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Choice of metrics matters—Future scenarios on milk and beef production in Norway using an LCA approach

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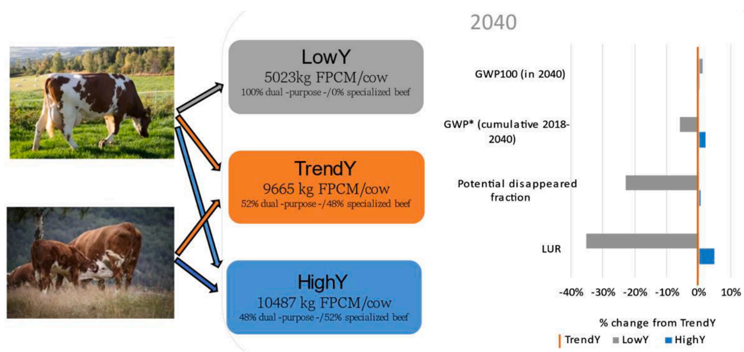
HIGHLIGHTS

- Climate change, biodiversity, and land use ratio were assessed for future domestic milk and beef production scenarios in Norway.
- The choice of GWP metrics and time frame are highly affecting the results.
- Traditional GWP_{100} metrics favor the HighY scenario with high milk yield.
- The GWP* metrics favor the LowY scenario with low milk yield and no suckler cows.
- The LowY scenario increased land use efficiency and lowered biodiversity loss.

GRAPHICAL ABSTRACT



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ABSTRACT

The consumption of dairy and beef products is expected to increase globally in the future, and at the same time, food must be produced in a more sustainable way, including reduced greenhouse gas (GHG) emissions, avoided feed-food competition, and reduced biodiversity loss. The purpose of the study was to a) provide an overall life cycle assessment (LCA) of these impacts for various future milk and beef production systems in Norway and b) determine how the choice of metrics for climate change affects the results. System boundaries were from cradle to farm gate and the temporal boundary was 2017 with future scenarios for 2040. The actual production and consumption in Norway in 2017 was used as a baseline (BL), and the sustainability of future Norwegian domestic production of milk and beef was assessed through three scenarios for 2040: 1) a trend yield scenario (TrendY) based on an expected increase in milk yield following the present trend, 2) a high yield scenario (HighY) with higher increase in the milk yield per cow per year than the trend, and 3) a low yield scenario (LowY) where the milk yield per cow per year was adjusted for covering the domestic demand for beef solely from dual-purpose production and no domestic specialized beef production. The beef production per dual-purpose cow was kept constant and the remaining domestic demand in scenario 1 and 2 were covered by specialized beef production.

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Climate change was assessed using both a GWP_{100} and a GWP* approach. The HighY scenario had the lowest impact on climate change using GWP_{100}, but when taking the different behaviors of short- and long-term climate pollutants into account (GWP*), the ranking of the future scenarios changed and favored LowY. The potential biodiversity loss was lower for the LowY scenario because the proportion of concentrates in the dairy cow ration was decreased due to lower milk yield. Similarly, the feed-food competition was lower (land use ratio < 1) for the LowY. The results of our study suggest that the choice of metric for GWP and time frame highly affects the results and conclusions and strategies for climate smart and sustainable livestock production should therefore be made with caution.

1. Introduction

The global demand for dairy products and beef has increased in the last decades with the highest consumption per capita in the European region (FAO, 2022a, 2022b). A further increase in the global demand is expected due to human population growth and as a consequence of rising income and subsequent higher consumption of animal source foods in low- and middle-income countries (Henchion et al., 2021). However, as for the rest of the food system, the production of milk and beef is facing challenges including greenhouse gas (GHG) emissions, feed-food competition, and loss of biodiversity linked to land use and land expansion (IPCC, 2019). In the public debate on sustainable food systems, a lot of emphasis is given to GHG emissions (Jones et al., 2016; Ridoutt et al., 2017). Considering only GHG emissions, food products from ruminants have high impacts and are considered to be unsustainable (Garnett et al., 2017). Beef products are reckoned to have a large environmental impact per kg product compared to other livestock products and account for a large proportion of the total GHG emissions from the global food system (Gerber et al., 2013; Poore and Nemecek, 2018).

The production of beef is divided into two main production systems: 1) beef from culled cows and surplus calves from dairy and dual-purpose dairy production and 2) beef from specialized beef breeds. Dual-purpose production of milk and beef is considered to be more climate friendly as specialized beef production has higher GHG emission intensities (i.e., CO_2 eq per kg) compared to beef produced in dairy systems due to the allocation of emissions to both milk and beef (de Vries et al., 2015; Probst et al., 2019). Several studies have investigated the GHG emissions from dairy (e.g., Bonesmo et al., 2013; Mazzetto et al., 2022) and beef production (e.g., Samsonstuen et al., 2020; Pishgar-Komleh and Beldman, 2022), but few studies have assessed the entire production system including the link between the two (Zehetmeier et al., 2012). Ripple et al. (2014) stated that increased animal productivity (e.g., milk yield, growth) can provide the ability to produce the same amount of e.g. milk from a lower number of cows, thereby reducing both enteric and manure methane (CH_4) emissions and the total GHG emissions from the production. Increasing milk yield has therefore been proposed as a strategy to reduce emissions from dairy production (Gerber et al., 2011). However, due to integrated milk- and beef production, focus on optimizing milk production per cow will have trade-offs and affect the beef production (Vellinga and de Vries, 2018) and mitigation options reducing carbon footprint per litre of milk, reduce the carcass production from dairy breeds (Flysjö et al., 2012; Vellinga and de Vries, 2018) leading to a larger proportion of beef produced from specialized beef breeds to obtain the same amount of beef.

Climate change includes many greenhouse gases, but for most studies on food and agriculture it is carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) that constitute the main climate impacts. These emissions are traditionally weighted together as CO_2 equivalents (CO_2 eq) emissions using the emission metric Global Warming Potential with a time horizon of 100 years (GWP_{100}; IPCC, 1990) to reflect the global warming arising as a consequence of the production considered. GWP_{100} values for CH_4 and N_2O have changed over time as estimates of radiative forcing and atmospheric lifetimes of gases change, with the most recent estimate from IPCC Sixth Assessment Report (AR6; Forster et al., 2021). The GWP_{100} metric has been heavily criticized (e.g., Fuglestvedt et al., 2003; Shine, 2009) for e.g., the lack of equivalence to the climate impact of the emissions, especially the response of short-lived climate pollutants (SLCP), like CH_4. The emission metric GWP* has been proposed to evaluate the temperature response of the production (Allen et al., 2018), as this metric better accounts for the global temperature impact of SLCP emissions. The GWP* metric accounts for that a pulse emission (i.e., one-time emission) of CO_2 leads to a similar temperature response as an increase in the emission rate of an SLCP, such as CH_4, and weigh emissions together in CO_2 warming equivalent (CO_2 we) emissions. That cannot be compared directly with CO_2 eq emissions based on GWP_{100}, as GPW_{100} considers the accumulated radiative forcing after a pulse emission for all types of emissions. The concept and mathematical formula of GWP* has been improved through several papers (Allen et al., 2016, 2018; Cain et al., 2019; Lynch et al., 2020), with the latest from Smith et al. (2021). GWP* has also been criticized e.g., for being a climate model rather than a metric (Meinshausen and Nicholls, 2022) and for being sensitive to historical emissions of SLCPs, thereby raising questions of equity and fairness when applied on national levels rather than at a global level (Rogelj and Schleussner, 2019; Schleussner et al., 2019). Since 2021, applications of GWP* in various forms have started to emerge in studies on food and agriculture (e.g., Lesschen, 2021; Pérez-Domínguez et al., 2021; Ridoutt et al., 2022a; McAuliffe et al., 2023; McCabe et al., 2023; Pressman et al., 2023). However, the application of the method is not straight forward and Lesschen (2021) concludes that due to the different weighting of CH_4, the choice of using GWP_{100} (global warming) or GWP* (temperature impact) in the assessment can highly affect which climate mitigation policy options are seen as most beneficial, especially under stringent mitigation scenarios with large cuts of CH_4 emissions.

The intensification of livestock production and the use of concentrate feed have increased the demand for arable land, and globally, livestock and feed production occupy approximately 40 % of arable land (Mottet et al., 2017). Limiting land occupation is important to reduce the environmental impact of livestock (Steinfeld et al., 2006) and increasing yields on existing land is reckoned to improve land use efficiency (Tilman et al., 2011). However, the production of high-quality feed on arable land instead of cereals for direct human consumption causes feed-food competition (van Zanten et al., 2019). Land use and expansion of agricultural land is one of the main drivers of biodiversity loss from agricultural production (Millennium Ecosystem Assessment, 2005). However, semi-natural habitats formed by harvesting forage and grazing are among the most species-rich environments in Scandinavia, and grazing is essential to preserve this biodiversity (Austrheim and Eriksson, 2001; Fjellstad et al., 2010).

