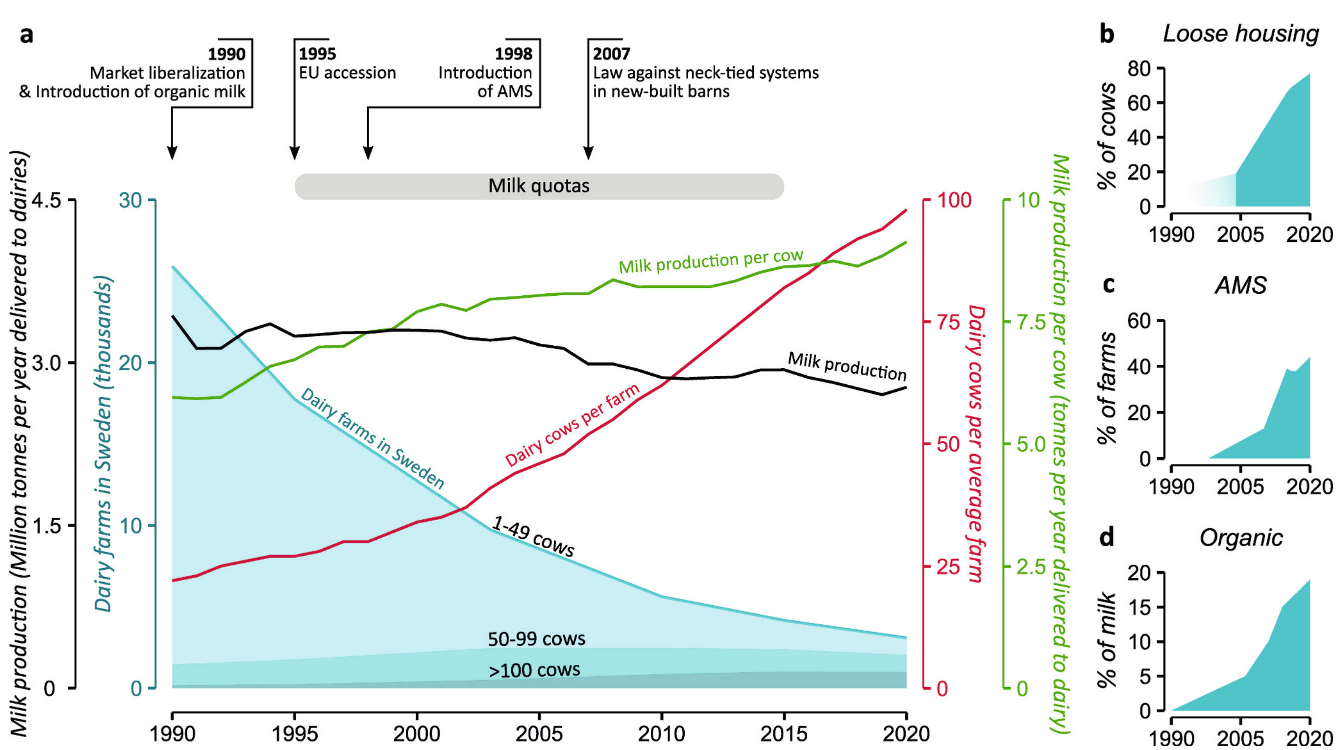

Fig. 1. Changes in the Swedish dairy sector between 1990 and 2020. (a) Number of dairy farms in Sweden subdivided by herd size (blue filled areas), milk delivered to dairies in total (black line) and per cow (green line) and average number of dairy cows per farm (red line). On the top of this panel, selected events with relevance for the Swedish dairy sector are indicated. (b) Percentage of dairy cows kept in loose housing systems. (c) Percentage of farms with automatic milking systems (AMS). (d) Percentage of milk produced organically. Data sources: Statistics Sweden (2010), Swedish Board of Agriculture (2022), Växa Sverige (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

preventive healthcare and restrictive use of antibiotics (EU, 2018). The latter two measures have also been introduced for conventional herds, but arguably more so for their organic counterparts. The organic standards used in Sweden (KRAV system) are based on IFOAM principles and EU regulations, but are in several respects more far-reaching and detailed (KRAV, 2022). For example, dairy cows must be allowed outdoor for an extended period in addition to the grazing period. During the grazing period, they must be outdoors for at least 12 h per day and a minimum amount of the roughage should be grazed grass. Despite the expansion of organic dairy farming, there has been a general trend for reduced grazing for dairy cows over recent decades in most European countries (van den Pol-van Dasselaar et al., 2020). Swedish law stipulates that all dairy cows must be kept on pasture in the summer (Swedish Board of Agriculture, 2019b), but the share of feed intake from grazing is not regulated for conventional dairy cows in the same way as for organic dairy cows.

3. A framework for tracking progress on sustainability in the Swedish dairy sector

As the aim in this study was to cover all three dimensions of sustainability, a research team with expertise from different disciplines (animal husbandry, cropping systems, environmental systems analysis, economics, agrarian history) was formed. First, key areas of sustainability concern associated with the Swedish dairy sector were identified based on the team members′ expertise and experiences from stakeholder dialogues carried out in broad societal contexts. One or several indicator (s) were then developed for each area of sustainability concern in order to track progress.

Criteria for selecting and including indicators were based on Fanzo et al. (2021), who state that indicators must be i) relevant, ii) of high quality, iii) interpretable and iv) useful. In the present study, an indicator was deemed relevant if meaningful for different stakeholders over time and across settings. High quality was considered by populating the indicators with data based on well-documented methodology with underlying data available and updated on a regular basis. The interpretability requirement was fulfilled using quantitative indicators that are easy to communicate to various stakeholders, while usefulness considered the potential of indicators to support policy and decision-making and influence changes.

When testing and finally selecting the set of indicators, a data-driven approach was used, as it must be possible to calculate the indicators from existing data sources. Such an approach is often needed when analysing changes over time retrospectively (Lebacq et al., 2013), as collection of new primary data several decades back is not possible. The indicators selected were mainly based on farm-level data, aggregated (from samples or the whole population) to represent the dairy sector as a whole. In addition, some indicators were expressed per land area, per volume of milk produced or per cow, to increase their interpretability in terms of changes in the dairy sector.

3.1. Areas of sustainability concern and associated indicators

We identified four principal areas of concern for sustainability in the Swedish dairy sector, two related to environmental sustainability ("Supporting ecosystems" and "Climate impact") and two related to social and economic sustainability ("Animal welfare" and "Farm viability"). Another important area of sustainability concern is plant nutrient management. Nutrient use efficiency or nutrient surplus are commonly proposed as indicators in sustainability frameworks (e.g. Fanzo et al., 2021; Hebinck et al., 2021). However, statistics for nitrogen and phosphorous surpluses are not presented for Swedish dairy farms over time (Statistics Sweden, 2021). Data from nutrient budgets calculated at farm level by the advisory service since 2001 are available, but as the scheme initially only included farms in the southernmost parts of Sweden this data presently does not allow calculation of indicators representative of the entire Swedish dairy sector. The requirement for high-quality retrospective data available for constructing indicators was therefore deemed not to be met for plant nutrient management.

