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# Environmental impact and economic performance of Norwegian dairy farms

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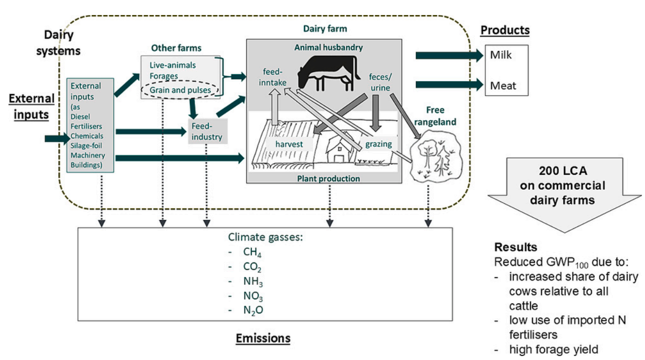
## HIGHLIGHTS

- LCA on dairy farms highlights factors affecting environmental impact and profits.
- Increasing share of dairy cows reduced GHG, N and E intensities, and land use.
- Increasing N fertiliser per ha increased GHG, N and E intensities.

## GRAPHICAL ABSTRACT

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## ABSTRACT

*Context:* Dairy farming contributes approximately 2.5 % of annual global anthropogenic greenhouse gas (GHG) emissions, necessitating effective mitigation strategies. Two approaches are often discussed: low-intensity, low-cost production with minimal reliance on purchased inputs; and high-intensity production with higher-yielding cows to reduce land use and reduce methane emissions per unit of milk.
*Objective:* The objective was to identify management factors and farm characteristics that explain variations in GHG emissions, environmental, and economic performance. Indicators included were GHG emissions, land use occupation, energy intensity, nitrogen intensity, and gross margin.
*Methods:* Life Cycle Assessment (LCA) was used to calculate the environmental impacts for 200 commercial dairy farms in Central Norway based on farm activities, purchased inputs, machinery, and buildings from 2014 to 2016. A multiple regression analysis with backward elimination was conducted to highlight important variables for environmental impact and economic outcome.
*Results and conclusions:* A higher share of dairy cows was found to be the most important factor in reducing GHG emissions, energy and nitrogen intensity, and land use but also to decrease gross margin. Additional key factors

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for reducing environmental impact included less purchased nitrogen fertiliser, and higher forage yield. There were no statistical correlations between GHG emissions and gross margin per MJ of human-edible energy delivered.

*Significance:* Conducting LCA for many dairy farms allows to highlight important factors influencing environmental impact and economic outcome. Using the delivery of human-edible energy from milk and meat as a functional unit allows for a combined evaluation of milk and meat production on a farm.

## 1. Introduction

Dairy farming contributes approximately 2.5 % of the annual global anthropogenic greenhouse gas (GHG) emissions (IPCC, 2021). Demographic, socio-economic and political factors influence farmers' adaptability to climate change (Dang et al., 2019), which impacts their long-term economic performance and livelihoods.

The discourse on GHG mitigation on dairy farms mainly presents two approaches, often framed as the "land share" vs. "land spare" debate. The land share approach proposes low-intensive and low-cost methods like pasture-based systems with minimal reliance on purchased inputs (Basset-Mens et al., 2009; Casey and Holden, 2005). This approach potentially reduces the competition between ruminant feed and human food production, particularly when feed is produced in areas unsuitable for direct food production (Rouillé et al., 2023). However, these systems may increase enteric methane emissions per cow and the demand of agricultural area due to lower milk yields (Beauchemin et al., 2009). Conversely, the land spare approach favours high-intensity production with higher-yielding cows, which reduces methane emissions per unit of milk (Capper et al., 2009) and subsequently lowers land use. Using more concentrates in the feed ration also alters enteric fermentation, leading to lower methane emissions per unit of energy fed, although it increases emissions from manure storage (Crosson et al., 2011; Kristensen et al., 2011).

Life Cycle Assessment (LCA) has been utilized widely to evaluate dairy farm production (e.g. Cederberg and Mattsson, 2000; Haas et al., 2001). The method accounts for environmental and climatic implications across the product life cycle. GHG emissions are estimated for a 100-year Horizon using the metric for Global Warming Potential ($GWP_{100}$) with factors for $CO_2$-equivalents from the fourth ($AR_4$) and sixth assessment report ($AR_6$) from IPCC (2007, 2021), and one for Global Temperature Change Potential ($GTP_{100}$), described by IPCC (2021). $GWP_{100}$ expresses the energy from solar radiation the different gasses trap in the atmosphere over a century relative to 1 kg $CO_2$ as kg $CO_2$-equivalent. In the sixth IPCC report, the $CO_2$-equivalent for non fossil methane were raised from 25 in the fourth report to 27.2 $CO_2$-equivalents, while for nitrous oxide it was lowered from 298 to 273 $CO_2$-equivalents. $GTP_{100}$ was introduced as a metric in the sixth assessment report (IPCC, 2021), describing the impact of climate gases over a century on measured global temperature change caused by different climate gases. The $CO_2$-equivalents for $GTP_{100}$ are for non fossil methane 4.7 and for nitrous oxide 223 (see Table 2).

Indicators for GHG emissions, energy (E) intensity, nitrogen (N) intensity, and land use occupation are highly relevant for todays' climatic and environmental threats (Richardson et al., 2023) and can be calculated from dairy farm accounts and herd records. The impact of energy use is indirect and stems from the environmental burdens from the use of fossil fuels or renewable energy. It is not possible to quantify the total impact of energy intensity exactly with the present data. Gross margin has been chosen as a proxy for economic sustainability of the farm production. These factors are influenced by various management factors (Asgedom and Kebreab, 2011; Jayasundara et al., 2019; Kiefer et al., 2014; O'Brien et al., 2015; Flaten et al., 2019). The management factors encompass purchased inputs, farm characteristics, soil and climatic conditions, and farming systems such as organic or conventional management. In this study we used the term management factors and farm characteristics to denote all these factors. Previous environmental and economic assessments of dairy farms often involve small samples sizes which differ in their economic considerations or apply few environmental impact categories. Such broad investigations as the present one have only to a limited degree been carried out at Norwegian farms. These limitations are likely due to the challenges associated with collecting and analyzing data from the large number of farms required to conduct comprehensive LCAs and economic assessments. Most Norwegian dairy farms are dual purpose, focusing on both dairy and beef production using the Norwegian Red cattle breed, though the emphasis on beef production varies (Norwegian Dairy Herd Recording System, TINE, 2024).

Analyzing a larger number of farms can provide valuable insights into cost-effective strategies for reducing environmental and climatic impacts. To mitigate the influence of conditions from a single year of production, three years of data from 200 commercial Norwegian dairy farms were utilized. The objective was to identify management factors and farm characteristics that explain variations in GHG emissions, environmental and economic performance. The indicators included GHG emissions ($GWP_{100\text{-}AR4}$, $GWP_{100\text{-}AR6}$, and $GTP_{100\text{-}AR6}$), land use occupation, energy intensity, N intensity, and gross margin. Additionally, we aimed to identify the level of impact, synergies and trade-offs between farm management practices and environmental and economic performance.

## 2. Materials and methods

### 2.1. Farm data

Production data from farms in central Norway were obtained from the Norwegian Dairy Herd Recording System collected by the dairy cooperative's (TINE) Advisory Service (TAS) for the calendar years 2014 to 2016. The studied farms are in the counties of *Møre og Romsdal* and *Trøndelag* between 62° and 64°N. In this region, the average temperature in January is −2 °C near the coast and −10 °C in inland areas and in July 14 °C near the coast and 10–15 °C in inland areas, respectively. The mean annual precipitation ranges from 1000 mm to 2000 mm near the coast and 800 mm to 1000 mm in inland areas, mainly evenly distributed through the year (Dannevig, 2020, 2019).

In central Norway, 200 of the 345 farms participating in TAS's program to monitor farm economic performance were selected based on consistency of data across three years. The criteria included the invariability of farm area, herd size, milk quota, milking system, and housing system. The farms are located in four different regional deficiency payment zones, depending on differences in altitude, local climate, and soil conditions, potentially impacting yield levels.

#### 2.1.1. Farm area

Dairy farm agricultural area (DF) includes arable land and permanent pasture. Free rangeland in mountain or forest areas, used solely for grazing, can contribute to the feed supply but is not included in the agricultural land calculated in this study because the free rangeland area, grazed by the animals, is hard to define and there are large variations in feed availability. While free rangeland was not included as farm area, feed intake from these areas was estimated based on feed demand, allowing to calculate climate gas emissions from digestion and excretion of faeces and urine.

Off-farm area refers to agricultural land on other farms used to

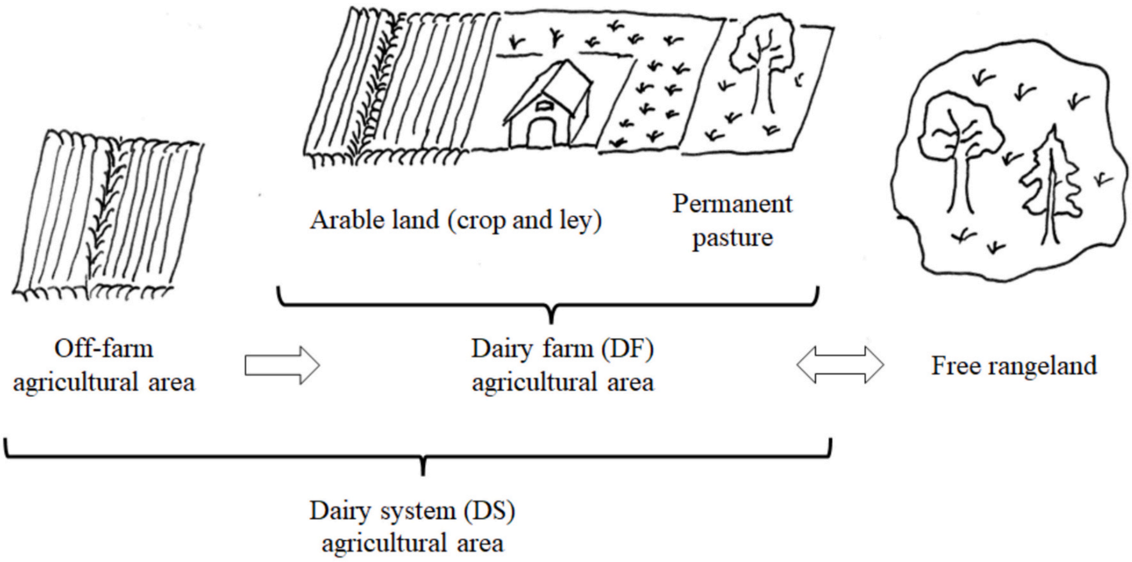


**Fig. 1.** The different areas of the dairy farm and dairy system.

produce forage or ingredients for concentrates or to raise cattle imported by the dairy farm. The dairy system agricultural area (DS) includes the off-farm area. In this research, land use occupation for the dairy system includes the off-farm and dairy farm areas.

In the region covered by this study, dairy cows typically graze for a maximum of three months, while heifers graze for up to four months annually. Otherwise, the animals stay inside the barn due to the climate conditions at the farm, where they are mostly fed silage and purchased concentrates. During late autumn, early spring, and winter months, plant production is limited or not possible at the investigated farms. On the farm's arable land, grass and grass-clover leys are cultivated. Occasionally, cereals are used as a cover crop when establishing new leys and harvested as whole crop silage. As a cover crop grain is used to suppress weed growth. In such cases, grain is harvested at the early heading stage as a whole crop and ensiled. Depending on the individual structure of each dairy farm, animals are fed forages on arable land, such as preserved forage from temporary grasslands and whole crops, preserved forage from permanent grasslands, and grazed forage from temporary and permanent grasslands as well from rangelands (Fig. 1). When housed indoors, the livestock are primarily fed farm-produced silages and purchased concentrates.