In Norway, the intensification of the agricultural sector including selection of dairy cows for increased milk yield has decreased the number of dairy cattle and increased the number of specialized beef breeds to be able to produce the same amount of beef (van Arendonk and Liinamo, 2003; Statistics Norway, 2022). Cederberg and Stadig (2003) stated the importance of modelling and analyzing milk and beef production simultaneously when studying the consequences of changing milk and beef production systems at the national level. Furthermore, highly relevant aspects such as eco-system services and feed-food competition (van Zanten et al., 2019) of intensive or extensive production systems, are also important to include to identify trade-offs between milk and beef systems. Thus, the objectives of this study were to assess the effects of three plausible milk and beef production scenarios on: 1) greenhouse gas emissions reported using two alternative metrics – GWP_{100} (CO_2 eq) and GWP* (CO_2 we); 2) potential biodiversity loss; and 3) feed-food competition in 2040; and examine how the choice of metrics for the estimation of GHG emissions affect the results. The current (2017 is used as a model year) milk and beef production and consumption in Norway is used as a baseline, and three scenarios for the milk and beef production in Norway in 2040 have been developed with different levels of milk yield per cow per year and thereby different number of dairy cows needed to maintain the same domestic total milk production and also different numbers of specialized beef cattle needed to maintain the same total amount of beef produced (dairy + beef breed).

2. Material and methods

The study included a baseline (BL) for milk and beef production, with real data, and three future scenarios. The BL included average domestic production data for 2017 for dual-purpose and specialized beef production (Table 1). The scenarios were designed to cover three future directions for milk and beef production, based on the Norwegian population's projected demand for milk and beef in 2040 (NIBIO, 2019). Therefore, the total domestic production of milk and beef was assumed similar for the future scenarios, but the milk yield per cow per year and the number of dairy and beef breed cows differed. The baseline amount of imported milk (180,439 ton) and meat (16,299 ton beef carcass) was kept constant across scenarios and was not included as a part of the further analysis. Therefore, due to the expected population growth, based on projections from Statistics Norway (Statistics Norway, 2021), the total amount of domestic production of beef needed to increase (Table 1).

2.1. Baseline

The baseline (BL) represented typical Norwegian cattle herds of dual-purpose production and specialized beef production in terms of scale and feeding regimes with production levels corresponding to average milk yields, growth performance, and beef production in Norway in 2017. The dual-purpose dairy production was based on production data of Norwegian Red (NR) obtained from the Norwegian Dairy Herd Recording System (NDHRS) and data for specialized beef production was weighted between British and Continental breeds based on the proportion of breeds from the Norwegian Beef Herd Recording System (NBHRS; Table 2). Diet compositions for dairy cattle were available through TINE Mjølkonomi®, an economic tool for milk producers, and for beef cattle through Samsonstuen et al. (2020; Table 2) which was representative for the broad spectrum of beef cattle farms in Norway. The composition of typical concentrate feeds for dairy cattle and non-dairy cattle (i.e., suckler cows, heifers, young bulls) was given by Felleskjøpet Fôrutvikling (Table S1). Manure was assumed to be deposited on pasture during summer (pasture season typically from mid-May to mid-September with a longer grazing period for specialized beef cattle; Table S3). During housing, the manure management system considered for each animal category (i.e., dairy cow, suckler cow, heifer, young bull) was based on a manure management survey (Kolle and Oguz-Alper, 2020; Table S2). To account for all emissions from manure spreading, manure was assumed to be applied on ley area for forage production during spring. Grass silage dry matter (DM) yield (6320 kg DM ha^{-1}) and the use of fertilizer (159 kg N ha^{-1}), lime (51.9 kg ha^{-1}), herbicides (1.9 L glyphosate ha^{-1} and 560 ml MCPA; 2-methyl-4-chlorophenoxyacetic acid ha^{-1}) (NIBIO, 2018; Statistics Norway, 2012; TINE, 2022), and diesel (8.02 L ha^{-1}) (Korsaeth et al., 2016) for a typical Norwegian farm was made available through TINE. The ley and pasture area corresponded to the calculated forage requirements.

2.2. Future scenarios

It was assumed that the future, domestic cattle production was covering a total consumption of 282.5 L milk and 17.8 kg beef carcass and per person as projected by NIBIO (2019), which gave a reduction per person of 15 % and 8 %, respectively, from the baseline level. The trend yield (TrendY) scenario expected an increase in milk yield per cow from BL level in 2017 from 8139 kg fat and protein corrected milk; FPCM $year^{-1}$ to 9665 kg FPCM $year^{-1}$ by 2040, from a projection of the historical trend in development in yield per cow per year (Table 1), as described by NIBIO (2019). The alternative high yield (HighY) scenario considered a further increase in milk yield, beyond trend, to the level of the upper quartile of Norwegian red in the NDHRS (10,487 kg FPCM $year^{-1}$). Both in the TrendY and the HighY scenarios, the specialized beef production was adapted to the amount of beef produced from dual production to cover the same total domestic production of beef (from dairy and specialized beef breeds). In the low yield (LowY) scenario, it was assumed that the domestic production of milk and beef was exclusively covered by dual-purpose production from the Norwegian Red and that the beef production per dairy cow was the same as in the other future scenarios. Consequently, the considerable increase in number of animals to maintain the domestic beef production, forced the milk yield per cow downwards to cover the assumed demand for milk. Therefore, the individual milk production was adjusted to a low yield (5023 kg FPCM) per cow $year^{-1}$ (Table 1) which is similar to the milk yield in the

Table 1
Population numbers for 2017 and 2040 (expected), domestic consumption and production of milk and beef in baseline (BL) and the three future scenarios for 2040: TrendY (projection of current trends for milk yield per cow), HighY (average milk yield corresponding to the upper quartile of Norwegian red in 2017), and LowY (adjusted yield to cover demand for both milk and beef only from dual -purpose cattle).

	Unit	2017 BL	2040 TrendY	HighY	LowY
Population of Norway[a]	(number)	5258,317	5856,848	5856,848	5856,848
Milk consumption per person[b]	(L)	323.0[c]	282.5[d]	282.5[d]	282.5[d]
Beef consumption per person[b]	(kg carcass)	19.3[e]	17.8[d]	17.8[d]	17.8[d]
Domestic milk production	(1000 L)	1518,945	1474,121	1474,121	1474,121
Total domestic beef production	(ton carcass)	84,981	87,847	87,847	87,847
Domestic dual-purpose beef	(ton carcass)	55,887	45,655	42,078	87,847
Domestic specialized beef	(ton carcass)	29,094	42,192	45,769	N.A.
Milk yield	(kg FPCM dairy cow^{-1})	8139	9665	10,487	5023

FPCM= fat and protein corrected milk standardized according to IDF (2015) with 4 % fat and 3.3 % protein.
[a] Statistics Norway (2021).
[b] Including imports; 180,438,614 L milk and 16,299,300 kg carcass.
[c] Calculated based on milk yield, milk delivery percentage and number of dairy cows from NDHRS (2020).
[d] Projections by Norwegian Institute of Bioeconomy Research Bioeconomy (NIBIO, 2019).
[e] Animalia (2020).

Table 2
Average Norwegian farm data for dual-purpose dairy production and specialized beef production in the baseline (BL) (2017) and the three future scenarios for 2040: TrendY (projection of current milk yield trends), HighY (expressed as the average milk yield of the upper quartile of Norwegian red in 2017), and LowY (adjusted yield to cover entire beef production from dual-purpose cattle).