The need for agricultural practices that support ecosystems and biodiversity conservation has become increasingly clear through the use of conceptualisations such as ecosystem services (IPBES, 2019). 'A rich agricultural landscape' that supports farmland biodiversity is also one of Sweden's environmental quality objectives. Likewise, reduced climate impact is a key sustainability priority for all sectors of society and major actors in the Swedish beef and dairy industry have made their own climate pledges (HKScan et al, 2021). Efforts to improve animal welfare are driven by increasing public awareness and scientific knowledge of animal suffering, but also by the relationship between animal welfare and economic performance (Owusu-Sekyere et al., 2021). Finally, having viable farms that can economically sustain themselves and recruit new social capital through e.g. farm succession is vital for the long-term survival of Swedish dairy farming.

Table 1 provides an overview of the indicators used to track developments on each area of sustainability concern. The following sections elaborate on each area of sustainability concern and describe the indicators used in more detail, including methods and data for their quantification.

3.1.1. Supporting ecosystems

To assess changes in the contribution of the dairy sector to

Table 1
Summary of indicators and data used for each area of sustainability concern.

Areas of concern and indicators	Description	Data sources and availability
Supporting ecosystems		
Semi-natural grasslands	Area of semi-natural grassland on dairy farms expressed per unit milk, per cow or for the sector as a whole	Data from the Swedish Farm Register available on request from the Swedish Board of Agriculture
Ley area	Area of ley (perennial grass/legume forage crops) on dairy farms expressed per unit milk, per cow or for the sector as a whole	See above
Mean field size	Mean size of agricultural parcels on dairy farms	Agricultural parcels in the Integrated Administration and Control System (IACS) database with farmer identification numbers corresponding to dairy farms in the 2016 Swedish Farm Register
Climate change		
Enteric methane emissions	Enteric methane emissions from dairy cows and replacement animals expressed per unit milk, per cow or for the sector as a whole	Sweden's National Inventory Reports
Animal Welfare		
Cows culled due to disease	Percentage of culled cows culled due to a disease	Publicly available data from the Swedish Official Milk Recording Scheme
Disease prevalence	Percentage of cows treated for different diseases	See above
Farm viability		
Potential to pay competitive wages	Modified farm net value added per annual work unit compared to threshold wages	Publicly available data from the Farm Accountancy Data Network (FADN)
Farmer age	Proportion of agricultural land on dairy farms managed by farmers in different age cohorts	Publicly available data from the Swedish Board of Agriculture

supporting ecosystems over time, we analysed three indicators: i) area of semi-natural grassland, ii) area of ley and iii) mean field size.

Swedish semi-natural grassland (i.e. pastures and meadows on non-arable land) is the result of traditional farming practices involving mowing and grazing (Emanuelsson, 2009), where ecosystems have developed to create some of the most species-rich biomes in Sweden (Swedish EPA, 2020). Today, only a fraction of Sweden's historical semi-natural grassland area remains (Kumm, 2003) and without the presence of grazing livestock grassland habitats may become overgrown, threatening the life-support system for associated species (Dahlström et al., 2006; Spörndly and Glimskär, 2018). Due to its importance for farmland biodiversity, area of semi-natural grassland is an indicator for Sweden's environmental quality objective ‘A rich agricultural landscape’.

Ley cultivation (i.e. perennial grass or grass-legume mixtures grown on arable land) can benefit farmland biodiversity, favouring e.g. earthworms (Prendergast-Miller et al., 2021) and promoting carbon sequestration (Henryson et al., 2022). Pesticide use is also lower for leys than for other forage crops such as maize silage (Urruty et al., 2016). If integrated into a crop rotation, perennial forage crops may reduce weed problems (Meiss et al., 2010; Martin et al., 2020) and supply nitrogen to succeeding arable crops (Martin et al., 2020). Ley cultivation can thus lower the need for chemical plant protection and fertilisers and thereby reduce associated environmental impacts.

Mean field size is increasing throughout European landscapes, driven by increasing farm size, land consolidation and economic incentives for managing land in larger units (Clough et al., 2020). Smaller mean field size has been shown to benefit farmland biodiversity even in the absence of semi-natural vegetation between the fields (Sirami et al., 2019; Clough et al., 2020). Avoiding further field size increases and re-creating more fine-grained agricultural landscapes has therefore been proposed as an important policy strategy in safeguarding European farmland biodiversity (Clough et al., 2020).

Data on the total area of semi-natural grassland and ley on Swedish farms keeping dairy cows was retrieved from the Swedish Farm Register (Swedish Board of Agriculture, 2018) for the years 1990–2020. Mean field sizes were calculated from data in the Integrated Assessment and Control System (IACS) database, which contains detailed accounts of the agricultural parcels for which farmers have applied for agricultural support within the CAP and includes e.g. parcel size, crop sown and a farmer identification number. Farmer identification numbers that corresponded to dairy farms were identified from the 2016 Swedish Farm Register, with all farmer identification numbers classified as dairy farms in 2016 being assumed to represent dairy farms also in preceding and succeeding years. Annual data from the IACS database were available for the period 2005–2019 and this indicator was therefore only calculated for this period. The mean size of all agricultural parcels classified as on dairy farms were then calculated for each year per region (see map in Fig. 2). In addition, the rate of change in mean field size was also calculated per farm as the difference in mean field size between the first and last year for which data were available for that farm, divided by the number of years between those two points in time. These data are presented aggregated for different size groups and for dairy and non-dairy farms in the Supplementary Information.

The sample of farms used to calculate mean field size in 2016 included 99% of all dairy farms. However, as the number of farms has declined rapidly and as it was not possible to follow all farms identified as dairy farms in 2016 throughout the entire period, the number of farms included in 2005 equated to only 36% of the total number of dairy farms in that year. The sample of farms included in calculating this indicator thus only includes farms that have remained in dairy farming through time, which represents a bias by not including farms that have ceased their operations or converted to e.g. beef production. The results are thus not representative of the development for the entire Swedish dairy sector over time.

3.1.2. *Climate impact*

The selected indicator for climate impact was methane emissions from enteric fermentation, which constitutes a major part of the carbon footprint from milk production. It is estimated to account for close to 50% of total emissions from Swedish dairy production when methane, nitrous oxide and fossil carbon dioxide are included (Flysjö et al., 2011). This indicator was used to describe how emissions of greenhouse gases from the dairy sector have changed and was chosen based on its importance in climate mitigation actions and because data based on well-documented methodology enabling direct attribution of emissions to the dairy sector are available on a yearly basis.

Data on emission factors for methane from enteric fermentation for different livestock categories were retrieved from the National Inventory Report of Greenhouse Gases (NIR), which is updated yearly and reported to the United Nations Framework Convention on Climate Change and the Kyoto Protocol (NIR, 2017, 2019, 2022). Data were available for every year since 2013 and for every fifth year between 1990 and 2010. Important input data for calculating emission factors are feed intake and feed composition. The methodology used for modelling enteric methane was based on equations developed by Nielsen et al. (2013). When calculating total methane emissions from enteric fermentation, we included the number of dairy cows as reported in NIR, which is based on official Swedish statistics. For the number of calves and heifers for replacing dairy cows we used a factor of on average 0.85 to calculate the number of replacement heifers (0–28 months) needed to achieve a replacement rate of on average 37% (Växa Växa Sverige, 2020). All methane emissions from enteric fermentation were allocated to milk production. The resulting values were expressed as change in relation to the year 1990, per kg energy-corrected milk (ECM), per dairy cow (including replacement) and for the dairy sector as a whole.