#### 2.1.2. Production data

There were large variations among the selected farms, in terms of, e.g., numbers of dairy cows, milk yield per cow, farm area per cow, and purchased inputs such as N fertiliser and concentrates (Table 1). Of the 200 farms, 185 were managed conventionally and 15 were managed organically. Seventy-eight farms had automatic milking systems (milking robots), while 122 had conventional milking systems (parlour or pipeline). Eighty-four farms had tie-stall barns and 116 had free-stall housing. Most farms, 160 of 200, were single-farm enterprises, while 40 were joint venture farming operations. Delivered meat included both sold live animals and animals sent for slaughter.

#### 2.1.3. Purchased inputs

The farm account data collected by TAS were used alongside annual product prices for Norwegian farmers (Hjukse, 2017) to calculate the physical amount of purchased inputs. The data on concentrate types used at regional level and their composition as well as the origin of the different ingredients were obtained from the Norwegian Agricultural Purchasing and Marketing Co-operation (Felleskjøpet), both for conventional and organic concentrate-types. Basic data and methodology for calculation of the environmental impact during production of purchased forage, livestock, machinery and buildings were based on data from a previous project in the region (Koesling et al., 2017b, 2015). The estimated impact per unit of purchase were multiplied with relevant units like kg fodder, number of animals, amount of machinery etc. for each purchase. Burdens from all raw materials and production of the purchase were included. To include the environmental impact of raw materials and producing the different ingredients of the purchased fertilisers, data from the Norwegian Agricultural Purchasing and Marketing Co-operation for the different types of fertilisers sold during the study period in the two counties were used.

### 2.2. Functional unit

The first functional unit (FU) was defined as 2.78 MJ of edible energy from milk and meat, delivered at the farm gate (2.78 $MJ_{MM}$). This value represents the edible energy content of 1.0 kg of Energy Corrected Milk (ECM) (Norwegian Food Safety Authority, 2015) and is equivalent to 0.42 kg of meat (Heseker, 2013). The FU can be used for any combination of milk and meat delivered at the farm gate (Koesling et al., 2017b) without needing allocation between them. Sold life animals were converted to carcass weight and then to edible energy for inclusion in the FU.

The FU reflects the dual-purpose Norwegian Red breed, bred for both milk and meat production. It acknowledges that farmers prioritize milk or meat based on specific farm factors such as yield, prices of milk and

**Table 1**
Key characteristics of the 200 commercial dairy farms (DF) in the study, average across the years 2014–2016.

| Variable | Unit | Mean | SD[a] | CV[a] | Min | Max |
|---|---|---|---|---|---|---|
| Animal herd | | | | | | |
| Milking Cow unit[b] | $MCU_{dairy}$/farm | 36.5 | 18.7 | 0.51 | 9.15 | 96.5 |
| All cattle[c] | $MCU_{all}$/farm | 56.8 | 32.8 | 0.58 | 13.1 | 173 |
| Non-dairy cattle[d] | $MCU_{cattle}$/farm | 20.4 | 16.0 | 0.79 | 0.30 | 99.8 |
| Dairy cow share | $MCU_{dairy}$/$MCU_{all}$ | 0.67 | 0.09 | 0.14 | 0.33 | 0.98 |
| Heifers | Number | 39.9 | 23.4 | 0.59 | 0.95 | 124 |
| Bulls | Number | 21.2 | 24.8 | 1.17 | 0.56 | 154 |
| Stocking density, cows | $MCU_{dairy}$/$ha_{DF}$ | 1.26 | 0.34 | 0.27 | 0.55 | 2.56 |
| Animal health | | | | | | |
| Age cows | Months | 46.5 | 3.60 | 0.08 | 37.5 | 57.6 |
| Age at first calving | Months | 25.6 | 1.29 | 0.05 | 22.7 | 31.6 |
| Calving interval | Months | 12.3 | 0.70 | 0.05 | 11 | 15.4 |
| Replacement rate | Share | 0.45 | 0.10 | 0.22 | 0.25 | 0.75 |
| Milk somatic cell count | 1000/l | 127 | 27.47 | 0.22 | 43.0 | 194 |
| Days from parturition to last insemination | Days | 99.6 | 17.4 | 0.17 | 55.2 | 214 |
| Feeding | | | | | | |
| Concentrate use, dairy cows[e,f] | $MJ_{NEL}$/$MCU_{dairy}$ | 18,900 | 2900 | 0.15 | 8600 | 24,600 |
| Concentrate use, all cattle | $MJ_{NEL}$/$MCU_{all}$ | 16,100 | 2300 | 0.14 | 7600 | 20,700 |
| Forage share in diet, cows | $MJ_{forage}$/$MJ_{dairy}$ | 0.56 | 0.06 | 0.10 | 0.44 | 0.80 |
| Pasture share in diet, all cattle | $MJ_{pasture}$/$MJ_{all}$ | 0.17 | 0.08 | 0.49 | 0.00 | 0.39 |
| Pasture share in diet, cows | $MJ_{pasture}$/$MJ_{dairy}$ | 0.08 | 0.06 | 0.72 | 0.00 | 0.25 |
| Concentrate use | $MJ_{concentrates}$/kg ECM | 233 | 28.2 | 0.12 | 123 | 292 |
| Farm and feed production | | | | | | |
| Diesel usage | litre/$ha_{DF}$ | 133 | 53.4 | 0.40 | 6.07 | 325 |
| Electricity per ECM | kWh/kg ECM | 0.25 | 0.09 | 0.36 | 0.03 | 0.68 |
| Farm agricultural area | ha | 46.2 | 26.6 | 0.58 | 12.00 | 185 |
| Share of arable land | $ha_{arable}$/$ha_{DF}$ | 0.89 | 0.12 | 0.13 | 0.36 | 1.00 |
| Off-farm area[g] | ha | 40.6 | 26.7 | 0.66 | 7.68 | 157 |
| Fertiliser import, nitrogen | kg N/$ha_{DF}$ | 117 | 49 | 0.42 | 0.00 | 271 |
| Forage yield | MJ/$ha_{DF}$ | 34,100 | 7900 | 0.23 | 13,600 | 55,800 |
| Baling by contractor | bales/$ha_{DF}$ | 6.96 | 8.15 | 1.17 | 0.00 | 34.5 |
| Production and economy | | | | | | |
| Milk yield produced | kg ECM/$MCU_{dairy}$ | 8360 | 846 | 0.10 | 5330 | 10,400 |
| Milk quota | 1000 l/farm | 280,000 | 153,000 | 0.55 | 72,000 | 781,000 |
| Milk delivered | kg/farm | 274,000 | 153,000 | 0.56 | 73,000 | 756,000 |
| Milk, delivered of total quota | Share | 0.93 | 0.04 | 0.04 | 0.80 | 1.06 |
| Milk price | NOK/l | 5.32 | 0.22 | 0.04 | 47.54 | 62.28 |
| Regional deficiency payment milk | NOK/kg ECM | 0.31 | 0.13 | 0.42 | 0.07 | 0.62 |
| Meat delivered | kg/$MCU_{all}$ | 137 | 58.1 | 0.42 | 50.9 | 388 |
| Meat price | NOK/kg | 47.75 | 3.87 | 0.08 | 47.54 | 62.28 |
| Regional deficiency payment meat | NOK/kg meat | 4.42 | 1.65 | 0.37 | 0.00 | 7.39 |

[a] SD: Standard Deviation and CV: Coefficient Variation.
[b] Milking Cow Unit (MCU) is standardised to an annual NEL (net energy lactation) requirement of 42,000 MJ. For example, this is the energy requirement of a 640 kg cow, including foetal growth and the annual production of 7000 kg milk (Benoit and Veysset, 2021).
[c] The whole herd on each farm is expressed as MCU equivalent.
[d] Non milking cattle in herd expressed as MCU.
[e] NEL is Net Energy Lactation in MJ.
[f] Total concentrate use in relation to dairy cows and all cattle.
[g] Off-farm area refers to agricultural land on other farms used to produce forage or ingredients for concentrates or to raise cattle imported by the dairy farm (Hjukse, 2017, 2016).

meat, land availability, and barn space. A fixed allocation factor as proposed as one solution by the International Dairy Federation (2010) would not reflect these differences. The choice of allocation method between milk and meat affects the reported emission levels for milk (Kristensen et al., 2011).

The entire number (n) of FUs produced on each farm was calculated as shown in Eq. (1).

$$FU\ (n) = \frac{\left(\text{ECM (kg delivered)} \times 2.78\left(\frac{\text{MJ}}{\text{kg}}\right)\right) + \left(\text{carcass (kg delivered)} \times 6.47\left(\frac{\text{MJ}}{\text{kg}}\right)\right)}{2.78\ (\text{MJ})} \quad (1)$$

By dividing the sum of climate gases, energy input, N input, or land use occupation - including the values for purchased inputs and gross margin - by the number of functional units produced on a farm, the value per functional unit is obtained (see Table 3).

Additionally, a second and more commonly used FU was used: 1 kg ECM delivered at the farm gate, where only the environmental impact allocated to milk was included. This biophysical allocation approach allows easier comparison with other studies. The allocation between milk and meat was specific for each farm, based on the energy requirements for producing milk and meat. Calculations used average net energy requirements per animal grouped as calves, heifers, dairy cows, suckling cows and bulls, utilizing Norwegian feed requirement data

**Table 2**
Emission metrics relative to $CO_2$ as suggested by the IPCC.

| Common name | Formula | Global warming potential for a 100-year time horizon $GWP_{100\text{-}AR4}$ | Global warming potential for a 100-year time horizon $GWP_{100\text{-}AR6}$ | Global temperature change potential for a 100-year time horizon $GTP_{100\text{-}AR6}$ |
|---|---|---|---|---|
| | | IPCC (2007) | IPCC (2021) | IPCC (2021) |
| Carbon dioxide | $CO_2$ | 1.0 | 1.0 | 1.0 |
| Methane non fossil | $CH_4$ | 25[a] | 27.2 ± 11 | 4.7 ± 2.9 |
| Nitrous oxide | $N_2O$ | 298[a] | 273 ± 130 | 233 ± 110 |

[a] No uncertainty range given.

(Breines et al., 2002). Energy requirement for milk production and dairy cow maintenance was allocated to milk, while energy for fetal growth in cows and heifers during gestation, and for rearing calves and heifers needed for replacement, was also allocated to milk. Energy for calves and heifers not needed for replacement, as well as for bull-calves, bulls, and suckler cows, was allocated to meat.

### 2.3. Environmental impact

The LCA was conducted using the FARMnor model (Flow Analysis and Resource Management for Norway), which was developed to calculate the environmental impact of milk and meat production at the farm gate based on the Farm model (Schueler, 2019). The model, developed and run using the LCA software Umberto (ifu Hamburg, 2017), allows for an LCA from cradle to farm-gate, adhering to the standards ISO 14040 and ISO 14044 (ISO, 2006a, 2006b). The assessments included environmental impacts on each farm, from various farm activities, purchased inputs, machinery, and buildings, as well as emissions from grazing rangeland. Details on calculated emissions, emissions factors and equations used in the calculations are given in Supplementary Table A1.

#### 2.3.1. Greenhouse gas emissions

The Global Warming Potential (GWP) and the Global Temperature Change Potential (GTP) were calculated using metrics from the Fourth (IPCC, 2007) and Sixth Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC, 2021) for a one-hundred-year horizon (Table 2). To refer to the reports and the time-horizon, the results were denoted as $GWP_{100\text{-}AR4}$, $GWP_{100\text{-}AR6}$ and $GTP_{100\text{-}AR6}$.