	Unit	2017 BL Dual-purpose	Specialized beef	2040 TrendY Dual-purpose	Specialized beef	HighY Dual-purpose	Specialized beef	LowY Dual-purpose
Production system								
Cows		215,849	87,089	176,329	125,977	162,513	136,658	339,281
Farms		8145	4269	6654	6175	6133	6699	12,803
Farm size and management								
Dairy cows	LU	26.5	20.4	26.5	20.4	26.5	20.4	26.5
Heifers, 0–25 months	LU	29.1	22.2	29.1	22.2	29.1	22.2	29.1
Bulls, 0–slaughter months	LU	17.5	14.2	17.5	14.2	17.5	14.2	17.5
Average weight, cows	kg LW	650	622	650	622	650	622	650
Average weight, heifers	kg LW	281	353	281	353	281	353	281
Average weight, bulls	kg LW	354	373	354	373	354	373	354
Age at calving, heifers	months	25.8	26.2	25.8	26.2	25.8	26.2	25.8
Age at slaughter, bulls	months	18	16.7	18	16.7	18	16.7	18
Slaughter weight, heifers	kg CW	284	236	284	236	284	236	284
Slaughter weight, bulls	kg CW	295	329	295	329	295	329	295
Carcass production	kg cow^{-1}	260[a]	335[b]	260[a]	335[b]	260[a]	335[b]	260[a]
Time on pasture, cow	% of days	13.8	28.6	12.5	28.6	11.8	28.6	34.3
Time on pasture, heifers	% of days	16.8	29.8	16.8	29.8	16.8	29.8	16.8
Time on pasture, bulls[c]	% of days	0.4	23.7	0.4	23.7	0.4	23.7	0.4
Feed intake cows[d]								
Concentrate mixture dairy (6.84 MJ/kg DM[e])	kg DM/LU	2543	N.A.	2732	N.A.	3234	N.A.	534
Concentrate mixture non-dairy (6.79 MJ/kg DM[e])	kg DM/LU	N.A.	115	N.A.	115	N.A.	115	N.A.
Grass silage (6.16 MJ/kg DM[e])	kg DM/LU	3543	2243	3951	2243	3857	2243	3632
NH_3 straw (4.04 MJ/kg DM[e])	kg DM/LU	N.A.	353	N.A.	353	N.A.	353	N.A.
Straw (2.84 MJ/kg DM[e])	kg DM/LU	N.A.	62	N.A.	62	N.A.	62	N.A.
Grazing, arable land (6.57 MJ/kg DM[e])	kg DM/LU	283	523	283	523	283	523	544
Grazing, permanent pasture[e] (6.57 MJ/kg DM[e])	kg DM/LU	108	326	108	326	108	326	208
Grazing, outfield pasture[f] (6.21 MJ/kg DM[e])	kg DM/LU	49	161	49	161	49	161	71
DE total diet	% DM	67.82	63.63	67.76	63.63	68.05	63.63	66.31

LU= livestock units (sum of the number of days over individual animals in the category divided by 365 days); CW= carcass weight; LW= live weight; DM= dry matter; DE= digestible energy.
[a] Calculated based on carcass delivered to slaughterhouse and number of dairy cows in the Norwegian Dairy Herd Recording System in 2017.
[b] Calculated based on carcass delivered to slaughterhouse and number of cows in the Norwegian Beef Herd Recording System in 2017.
[c] The Norwegian law regulates bulls on outfield and permanent pastures. Thus, the time on pasture for bulls are before they reach 6 months.
[d] Feed intake for dairy cows was obtained using the Nordic feed evaluation system (NorFor; Volden, 2011) through TINE Optifor, including 3 % wastage. dExpressed in MJ/kg DM NEL20 (net energy lactation) equal to the feed value in a ration with 20 kg DM.
[e] Grass and herbs of good feed value on agricultural land with a clear cultural character not suitable for mechanical harvesting. Permanent pastures are normally enclosed by fences.
[f] Natural areas with meadows, heath, and moor which does not meet the requirements of permanent pastures with grazing plants spread over larger areas and lower nutritional value per area unit. Life cycle assessment.

early 90 s when the number of dairy- and specialized beef cows in Norway was 339,976 and 8298, respectively (NDHRS, 2020; Statistics Norway, 2022).

The herd size and structure (number of cows and replacement heifers) at farm level were kept constant corresponding to the BL scenario, resulting in a varying number of farms in each scenario to produce the given amount of milk and beef. In the scenarios, energy requirements and diet composition for dairy cows was obtained using the Nordic feed evaluation system (NorFor; Volden, 2011) through TINE Optifor. However, when comparing with the data given in TINE Mjølkonomi®, which are actual farm data, feed consumption was on average 3 % higher than the optimized ration. To use realistic data and have comparable diet levels in baseline and future scenarios, 3 % was therefore added to the optimized feed diet, assuming this to be storage and feeding losses (Table 2). Feed intake for heifers and bulls was kept constant at baseline level across scenarios and is given in Table S3. Ley and pasture area (ha) (i.e., for grass silage production and grazing, respectively) varied across scenarios and corresponded to the forage requirements, including loss (Table 2). Forage yields (kg ha^{-1}) and use of fertilizers (kg N ha^{-1}), herbicides (L ha^{-1}), and fuel (L ha^{-1}) were kept constant per ha, yielding different total amounts for each scenario depending on diet composition and feed requirements.

2.3. Life cycle assessment

The LCA analysis of the dual purposed dairy and the specialized beef production was conducted with SimaPro 9.0.0.30, including the impact categories climate change, land occupation, and potential loss of biodiversity (see section 2.3.4). The land use ratio (LUR) developed by van Zanten et al. (2016) was used to assess the feed-food competition through land use efficiency.

2.3.1. Functional unit

Several functional units have been used in the study (all products at the farm gate): 1) the total production of milk and beef in Norway in 2017 and 2040, 2) 1 kg fat and protein corrected milk (FPCM) produced in Norway, and 3) 1 kg beef carcass (weighted average of all beef products in each scenario). The FPCM is standardized according to IDF (2015) with 4 % fat and 3.3 % protein:

$$FPCM\ (\mathrm{kg/yr}) = Production(\mathrm{kg/yr}) \times (0.1226 \times Fat\% + 0.0776 \times Protein\% + 0.2534)$$

The quantity of milk and beef was calculated based on consumption per person in 2017 and 2040 respectively and multiplied by the number of inhabitants taking population growth into account. Intake of other dairy products, such as cheese, was converted to milk.

2.3.2. System boundaries and farm model description

The two farm models of milk- and beef production included processes from cradle to farm gate for dual purposed dairy production and for specialized beef breed production, including off-farm production of e.g., imported feed, fertilizer, transport, energy, and inputs used on the farm (Fig. 1). In terms of on-farm livestock GHG emissions, the model considered direct emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) from livestock production and indirect N_2O and CO_2 emissions associated with ammonia volatilization, run-off, and nitrate leaching, see section 2.4.3.

2.3.3. Greenhouse gas emissions

The enteric CH_4 emissions were calculated for each age and sex class using an IPCC (2006) Tier 2 approach. The gross energy (GE) intake was estimated from the energy density of the diet (18.45 MJ kg^{-1}) and enteric CH_4 emissions were estimated using a diet-specific CH_4 conversion factor for each cattle group (Ym = 0.065; IPCC, 2006) adjusted for the digestibility of the diet as suggested by Beauchemin et al. (2010; Table 3). Estimates of CH_4 emissions from manure management were based on the production of volatile solids (VS) according to IPCC (2006). The VS production was multiplied by a maximum CH_4 producing capacity (B_o) of the manure, a methane conversion factor (MCF) specific for the manure management practice, and a conversion factor from volume to mass of 0.67 kg m^{-3} (Table 3). The VS production was calculated as a percentage of manure dry matter (DM) content (Morken et al., 2013), which was estimated according to Karlengen et al. (2012; Table 3).

The emissions of N_2O were calculated using a stepwise approach described in detail by Carbon Limits (2020a). Direct N_2O emissions from manure storage were calculated by multiplying the N content of the manure with an emission factor (EF) for the manure handling system (Table S2). The N content of the manure was estimated according to Karlengen et al. (2012), based on the dry matter intake (DMI), crude protein (CP; 6.21 × *N*) content of the diet, and N retention by the animals (Table 3). Indirect N_2O emissions from volatilization of NH_3 and NOx was calculated as a proportion of NH_3 and NO_x loss from housing and manure storage (0.01 kg N_2O—N (kg NH_3—N)$^{-1}$ and (kg NO_x-N)$^{-1}$ volatilized; IPCC, 2006). Volatalization of NH_3 was calculated based on the unabated EFs from EMEP/EEA (2016), including a 50 % reduction on slatted floors. As suggested by Carbon Limits (2020b), a temperature correction factor (TCF) of 0.93 was applied to the EFs given in EMEP/EEA (2016) to account for the climatic conditions in Norway. To account for the NH_3 reduction potential of different manure storage systems, a storage-specific abatement factor (Bittman et al., 2014; Rivedal et al., 2019) was included in the model (Table S2). To account for a difference of 4.5°C in the annual average outdoor temperature between Norway and Central Europe resulting in a reduction of 15 % in ammonia volatilization, a TCF of 0.85 was applied to the EFs for storage given in EMEP/EEA (2016). Losses of NO and N_2 were estimated based on EFs given in EMEP/EEA (2016; Table S2). Indirect N_2O from leaching and runoff during storage were estimated based on the proportion of manure in different manure management systems from the manure management survey (Kolle and Oguz-Alper, 2020; Table S2) using default EFs given in IPCC (2006; Table S2).