For comparison, we also present previously published results of complete lifecycle greenhouse gas emissions from Swedish dairy production (Cederberg et al., 2009). All emissions incurred in feed production, energy use, manure management etc. up until produced milk leaves the farm gate were included, based on data available for the years 1990 and 2005.

3.1.3. *Animal welfare*

Animal welfare is essentially an individual animal's ability to cope with its environment, but it is a multidimensional concept where several criteria are important and cannot compensate for one another. For example, animal health cannot compensate for the ability to exhibit appropriate behaviour in a given situation, or vice versa. Animal welfare is often defined as the five freedoms (freedom from hunger and thirst, freedom from discomfort, freedom from pain, injury or disease, freedom from fear and distress, and freedom to express normal behaviour) (FAWC, 2009). Good animal welfare also requires disease prevention and veterinary treatment in the event of illness and injury, appropriate protection and nutrition and humane handling and slaughter/killing (OIE, 2022). Most of the quantifiable measures used conventionally to assess animal welfare relate to different aspects of impaired health. However, new methods for determining the emotional state of animals have begun to emerge, although there is still no consensus about how to interpret the responses of animals (Barrel, 2019).

Indicators of animal welfare are generally assessed using statistics on the occurrence of diseases, absence of pain (e.g. during dehorning in cattle) and if the animal is able to live according to its nature (e.g. grazing of cattle) (von Keyserlingk et al., 2009). However, in response to public awareness, Welfare Quality® protocols have been introduced and further developed for use in practice (Andreasen et al., 2014). The necessity of methods for regular assessment of animal welfare in dairy herds and the relevancy and creditability to the public are discussed by Hultgren (2017), who also mention risk assessment systems and official monitoring. Keeling et al. (2021) reviewed possible welfare indicators with the aim of identifying a positive welfare protocol, including indicators such as ear position, play, allogrooming and brush use, in

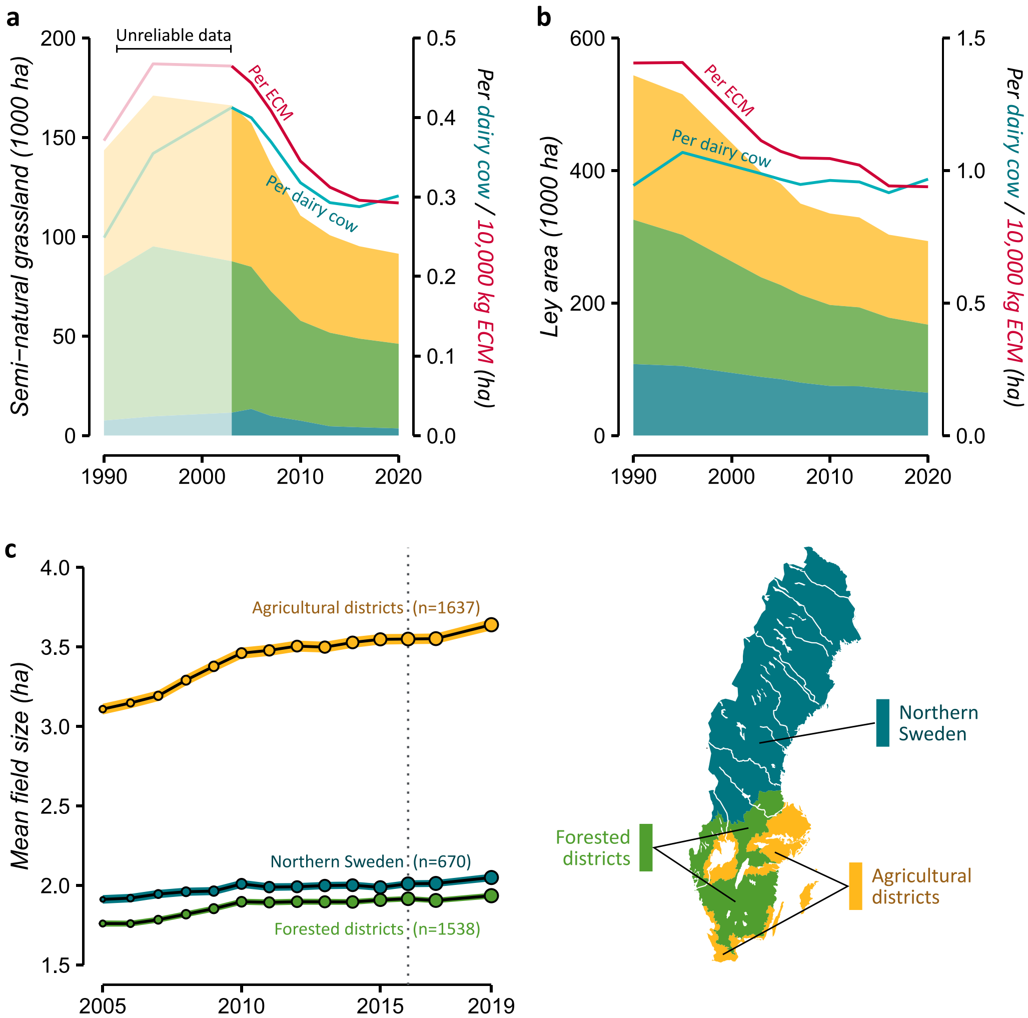

Fig. 2. Changes in the area of (a) semi-natural grassland and (b) mown and/or grazed leys on Swedish dairy farms between 1990 and 2020. The total area in Sweden and in its three main regions (see map) are shown as stacked areas relating to the left-hand axes. Lines relating to the right-hand axes show area of semi-natural grassland and ley per dairy cow (blue lines) or per 10,000 kg energy-corrected milk (ECM) delivered to dairies (red lines). (c) Changes in mean field size on dairy farms in each Swedish region from 2005 to 2019. Shaded areas show 95% confidence interval of the mean and point size is proportional to the number of farms included in calculating mean field size in relation to total number of dairy farms in a region in that year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

contrast to conventional protocols focusing on the absence of poor welfare and diseases.

To describe changes in animal welfare over the period 1990–2020 when no welfare protocols had yet been implemented in the Swedish dairy sector, we used veterinary treatments (total and disease specific) and percentage of cows culled due to disease as indicators. We also considered potential animal welfare implications of the increased importance of loose housing systems and organic farming (see Fig. 1b, d).

Data on veterinary treatments and reasons for culling were obtained from the Swedish Official Milk Recording Scheme, which covers on average 80% of all dairy cows in Sweden (Växa Sverige, 2020). The data is reported by the treating veterinarian, state employed or private, and based on identification of the individual cow in the Milk Recording System. All severe sickness involve veterinarians since medicines are only available after prescription in Sweden. The data is collected and checked by the Swedish Board of Agriculture and accepted to represent the entire cow population although ther has been reports of some private veterinarians failing in their reporting. The data is managed and the results published annually by the national farmer's organisation Växa (Växa Sverige, 2020).