For each farm, the environmental impact was calculated based on the amount of purchased inputs such as diesel, electricity, fertiliser, lime, silage foil, chemicals, machinery, buildings, and feed ingredients sourced from Norway or other countries. Data from the ecoinvent© life cycle inventory (LCI) database version 3.6 (Wernet et al., 2016) were used for these inputs. The environmental impact of domestically produced grain used as ingredients in concentrates was also included, based on results from (Korsaeth et al., 2012).

The forage intake for the different animal categories (calves, heifers, dairy cows, suckling cows and bulls) on each farm was estimated by TAS. It was calculated from the total net energy intake requirements for maintenance, growth and milk production of the different animal categories with subtraction of net energy intake from concentrates. The transport of purchased inputs from their origin to the farm was included in the LCA calculations. The amounts of the inputs were calculated on a three-year average using annual farm accounting data combined with Norwegian annual prices for farmers (Hjukse, 2017) to estimate the physical amount of purchased inputs.

In addition to the environmental impact from purchased inputs, on-farm emissions were calculated for each farm based on farm-specific data. The emission factors used are shown in Appendix Table A1. On-farm methane emissions were calculated using a Tier 2 approach with a fixed methane energy conversion factor. Results for Norwegian dairy cows (Storlien et al., 2014) were used to calculate the emissions based on dry matter intake. Enteric methane emissions for various animal groups, including dairy cows, suckling cows, calves, heifers, and bulls, were calculated based on the average feed demand for animals in each group, considering their weight, weight gain and milk yield under Norwegian conditions (Breines et al., 2002). From the entire feed demand, the amount of purchased concentrates and purchased forage was subtracted, and the resulting amount was used to estimate both grazed and harvested yields on the dairy farm. Expected dry matter losses from gross yield to intake by animals were included as 0.03 for concentrates and 0.15 for forage based on Steinshamn et al. (2004).

It was assumed that the soil carbon content was stable on the farms because the fields are semi- permanent or permanent grassland (Herron et al., 2019), where soil organic carbon decreases after ploughing for renewal and increases in years used as meadow. Results for Norway show that soil carbon is relatively stable in leys on mineral soils, independent of renewing interval (Rasse et al., 2019), while there can be large soil C losses from peat soil (Grønlund et al., 2008). Plant-available N was calculated based on purchased fertilisers, manure, atmospheric deposition, biological N fixation, and droppings (Koesling et al., 2017a). Farm-specific emissions from plant production, including fertilization, diesel combustion, and manure management, were calculated based on IPCC (2019) guidelines and ecoinvent© 3.6.

#### 2.3.2. Nitrogen intensity, energy intensity, and land use occupation

Nitrogen (N) intensity was calculated as the sum of N from purchased inputs, the N-surplus from the production of purchased feed and livestock, biological N-fixation, and atmospheric N-deposition, divided by the N in delivered milk and meat (kg N/kg N). Purchased inputs included concentrates, forage, fertiliser, imported manure, and purchased livestock. The N-surplus from off-farm production of forage and ingredients for concentrates, as well as for purchased livestock, were included as input in the calculations of N-intensity (Koesling et al., 2017a).

Energy (E) intensity was calculated as the total amount of direct and embodied energy, used to produce milk and meat, divided by the number of FUs delivered. Embodied energy is the energy which was necessary to produce machinery and infrastructure. Energy demand for transporting the ingredients was calculated using ecoinvent v3.6, considering the varying types of transportation and distances from the country of origin to the farmers' reseller in the region.

The land use occupation for the dairy system was calculated as the sum of off-farm area and on-farm farm agricultural area (see Fig. 1) divided by the number of FUs delivered. In addition, the land use occupation of DF and DS area per kilogram ECM was calculated ($m^2_{DF}$/kg ECM and $m^2_{DS}$/kg ECM).

### 2.4. Economic calculations

Farm accounting data provided by TAS from 2014 to 2016 were utilized to calculate the gross margin in Norwegian kroner (NOK). The average exchange rate was 8.7 NOK to 1.0 € for these years. The gross margin was derived from total revenues, including income from milk and meat and direct governmental payments. Variable production costs, such as concentrates, forage cultivation costs (mainly fertilisers, diesel, pesticides, and lime), and other variable production costs, were subtracted from the total revenue (Steinshamn et al., 2021b) to calculate the gross margin. The gross margin was expressed as NOK per number of 2.78 $MJ_{MM}$ delivered, and NOK per MCU.

### 2.5. Statistical analysis

To assess the influence of farm data uncertainty and the values applied in the model's formulas on various impact categories, we conducted both sensitivity and uncertainty analysis (Igos et al., 2019). These analyses can show possible limitations but also enhance the reliability of their findings from this study (Guo and Murphy, 2012). An overview of the sensitivity and uncertainty analysis and its results is provided in the appendix (Table A2 and Fig. A1).

A multiple regression analysis with backward elimination was conducted using the REG procedure of the statistical software SAS (SAS Institute, 2013). This analysis aimed to ascertain if a reduced set of independent variables could describe the environmental performance with sufficient accuracy (Pascual-González et al., 2015). Variables that remained in the model generated F statistics significant at a $P < 0.01$ cutoff. To address skewness in the distribution of the residuals of the linear model, GHG emissions, and energy intensity, where transformed using Box-Cox with $\lambda = -1$, while land use occupation had an optimum $\lambda = -0.25$. Gross margin and Nitrogen intensity were transformed using log10 transformation. To manage covariation, the Variable Inflation Factor (VIF) was assessed, and factors with a VIF higher than five were removed. The different variables were ranked based on Squared Partial Correlation Type II. The Squared Partial Correlation Type II measures the proportion of variance in the dependent variable that is uniquely explained by each specific independent variable, after accounting for the effects of all other independent variables.

Principal component analysis (PCA) was conducted to examine the relationships between the environmental and economic impact categories - including GHG emissions, N intensity, E intensity, agricultural land use occupation, and gross margin - and the farm characteristic variables identified in the multiple regression. The analysis utilized PROC PRINCOM and PRINQUAL in SAS. Biplots were created including all variables from the PCA with PC1 and PC2 values serving as the x- and y-axis, respectively.

## 3. Results

### 3.1. Greenhouse gas emissions, gross margin, energy intensity, nitrogen intensity, and land use occupation

The average greenhouse gas (GHG) emission of farms, calculated as $GWP_{100\text{-}AR4}$, was 1.4 kg $CO_2$-eq/2.78 $MJ_{MM}$ (Table 3). The average estimate was higher for $GWP_{100\text{-}AR6}$, at 1.52 kg $CO_2$-eq/2.78 $MJ_{MM}$. The $GTP_{100\text{-}AR6}$ result were lower (0.83 kg $CO_2$-eq/2.78 $MJ_{MM}$) than the estimates based for GWP. This difference was due to lower values for $CO_2$ equivalents of non-fossil methane and nitrous oxide (Table 2). The gross margin on the farms averaged 5.87 NOK/2.78 $MJ_{MM}$, while the average gross margin per dairy cow was 30,427 NOK. The average N intensity for the farms was 6.77 kg N/kg N. The energy intensity was, on average, 6.33 MJ/2.78 $MJ_{MM}$, and the land use occupation was, on average, 2.97 $m^2_{DS}$/2.78 $MJ_{MM}$ delivered. When related to kg ECM delivered, the average land use occupation was 1.58 $m^2_{DF}$/kg ECM and 2.87 $m^2_{DS}$/kg ECM.

When emissions from the production and transportation of purchased products and on-farm activities were allocated between milk and meat, the emissions calculated as $GWP_{100\text{-}AR4}$ were, on average, 1.07 kg $CO_2$-eq/kg ECM (Table 4). The lower estimated GHG emissions allocated to solely milk can be explained by higher energy demand and thus higher GHG emissions from producing edible energy in meat compared to milk.

A principal component analysis was performed to examine the relationship between environmental indicators and the key variables, and a biplot created (Fig. 2 shows a reduced number of variables, Fig. A9 shows all variables). Component 1 represents the primary direction along which the samples show the largest variation (23.4 %), while Component 2 represents the second most significant direction (17.7 %). Organic farms were clustered together, almost separate from conventional farms, and were characterized by lower N intensity (NI) and energy intensity (EI), as well as lower GHG emissions compared to conventional farms. GHG emissions, estimated using different IPCC metrics (only $GWP_{100\text{-}AR6}$ included in Fig. 2), were positively associated with both energy and N intensity (the vectors point in the same direction and have similar lengths). Land use occupation (LO) and gross margin (GM) were strongly associated but had week correlations with GHG metrics and N intensity. The biplot revealed that GHG and N intensity were negatively associated with a high proportion of dairy cows in the herd, and they had low association with livestock density, concentrate use, and milk yield per cow. Organic production was also associated with a high share of dairy cows and negatively associated with N fertilization, GHG emissions estimated after the different IPCC metrics ($GWP_{100\text{-}AR4}$, $GWP_{100\text{-}AR6}$, $GTP_{100\text{-}AR6}$) were strongly and positively correlated with both energy and N intensity. Land use occupation correlated positively with gross margin. However, gross margin was not correlated with the different GHG metrics.

GHG emissions estimated after the different IPCC metrics ($GWP_{100\text{-}AR4}$, $GWP_{100\text{-}AR6}$, $GTP_{100\text{-}AR6}$) were strongly and positively correlated with both energy and N intensity. Land use occupation correlated positively with gross margin. However, gross margin was not correlated with the different GHG metrics.

The GHG emissions, N intensity, and E intensity were higher at the conventional farms than at the organic managed ones. However, the organic managed farms had a higher land use occupation and gross margin than the conventional managed farms (Table 5).

**Table 3**
Results for the different environmental impact categories GHG emissions, N intensity, E intensity, agricultural land use occupation, and gross margin.

| Variable | Unit | Mean | Median | CV[a] | Min | Max |
|---|---|---|---|---|---|---|
| $GWP_{100\text{-}AR4}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | 1.40 | 1.36 | 0.21 | 0.66 | 2.98 |
| $GWP_{100\text{-}AR6}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | 1.52 | 1.48 | 0.20 | 0.76 | 3.22 |
| $GTP_{100\text{-}AR6}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | 0.83 | 0.80 | 0.24 | 0.34 | 1.83 |
| Gross margin | NOK/2.78 $MJ_{MM}$ | 5.87 | 5.76 | 0.15 | 4.05 | 8.88 |
| Gross margin | NOK/MCU[b] | 30,427 | 30,258 | 0.13 | 20,409 | 43,609 |
| Energy intensity | MJ/2.78 $MJ_{MM}$ | 6.33 | 6.12 | 0.23 | 3.35 | 13.03 |
| Nitrogen intensity | kg $N_{DS}$/kg $N_{MM}$ | 6.77 | 6.58 | 0.20 | 3.30 | 12.18 |
| Land use occupation | $m^2_{DS}$/2.78 $MJ_{MM}$ | 2.97 | 2.83 | 0.21 | 1.78 | 6.15 |
| Land use occupation | $m^2_{DS}$/kg ECM | 2.87 | 2.71 | 0.24 | 1.69 | 7.22 |
| Land use occupation | $m^2_{DF}$/kg ECM | 1.58 | 1.47 | 0.34 | 0.64 | 3.53 |

[a] CV: Coefficient Variation.
[b] Milking Cow Unit (MCU) is standardised to an annual NEL feed requirement of 42,000 MJ.