2.3.4. Allocation

The allocation principles for feed production were based on the Product Environmental Footprint Category Rules PEFCR for feed (FEFAC, 2018) using economic allocation to distribute impacts of co-products from crop production. For allocation between meat and milk products at the farm, biophysical allocation was used according to the PEFCR for dairy products (EDA, 2018):

$$AF_{milk} = 1 - 6.04 \cdot \frac{M_{meat}}{M_{milk}}$$

where 6.04 is a constant for the empirical relationship, AF_{milk} is the proportion of emissions allocated to milk, M_{meat} is the kg live weight sold per year converted to carcass weight and M_{milk} is the mass of fat and protein corrected milk (FPCM).

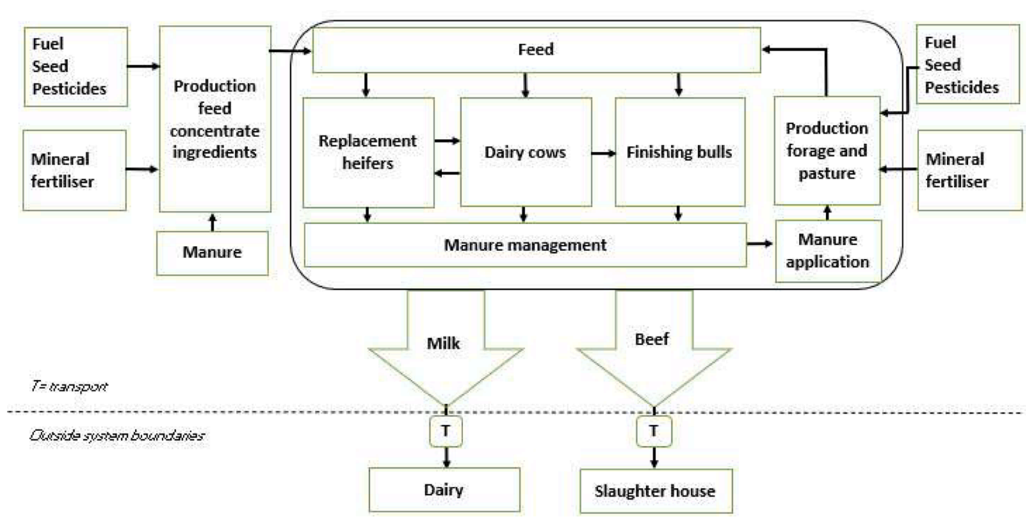

Fig. 1. General system description for the dual purposed production system. Similar system boundaries are used for specialized beef production with beef as the only product.

Table 3
Sources of GHG emissions and pollution, emission factors or equations used and their sources (see explanation of abbreviations below table).

Gas/source	Emission factor/equation	Reference
Methane (CH_4)	(0.065/55.64) kg CH_4 (MJ GEI)$^{-1}$	IPCC (2006)
Enteric fermentation		
Relative effect of digestibility (DE%) of feed, dairy	0.1150–0.0008 × DE	Bonesmo et al. (2013)[a]
Relative effect of digestibility (DE%) of feed, beef	0.1058–0.0006 × DE	Samsonstuen et al. (2019)[a]
Manure methane[b]	(0.67 × B_o × MCF) kg CH_4 (kg VS)$^{-1}$	IPCC (2006)
VS	VS% × Manure DM	Morken et al. (2013)
Manure DM, dairy cow	(514.719+(0.115 × *Y*)+(0.561 × *W*)) × 1.23	Karlengen et al. (2012)
Manure DM, beef cow	(514.719+(0.115 × *Y*)+(0.561 × *W*)) × 1.22	Karlengen et al. (2012)
Manure DM, heifer	(−677.460+(2.436 × *W*)+(27.320 × FP)-(1.326 × PF)) × 1.27	Karlengen et al. (2012)
Manure DM, young bull	(−520.898+(3.202 × SW)+(27.967 × SA)-(0.671 × PF)) × 1.26	Karlengen et al. (2012)
VS% (of DM)	0.88	
Max. CH_4 producing capacity of manure, dairy (B_o)	0.23 m^3 CH_4 kg^{-1}	Morken et al. (2013)
Max. CH_4 producing capacity of manure, non-dairy cattle (B_o)	0.18 m^3 CH_4 kg^{-1}	IPCC (2006)
Max.CH_4 producing capacity of pasture manure (B_o)	0.19 m^3 CH_4 kg^{-1}	Cai et al. (2017)
Nitrous oxide (N_2O)		
Direct N_2O manure storage[b]	EF direct kg N_2O—N (kg N)$^{-1}$	IPCC (2006)
Indirect N_2O manure storage, volatilization	0.01 kg N_2O—N (kg N) $^{-1}$ × (kg NH_3—N + NO_x-N)$^{-1}$	IPCC (2006)
Indirect N_2O, manure storage leaching	0.0075 kg N_2O—N (kg N)$^{-1}$ × Frac leach[c]	IPCC (2006)
Manure N excretion, dairy and beef cows	−120.827+(0.00798 × *Y*)+(0.0433 × *W*)+(0.605 × PF)+(0.355 × PC)	Karlengen et al. (2012)
Manure N excretion, heifer	−166.680+(0.221 × *W*)+(1.689 × FP)+(0.513 × PF)+(0.119 × PC)	Karlengen et al., 2012)
Manure N excretion, young bull	−130.554+(0.319 × SW)+(1.283 × SA)+(0.342 × PF)+(0.168 × PC)	Karlengen et al. (2012)
Direct N_2O soil N inputs	0.01 kg N_2O—N (kg N)$^{-1}$	IPCC (2006)
Indirect N_2O soil N inputs, volatilization	0.01 kg N_2O-N × 0.1 kg N volatilized (kg N)$^{-1}$	IPCC (2006)
Indirect N_2O, soil N inputs leaching[b]	0.0075 kg N_2O—N (kg N)$^{-1}$ × 0.22 kg N leached (kg N)$^{-1}$	Bechmann et al. (2012); IPCC (2006)
Phosphorus (P)		
Manure P excretion dairy and beef cows	3.358+(0.00128 × Y)+(0.00286 × W)	Karlengen et al., 2012)
Manure P excretion, heifer	−8.692+(0.0275 × W)+(0.164 × FP)	(Karlengen et al., 2012)
Manure P excretion, young bull	−5.957+(0.0403 × SW)+(0.0669 × SA)	(Karlengen et al., 2012)

GEI= Gross energy intake; DE= Digestible energy; B_o= methane potential; MCF = methane conversion factor; VS = volatile solids; DM= dry matter; Frac leach= fraction leaching; Y= milk yield, kg ECM/year; W=weight in kg; FP= feeding period in months; PF= protein content in forage,% of DM; PC= protein content in forage, % of DM; SW= slaughter weight in kg, SA= age at slaughter in months; N= nitrogen; P= phosphorus.
[a] Equation derived by Bonesmo et al. (2013) based on IPCC (2006), Little et al. (2008) and Beauchemin et al. (2010).
[b] Emission factors for specific manure management systems are given in Supplementary Table S2.
[c] Fraction leaching for specific manure management systems are given in Supplementary Table S2.

2.3.5. Impact assessment

The livestock sector is a significant contributor to several environmental problems (Steinfeld et al., 2006) among the most important are climate change, which are included in this study. Land use ratio (LUR) and potential loss of biodiversity are also included as it is important indicators from a food production perspective. Soil carbon balance was not included in climate change according to the PEFCR for dairy products (EDA, 2018) and PEFCR for feed (FEFAC, 2018). In LCA, GWP_{100} is traditionally used as the metric for the climate change indicator. To consider the different behaviors of long-lived greenhouse gases (LLGHG) and short-lived climate pollutants (SLCP), GWP* was also applied in this study and the results of the two methods were compared.

The climate change (GWP_{100}) was expressed as CO_2 equivalent (eq) emissions to account for the global warming potential of the respective gases for a time horizon of 100 years: CO_2 eq = $CH_{4_{fossil}}(kg) \times 29.8 + CH_{4_{non-fossil}}(kg) \times 27 + N_2O(kg) \times 273 + CO_2(kg) \times 1$ (Forster et al., 2021; IPCC, 2021), where we accounted for differences between emissions of CH_4 from fossil and biological sources.