3.1.4. Farm viability

Farm viability, i.e. the ability of a farmer to continue a farming business, can be defined and measured in several ways, e.g. as demographic viability of a farm business, which is a question of succession and provision of management or labour personnel. Across many European countries, the age of farmers is increasing, which is seen as a problem for the acquisition of new human capital by the farming sector (Dillon et al., 2010; Ryan et al., 2016). Economic or financial viability, on the other hand, involves balancing expenditures and revenues so that the farm can be sustained or even grow if this matches business objectives (Dolman et al., 2014; Barnes et al., 2015). Therefore, economic viability, particularly in the long run, can be interpreted as reflecting the economic sustainability of a farm (Hennessy et al., 2013; Ryan et al., 2016; Spicka et al., 2019). O'Donoghue et al. (2016) review different definitions of farm economic viability and show that a common indicator in the agricultural economics literature is the potential of the farm business to provide income at a level equivalent to a national or comparable sector average wage, for paid labour and unpaid family labour (O'Donoghue et al., 2016; Barnes et al., 2015).

We used two indicators to analyse the viability of Swedish dairy farms over time: the potential to provide a competitive wage for all labour input and the age structure of farmers. The economic indicator was mainly constructed from the standard results in the Farm Accountancy Data Network (FADN) public database. The FADN economic survey classifies all EU agricultural holdings by economic size, according to potential gross production (standard output[1]), and provides microeconomic data at farm level. Specialist dairy holdings listed in FADN are determined based on the contribution of milk production to total standard output using data from a stratified sample weighted to represent the population, with a view of providing good averages for groups, rather than total values (European Commission, 2020). The sample used in this study represented specialist dairy farms with standard output exceeding 50,000 Euro. Before 2007, farms in FADN were categorised according to standard gross margin, but data recalculated according to standard output are available from 2004, which is therefore the first year for which we could calculate the economic viability indicator. In FADN, changes in valuation are taken into account in production through changes in the opening and closing valuation for each year's production values (European Commission, 2020). As such, specific prices are not observed in FADN data, only in terms of farm income and expenses. Data on average wages, nationally and for agricultural work (including crop and livestock farming, but excluding forestry) and historical exchange rates were sourced from Statistics Sweden (2022a, 2022b) and the central bank of Sweden (Sveriges Riksbank, 2022), respectively.

To construct the economic viability indicator of competitive wages, we followed Spicka et al. (2019), who recommend using a modified farm net value added (MFNVA) as an indicator to assess income level per annual work unit (AWU). Farm net value added (FNVA) in FADN standard results includes total production output plus all subsidies (except on investments) minus intermediate costs of production and depreciation, and represents remuneration on fixed factors of production (capital, labour and land). MFNVA additionally deducts costs of capital and land to measure potential income per AWU, which is suitable to compare with average threshold wages (Spicka et al., 2019). We also show the difference in wage levels by using both the average agricultural wage and national average wage as threshold wages (Ryan et al., 2016; O'Donoghue et al., 2016).

In addition to paying a competitive wage for work hours, a viable farm business should also provide a certain return on own non-land assets, reflecting the opportunity costs of capital investments as the foregone revenue of an alternative low-risk conservative investment, such as a bank account (Hennessy et al., 2008). While it is common to use a 5% return on non-land assets given the low interest rates in recent years, a more realistic comparison is the interest rate on long-term government bonds (O'Donoghue et al., 2016). We therefore included the opportunity cost of capital investments as a fixed percentage condition on the MFNVA indicator based on an average interest of 2.1% for Swedish 10-year government bonds (Sveriges Riksbank, 2022). Land was excluded from assets in the indicator due to low liquidity and high proportions of leased land (Spicka et al., 2019).

As an indicator for demographic viability, we used proportion of the agricultural land on dairy farms managed by farmers in different age cohorts (or by a legal entity where age is unknown). Data were retrieved from the Swedish Board of Agriculture (2022) for farms defined as dairy farms in the Swedish Farm Register.

4. Results and discussion

4.1. Supporting ecosystems

The area of semi-natural grassland on dairy farms decreased by 45% (or 74,600 ha) between 2003 and 2020 (Fig. 2a) and the proportion of agricultural area on dairy farms represented by semi-natural grasslands decreased from 19% to 16% during the same period. This trend was evident across Sweden but the strongest relative decline was in northern Sweden, where up to 69% of the semi-natural grassland area on dairy farms in 2003 had been lost by 2020. However, it should be noted that a large part of the semi-natural grassland no longer found on dairy farms is now in use on other farm types. The total loss of semi-natural grassland has therefore been less dramatic, with a 6% (30,900 ha) reduction between 2003 and 2020 and a slow increase in area from 2015 onwards (Fig. S1) The proportion of total semi-natural grassland located on dairy farms decreased from 34% in 2003 to 20% in 2020, but the dairy sector still contributes to grazing semi-natural grassland, with previous estimates showing that 50% of cattle on Swedish semi-natural grasslands originate from dairy production (Spörndly and Glimskär, 2018). Data on semi-natural grassland area prior to 2003 are uncertain, as Sweden's entry into the EU in 1995 and reforms to support payments in 2003 both increased the area of semi-natural grassland included in support applications. The increase in area observed between 1990 and 2003 thus mainly corresponds to areas previously not included as semi-natural grassland in the statistics, and not to an actual increase in area (Swedish Board of Agriculture, 2007).

The loss of semi-natural grassland was due to both an absolute decline in the number of dairy cows and a reduced area of semi-natural grassland per cow (Fig. 2a). On dairy farms, it is mainly replacement heifers that graze semi-natural grasslands, which are often scattered in the landscape and may be located far from the farm centre (Holmström et al., 2018). The number of young animals per dairy cow on dairy farms decreased from 1.40 in 1995 to 1.28 in 2020. In 1990 the number of young animals per dairy cow was low (1.23), likely due to turmoil in the Swedish dairy sector around that year, with a temporary quota system introduced in 1986 but scrapped before 1990 when the milk market was liberalised prior to introduction of the EU quota system in 1995. This turmoil seems to have affected dairy cattle herds, with an increase in the number of dairy cows in the years leading up to 1990 followed by a sharp decline (Fig. S1). After 2003, the decrease in young animals per dairy cow went hand-in-hand with a 27% decline in grassland area per cow. These trends indicate that dairy farms have increasingly specialised in keeping milking cows, while fattening of calves is increasingly "outsourced" to other farms. The latter farms have likely taken over some of the semi-natural grassland area lost from dairy farms which have ceased production or converted to other forms of production, highlighting the difficulty in assessing the extent to which the dairy sector contributes to supporting ecosystems as dairy cow offspring are also found on other farms. However, the area of semi-natural grassland per young animal on dairy farms has declined, which suggests that the net contribution of the dairy sector to grazing semi-natural grasslands has in fact declined. The number of suckler cows in Sweden has increased by 26% since 2003 and has more than doubled since 1990 (Fig. S1), and specialist beef farms tend to have a higher proportion of semi-natural grasslands in their agricultural area (Karlsson et al., 2022).