### 3.2. Management factors and farm characteristics affecting environmental impact and gross margin

The most significant influence on the gross margin and all environmental indicators, excluding N intensity, was the *dairy cow share* of the total cattle herd (Table 6 and Figs. A2 to A8). An increase in the *dairy cow share* was found to reduce GHG emissions but also to decrease the *gross margin* per 2.78 $MJ_{MM}$. For N intensity, *dairy cow share* had a lower contribution compared to *purchased nitrogen fertiliser*. Increased use of *purchased nitrogen fertiliser* resulted in higher N intensity and was the second most important variable for $GWP_{100\text{-}AR4}$, $GWP_{100\text{-}AR\ 6}$, and $GTP_{100\text{-}AR6}$ associated with increased GHG emissions per 2.78 $MJ_{MM}$. For E intensity, the positive correlation with *purchased nitrogen fertiliser*

**Table 4**
GHG emissions from purchased products and on-farm activities allocated to milk-production per kg ECM and from milk and meat production per 2.78 $MJ_{MM}$, delivered at farm gate.

| | GHG emissions allocated to the production of 1 kg ECM delivered at farm gate | | | | GHG emissions to produce 2.78 MJ of edible energy from milk and meat, delivered at farm gate | | | | Ratio[b] |
|---|---|---|---|---|---|---|---|---|---|
| | unit for $GWP_{100\text{-}AR4}$ | Mean | CV[a] | Median | Unit for $GWP_{100\text{-}AR4}$ | Mean | CV[a] | Median | |
| Emissions from purchased products | | | | | | | | | |
| Purchased silage | kg $CO_2$-eq/kg ECM | 0.01 | 1.09 | 0.01 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.02 | 1.06 | 0.01 | 1.27 |
| Concentrates | kg $CO_2$-eq/kg ECM | 0.16 | 0.22 | 0.16 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.21 | 0.24 | 0.21 | 1.30 |
| Other inputs | kg $CO_2$-eq/kg ECM | 0.15 | 0.43 | 0.14 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.20 | 0.44 | 0.19 | 1.32 |
| Infrastructure | kg $CO_2$-eq/kg ECM | 0.07 | 0.31 | 0.07 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.10 | 0.28 | 0.09 | 1.35 |
| Sum purchased products | kg CO2-eq/kg ECM | 0.39 | 0.23 | 0.39 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.52 | 0.25 | 0.50 | 1.32 |
| Emissions from on-farm activities | | | | | | | | | |
| Plant production | kg $CO_2$-eq/kg ECM | 0.22 | 0.31 | 0.22 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.28 | 0.32 | 0.27 | 1.28 |
| Manure storage | kg $CO_2$-eq/kg ECM | 0.04 | 0.59 | 0.04 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.05 | 0.59 | 0.06 | 1.28 |
| Animals grazing | kg $CO_2$-eq/kg ECM | 0.03 | 1.10 | 0.02 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.04 | 0.69 | 0.04 | 1.80 |
| Animals in barn | kg $CO_2$-eq/kg ECM | 0.40 | 0.12 | 0.40 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.50 | 0.16 | 0.49 | 1.25 |
| Sum on-farm emissions | kg CO2-eq/kg ECM | 0.68 | 0.15 | 0.68 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 0.87 | 0.17 | 0.85 | 1.28 |
| Total emissions | kg $CO_2$-eq/kg ECM | 1.07 | 0.16 | 1.07 | kg $CO_2$-eq/2.78 $MJ_{MM}$ | 1.40 | 0.19 | 1.36 | 1.29 |

[a] CV: Coefficient of variation.
[b] Ratio of mean GHG emission as kg $CO_2$-eq/2.78 $MJ_{MM}$ to kg $CO_2$-eq/kg ECM.

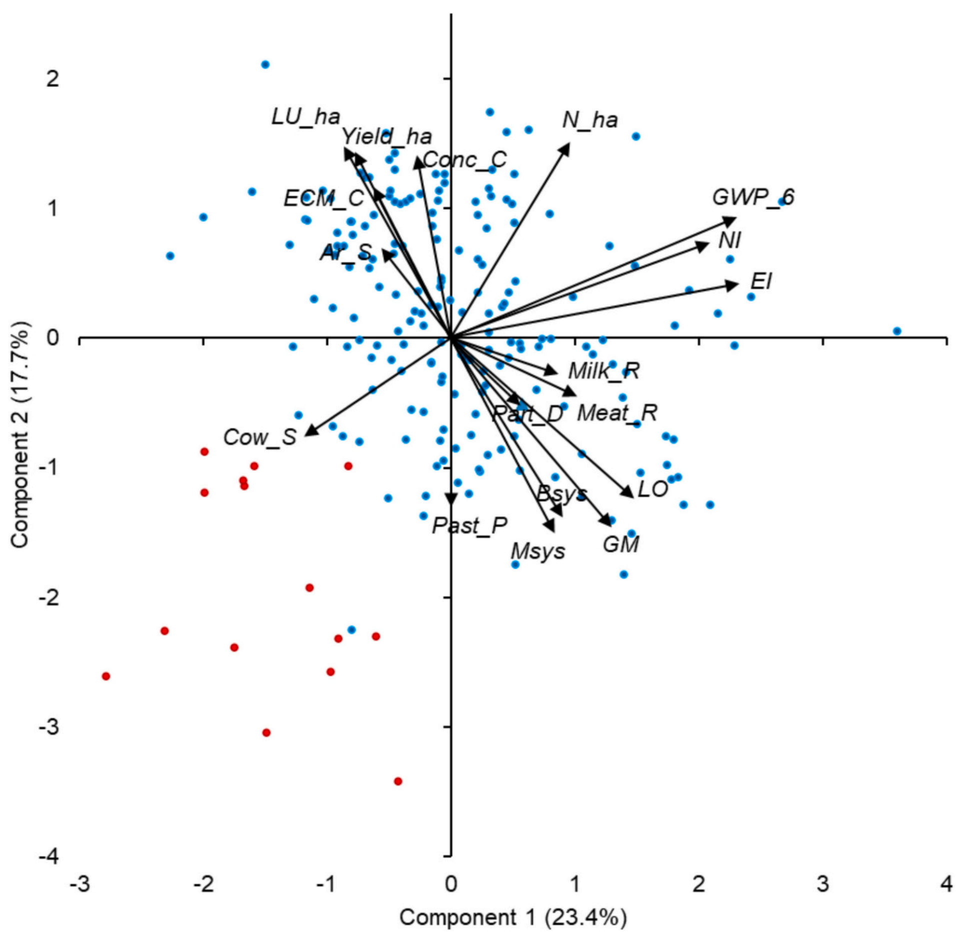


**Fig. 2.** Biplot from principal component analysis (PCA) showing the relationship between GWP_6 = Box-cox transformed $GWP_{100\text{-}AR6}$ ($CO_2$-eq/2.78 $MJ_{MM}$), EI = Box-cox transformed Energy intensity (MJ/2.78 $MJ_{MM}$), NI = Log10 transformed nitrogen intensity (MJ/2.78 $MJ_{MM}$), LO = Land use occupation ($m^2$/2.78 $MJ_{MM}$), GM = Log10 transformed gross margin (NOK/2.78 $MJ_{MM}$), Bsys = Barn system (0 = Loose housing, 1 = Tie stall), Msys = Milking system (0 = Automated milking systems, 1 = Parlour or pipeline), Cow_F = Milking Cow Unit ($MCU_{dairy}$/farm), LU_ha = Stocking density, cattle ($MCU_{cattle}/ha_{DF}$), Cow_S = Dairy cow share ($MCU_{dairy}/MCU_{all}$), ECM_C = Milk yield produced (kg ECM/$MCU_{dairy}$), Part_D = Days from parturition to last insemination, Conc_C = Concentrate use, dairy cows (MJ NEL/$MCU_{dairy}$), Past_P = Pasture share in diet for all cattle ($MJ_{pasture}/MJ_{total}$), Arable_S = Share of arable land ($ha_{arable}/ha_{total}$), Yield_ha = Forage yield (MJ/$ha_{DF}$), N_ha = Purchased nitrogen fertiliser (kg N/$ha_{DF}$), Milk_R = Regional deficiency payment for milk (NOK/kg ECM), and Meat_R = Regional deficiency payment for meat (NOK/kg meat). The PCA was conducted for the relationship between all environmental indicators and gross margin and all key variables selected by multiple regression (see Table 6).

**Table 5**
Results for the different environmental impact categories GHG emissions, N intensity, E intensity, agricultural land use occupation, and gross margin after conventional management ($n = 185$) organic managed farms ($n = 15$), farms with milking robots ($n = 78$), conventional milking system ($n = 122$), tie-stall barns ($n = 84$), free-stall housing ($n = 116$).

| Variable | Unit | | Conventional management (n = 185) | Organic management (n = 15) | Free-stall housing (n = 116) | Tie-stall barns (n = 84) | Automated milking system (n = 78) | Parlour or pipeline (n = 122) |
|---|---|---|---|---|---|---|---|---|
| $GWP_{100\text{-}AR4}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | Mean | 1.42 | 0.98 | 1.39 | 1.42 | 1.37 | 1.42 |
| | | Median | 1.38 | 1.00 | 1.37 | 1.33 | 1.37 | 1.35 |
| | | CV[a] | 0.19 | 0.16 | 0.19 | 0.23 | 0.15 | 0.23 |
| $GWP_{100\text{-}AR6}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | Mean | 1.55 | 1.13 | 1.51 | 1.53 | 1.49 | 1.54 |
| | | Median | 1.50 | 1.15 | 1.50 | 1.45 | 1.49 | 1.46 |
| | | CV[a] | 0.18 | 0.17 | 0.17 | 0.22 | 0.14 | 0.22 |
| $GTP_{100\text{-}AR6}$ | kg $CO_2$-eq/ 2.78 $MJ_{MM}$ | Mean | 0.86 | 0.49 | 0.80 | 0.87 | 0.80 | 0.85 |
| | | Median | 0.81 | 0.50 | 0.80 | 0.81 | 0.80 | 0.81 |
| | | CV[a] | 0.21 | 0.15 | 0.23 | 0.26 | 0.17 | 0.27 |
| Gross margin | NOK/2.78 $MJ_{MM}$ | Mean | 30,100 | 34,400 | 29,500 | 31,700 | 29,000 | 31,300 |
| | | Median | 30,000 | 34,600 | 29,000 | 31,600 | 28,700 | 31,000 |
| | | CV[a] | 0.12 | 0.13 | 0.13 | 0.12 | 0.11 | 0.13 |
| Gross margin | NOK/MCU[b] | Mean | 5.82 | 6.50 | 5.57 | 6.27 | 5.36 | 6.19 |
| | | Median | 5.69 | 6.62 | 5.50 | 6.15 | 5.30 | 6.07 |
| | | CV[a] | 0.14 | 0.15 | 0.13 | 0.14 | 0.11 | 0.14 |
| Energy intensity | MJ/2.78 $MJ_{MM}$ | Mean | 4.10 | 3.14 | 3.84 | 4.29 | 3.76 | 4.20 |
| | | Median | 3.91 | 3.07 | 3.66 | 4.12 | 3.67 | 3.99 |
| | | CV[a] | 0.22 | 0.11 | 0.21 | 0.24 | 0.16 | 0.25 |
| Nitrogen intensity | kg $N_{DS}$/kg $N_{MM}$ | Mean | 6.91 | 5.04 | 6.56 | 7.05 | 6.50 | 6.94 |
| | | Median | 6.65 | 5.07 | 6.36 | 6.77 | 6.34 | 6.67 |
| | | CV[a] | 0.18 | 0.17 | 0.18 | 0.22 | 0.14 | 0.22 |
| Land use occupation | $m^2_{DS}$/2.78 $MJ_{MM}$ | Mean | 2.92 | 3.57 | 2.82 | 3.17 | 2.74 | 3.11 |
| | | Median | 2.78 | 3.40 | 2.71 | 3.01 | 2.68 | 2.99 |
| | | CV[a] | 0.21 | 0.14 | 0.18 | 0.23 | 0.16 | 0.22 |

[a] CV: Coefficient Variation.
[b] Milking Cow Unit (MCU) is standardised to an annual NEL feed requirement of 42,000 MJ.

was ranked lower than for GWP.