Calculations with GWP* were also based on parameters from IPCC, AR6 (Forster et al., 2021; IPCC, 2021) and were expressed as CO_2 warming equivalent (we) emissions to account for warming response of the gases in a time horizon of 100 years. According to Collins et al. (2020) who argued that gases with longer atmospheric lifetimes than 50 years can be considered long-lived in such analysis, N_2O and CO_2 were treated as long-lived (i.e. CO_2 we = CO_2 eq): CO2 we = N2O(kg) × 273 + CO2(kg) × 1 (Forster et al., 2021; IPCC, 2021). As a SLCP, CH_4 is handled differently and the formula in Smith et al. (2021) was applied:

$$CO_2\ we\ = 1.13 * \left(0.75 * \frac{\Delta E_{CH_4}}{\Delta t} * GWP_H * 100 + 0.25 * E_{CH_4} * GWP_H\right)$$

where 1.13 is the scaling factor, 0.75 is the weight assigned to the rate contributions (the pulse emissions of CH_4), 0.25 is the weight assigned to the stock contributions adding the long-term effect of CH_4 through warming the deep oceans, ΔE_{CH4} is the change in CH_4 emission rate, GWP_H is the conventional global warming potential for fossil or non-fossil CH_4 (i.e. 29.8 or 27; Forster et al., 2021; IPCC, 2021) over a time horizon of 100 years, E_{CH4} is the CH_4 emissions for the year of interest (e.g. 2040) and Δt is the time period. The time period is often set to 20 years to smooth out year-to-year fluctuations but can in theory take any time period. As we were comparing emissions in 2017 with 2040 and have not made emission time series, we set $\Delta t = 1$ year to evaluate the total effect in 2040. The cumulative CO_2 we over time resemble the curve of global temperature for the emissions and was estimated by assuming the emission trend between 2017 and 2040 to be linear. After 2040, the emissions were assumed to be constant.

The land use ratio indicator (LUR; van Zanten et al., 2016) was used to assess feed-food competition from producing feed on arable land:

$LUR = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(LO_{ij}\ x\ HDP\ m^{-2}\ y_j^{-1})}{HDP\ of\ 1\ kg\ ASF}$ where LO_{ij} is the required land area (m^2) occupied in year (y) for cultivating the feed ingredient i ($i = 1$, n) in country j ($j = 1$, m) to produce 1 kg animal-source food (ASF), and HDP_j is the maximum human digestible protein (HDP) produced per m^2 in country j when cultivating food crops directly. The denominator is the amount of HDP produced from ASF when occupying the same area. The land area required to cultivate feed ingredients per functional unit was quantified and the suitability of the occupied land to directly produce food crops was determined (Table S4). It was assumed that areas used for forage production and pasture were not suitable to produce food crops. For all imported feed ingredients and domestic concentrate ingredients, all areas were considered suitable for direct food production, and HDP was calculated using country-average yields (FAO, 2019), dry matter content, digestibility, and crude protein content for the protein crop with the highest HDP yield (e.g., wheat in Norway; van Zanten et al., 2016; Table S5). The HDP from the milk and beef produced (ASF) was calculated using the average protein content of beef (0.170 kg protein per kg beef as carcass), made available through Animalia, and milk (0.033 kg protein per kg FPCM) based on a conversion from carcass to boneless beef. The digestibility of milk and beef is listed in the paper by van Zanten et al. (2016).

Land use and land use change are among the main drivers of the ongoing loss of biodiversity at a global scale (Maier et al., 2019) and, according to Rockström et al. (2009), the rate of biodiversity loss has already exceeded the planetary boundaries. The land occupation was calculated based on the areas required for feed and pastures and were expressed both including and excluding extensive grazing on outfield pastures, which under Norwegian conditions are assumed to be unsuitable for other use. Impacts on the biodiversity was assessed for the total area based on the biodiversity damage potential method by Knudsen et al. (2017), using plant species richness compared to natural conditions (i.e. forest with no management or cultivation). The biodiversity method was chosen as it includes characterization factors for permanent pasture, which is relevant for quantifying the biodiversity in a forage- and pasture-based production system where the proportion of concentrates in the diet varies, and the concentrate ingredients are similar across scenarios. The suggested characterization factors in Knudsen et al. (2017) express the potential disappeared fraction (PDF) of plant species in different spatially categorized land areas used for agriculture. In this study, the PDF values per m^2 for a conventional production system according to Knudsen et al. (2019) were used. Thus, a PDF for grass in rotation of 0.12 m^{-2} and for grass-clover in rotation 0.09 m^{-2} was used for grass silage production and grazing on arable land, respectively. To quantify the impact on biodiversity of the feed ingredients produced for concentrates, a PDF for annual crops of 0.68 m^{-2} was used for both domestically produced and imported ingredients. The PDF for permanent pastures of -0.23 m^{-2} was used for both grazing on permanent pastures and grazing on natural outfield pastures. A negative value of the PDF indicates a higher plant species diversity than in the semi-natural woodland, which is the reference (Knudsen et al., 2017).

2.3.6. Sensitivity analysis

The robustness of the climate results was analyzed with a sensitivity analysis that accounts for uncertainty (1 standard deviation) and by using a Monte Carlo simulation with 1000,000 runs. We apply the uncertainty for GWP_{100} estimated by IPCC (Smith et al., 2021). For CO_2, we account for uncertainty in radiative efficiency and CO_2 impulse response, giving a percentage uncertainty of 16 %. For CH_4 and N_2O, we sum the uncertainties for radiative efficiency, chemical response, and lifetime, in total 17 % and 24 %, respectively. We assume $CH4_{fossil}$ and $CH4_{non\text{-}fossil}$ to be dependent and have the same uncertainties, as the additional uncertainty for the fossil fuel oxidation for $CH4_{fossil}$ is small compared to the other uncertainties.

The uncertainties are estimated based on the emission differences for each GHG (CH_4, N_2O and CO_2) for HighY and LowY scenarios relative to the TrendY scenario. We treat the CO_2 eq emissions with GWP_{100} and CO_2 we emissions with GWP* for each GHG as random variables. The distribution for the total uncertainty is derived by summing the probability density functions of all GHGs. We assume that the uncertainties for each GHG are independent in these calculations. Previous work by Aamaas et al. (2016) shows that the assumption of independent radiative forcing uncertainties gives a total uncertainty range for emission reductions for a mix of species that is like the range seen between different models. In addition, they also found robustness for the method we use here for models agreeing on whether scenarios lead to relative warming or cooling.

3. Results

3.1. Climate change

At a product level, the impact of climate change (CO_2 eq, GWP_{100}) for milk and beef produced in Norway in 2017 (BL) was estimated to be 1.14 kg CO_2 eq (kg FPCM)$^{-1}$ and 22.73 kg CO_2 eq (kg carcass)$^{-1}$ from dual-purpose production and 33.75 kg CO_2 eq (kg carcass)$^{-1}$ from specialized beef production (Table S6). All future scenarios reduced the emission intensities of milk compared to BL. Across scenarios, enteric CH_4 contributed most to the climate change impact per kg FPCM and per kg beef carcass, accounting for 36–38 % of emissions from dual-production and 46 % from specialized beef production. Emissions from forage production and pasture were the second largest source, accounting for 28–34 % of total emissions from dual-production and 34 % of emissions from specialized beef production. For dual production, the proportion of emissions from the production of concentrate decreased with decreased milk yield and reduced concentrate consumption, whereas the proportion of emissions from forage production and pasture increased (Table S6).

Considering the total emissions at a national system level, including all domestic milk and beef production in Norway, the GHG emissions (GWP_{100}) were slightly reduced from 4.12 to 4.10 Mt CO_2 eq from 2017 to 2040 with the TrendY scenario. This was due to a large reduction in emissions from total dual-production and almost as large increase in emissions from total specialized beef production (see Table 4). Both the HighY and LowY scenarios led to a small increase in emissions compared to the TrendY (0.3 % and 1.1 %, respectively), due to opposite reasons. In the HighY scenario, the number of animals in thedual-purpose production was reduced when increasing the milk yield per cow. However, the relative impact from the specialized beef production increased as more beef cattle are needed to maintain the same production of beef, thereby increasing the total impact from the production system marginally, mainly due to increased CH_4 emissions. The LowY scenarios led to emissions of 4.14 Mt CO_2 eq, which was due to increase of N_2O emissions from manure deposited on the ground due to more extensive use of pastures in the dual-purpose production. Emissions of CH_4 was reduced as specialized beef production was not needed to cover the beef demand, but this reduction was about 70 % of the increase in N_2O when applying GWP_{100}.