Towards the end of the study period (1990–2020), the rate of loss of semi-natural grassland from dairy farms seemed to level off and in most production districts the number of young animals and the area of semi-natural grassland per dairy cow increased slightly. This was possibly an effect of high meat prices in relation to milk prices (Fig. S2b) incentivising dairy farmers to increase on-farm meat production.

The area of ley on dairy farms decreased by 46% during the study period (Fig. 2b), but expressed per dairy cow the area remained relatively constant. However, the figure for the whole of Sweden masked regional differences, with reductions in ley area per dairy cow in southern Sweden and increases in the north. The area of maize and other green fodder per dairy cow more than doubled during the study period (Fig. S3), which may explain the reduced area of ley per cow in southern Sweden. However, the proportion of cropland on dairy farms used for ley increased in all regions, at the expense of cereals and other non-

[1] Standard output (SO) is an average monetary value of the agricultural output at farm-gate prices, in Euro per hectare or per head of livestock. There are regional SO coefficients for each product, as an average value over a reference period (usually five years).

fodder crops (Fig. S3), which is in line with the changes in dairy cow diets towards more roughage and replacement of cereal grains with cereal by-products. The major reform of the CAP in 2005 (MTR) to provide direct farm support, irrespective of crops cultivated, promoted ley cultivation, together with environmental subsides specifically aimed at ley cultivation (Swedish Board of Agriculture, 2013). The proportion of ley on farms is positively correlated to carbon sequestration, e.g. a study based on a national soil-monitoring programme revealed that decadal topsoil carbon sequestration was higher on dairy farms than on other farm types in Sweden (Henryson et al., 2022).

Mean field size increased by 12% (from 2.3 to 2.6 ha) on the dairy farms that were active in 2016 between 2005 and 2019 (Fig. 2c). This trend was observed for all production districts in Sweden, with the strongest increases in agriculture-dominated districts (+17%, from 3.1 to 3.6 ha). Compared with other farm types, mean field size increased faster on dairy farms, but there was no marked difference for dairy farms compared with other farms of comparable size (Fig. S4). It is important to note that the sample of farms included in this indicator excludes all dairy farms that ceased their dairy operations between 2005 and 2016 so the results are not representative of changes in the sector as a whole over time. It is feasible to assume that farms in less productive tracts with smaller field sizes have ceased their operations or converted to beef production to a larger extent than farms with initially larger field sizes.

4.2. Climate impact

Enteric methane emissions (from cows and replacement heifers) per dairy cow increased by 22% between 1990 and 2020 due to higher feed intake to support increased milk yield. This increase was outweighed by increased productivity diluting maintenance energy requirements and methane emissions over a larger milk volume, resulting in a 21% reduction in enteric methane emissions per kg ECM (Fig. 3). This reduction in emission intensity is likely a combined effect of improvements in feed digestibility, which is important for methane emissions mitigation (Hristov et al., 2013), and other aspects of improved efficiency. Total enteric methane emissions from the Swedish dairy sector declined by 36% between 1990 and 2020, due partly to improved efficiency but also to absolute reductions in milk production and dairy cow numbers. The changes in enteric methane emissions per dairy cow and per kg ECM closely resembled those observed by Huhtanen et al. (2022) in Finland, where changes in milk yield were similar to those in Sweden during the period.

The trends in enteric methane emissions followed changes in total greenhouse gas emissions reported by Cederberg et al. (2009), which include emissions from all on and off-farm processes evaluated using life cycle assessment. However, the relative decrease in total emissions per kg ECM between 1990 and 2005 was stronger than that of enteric methane emissions alone, with important measures for achieving the dairy sector's climate footprint reduction being improved feed efficiency for the cows and lowered use of synthetic nitrogen fertilisers in the leys (Cederberg et al., 2013). This shows that while methane emissions from enteric fermentation as a single climate indicator captured the overall trends between 1990 and 2005, it disregarded processes relevant for changes in climate impacts from the dairy sector.

4.3. Animal welfare

Veterinary treatments for diseases such as mastitis, parturient paresis, retained placenta, ketosis and displaced abomasum all decreased during the study period, while treatments for hoof conditions increased (Fig. 4a). In total, the proportion of cows in the Swedish official milk recording scheme treated for a disease decreased from 45% in 1990 to 21% in 2020. While this decrease could have been achieved by increased culling of sick animals, records of diseases as causes of culling also showed a decreasing trend throughout the period (Fig. 4b), while the culling of healthy cows increased. The two main reasons stated for culling cows were low fertility and mastitis, which decreased from 29% to 18% and from 21% to 15%, respectively, from 1990 to 2020. The only culling due to disease that increased was for hoof problems, which is in line with the data on veterinary treatments and is known to be a consequence of loose-housing systems where cows stand and walk on floors wet with faeces and urine (Manske, 2002). The drastic increase in

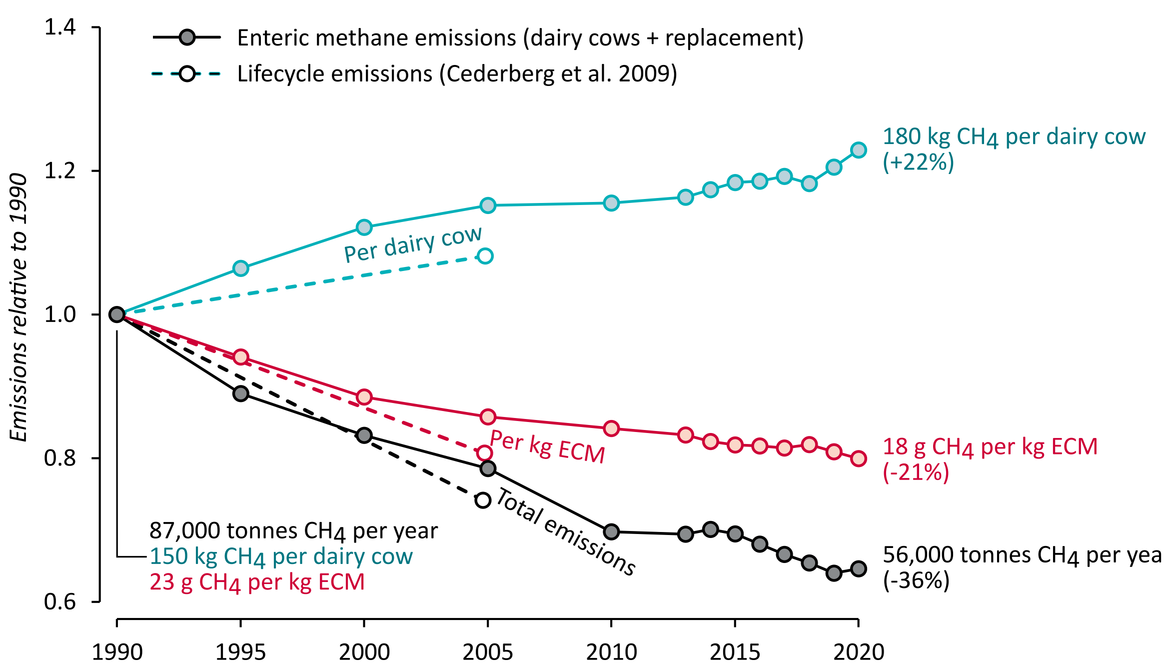

Fig. 3. Changes in the climate impact of Swedish dairy farms measured as enteric methane (CH_4) emissions from dairy cows and replacement animals (solid lines) and life cycle emissions of methane, nitrous oxide and carbon dioxide (dashed lines) in 1990 and 2005 (values from Cederberg et al., 2009). Emissions are shown relative to those in 1990 and expressed in terms of total emissions (black lines), emissions per dairy cow (blue lines) and emissions per kg energy-corrected milk (ECM; red lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