Higher levels of *forage yield* and a greater *share of arable land* were associated with lower GHG emissions per 2.78 $MJ_{MM}$ ($GWP_{100\text{-}AR4}$ and $GWP_{100\text{-}AR6}$). For GHG emissions calculated by $GTP_{100\text{-}AR6}$, *milk yield produced* per cow was more important than GHG emissions per 2.78 $MJ_{MM}$ calculated by $GWP_{100\text{-}AR4}$ and $GWP_{100\text{-}AR6}$. A higher gross margin was associated with a lower *dairy cow share* and lower *concentrate use* for dairy cows. The *regional deficiency payment for milk* positively contributed to the gross margin. When a regression analysis was conducted for the functional unit of 1 kg ECM delivered, including only GHG emissions allocated to milk, the impact of variables on GHG emissions ($GWP_{100}$) changed compared to the results for 2.78 $MJ_{MM}$ delivered at farmgate. Although the *dairy cow share* was ranked as the most importance for GHG emissions related to 2.78 $MJ_{MM}$, it was not selected as an important factor for emissions related per kg ECM delivered. However, the other main drivers remained similar in order, as *purchased nitrogen fertiliser* (+0.003, $P < 0.001$, rank 1), *forage yield* (−0.00001, $P < 0.001$, rank 2), and *share of arable land* (−0.74, $P < 0.001$, rank 3) (see appendix Table A3).

## 4. Discussion

#### 4.1.1. Greenhouse gas emissions

The estimated GHG emissions were higher per unit of 2.78$MJ_{MM}$ than per kg ECM (1.4 $CO_2$-eq/2.78$MJ_{MM}$ vs 1.07 $CO_2$-eq/kg ECM) due to higher feed conversion efficiency for milk over meat (Alexander et al., 2016). The average GHG emissions (1.07 $CO_2$-eq/kg ECM) were lower than the global average for dairy production (2.4 $CO_2$-eq/kg FPCM, FAO, 2010) and within the range of other industrialised countries (0.8–1.5 $CO_2$-eq/kg ECM, Wattiaux et al., 2019). Compared to Norwegian studies, the estimated GHG emissions in this study were close to those reported by Bonesmo et al. (2013), which found 1.02 kg $CO_2$-eq/kg FPCM, and the baseline scenario by Samsonstuen et al. (2024), reporting 1.14 kg $CO_2$-eq/kg FPCM. In this study estimated GHG emission per kg ECM were lower than the 1.5–1.6 kg $CO_2$-eq/kg ECM found by Roer et al. (2013), modelling three representative Norwegian Dairy farms. All the modelled farms investigated by Roer et al. (2013) had lower milk yields per cow, and two of the scenarios had higher imports of mineral N fertilisers than the average for farms in the current study. In addition, the study of Roer et al. (2013) differs from the approach in this study by using economic allocation between milk and meat, contributing to higher estimated GHG emissions for milk.

#### 4.1.2. Nitrogen intensity

The N intensity in this study (6.77 kg N/kg N) was comparable to Koesling et al. (2017a) for 20 Norwegian dairy farms in the same region, reporting values of 7.38 kg N/kg N for conventional and 5.26 kg N/kg N for organically managed dairy farms. The N intensity was within the higher range reported by Bleken et al. (2005) for European farms ranging from 2.7 to 7.0 kg N/kg N. The farms in this study had relatively high milk yields compared to European (Eurostat, 2024) and previous studies in Norway (e.g. Flaten et al., 2019). The farms imported higher levels of N in concentrates and fertilisers, compared to the earlier mentioned studies, relative to the milk delivered. Thus, a reduction in N intensity may be achieved by extensification, as suggested by Quemada et al. (2020). If the path of extensification were followed while maintaining milk and meat yields, external measures are likely needed, such as producing high-quality silage and emphasising cow longevity by improving reproductive performance (Clasen et al., 2024; Beauchemin et al., 2009).

#### 4.1.3. Energy intensity

The E intensity in this study was 6.33 MJ/2.78 $MJ_{MM}$ (2.28 MJ input/MJ output) and included the energy needed to produce machinery and buildings (embodied energy). The results are within the range found by Koesling et al. (2017b) for conventional farms (2.6 ± 0.4 MJ input/MJ output) but higher than for organic farms (2.1 ± 0.3 MJ input/MJ

**Table 6**
Results from the regression analysis identifying key variables influencing environmental impact and gross margin. The response variables presented in the table were transformed using Box-Cox transformation before the statistical analysis. The standard error (SE) is given for each variable inside the brackets.

| Variable | Unit | $GWP_{100\text{-}AR4}$ | | $GWP_{100\text{-}AR6}$ | | $GTP_{100\text{-}AR6}$ | | Gross margin | | Energy intensity | | Nitrogen intensity | | Land use occupation | Rank[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$-eq/2.78 $MJ_{MM}$ | | $CO_2$-eq/2.78 $MJ_{MM}$ | | $CO_2$-eq/2.78 $MJ_{MM}$ | | NOK/2.78 $MJ_{MM}$ | | MJ/2.78 $MJ_{MM}$ | | kg N/kg N | | $m^2$/2.78 $MJ_{MM}$ | |
| | | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[a,b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | |
| R-squared | | 0.81 | | 0.8 | | 0.83 | | 0.8 | | 0.86 | | 0.79 | | 0.88 | |
| Constant | | 2.52 *** (0.20) | | 2.58 *** (0.18) | | 1.28*** (0.13) | | 1.19*** (0.03) | | 2.39 *** (0.07) | | 1.58 *** (0.10) | | 1.61 *** (0.06) | |
| Farming system[2] | $FS_{organic}/FS_{all}$ | −0.11 ** (0.03) | 7 | −0.09 ** (0.03) | 8 | −0.20 *** (0.04) | 5 | | | −0.15 *** (0.02) | 5 | 0.06 *** (0.02) | 8 | 0.05 *** (0.01) | 4 |
| Milking system[1] | $MS_{parlour+pipeline}/MS_{all}$ | | | | | | | 0.02 ** (0.01) | 7 | | | | | 0.01 ** (0.004) | 9 |
| Barn system[3] | $BS_{tie\ stall}/BS_{all}$ | | | −0.04 ** (0.01) | 9 | −0.06 ** (0.017) | 8 | | | | | | | | |
| Milking Cow Unit[4] | $MCU_{dairy}$/farm | | | | | | | −0.001 *** (<0.001) | 3 | | | | | | |
| Stocking density, cattle | $MCU_{cattle}/ha_{DF}$ | | | | | −0.15 *** (0.03) | 6 | −0.05 *** (0.01) | 5 | −0.18 *** (0.02) | 2 | −0.05 *** (0.01) | 7 | −0.008 *** (0.007) | 2 |
| Dairy cow share | $MCU_{dairy}/MCU_{all}$[5] | −1.09 *** (0.07) | 1 | −1.07 *** (0.06) | 1 | −1.26 *** (0.08) | 1 | −0.37 *** (0.02) | 1 | −0.65 *** (0.05) | 1 | −0.32*** (0.03) | 2 | −0.387 *** (0.02) | 1 |
| Milk yield produced | kg ECM/$MCU_{dairy}$ | $-5.2 \times 10^{-5}$ *** (<0.001) | 6 | $-5.4 \times 10^{-5}$ *** (<0.001) | 5 | $-5.3 \times 10^{-5}$ *** (<0.001) | 3 | | | $-2.8 \times 10^{-5}$ *** (<0.001) | 8 | $-2.4 \times 10^{-5}$ *** (<0.001) | 4 | 0.02 *** (<0.001) | 3 |
| Milk, delivered of produced | Share | −0.57 ** (0.17) | 8 | −0.54 ** (0.16) | 7 | | | | | | | −0.24 ** (0.08) | 9 | −0.28 * (0.05) | 7 |
| Parturition to last insemination | Days | | | | | 0.001 ** (<0.001) | 10 | | | | | | | | |
| Milk somatic cell count | 1000/l | | | | | | | | | | | | | $1.8 \times 10^{-4}$ (<0.001)** (<0.001) | 10 |
| Concentrate use, dairy cows | MJ NEL/$MCU_{dairy}$ | | | | | | | $-7.0 \times 10^{-6}$ (<0.001) *** (<0.001) | 2 | | | | | | |
| Pasture share in diet for all cattle | $MJ_{pasture}/MJ_{total}$ | −0.58 *** (0.08) | 5 | −0.52 *** (0.08) | 6 | | | | | −0.20 ** (0.06) | 11 | −0.22 *** (0.04) | 5 | −0.12*** (0.03) | 8 |
| Share of arable land | $ha_{arable}/ha_{total}$ | −0.44 *** (0.05) | 4 | −0.41 *** (0.05) | 4 | −0.34 *** (0.06) | 4 | | | −0.22 *** (0.04) | 7 | −0.12 *** (0.03) | 6 | −0.09 *** (0.02) | 6 |
| Forage yield | MJ/$ha_{DF}$ | $-7.7 \times 10^{-6}$ *** (<0.001) | 3 | $-7.6 \times 10^{-6}$ *** (<0.001) | 3 | $-5.9 \times 10^{-6}$ *** (<0.001) | 7 | $1.1 \times 10^{-6}$ ** (<0.001) | 8 | $-3.5 \times 10^{-6}$ *** (<0.001) | 10 | $-3.4 \times 10^{-6}$ *** (<0.001) | 3 | $-2.5 \times 10^{-6}$ *** (<0.001) | 5 |
| Purchased nitrogen fertiliser | kg N/$ha_{DF}$ | 0.001 *** (<0.001) | 2 | 0.002 *** (0.08) | 2 | 0.003 *** (<0.001) | 2 | $-2.6 \times 10^{-4}$ *** (<0.001) | 6 | 0.001 *** (<0.001) | 3 | 0.002 *** (<0.001) | 1 | | |

(*continued on next page*)

**Table 6** (*continued*)

| Variable | Unit | $GWP_{100\text{-}AR4}$ | | $GWP_{100\text{-}AR6}$ | | $GTP_{100\text{-}AR6}$ | | Gross margin | | Energy intensity | | Nitrogen intensity | | Land use occupation | Rank[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_2$-eq/2.78 $MJ_{MM}$ | | $CO_2$-eq/2.78 $MJ_{MM}$ | | $CO_2$-eq/2.78 $MJ_{MM}$ | | NOK/2.78 $MJ_{MM}$ | | MJ/2.78 $MJ_{MM}$ | | kg N/kg N | | $m^2$/2.78 $MJ_{MM}$ | |
| | | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[a,b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | Rank[b] | Parameter[a] (SE) | |
| Diesel use | Litre/$ha_{DF}$ | | | | | $3.8 \times 10^{-4}$ ** (<0.001) | 11 | | | $6.1 \times 10^{-4}$ *** (<0.001) | 4 | | | | |
| Electricity per ECM | kWh/kg ECM | | | | | | | | | 0.30 *** (0.05) | 6 | | | | |
| Baling by contractor | bales/$ha_{DF}$ | | | | | | | | | 0.003 *** (<0.001) | 9 | | | | |
| Regional deficiency payment for milk | NOK/kg ECM | | | | | | | 0.12 *** (<0.001) | 4 | −0.11 ** (0.04) | 13 | | | | |
| Regional deficiency payment for meat | NOK/kg meat | | | | | 0.01 ** (0.005) | 9 | | | 0.008 ** (0.003) | 12 | | | | |

Significant level at *** < 0.001; ** < 0.01; * < 0.05.
[a] Only variables where the parameter estimates with P < 0.01 were included in the final model.
[b] Ranking is based on Squared Partial Correlation Type II, with first place for highest influence.
[1] Milking system: 0 = Automated milking systems (AMS), 1 = Parlour or pipeline.
[2] Farming system: 0 = Conventional, 1 = Organic.
[3] Barn system: 0 = Loose housing, 1 = Tie stall.
[4] Milking Cow Unit (MCU) is standardised to an annual NEL requirement of 42,000 MJ.
[5] $MCU_{all}$ is the number of all cattle on the farm expressed as milking cow unit, i.e., the annual total feed requirement in net energy lactation (NEL) in the herd divided by the annual requirement of a standard dairy cow set to 42,000 MJ NEL.

output). The farms in this study had a lower average size concerning dairy cows, on 36.5 $MCU_{dairy}$ per farm, compared to the EU average of 58 dairy cows per farm in 2020 (EC, 2022), suggesting potential economies of scale in reducing E intensity (Kraatz, 2012).