As GWP* handles long-lived greenhouse gases (LLGHG) and short-lived climate pollutants (SLCP) differently, the scenarios re-ranked in terms of total emissions when using this metric (Fig. 2). The HighY scenario had 2.1 % higher emissions than the TrendY scenario, while the LowY scenario led to 6.0 % lower emissions, when considering the cumulative warming equivalent emissions over the 2017–2040 period. Hence, applying traditional GWP_{100} gave the conclusion that the LowY scenario had the largest impact on climate change in CO_2 eq, while using GWP* showed that the HighY scenario had the largest impact on temperature, by an even larger relative margin, in terms of CO_2 we. The GWP* methodology is sensitive to the reduction in CH_4 emissions (Fig. 2), which favored the LowY scenario where the domestic production of milk and beef was entirely covered by dual-purpose production.

This re-ranking will only apply in the period 2018–2097, as shown in Fig. 3, when assuming, for simplicity, constant emissions from 2040. The results from both GWP metrics show that from 2098 the HighY scenario give the lowest climate impact. In 2040, the HighY scenario has a cumulative effect relative to the TrendY scenario of 1.2 Mt CO_2 we, while the LowY scenario has a cumulative effect of -3.6 Mt CO_2 we. The difference between the scenarios disappears over time because of the constant N_2O emissions, which are the largest in the LowY scenario. However, if the emissions in the LowY and HighY scenarios continue to change after 2040 due to further changes in the production system, the re-ranking would continue.

Table 4
Total emissions (Mt CO_2 eq, calculated with GWP_{100}) for the domestic production of milk and beef (also specified by gas), biodiversity damage potential given as potential disappeared fraction (PDF), and land use ratio (LUR) for baseline (BL) and the three future scenarios for 2040: TrendY (projection of current trends), HighY (average milk yield corresponding to the upper quartile of Norwegian red in 2017), and LowY (only dual-purpose production; adjusted milk yield to cover demand for both milk and beef).

	Unit	2017 Baseline	2040 TrendY	HighY	LowY
Climate change, dual production	Mt CO_2 eq[a]	3.12	2.67	2.54	4.14
Climate change, specialized beef production	Mt CO_2 eq[a]	0.98	1.43	1.55	N.A.
Climate change, total production system	Mt CO_2 eq[a]	4.12	4.10	4.11	4.14
of which: CO_2 (fossil)	Mt CO_2 eq[a]	0.57	0.55	0.55	0.60
CO_2 (LULUC)[b]	Mt CO_2 eq[a]	0.13	0.12	0.12	0.10
CH_4 (biogenic)	Mt CO_2 eq[a]	1.93	1.92	1.93	1.86
CH_4 (fossil)	Mt CO_2 eq[a]	0.03	0.03	0.03	0.03
CH_4 (LULUC)[b]	Mt CO_2 eq[a]	0.00	0.00	0.00	0.00
N_2O	Mt CO_2 eq[a]	1.45	1.48	1.48	1.55
Land occupation, dual production, incl outfield pastures	1000 km^2	5081	4321	4092	7404
Land occupation, specialized beef production, incl outfield pastures	1000 km^2	2736	3968	4304	N.A
Land occupation, total production system, incl outfield pastures	1000 km^2	7817	8289	8395	7404
of which: annual crops, domestic	1000 km^2	1180	1119	1171	757
annual crops, imported	1000 km^2	354	331	351	193
grass in rotation for grass silage	1000 km^2	3031	3098	3021	3555
grass in rotation for pasture	1000 km^2	312	357	366	390
permanent pastures	1000 km^2	393	436	445	437
outfield pastures	1000 km^2	2533	2935	3028	2055
infrastructure	1000 km^2	14	13	13	15
Biodiversity damage potential, total production system[c]	PDF	773	639	627	548
Land use ratio, total production system	Dimensionless	1.26	1.21	1.27	0.79

[a] GWP100, AR6.
[b] Land Use (LU) and Land Use Change (LUC) are grouped together in the characterization method, but only emissions from LUC contribute to this impact category. The emissions occur in background processes for imported feed which are based on the Agri-footprint and ecoinvent databases. LU is not modelled for domestic feed.
[c] Including outfield pasture. Biodiversity damage potential is differentiated by type of land occupation in Fig. 4.

3.2. Land use ratio

In the Baseline, the total average LUR from the domestic Norwegian production of milk and beef from dual-purpose production and specialized beef production was 1.26 (Table 4 and Fig. 2). This is indicating that the area used for feed production would have been more efficiently used if growing human-edible food directly, in terms of protein content. In the HighY, when increasing the milk yield in the dual-production, LUR increased to 1.27, both because of increased consumption of concentrates for cows in dual-production and due to increased proportion of beef production from specialized beef production. The LowY had a LUR below 1 (i.e., 0.79), indicating the positive effect on land use efficiency of utilizing areas not suitable for direct food production.

3.3. Biodiversity damage potential

The biodiversity damage potential of domestic milk and beef production is linked to both domestic land occupation and land occupation abroad used for feed production (Fig. 4). For all scenarios, a large part of the potential disappeared fraction (PDF) was linked to the production of concentrate feed on arable land. For BL, TrendY, and HighY, the proportion was higher than the LowY because the concentrate level in the dairy cow ration was reduced due to reduced milk yield, thereby reducing both the total biodiversity damage potential and the proportion associated with the production of concentrate ingredients. The positive effect on biodiversity from grazing on outfield pastures reduced the PDF in all scenarios, because those grazed outfield pastures have negative PDF values, indicating that the plant species richness are higher than in the reference of semi-natural woodlands and much higher than the arable land.

3.4. Sensitivity analysis

The results of the sensitivity analysis (see Figs. 2 and 3) show that our climate change results are robust when accounting for uncertainty (1 standard deviation) in radiative efficiency and atmospheric lifetime for the GHGs. The ranking of the scenarios stays consistent. The uncertainties are, in general, larger when comparing LowY with TrendY than comparing HighY with TrendY, as the former is a sum of larger positive and negative contributions than the latter. With the best estimate, we observe a re-ranking occuring with GWP* in 2098 (see Fig. 3c). While the finding of a re-ranking is robust, the timing of this re-ranking can be moved a couple of decades either way when accounting for the uncertainties. Our best estimate is that the LowY scenario gives −6.0 % less emissions than the TrendY scenario in terms of CO_2 we for the 2018–2040 period (see Fig. 2). With uncertainties, we model that the difference varies between −7.4 % and −4.6 %. Similarly, the HighY scenario gives 2.1 % more emissions than the TrendY in our best estimate, with a range between 1.7 % and 2.4 %. The uncertainty spans are even smaller when applying CO_2 eq emissions in 2040, as the relative differences to TrendY scenario are smaller than when looking at CO_2 we emissions.

4. Discussion

Our study investigated the environmental impact of three future domestic production systems of milk and beef in Norway, producing the same total amount of milk and beef, but altering the production intensity of milk in the dual-purpose production. The study adopted the unique approach of using LCA of both milk and beef production systems because strategies changing the production intensity of one production system have trade-offs for the size of the other production when assuming the same total production of milk and beef. Several studies have investigated the environmental impact of milk and beef isolated (e.g., Bonesmo et al., 2013; Mogensen et al., 2015; Samsonstuen et al., 2020), and some studies have investigated the environmental impact of both dairy and beef production simultaneously (Hessle et al., 2017; Mazzetto et al., 2020). But, to the authors best knowledge, none have considered an entire cattle production system and total emissions from the Norwegian domestic production. The current study has not included soil carbon changes, due to the guideline in PEFCR for dairy products (EDA, 2018)

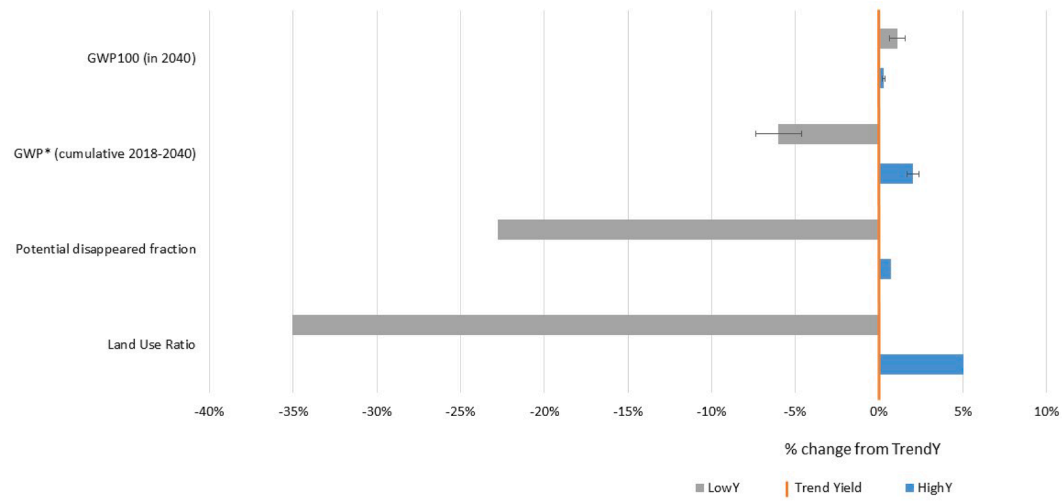

Fig. 2. Relative change from the TrendY (projection of current trends) for climate change given as GWP_{100}, GWP* in a 100-year perspective, biodiversity as potential disappeared fraction and land use ratio (LUR) for domestic production of milk and beef in the scenarios HighY (average milk yield corresponding to the upper quartile of Norwegian red in 2017), and LowY (only dual-purpose production; adjusted milk yield to cover demand for both milk and beef) in 2040. Error bars for GWP_{100} and GWP* represent one standard deviation when including the uncertainty of the emission factors in a Monte Carlo simulation.