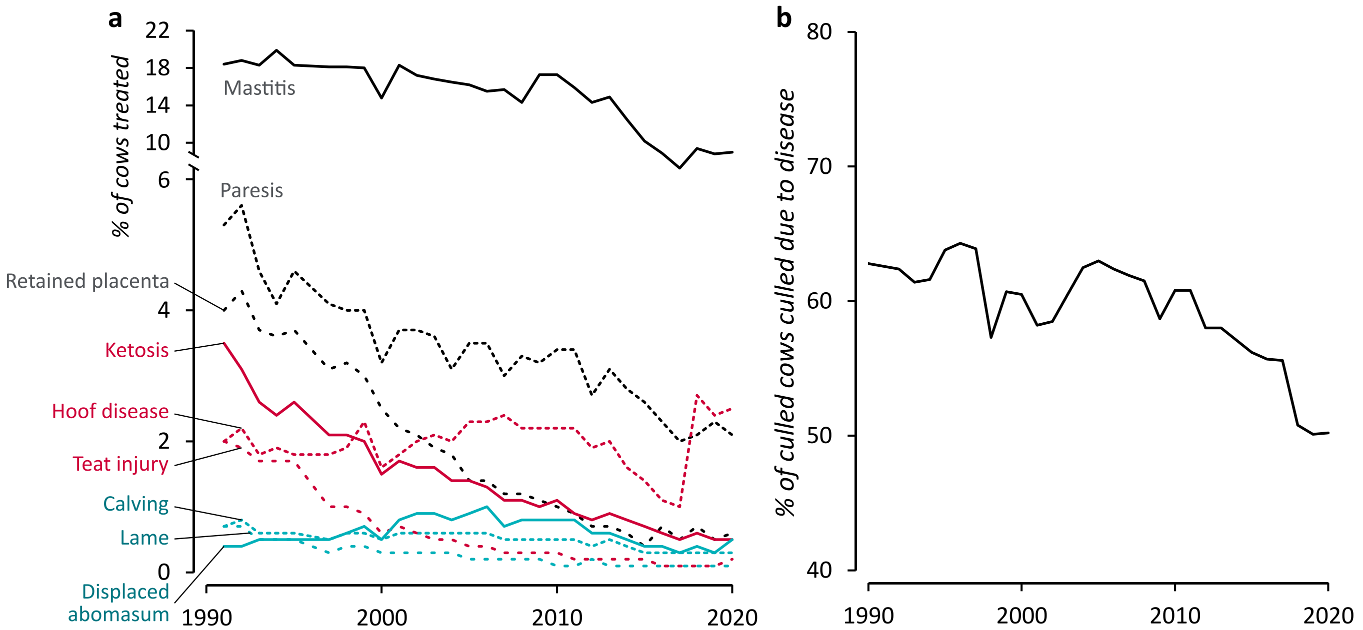

Fig. 4. (a) Disease rates in the Swedish dairy cow population, indicated by annual percentage of cows registered in Swedish official statistics receiving veterinary treatment. Each line in the diagram represents a different reason for treatment as indicated on the y-axis (note scale change above 6%). (b) Percentage of culled cows 1990–2020 for which the stated reason for culling was disease.

hoof disease reported around the year 2020 seen in Fig. 4 is however probably an effect of the introduction of a subsidy for hoof trimming in 2016, which stimulated farmers to take actions on hoof health. Total culling in dairy herds (i.e. recruitment percentage) remained stable over the period, at around 38% (Växa Sverige, 2020), probably driven by the endeavour to achieve genetic progress and by the high price paid for young cows at slaughter.

Apart from developments in the above-mentioned animal health indicators, we also observed other changes in dairy farming with implications for animal welfare. The ability of dairy cows to move freely in loose-housing systems increased over the study period (Fig. 1b), as did the number of cows kept in organic production (Fig. 1d). Under organic production standards, grazing time is mandatory and more strictly regulated than in conventional systems, and calves are weaned later. However, the trend for larger herds and higher productivity may constrain the potential for grazing by dairy cows (van der Pol-van Dasselaar et al., 2020). It has been found that cows decrease their time on pasture with increased walking distance to the grazing area (Arnott et al., 2017), so cows in large herds may have reduced grazing opportunities if the farm lacks large pasture areas close to the barn. Grazing opportunities may have been further reduced by increased adoption of AMS (Fig. 1c), which require a continuous flow of cows to be milked and thus rely on short walking distance from pasture to barn. High-yielding dairy cows have high nutrient requirements and require lush pastures with sufficient quantity and quality of forage to meet their nutritional needs. Grazing without supplementary feeding is therefore limited mainly to replacement heifers and dry cows, especially for grazing semi-natural grasslands, which are often located farther away from the farm centre. Use of “recreation pastures” for lactating cows, where cows are fed a complete ration indoors but have pasture access to comply with the legal requirement for summer grazing, has therefore become more common in conventional production.

4.4. Farm viability

For a farm to be viable in terms of being able to pay competitive wages, MFNVA per annual working unit should cover the total yearly labour costs. Total labour costs include both paid wages for employees and unpaid labour (e.g. unpaid family labour or farm manager working extra hours without pay). The share of unpaid labour in total labour input on Swedish dairy farms is still high, but decreased from 79% in 2004 to 64% in 2020. Farms were not able to remunerate all labour input with a wage in line with the Swedish average agricultural wages (i.e. the indicator had a value below zero) for around half of the years in the study period (Fig. 5a). This share increased to around two-thirds of years when the opportunity costs of non-land assets were accounted for by requiring that the MFNVA cover both wages and provide a return on invested capital equivalent to returns on 10-year government bonds. The indicator showed a slight positive change over time, from −8300 EUR in 2004 to 2500 EUR in 2020 compared with the average agricultural wage, and from −16,200 EUR to −9500 EUR compared with the national average wage. This implies that a competitive agricultural wage is just about affordable for the average Swedish dairy farm today, as opposed to the situation in 2004, but this can be attributed to the agricultural wage being lower than the national average wage, for which the indicator remained negative. During the study period, farm income as represented by MFNVA more than doubled, but total labour inputs, opportunity costs of own non-land assets and average agricultural wages also increased, explaining the modest increase in the indicator.

The economic viability indicator also showed large year-on-year variability. Incomes in agriculture are known to be volatile, mainly due to fluctuating market prices (see e.g. milk price volatility in Fig. S2a). A high level of specialisation in dairy farming has been identified as a restraining factor for farm economic performance in Sweden and England, one of the explanations being the dependency on a single market highly affected by global changes (Hansson, 2007; Hadley, 2006). However, there is also evidence that some farmers are not primarily motivated by growing their business or by deriving additional income from other employment, but by farming as a way of life (Ferguson and Hansson, 2013). In light of the modest development in the economic viability indicator, this reason seems to be of relevance for Swedish dairy farmers and should be considered when including (or not) the opportunity cost of investment in the viability indicator.