#### 4.1.4. Land use occupation

The total land use occupation was within the higher range found in comparable regions (Bakken et al., 2017; Cederberg and Flysjö, 2004). The average dairy farm area was 1.56 $m^2_{DF}$ per kg ECM delivered, accounting for approximately half of the total land use occupation of the dairy system (2.87 $m^2_{DS}$/kg ECM). The higher share of off-farm area suggests greater reliance on purchased feed than found in the earlier studies in Norway and Sweden (Bakken et al., 2017; Cederberg and Flysjö, 2004). This can be explained by an increase in milk yield per cow, mainly driven by the increased proportion of concentrate in the diet (TINE, 2024).

#### 4.1.5. GHG emissions, nitrogen intensity, energy intensity and land use occupation in conventional versus organic production

The GHG emissions (CO2-eq/2.78MJMM), E and N intensity, were higher at the conventional managed farms than at the organic managed farms. The main reason for the organic farms having less environmental impact than the conventional ones was the avoidance of N fertiliser and higher share of dairy cows in the herd. Some studies report lower GHG emissions at organic managed farms (e.g., Cederberg and Mattsson, 2000), while others do not find any differences between the two management forms per product unit (de Boer, 2003; Kristensen et al., 2011). Similar GHG emissions on organic and conventional managed farms, despite less purchase on organic farms, are often caused by lower milk yields at organic than conventional managed farms (e.g., de Boer, 2003). The Gross margin was lower for the automated milking system than the conventional milking system with parlour or pipeline.

### 4.2. Environmental and economic performance

#### 4.2.1. Environmental impacts

Increasing the share of dairy cows in the herd was important in reducing GHG emissions (if not otherwise stated GHG emissions are stated as kg $CO_2$-eq/2.78$MJ_{MM}$), E intensity, N intensity, and land use occupation. This can be attributed to the higher feed conversion efficiency for milk production than meat production by cattle (Alexander et al., 2016). Thus, producing higher levels of milk than meat reduces the impact of GHG emission, E and N intensities and land use occupation, at least within the system boundaries assessed. However, the share of dairy cows in the herd was not selected as an important variable to lower GHG emissions when expressed as kg $CO_2$-eq/kg ECM (Appendix Table A3). The beneficial effect of using more concentrates depends on the production of the ingredients and associated climate gas emissions since reduced methane emission from altered feeding practises and increased milk yield can be undermined if emissions related to import are higher than on farm forage production, as shown by Bakken et al. (2017).

Higher milk yield per cow was associated with lower GHG emissions, E, and N intensities and land use occupation per 2.78 MJ of edible energy from milk and meat, delivered at the farm gate. High milk yield, with the intake of large amounts of dry matter per cow, results in higher enteric methane emissions per cow while lowering the total methane emission in production of milk and meat as relatively less feed is needed for maintenance (Dida et al., 2024; Knapp et al., 2014). However, cows with high milk yields may be more susceptible to diseases like mastitis (Gröhn et al., 2004). A consequence of increased frequency of mastitis is that farmers need to replace cows more frequently to secure production and revenue, leading to higher replacement rates. The reduction of the proportion of dairy cows being replaced after their first lactation reduced the GHG emissions observed in dairy farm systems in Switzerland (Grandl et al., 2019). Emissions reduction both within and outside the system boundaries may be achieved by balancing a high dairy cow share and milk yields per cow with a low replacement rate. This can be achieved through measures such as improving animal welfare and feed quality, extending the lactation periods, using sex-separated semen to control milk vs meat production, and lowering the age at first calving (Clasen et al., 2024; von Soosten et al., 2020). Long-term genetic selection to increase milk productivity while increasing disease resilience, lowering the age at first calving and the replacement rate also seems important (Brito et al., 2021).

Choosing between land sparing or land sharing depends on the regional conditions for dairy production and the national demand for milk and meat. Samsonstuen et al. (2024) modelled future milk production scenarios in Norway. They found that increasing milk yield while meeting the national demand for milk and meat led to a slight national decrease in GHG emissions. The reduction in GHG emissions was attributed to lower emissions in dual-purpose dairy production despite increased emissions from specialized beef production. Decreasing the milk yield per dairy cow reduces the feed quality requirements in forage production, allowing the use of permanent pasture and free rangeland, which are unsuitable for growing food crops. This approach can contribute to a higher contribution from on-farm areas, which only accounted for about 50 % of the land used per farm in the present study. In a regional context, higher use of areas unsuitable for growing food crops and less import of concentrates would support the land sharing paradigm and improve food security, as production becomes less dependent on imported inputs at the farm level. Sacrificing high milk yield to lower feed quality demand, combined with less land use occupation outside the dairy farm, will likely increase GHG emissions and on-farm land use.

#### *4.2.2. Effects on gross margin*

Increasing *dairy cow share* in the herd was associated with decreasing gross margin. Since most farms in the study were close to filling their milk quota (on average with 93 %), farms with surplus areas could fatten animals instead of producing more milk and selling off the young stock, which may be more profitable. Producing milk instead of rearing young stock for beef is more profitable until the quota is reached. In addition, exceeding the quota leads to economic penalties, as a levy is imposed on each litre of milk produced above the quota (Norwegian Agriculture Agency, 2023). Previously, management traits such as implementing the automatic milking system (AMS), high beef production per cow, low age at first calving, and organic farming practices were found to be the main drivers in explaining the difference in revenue efficiency between dairy farms (Hansen et al., 2019b). In this study, AMS was associated with reduced gross margin relative to other milking systems. Earlier assessments of the effect of AMS have shown that dairy farms need at least 35 to 40 cows to become profitable, with profitability increasing as farm size grows (Hansen et al., 2019a). The introduction of AMS has also been shown to be profitable after a four-year transition period (Hansen et al., 2019a). However, as Vik et al. (2019) discussed investments in AMS may be motivated by additional factors beyond mere profit, such as improving the quality of life of the farmer and their family. The current study also showed that higher levels of purchased N fertilisers were associated with higher GHG emissions, E and N intensities, and lower gross margins. Strategies for better utilisation of cattle manure could reduce the need for N fertiliser and serve as an essential measure to reduce GHG emissions (Chadwick et al., 2011).

#### *4.2.3. Impact of different estimates of greenhouse gas emission by the Intergovernmental Panel on Climate Change*

The GHG emissions can be estimated according to different IPCC metrics, such as $GWP_{100}$ and $GTP_{100}$. The weighting differs for methane and for nitrous oxide, roughly 1/5 and 4/5 respectively, in the estimated $CO_2$-eq for $GTP_{100\text{-}AR6}$ compared to the two $GWP_{100}$ impact assessments. This difference in weighting has caused some variables to be ranked differently by the multiple regression between $GTP_{100\text{-}AR6}$ and the two $GWP_{100}$'s impact assessments. For $GTP_{100\text{-}AR6}$, the estimated relative importance of *milk yield* per cow increased for GHG emissions, and the importance of *forage yield* decreased compared to estimates using the two $GWP_{100}$ impact assessment methods. The selection of $GTP_{100\text{-}AR6}$ as metrics results in lower $CO_2$-eq from nitrous dioxide and methane on climate change and higher importance of $CO_2$ emissions from production and use of purchased inputs such as diesel and fertiliser, as well as from machinery and buildings, when the sum of emissions is lower. The farming system had a stronger impact on reducing GHG estimates when $GTP_{100\text{-}AR6}$ was used than the two $GWP_{100}$ indicators. This is probably likely a result of the combined effect of higher *dairy cow share* and lower *purchased nitrogen fertiliser* on organic farms than on conventional managed farms, leading to different effects when the weightings of methane and nitrous oxide change between the metrics.

#### *4.2.4. Potential improvements between the different impacts investigated*

In this study, higher use of concentrates was associated with reduced gross margin per product delivered. Using high proportions of concentrates can be beneficial for increasing milk yields and gross margin (Dida et al., 2024). The gross margin depends also on the relative price of concentrates to milk and meat, and how efficient on-farm feed is produced. However, reducing the use of concentrates without focusing on producing on-farm feed with high digestibility and reducing costs for producing on-farm feed is likely to reduce profitability. Therefore, a balanced approach considering the economic use of inputs and nutritional aspects of feed production is essential for maintaining or improving gross margins. In addition, Moitzi et al. (2010) pointed out that increasing the forage-to-concentrate ratio will likely improve E intensity. Additionally, central Norway's relatively short vegetation season and long indoor period contribute to higher energy intensity than in other regions of Europe. More resources are needed to obtain sufficient forage yields and maintain animals during the long indoor period.

A higher *pasture share in the diet for all cattle* was beneficial for reducing GHG emissions ($GWP_{100}$), E, N intensities, and land use occupation. Increased pasture use contributes to reducing GHG emissions because it reduces the need for feed storage capacity, labour, and manure handling (Rotz, 2018). Additionally, grazing needs no harvesting machinery, thus lowering GHG emissions and E intensity. In the study of Shine et al. (2020), pasture-based dairy systems reduced the overall energy use per kg ECM by 35 %. In addition, the results from O'Brien et al. (2015), found that increasing milk production per ha from grazed grass reduced carbon footprint and improved profitability. However, the *pasture share in the diet for all cattle* was not found to affect the gross margin. This is likely due to a low share of pasture in the total diet on the farms studied. The lack of beneficial effects on gross margin from the use of pastures may also contribute to a weaker relationship between a high gross margin per 2.78 $MJ_{MM}$ or per dairy cow and low GHG emissions. Grazing has been found to increase gross margin on dairy farms both in the Pó Valley in Italy and in central Norway, primarily driven by higher subsidies (Norway) and milk prices (Italy) (Steinshamn et al., 2021a). Therefore, while increased pasture use can reduce environmental impacts, its economic benefits may depend on regional factors such as subsidies, market conditions and the distance between barns and grazing areas.

Reduction of GHG emissions and E, and N intensities can be achieved through management practices such as increasing the *dairy cow share* and reducing *purchased nitrogen fertiliser*. Based on Flaten et al. (2019) and Jayasundara et al. (2019), we expected reduced GHG emissions and lower E, and N intensities to result in improved gross margin. While they found that an increased use of concentrates tended to improve gross margin, the findings in this study showed a negative association between concentrate use for dairy cows and gross margin, while no correlation was found between the use of concentrates for dairy cows and the environmental indicators. The findings in the present study can be affected by higher milk yield based on more concentrates given, leading to a diminishing effect of concentrates compared to the study of Flaten et al. (2019).