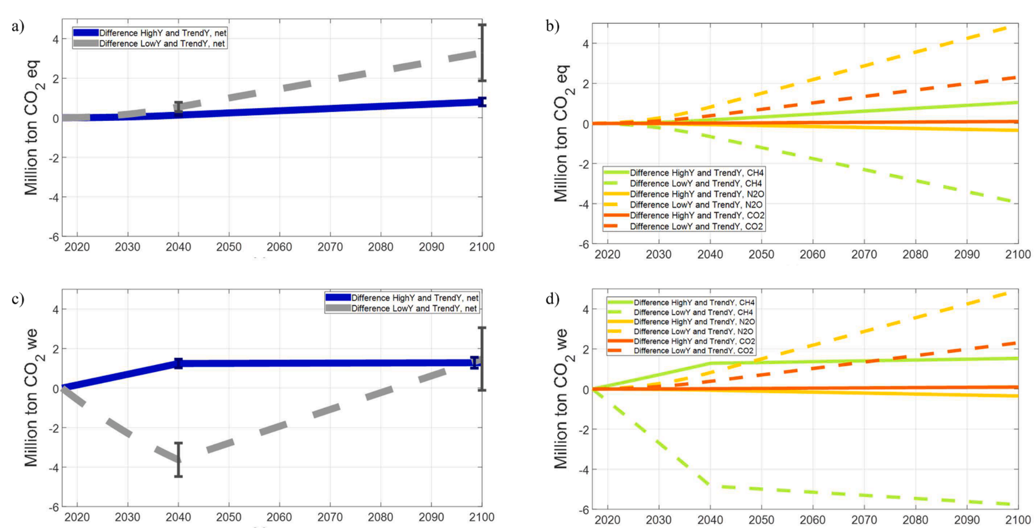

Fig. 3. a) Difference in Mt CO_2 eq from trend with GWP_{100} (AR6) for the scenarios HighY (average milk yield corresponding to the upper quartile of Norwegian red in 2017), LowY (only dual-purpose production; adjusted milk yield to cover demand for both milk and beef), b) difference in Mt CO_2 eq by gas with GWP_{100} (AR6) for the scenarios HighY and LowY, c) difference in Mt CO_2 we from the trend with GWP* for the scenarios High Yield and Low Yield, and d) difference in Mt CO_2 we by gas from the trend with GWP* for the scenarios High Yield and Low Yield. The error bars in a) and b) shows the effect of including the uncertainty (1 standard deviation) of the different cases in 2040 and in 2100 in a Monte Carlo simulation.

and PEFCR for feed (FEFAC, 2018). The new guidelines for calculating carbon sequestration in cattle production systems recommend to report sequestration separately to the carbon footprint results from the LCA (IDF, 2022). Precise estimations of soil carbon changes would require site-specific data on initial soil organic carbon content, soil moisture, and temperature in addition to the yields, mineral fertilizer, and manure application. Thus, for the purpose of modelling representative farms without a specific location, the inclusion of soil carbon changes would increase the uncertainty of the estimated results.

In the current study, the level of the estimated emission intensities (in kg CO_2 eq) from dual-purpose production and specialized beef production in the BL are in line with other studies (Bonesmo et al., 2013; Roer et al., 2013; Knudsen et al., 2019; Samsonstuen et al., 2020). When considering the total CO_2 eq emissions from the domestic production of milk and beef, the TrendY scenario had 0.3 % and 1.1 % lower emissions than HighY and LowY, respectively, when using GWP_{100} characterization factors. As the beef products from specialized beef production have a higher impact compared to dual-purpose beef, the lower total impact from the TrendY is due to a relatively higher contribution from the dual-purpose production. Enteric CH_4 accounted for 36–38 % of the emissions from dual production and 46 % from specialized beef production. Due to the high contribution of enteric CH_4, mitigation options are often directed to the diet, e.g., improved forage quality, forage to concentrate-ratio, and dietary supplements to reduce emissions from ruminant production. How emissions of CH_4 are weighted relative to N_2O and CO_2 will therefore have a large impact on what mitigation options are seen as most beneficial (Lesschen, 2021). Thus, with the introduction of GWP*, it has been argued that this metric is more fitting for agricultural emissions (Lynch et al., 2021). While comparing calculations for two separate years on a given timeline only gives a snapshot of the emissions, the full effect of the emissions can be seen with cumulative CO_2 we (warming equivalent) emissions, which

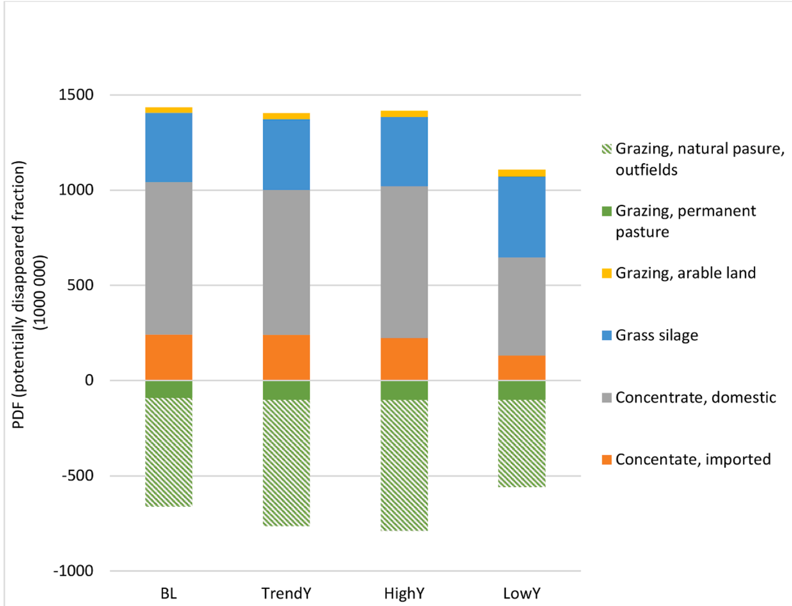

Fig. 4. Biodiversity as potential disappeared fraction (PDF; Knudsen et al., 2017) from domestic production of milk and beef for baseline (BL) and the three future scenarios for 2040: TrendY (projection of current trends), HighY (average milk yield corresponding to the upper quartile of Norwegian red in 2017), LowY (only dual-purpose production; adjusted milk yield to cover demand for both milk and beef). Net results for all scenarios are given in Table 4.

matches the changes in global temperature (e.g., Cain et al., 2019). Most studies within agriculture have not investigated the cumulative CO_2 we emissions, except for Barnsley et al. (2021) and Pressman et al. (2023), or discussed what happens after the mitigation processes have been completed. The present study considered both the cumulative CO_2 we emissions over the 2017–2040 period and extended the analysis beyond the period of interest. Relative to the GWP_{100} results, the scenarios re-ranked in terms of total emissions when considering the cumulative warming equivalent over the 2017–2040 period, favoring the LowY scenario which had 6 % lower CO_2 we emissions than the TrendY scenario. The main reason was that when using GWP_{100} the increase of N_2O emissions from the manure deposited on the ground from more extensive use of pastures dominated in dual production in the LowY scenario. In addition, the reduced warming in the LowY was related to the reduced CH_4 emissions compared to the BL. Similarly, Ridoutt (2021) compared Australian livestock production in 1990 and 2018 with both GWP_{100} and GWP*, but with no time series. Barnsley et al. (2021) investigated the cumulative effect of a diet transition to less meat and found a reduction of cumulative warming of 12–15 % but did not compare with GWP_{100}.