The age structure of Swedish dairy farmers changed rapidly between 2003 and 2020, when the proportion of land managed by farmers aged 60 years or older increased from 12% to 22% while the proportion of

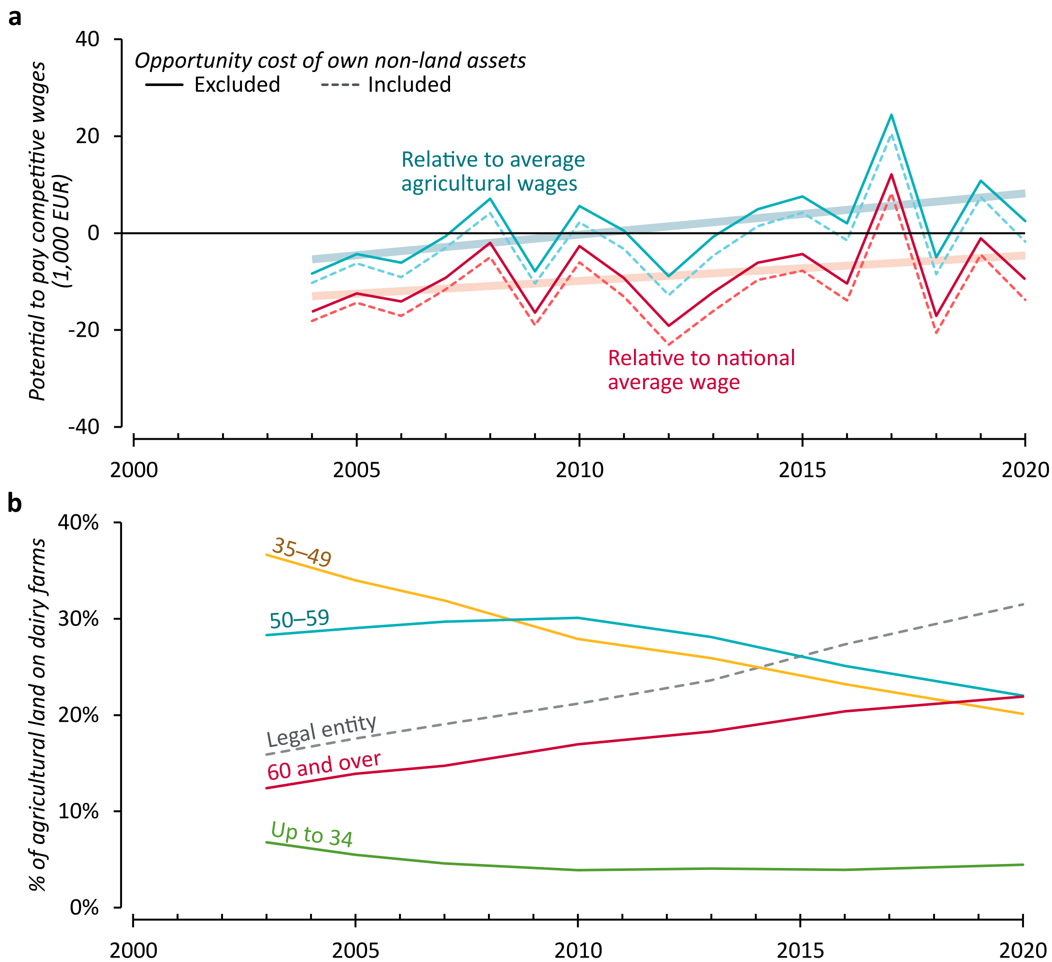

Fig. 5. (a) Modified farm net value added (MFNVA) with (solid lines) or without (dotted lines) the opportunity cost of own non-land assets deducted per total annual work units on Swedish dairy farms in the period 2000–2020 relative to the average agricultural sector (blue lines) or national (red lines) wage. (b) Changes in the age structure of dairy farmers in the same period, where lines indicate percentage of agricultural land on dairy farms managed by farmers in a specific age group. The category "Legal entity" refers to farms run by e.g. a joint-stock company, where age is not applicable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

land managed by all other age groups declined (Fig. 5b). This indicates challenges in demographic viability and recruitment of new social capital into the sector. However, the proportion of land managed by a legal entity increased from 16% to 31% in the period. This indicates a shift in corporate form and could mask succession, e.g. where younger and older generations of farmers run the farm together through a joint stock company.

5. Synergies and trade-offs across areas of sustainability concern

Over the past 30 years, Sweden's dairy sector has undergone a radical restructure with wide-scale closure and loss of dairy farms, leading to a situation where milk production occurs on a relatively small number of large farms. By developing and quantifying a set of indicators for four areas of sustainability concern, we investigated the effects of this development. Overall, the changes in the Swedish dairy sector led to positive trends for the sustainability areas of *climate change* and *animal welfare*, both positive and negative trends for *farm viability*, and negative trends for *supporting ecosystems* (Table 2). Important events such as EU entry (1995) and introduction of milk quotas did not show a clear influence on any of the indicators analysed. Rather, transformation of the sector seemed to be driven by general economic incentives to increase revenues by increasing milk yield per cow, adopting organic production practices (with a price premium), keeping larger herds and investing in more mechanised feeding and milking systems.

Milk and beef production are closely connected, indirectly at sector level and directly at farm level, so there are drawbacks with analysing the dairy sector separately since effects (positive or negative) from changes in the dairy sector may spill over to the beef sector. As shown by Flysjö et al. (2012) it is critical to consider the link between milk and beef when studying future milk production, as increasing milk yield per cow leads to less meat production per unit milk. If market demand for beef is unchanged or increases, the loss of meat as a by-product from the dairy sector when yield per cow increases and the dairy herd is reduced will thus require increased production of beef from dedicated suckler cow herds. This is exactly what has happened in Sweden over the past 30 years. In 1990, 85% of total Swedish beef originated from the dairy sector, as meat from culled dairy cows and surplus dairy calves (mostly bulls), but by 2005 the figure was only 65% (Cederberg et al., 2013). Today, around 55% of Sweden's beef is sourced from animals originating from dairy farms. Thus, it can be questioned whether the indicator trend for climate impact was actually positive (21% emissions reduction per kg milk; see Fig. 3), given that the suckler cow herd increased by around 175% (Fig. S1) during the study period to sustain domestic beef production. Obviously, a large part of the dairy sector's methane emissions reduction has been achieved at the expense of higher emissions in the beef sector. The indicator trends for supporting ecosystems can also be discussed in light of changes in the beef sector; there was a clear reduction in area of grazed semi-natural grassland per unit milk produced during the 30-year period and today these valuable grasslands are

Table 2
Summary of results for all four key areas of concern for sustainability in the Swedish dairy sector (bold) and for all selected indicators (italics). Positive and negative trends (from a sustainability perspective) in indicator values are indicated, respectively, by (+) on a green background and (−) on a red background. Values are presented for the dairy sector as a whole and (if applicable) per unit of milk produced.