### 4.3. Limitations and uncertainty

The study's findings may be biased since farmers pay an extra fee to participate in the extended Tine Advisory Service. Participating farmers may represent a group more focused on improving production and economic outcomes.

The amount of purchased inputs was calculated from farm accountancy data to physical units, while the milk and meat output of the farm were recorded as physical outputs. The results from the sensitivity analysis showed that the number of bulls had the highest impact on GHG emission when reduced due to high variability between farms, with some farms producing zero bulls. This led to no feed requirements or meat production from bulls at farms having zero production of bulls, while purchased inputs on farms remained constant, significantly affecting GHG results. The number of heifers showed similar but less variable impacts (see Appendix, Table A2).

The calculation of methane emissions was based on estimated dry matter intake (DMI) and had a high impact on the GHG emissions, comparable to what was shown in the sensitivity analysis by Niu et al. (2021), based on measuring feed uptake and methane emissions. Better knowledge of feed intake and resulting methane emissions would contribute to more exact estimates of actual GHG emissions. When converting the NEL intake to DM intake, important for estimating enteric methane production, we assumed that forage energy values were similar across the different farms. However, the forage NEL value was probably underestimated for high-yielding cows while being overestimated for low-yielding farms.

More precise on-farm data may improve the estimated environmental impact level. However, the relative importance of the independent variables to the dependent variables should remain relatively constant, with little effect on the conclusion drawn.

The findings in the current study are based on associations, which do not imply causality since the regression is sensitive to variable selection and interactions. The current study did not assess other potentially relevant variables, such as agricultural education level, weather parameters, soil conditions, and soil carbon changes. This LCA study utilises farm characteristics, such as farm area, number of animals in different sex and age categories, purchased concentrate, and diesel usage (Table 1), along with emission factors to estimate environmental performance. Multicollinearity was handled with a removal criterion of VIF $>$ 5. Such variables may affect the amplitude of the estimates between the independent and the dependent variables (Schneider et al., 2010).

This study does not include the impact of labour costs on the gross margin. Additionally, water use was not included because it is not a limiting factor for dairy production in this region of Norway. Biodiversity was not included, as it is still developing within the LCA framework (e.g. Knudsen et al., 2019). Assessment of these factors could also be of interest for future environmental impact assessments.

### 4.4. Merging milk and meat delivered in one functional unit

Conducting LCA for dairy production using separate functional units for meat and milk and allocating the environmental impact between the two products, is useful to calculate emissions and to find pathways to reduce them. However, using human edible energy as functional unit, as shown in this study, allows for a combined evaluation of milk and meat production on a farm and related emissions.

We expect that using human edible protein from milk and meat will yield similar results in identifying key factors for reduced environmental impact, as seen in Letelier et al. (2022). Many of the important factors identified in this study align with those in other publications. However, our finding that a higher share of cows with high milk production is advantageous, novel and achievable only by using human edible energy or protein from milk and meat as functional units. Despite its advantages, human edible energy as a functional unit cannot replace the use of separate functional units for milk and meat.

## 5. Conclusions

This study offers insights into the balance between environmental impact and economic performance in dairy farming. An increased share of dairy cows relative to all cattle on the farm was associated with lower environmental impacts, including reduced GHG emissions, lower E intensity, lower N intensity, and less land use occupation per unit of edible energy from milk and meat delivered. However, while linked with lower environmental impact, an increase in the share of dairy cows was linked to a decrease in gross margin because exceeding the quota leads to economic penalties.

In addition to a high share of dairy cows, key factors for reducing environmental impact included less purchased N fertiliser, higher forage yield, higher share of arable land, and a higher milk yield per cow. No association between concentrate use and environmental impact was found, but an increased use of concentrates slightly reduced the gross margin.

## CRediT authorship contribution statement

**Matthias Koesling:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation. **Kristian Nikolai Jæger Hansen:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Sissel Hansen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Håvard Steinshamn:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

The authors used a closed version of Chat GPT 4.0, which is a restricted access model of the artificial intelligence developed by OpenAI, to get suggestions on how to improve wording of sentences. The authors subsequently reviewed and edited the suggested changes and take full responsibility for the content.

## Declaration of competing interest

The authors declare no conflicts of interest.

## Data availability

The data that has been used is confidential.

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## Appendix A. Supplementary data

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## References


Alexander, P., Brown, C., Arneth, A., Finnigan, J., Rounsevell, M.D.A., 2016. Human appropriation of land for food: the role of diet. Glob. Environ. Chang. 41, 88–98. https://doi.org/10.1016/j.gloenvcha.2016.09.005.

Asgedom, H., Kebreab, E., 2011. Beneficial management practices and mitigation of greenhouse gas emissions in the agriculture of the Canadian Prairie: a review. Agron. Sustain. Dev. 31 (3), 433–451. https://doi.org/10.1007/s13593-011-0016-2.

Bakken, A.K., Daugstad, K., Johansen, A., Hjelkrem, A.G.R., Fystro, G., Strømman, A.H., Korsaeth, A., 2017. Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments. Agr. Syst. 158, 50–60. https://doi.org/10.1016/j.agsy.2017.09.001.

Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68 (6), 1615–1625. https://doi.org/10.1016/j.ecolecon.2007.11.017.

Beauchemin, K.A., McAllister, T.A., McGinn, S.M., 2009. Dietary mitigation of enteric methane from cattle. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources. 4 (35), 1–18. https://doi.org/10.1079/PAVSNNR20094035.

Benoit, M., Veysset, P., 2021. Livestock unit calculation: a method based on energy needs to refine the study of livestock farming systems. INRA Prod Anim. 34 (2), 139e–160e. https://doi.org/10.20870/productions-animales.2021.34.2.4855.

Bleken, M.A., Steinshamn, H., Hansen, S., 2005. High nitrogen costs of dairy production in Europe: worsened by intensification. AMBIO: J. Human Environ. 34 (8), 598–606. https://doi.org/10.1579/0044-7447-34.8.598.

Bonesmo, H., Beauchemin, K.A., Harstad, O.M., Skjelvåg, A.O., 2013. Greenhouse gas emission intensities of grass silage based dairy and beef production: a systems analysis of Norwegian farms. Livest. Sci. 152 (2–3), 239–252. https://doi.org/10.1016/J.LIVSCI.2012.12.016.

Breines, D., Folgerø, B.F., Grøva, L., Haug, I., Mo, M., Røe, M., Solberg, A., Strøm, T., 2002. Fôring og stell av storfe (in Norwegian), 1. ed. GAN Forlag AS, Oslo.

Brito, L.F., Bedere, N., Douhard, F., Oliveira, H.R., Arnal, M., Peñagaricano, F., Schinckel, A.P., Baes, C.F., Miglior, F., 2021. Review: genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Animal 15 (1), 1000292. https://doi.org/10.1016/j.animal.2021.100292.

Capper, J.L., Cady, R.A., Bauman, D.E., 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87 (6), 2160–2167. https://doi.org/10.2527/jas.2009-1781.

Casey, J.W., Holden, N.M., 2005. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. J. Environ. Qual. 34 (2), 429–436. https://doi.org/10.2134/jeq2005.0429.

Cederberg, Christel, Flysjö, Anna, 2004. Life Cycle Inventory of 23 Dairy Farms in South-Western Sweden. SIK Report No. 728. The Swedish Institute for Food and Biotechnology (SIK), Gothenburg, Sweden.

Cederberg, C., Mattsson, B., 2000. Life cycle assessment of milk production-a comparison of conventional and organic farming. J. Clean. Prod. 8 (1), 49–60. https://doi.org/10.1016/S0959-6526(99)00311-X.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., Misselbrook, T., 2011. Manure management: implications for greenhouse gas emissions. Anim. Feed Sci. Technol. 166–167, 514–531. https://doi.org/10.1016/j.anifeedsci.2011.04.036.

Clasen, J.B., Fikse, W.F., Ramin, M., Lindberg, M., 2024. Effects of herd management decisions on dairy cow longevity, farm profitability, and emissions of enteric methane – a simulation study of milk and beef production. Animal 18 (2), 101051. https://doi.org/10.1016/j.animal.2023.101051.

Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A., Boland, T.M., Kenny, D. A., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Anim. Feed Sci. Technol. 166–167, 29–45. https://doi.org/10.1016/j.anifeedsci.2011.04.001.

Dang, H. Le, Li, E., Nuberg, I., Bruwer, J., 2019. Factors influencing the adaptation of farmers in response to climate change: a review. Clim. Dev. 11 (9), 756–774. https://doi.org/10.1080/17565529.2018.1562866.

Dannevig, P., 2019. Møre og Romsdal - klima (In Norwegian). http://snl.no/Møre_og_Romsdal/klima (accessed 1. June 2024).

Dannevig, P., 2020. Trøndelag - klima (In Norwegian). https://snl.no/Trøndelag-klima (accessed 1. June 2024).

de Boer, I.J.M., 2003. Environmental impact assessment of conventional and organic milk production. Livest. Prod. Sci. 80, 69–77. https://doi.org/10.1016/S0301-6226(02)00322-6.

Dida, M.F., Garcia, S.C., Gonzalez, L.A., 2024. Dietary concentrate supplementation increases milk production and reduces predicted greenhouse gas emissions intensity in pasture-based commercial dairy farms. J. Dairy Sci. 107 (8), 5639–5652. https://doi.org/10.3168/jds.2023-24303.

EC, 2022. EU Agricultural Outlook for Markets, Income and Environment, 2022-2032. European Commission, DG Agriculture and Rural Development, Brussels. https://doi.org/10.2762/29222.

Eurostat, 2024. Milk and milk product statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics#Milk_production (accessed 9. September 2024).

FAO, 2010. Greenhouse Gas Emissions From the Dairy Sector A Life Cycle Assessment. Food and Agriculture Organization of the United Nations, Rome, Italy.

Flaten, O., Koesling, M., Hansen, S., Veidal, A., 2019. Links between profitability, nitrogen surplus, greenhouse gas emissions, and energy intensity on organic and conventional dairy farms. Agroecol. Sustain. Food Syst. 43 (9), 957–983. https://doi.org/10.1080/21683565.2018.1544960.

Grandl, F., Furger, M., Kreuzer, M., Zehetmeier, M., 2019. Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. Animal 13 (1), 198–208. https://doi.org/10.1017/S175173111800112X.

Gröhn, Y.T., Wilson, D.J., González, R.N., Hertl, J.A., Schulte, H., Bennett, G., Schukken, Y.H., 2004. Effect of pathogen-specific clinical mastitis on milk yield in dairy cows. J. Dairy Sci. 87 (10), 3358–3374. https://doi.org/10.3168/jds.S0022-0302(04)73472-4.

Grønlund, A., Hauge, A., Hovde, A., Rasse, D.P., 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. Nutr. Cycl. Agroecosyst. 81, 157–167. https://doi.org/10.1007/s10705-008-9171-5.

Guo, M., Murphy, R.J., 2012. LCA data quality: sensitivity and uncertainty analysis. Sci. Total Environ. 435–436, 230–243. https://doi.org/10.1016/j.scitotenv.2012.07.006.

Haas, G., Wetterich, F., Köpke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment, ecosystems and environment. Agric Ecosyst Environ. 82 (1–2), 43–53. https://doi.org/10.1016/S0167-8809(00)00160-2.

Hansen, B.G., Herje, H.O., Höva, J., 2019a. Profitability on dairy farms with automatic milking systems compared to farms with conventional milking systems. International Food and Agribusiness Management Review. 22 (2), 215–228. https://doi.org/10.22434/IFAMR2018.0028.