Which scenario leading to the smallest climate impact, when applying GWP*, depends on the time perspective. Since a linear change was assumed until 2040 and constant emissions thereafter, the difference between the scenarios stop to change in 2040 and the changes in emission rates goes to zero. Therefore, a reversing of the CO_2 we impact is seen as the calculations become more similar when using GWP* and GWP_{100} of which CH_4 is weighted less when applying the GWP* with the formulation in Smith et al. (2021), relative to applying GWP_{100}. The re-ranking of the scenarios in the current study, when comparing to GWP_{100}, therefore only applies in the period 2018–2097. Hence, when applying GWP*, the analysis should be extended beyond the time period of interest, as the conclusions based on short-term and long-term perspectives may differ.

In this study of future scenarios, we have changed only a few production parameters, keeping the total amount of milk and beef constant, thus there are only marginal differences in CO_2 eq and CO_2 we emissions. However, as GWP* is very sensitive to emission changes in CH_4, the differences between applying GWP_{100} and GWP* would be much larger by including mitigation options aiming at reducing CH_4 emissions such as improved feed efficiency (Lovendahl et al., 2018), forage quality (e.g., Åby et al., 2019), feed additives (e.g., 3-NOP; Dijkstra et al., 2018) or production of biogas (e.g., Lyng et al., 2015). Applying GWP* for documenting emissions that are near constant or declining over time estimate climate impact relatively lower than when applying GWP_{100}. By using GWP* with declining emissions the results will show a stronger and faster reduction in emissions from agriculture. It is therefore important that both methods are considered when for instance governments are looking for mitigation options to achieve ambitious emission targets. There is urgent need for reduction in emissions to limit global warming (IPCC, 2022) and the use of GWP* shows that the greatest effect is achieved in the short term by focusing on CH_4 to limit the increase in global temperature. At the same time, it is important to reduce emissions of long-lived gases (i.e., N_2O and CO_2) for long-term climate stabilization, as these have an accumulative effect. If the CH_4 emissions from the Norwegian agricultural sector were removed completely from one year to another, that would balance out more than 4 years of national emissions from all sectors in Norway when applying GWP* (Aamaas and Berntsen, 2021).

Mitigation options to reduce GHG emissions, such as diets with a high share of concentrates (de Oliveira et al., 2007; Beauchemin et al., 2008) and shorter finishing periods (Lovett et al., 2010), have been shown to reduce the environmental impact of ruminant production through reduced enteric methane emissions. But the intensification of the ruminant production with higher yield and subsequent use of high-quality feed have also increased the feed-food competition (Wilkinson, 2011) by using human-edible food directly in the feed, or by using areas suitable for food production for production of feed. Whereas the largest advance of the ruminant production is the ability to utilize land unsuitable for arable crop production (de Vries et al., 2015). Although the total land occupation on arable land in the three future scenarios are quite similar, the current study shows substantial differences in land use efficiency, measured through the land use ratio (LUR), between the LowY scenario (0.79) and the scenarios with higher milk production intensity (1.21–1.27 for TrendY and HighY, respectively). The differences in LUR were dependent on the diet composition and were connected to the land use for production of concentrate ingredients. The LowY scenario with a LUR <1.0 demonstrate the ability of the dairy and beef production system to turn human-inedible feed ingredients into human-edible products such as milk and beef, thereby contributing to efficient land use. Hennessy et al. (2021) estimated similar LUR for low yielding dairy cows in a pasture Irish production system. LUR is an important indicator of area efficiency and due to trade-offs between different impact categories, it should be considered together with other impact categories, such as the contribution to global warming and biodiversity (van Zanten et al., 2016) as done in this study. Although the proportion of pasture in the dual-purpose cow diet increase in the LowY scenario, the total land occupation including outfield pastures were lower for the LowY scenario compared to both TrendY and HighY due to the absence of specialized beef production which had a greater proportion of outfield pastures in the diet. Feeding of calves, heifers, and young bulls were similar across scenarios, and thus, changes in management and feeding of young animals could potentially increase the utilization of outfield pastures in the diet and give larger differences in land occupation across the scenarios.

Although agricultural production is a potential driver of biodiversity loss, agricultural practices such as grazing could also enhance biodiversity (Kleijn and Sutherland, 2003; Oldén et al., 2016; Pykala, 2003; Fjellstad et al., 2010; Cederberg et al., 2018). Considering the total impact on potential biodiversity loss from the domestic production of milk and beef, the PDF of the LowY scenario was lower than the other scenarios due to a lower proportion of concentrates in the dual purposed dairy cow diet when reducing the milk yield and the lower characterization factors for pasture and grass. Like Kok et al. (2020), our study showed that across scenarios, extensive grasslands offset part of the potential biodiversity loss from crop production or intensive grasslands. The chosen methodology by Knudsen et al. (2017) is designed to indicate the potential loss connected to land use using plant species richness. However, the methodology has been developed for the Temperate Broadleaf and Mixed Forest biome, which includes large parts of Europe but not the northern part to which this study applies. Nevertheless, it is assumed that the same differences between cropland and pastures apply here as well. The method does not differentiate between permanent and natural pastures, which can be argued to differ under Norwegian conditions (Fjellstad et al., 2010) and the diversity of pastures might be underestimated as optimal management and stocking densities support greater species richness than natural conditions.

Of the three future scenarios analyzed in this study, the LowY may seem the least likely because it is the opposite of the current trend. There are nevertheless some factors that can make this scenario more realistic. Firstly, in a closed system, whether it is Norway or the total global supply, it is important to see the dairy production and beef cattle production in context. The milk yield per dairy cow has increased for many years, both due to genetic progress but also due to improved management and a greater proportion of concentrate feed in the dairy cow diet. High milk yield leads to fewer cows producing the same amount of milk and thus more suckler cows are needed to meet the demand for beef. In the LowY scenario this has been resolved by adjusting the milk yield and therefore avoiding the need for beef cattle. Secondly, in Norway only a small part of the land is suitable for grain production, while there are large areas suitable for grass production and grazing. Although these factors apply, there is still a need for political instruments to achieve a transition to a LowY scenario. In Norway, import duties are already an important instrument for protecting domestic livestock production, together with other instruments such as economic support for rural development and high political prioritization of self-sufficiency of agricultural products. Thus, there is a possibility to realize a LowY scenario, without it being at the expense of the individual farmer's economic and social situation. Even if this study has several limitations, it points out some important issues to be discussed regarding the role of ruminants for future food production, when balancing the impacts on climate change. Of course, a range of mitigation strategies as previously mentioned would potentially reduce the environmental impact within each scenario investigated. Nevertheless, the study shows the potential of the dual-purpose breed Norwegian Red in a future domestic production system by efficiently utilizing feed resources and providing milk and beef. By reducing the individual milk yield in the LowY scenario, the need for high-value feed also reduces, enabling the use of domestic forage and pasture resources in the dairy production. A change in management strategies, like holding castrates on pastures, could also contribute to increased use of pasture on outlands. In addition, through breeding one could allow for more selection on carcass traits thereby providing a more optimal dual-purpose cow for covering the future demand for milk and beef.

5. Conclusion

The study explored different directions of a given domestic milk and beef production in 2040 through scenarios with different levels of individual milk yield and proportion of dual-purpose dairy and specialized beef. When assessing the sustainability of the domestic milk and beef production the entire production system should be assessed to avoid trade-offs from other parts of the production system. The intensive scenario with increased individual milk yield per cow is favored when using the traditional GWP_{100}, but this has negative consequences in terms of increased feed-food competition and reduced biodiversity. Taking the lifespan of the different climate pollutants into account using GWP*, the LowY scenario is favored, having a cumulative warming effect of −6 % relative to TrendY for the period 2017–2040. However, a reversing is seen when the changes in emission rates go to zero (i.e., CH_4 reduction ceases). Hence, when applying GWP*, the analysis should be extended beyond the period of interest, as the short-term and long-term conclusions may differ. The LowY scenario demonstrates the ability to provide the market with milk and beef exclusively from the dual-purpose production with a lower feed-food competition (LUR<1) and reduced potential biodiversity loss. The results of our study suggest that the choice of metric for GWP (i.e., global warming or temperature impact) and time frame highly affects the results and conclusions sustainable and climate smart strategies for sustainable livestock production should therefore be made with caution.

CRediT authorship contribution statement

Stine Samsonstuen: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Hanne Møller:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Borgar Aamaas:** Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Marie Trydeman Knudsen:** Conceptualization, Writing – review & editing. **Lisbeth Mogensen:** Conceptualization, Writing – review & editing. **Hanne Fjerdingby Olsen:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declaration of Competing Interest

This manuscript has not been published and is not under consideration for publication elsewhere. All authors have approved the manuscript and agree with its submission to Livestock Science. We have no conflict of interest to disclose.

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Supplementary materials

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