Area of concern *Indicator*	**Dairy Sector**	**Per unit Milk**
Supporting ecosystems	**(-)**	**(-)**
Semi-natural grasslands	(-)	(-)
Ley area	(-)	(-)
Mean field size	(-)	*n/a*
Climate change	**(+)**	**(+)**
Enteric methane emissions	(+)	(+)
Animal welfare	**(+)**	***n/a***
Cows culled due to disease	(+)	*n/a*
Disease prevalence	(+)	*n/a*
Farm viability	**(+/-)**	***n/a***
Potential to pay competitive wages	(+)	*n/a*
Farmer age	(-)	*n/a*

increasingly grazed by livestock in the expanded suckler cow herd. In conclusion, a large share of the observed net climate benefits, and ecosystem drawbacks, of dairy intensification may be cancelled out by spillover effects into the beef sector.

Despite national and international targets for reversing biodiversity decline, the situation is not improving in Sweden's agricultural landscapes. Examples of policy measures suggested to stop the negative development are investment support to cattle farms with pasture-based production, higher area environmental subsides for maintaining semi-natural grasslands and economic support for grassland restauration (Swedish Board of Agriculture, 2019). The on-going loss of biodiversity has become an urgent sustainability challenge, and the dairy sector's negative trend for supporting ecosystems observed in this study should urge industry and policymakers in developing policy and support for a dairy sector supportive of agro-ecosystem diversity.

The redistribution of the Swedish cattle population to more dedicated beef herds may also have had animal welfare implications. When asked about welfare risks associated with different production systems, animal welfare experts consistently rate the risks to be higher for animals from dairy herds than for animals from dedicated beef herds (Mandel et al., 2022), which could imply an improvement in overall animal welfare from the observed restructuring of Swedish cattle herds. Similarly, Hultgren et al. (2022) found a positive association between compliance with animal welfare legislation on Swedish cattle farms and support payments for environmental values in semi-natural grasslands, which today are more common on beef farms.

Organic milk showed strong growth over the study period and currently around 20% of Swedish dairy cows are kept on organic dairy farms, which are among the largest and most technically equipped farms in Sweden and not particularly different from conventional farms in terms of yield or efficiency (Växa Sverige, 2020). Compared with conventional dairy farms, Swedish organic farms have been shown to have lower nitrogen surplus per hectare and lower nitrogen footprint per kg milk produced (Einarsson et al., 2018). At EU level, farms under organic production use less resources, emit considerably fewer eco-toxic chemicals and have a smaller negative impact on biodiversity than their conventional counterparts (Trydeman Knudsen et al., 2019). The organic standards also stipulate increased time for grazing, which is claimed to benefit cattle welfare (e.g. Arnott et al., 2017), although the evidence base has been deemed too thin to make conclusive statements (Harvey et al., 2022). In a Swedish context, no differences have been found in health or welfare between organic and conventional dairy herds (Fall et al., 2008; 2009). Nonetheless, the increased prevalence of organic farming has likely improved environmental outcomes of Swedish dairy farming through minimised use of agro-chemicals and lower nitrogen surpluses.

We were not able to devise an indicator on nutrient management due to lack of retrospective data representative of the entire Swedish dairy sector. A recent analysis, however found a 5% reduction in nitrogen surplus per hectare on dairy farms participating in an advisory scheme on nutrient management between 2001 and 2016 (Greppa Näringen, 2022). As the number farms participating in this advisory scheme and performing consecutive nutrient budgets increases over time, we see a potential in developing appropriate sector-level indicators for tracking plant nutrient management in the future based on this data.

Identifying indicators related to social sustainability that met our criterion of data availability was challenging. However, there is a strong link between economic viability and social sustainability, e.g. a survey of Swedish livestock farmers revealed that their social situation and self-reported life satisfaction were strongly related to their financial situation, but also to factors such as having a standard of living comparable to others, not experiencing too much stress, having a meaningful work life and decent working hours, and having a desirable family situation (Röös et al., 2019). Our economic viability indicator thus covered some areas of social sustainability, but other relevant aspects such as inequitable power relations among value-chain actors (Hebinck et al., 2021) and the need for a strong social fabric were not adequately covered in this assessment. As around 90% of farmers closed down their milk production enterprise between 1990 and 2020, dairy farmers have become rare, with no or few neighbouring colleagues. This has affected life on the dairy farm and in the local society, which deviates strongly from social and economic conditions in rural Sweden in the mid-20th century when small-scale dairy farms were present almost everywhere (Martiin, 2017). While the larger scale and doubling of average farm income have only slightly improved farm economic viability, they have made it possible to employ some staff, i.e. workmates, which was rare on medium-sized dairy farms in 1990. Dairy farmers have therefore increasingly become business leaders, with far-reaching responsibilities for all aspects related to the dairy farm (Martiin, n.d). The fact that Swedish dairy production now relies on very few farmers also poses questions about the resilience of the sector and local societies, especially considering the apparent difficulty with generational shifts as indicated by the increasing age of dairy farmers. If a large dairy farm of today gets into financial or personal difficulties, this may have more far-reaching consequences for production, employees, local societies and landscapes than it might have had 30 years ago. Furthermore, the large scale of operations, high land prices and investments and advanced machinery require potential new farmers to possess a wide skillset (including in personnel and business management) and to have access to substantial capital, which can make farm sale or generational shifts even more challenging than when the units were smaller (Hajdu et al., 2020; Martiin, n.d)Hajdu et al., 2020.

6. Conclusions

This paper provides a complex picture of how sustainability in the Swedish dairy sector has developed during the past 30 years and identifies some key areas of concern for the sector. First, today's more specialised dairy sector with high-yielding cows has lowered its greenhouse gas emissions intensity but is contributing less to supporting ecosystems and domestic meat production, with unclear net effects since dedicated suckler cow and beef farms have taken over some of these services and emissions. Second, disease prevalence in dairy cows has decreased, possibly owing to the larger scale of operations enabling investment in e.g. technology for early detection of disease and improvements in fertility. An increasing proportion of dairy cows can also behave in a more natural way in loose-housing systems, which have increasingly replaced tie-stall systems. Finally, strong industry consolidation has pushed many farmers out of business, while leaving the remaining dairy farmers with only marginally improved economic viability and challenges with demographic viability, but also increased capacity to employ staff, potentially improving work-life balance. Economic and social sustainability are evidently closely related, but the overall socio-economic effects of developments within Swedish dairy farming in the past 30 years remains elusive. Increased knowledge transfer and access to adequate education and capital can be ways to improve demographic viability and profitability in the sector, while economic support for smaller-scale pasture-based dairy production may be a way to increase the sector's contribution to supporting ecosystems. Although it is crucial to safeguard improvements made in greenhouse gas emissions intensity and animal welfare, it is as important to recognize that a sustainable development of the dairy sector cannot be achieved without fulfilling all dimensions of sustainability. The current trend indicates an emission reduction achieved at the cost of ecosystem support and diversity within the sector. Future policies targeting the dairy sector need to address this issue by e.g. incentivising use and restoration of semi-natural grasslands while considering its close connection to the beef sector and potential spillover effects.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103779.

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