Hansen, B.G., Moland, K., Lenning, M.I., 2019b. How can dairy farmers become more revenue efficient? Efficiency drivers on dairy farms. International Journal of Agricultural Management. 8 (2), 65–73. https://doi.org/10.5836/ijam/2019-08-65.

Herron, J., Curran, T.P., Moloney, A.P., O'Brien, D., 2019. Whole farm modelling the effect of grass silage harvest date and nitrogen fertiliser rate on nitrous oxide emissions from grass-based suckler to beef farming systems. Agr. Syst. 175 (7), 66–78. https://doi.org/10.1016/j.agsy.2019.05.013.

Heseker, B., 2013. Die Nährwerttabelle (in German). Neuer Umschau Buchverlag.

Hjukse, O., 2016. Totalkalkylen for jordbruket. Jordbrukets totalregnskap 2014 og 2015. Budsjett 2016 (in Norwegian). Budsjettnemda for jordbruket, Ås.

Hjukse, O., 2017. Totalkalkylen for landbruket. Jordbrukets totalregnskap 2015 og 2016. Budsjett 2017 (in Norwegian). Budsjettnemda for jordbruket, Ås.

ifu Hamburg, 2017. Umberto LCA+ (v10) User Manual. ifu Hamburg GmbH, Hamburg.

Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? Int. J. Life Cycle Assess. 24, 794–807. https://doi.org/10.1007/s11367-018-1477-1.

International Dairy Federation, 2010. A Common Carbon Footprint Approach for Dairy The IDF Guide to Standard Lifecycle Assessment Methodology for the Dairy Sector. Bulletin of the International Dairy Federation, No. 445. International Dairy Federation, Brussels, Belgium.

IPCC, 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

ISO, 2006a. 14040 Environmental Management-Life Cycle Assessment-Principles and Framework.

ISO, 2006b. 14044 (2006) Environmental Management-Life Cycle Assessment-Requirements and Guidelines.

Jayasundara, S., Worden, D., Weersink, A., Wright, T., VanderZaag, A., Gordon, R., Wagner-Riddle, C., 2019. Improving farm profitability also reduces the carbon footprint of milk production in intensive dairy production systems. J. Clean. Prod. 229, 1018–1028. https://doi.org/10.1016/j.jclepro.2019.04.013.

Kiefer, L., Menzel, F., Bahrs, E., 2014. The effect of feed demand on greenhouse gas emissions and farm profitability for organic and conventional dairy farms. J. Dairy Sci. 97 (12), 7564–7574. https://doi.org/10.3168/jds.2014-8284.

Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P., Tricarico, J.M., 2014. Invited review: enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. J. Dairy Sci. 97 (6), 3231–3261. https://doi.org/10.3168/jds.2013-7234.

Knudsen, M.T., Dorca-Preda, T., Djomo, S.N., Peña, N., Padel, S., Smith, L.G., Zollitsch, W., Hörtenhuber, S., Hermansen, J.E., 2019. The importance of including soil carbon changes, ecotoxicity and biodiversity impacts in environmental life cycle assessments of organic and conventional milk in Western Europe. J. Clean. Prod. 215, 433–443. https://doi.org/10.1016/j.jclepro.2018.12.273.

Koesling, M., Ruge, G., Fystro, G., Torp, T., Hansen, S., 2015. Embodied and operational energy in buildings on 20 Norwegian dairy farms - introducing the building

construction approach to agriculture. Energ. Buildings 108, 330–345. https://doi.org/10.1016/j.enbuild.2015.09.012.
Koesling, M., Hansen, S., Bleken, M.A., 2017a. Variations in nitrogen utilisation on conventional and organic dairy farms in Norway. Agr. Syst. 157, 11–21. https://doi.org/10.1016/j.agsy.2017.06.001.
Koesling, M., Hansen, S., Schueler, M., 2017b. Variations of energy intensities and potential for improvements in energy utilisation on conventional and organic Norwegian dairy farms. J. Clean. Prod. 164, 301–314. https://doi.org/10.1016/J.JCLEPRO.2017.06.124.
Korsaeth, A., Jacobsen, A.Z., Roer, A.G., Henriksen, T.M., Sonesson, U., Bonesmo, H., Skjelvåg, A.O., Strømman, A.H., 2012. Environmental life cycle assessment of cereal and bread production in Norway. Acta Agriculturae Scandinavica A: Animal Sciences. 62 (4), 242–253. https://doi.org/10.1080/09064702.2013.783619.
Kraatz, S., 2012. Energy intensity in livestock operations - modeling of dairy farming systems in Germany. Agr. Syst. 110, 90–106. https://doi.org/10.1016/j.agsy.2012.03.007.
Kristensen, T., Mogensen, L., Knudsen, M.T., Hermansen, J.E., 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livest. Sci. 140 (1–3), 136–148. https://doi.org/10.1016/j.livsci.2011.03.002.
Letelier, P., Aguirre-Villegas, H.A., Navarro, M.C., Wattiaux, M.A., 2022. Milk, meat, and human edible protein from dual-purpose cattle in Costa Rica: impact of functional unit and co-product handling methods on predicted enteric methane allocation. Livest. Sci. 263. https://doi.org/10.1016/j.livsci.2022.105013.
Moitzi, G., Damm, D., Weingartmann, H., Boxberger, J., 2010. Analysis of energy intensity in selected Austrian dairy farms with focus on concentrate level in feeding. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture 67 (1). https://doi.org/10.15835/buasvmcn-agr:5032.
Niu, P., Schwarm, A., Bonesmo, H., Kidane, A., Aspeholen Åby, B., Storlien, T.M., Kreuzer, M., Alvarez, C., Sommerseth, J.K., Prestløkken, E., 2021. A basic model to predict enteric methane emission from dairy cows and its application to update operational models for the national inventory in Norway. Animals 11 (7), 1891. https://doi.org/10.3390/ani11071891.
Norwegian Agriculture Agency, 2023. Pristilskudd og avgifter for melk som er levert til meieri (in Norwegian). In: Circular 2023, 15.
Norwegian Food Safety Authority, 2015. The Norwegian Directorate of Health, and University of Oslo. Norwegian Food Composition Database 2015. www.matvaretabellen.no (accessed 29. April 2016).
O'Brien, D., Hennessy, T., Moran, B., Shalloo, L., 2015. Relating the carbon footprint of milk from Irish dairy farms to economic performance. J. Dairy Sci. 98 (10), 7394–7407. https://doi.org/10.3168/jds.2014-9222.
Pascual-González, J., Pozo, C., Guillén-Gosálbez, G., Jiménez-Esteller, L., 2015. Combined use of MILP and multi-linear regression to simplify LCA studies. Comput. Chem. Eng. 82, 34–43. https://doi.org/10.1016/j.compchemeng.2015.06.002.
Quemada, M., Lassaletta, L., Jensen, L.S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S.K., Oenema, J., Richards, K.G., Oenema, O., 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agr. Syst. 177, 102689. https://doi.org/10.1016/j.agsy.2019.102689.
Rasse, D., Økland, I., Bárcena, T.G., Riley, H., Martinsen, V., Sturite, I., Joner, E., Øpstad, S., Cottis, T., Budai, A., 2019. Muligheter og utfordringer for økt karbonbinding i jordbruksjord. ISSN:2464-1162.
Richardson, J., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., et al., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9 (37). https://doi.org/10.1126/sciadv.adh2458.
Roer, A.G., Johansen, A., Bakken, A.K., Daugstad, K., Fystro, G., Strømman, A.H., 2013. Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries. Livest. Sci. 155, 384–396. https://doi.org/10.1016/j.livsci.2013.05.004.
Rotz, C.A., 2018. Modeling greenhouse gas emissions from dairy farms. J. Dairy Sci. 101 (7), 6675–6690. https://doi.org/10.3168/jds.2017-13272.
Rouillé, B., Jost, J., Fança, B., Bluet, B., Jacqueroud, M.P., Seegers, J., Charroin, T., Le Cozler, Y., 2023. Evaluating net energy and protein feed conversion efficiency for dairy ruminant systems in France. Livest. Sci. 269 (105170), 1–9. https://doi.org/10.1016/j.livsci.2023.105170.
Samsonstuen, S., Møller, H., Aamaas, B., Knudsen, M.T., Mogensen, L., Olsen, H.F., 2024. Choice of metrics matters—future scenarios on milk and beef production in Norway using an LCA approach. Livest. Sci. 279. https://doi.org/10.1016/j.livsci.2023.105393.
SAS Institute, 2013. Inc 2013. SAS/ACCESS® (Version 9.4). SAS Institute Inc., Cary, NC.
Schneider, A., Hommel, G., Blettner, M., 2010. Linear regression analysis - part 14 of a series on evaluation of scientific publications. Dtsch. Arztebl. Int. 107 (44), 776–782. https://doi.org/10.3238/arztebl.2010.0776.
Schueler, M., 2019. Using Life Cycle Assessment in Agriculture – Methodological Considerations of Variability and Uncertainty in Dairy Carbon Footprints. Dissertation. Humbolt University, Berlin.
Shine, P., Upton, J., Sefeedpari, P., Murphy, M.D., 2020. Energy consumption on dairy farms: a review of monitoring, prediction modelling, and analyses. Energies 13 (1288), 1–25. https://doi.org/10.3390/en13051288.
Steinshamn, H., Thuen, E., Bleken, M.A., Brenøe, U.T., Ekerholt, G., Yri, C., 2004. Utilization of nitrogen (N) and phosphorus (P) in an organic dairy farming system in Norway. Agric. Ecosyst. Environ. 104 (3), 509–522. https://doi.org/10.1016/j.agee.2004.01.022.
Steinshamn, H., Holmström, K., Riuzzi, G., Hessle, A., Nadeau, E., Walland, F., Gottardo, F., Butler, G., 2021a. Economy of Forage-based Cattle Beef and Milk Production. NIBIO Report 7(60). Norwegian Institute of Bioeconomy Research, Ås, Norway.
Steinshamn, H., Walland, F., Koesling, M., 2021b. Does It Matter for the Environment How Much Forage Our Dairy Cows Eat? NIBIO Report 7(61). Norwegian Institute of Bioeconomy Research, Ås, Norway.
Storlien, T.M., Volden, H., Almøy, T., Beauchemin, K.A., McAllister, T.A., Harstad, O.M., 2014. Prediction of enteric methane production from dairy cows. Acta Agriculturae Scandinavica A: Animal Sciences. 64 (2), 98–109. https://doi.org/10.1080/09064702.2014.959553.
TINE, 2024. Statistikksamling for ku- og geitekontrollen 2023 (in Norwegian). https://medlem.tine.no/aktuelt-fra-tine/statistikksamling-for-ku-og-geitekontrollen-2023 (Accessed 9. September 2024).
Vik, J., Stræte, E.P., Hansen, B.G., Nærland, T., 2019. The political robot – the structural consequences of automated milking systems (AMS) in Norway. NJAS - Wageningen Journal of Life Sciences 90–91. https://doi.org/10.1016/j.njas.2019.100305.
von Soosten, D., Meyer, U., Flachowsky, G., Dänicke, S., 2020. Dairy cow health and greenhouse gas emission intensity. Dairy 1 (1), 20–29. https://doi.org/10.3390/dairy1010003.
Wattiaux, M.A., Uddin, M.E., Letelier, P., Jackson, R.D., Larson, R.A., 2019. INVITED REVIEW: emission and mitigation of greenhouse gases from dairy farms: the cow, the manure, and the field. Applied Animal Science 35 (2), 238–254. https://doi.org/10.15232/aas.2018-01803.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.