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Environmental impacts along intensity gradients in Norwegian dairy production as evaluated by life cycle assessments

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Abstract

The aim of the study was to explore whether and how intensification would contribute to more environmentally friendly dairy production in Norway. Three typical farms were envisaged, representing intensive production strategies with regard to milk yield both per cow and per hectare in the three most important regions for dairy production in Norway. The scores on six impact categories for produced milk and meat were compared with corresponding scores obtained with a medium production intensity at a base case farm. Further, six scenario farms were derived from the base case. They were either intensified or made more extensive with regard to management practices that were likely to be varied and implemented under northern temperate conditions. The practices covered the proportion and composition of concentrates in animal diets and the production and feeding of forages with different energy concentration. Processes from cradle to farm gate were incorporated in the assessments, including on-farm activities, capital goods, machinery and production inputs. Compared to milk produced in a base case with an annual yield of 7250 kg energy corrected milk (ECM) per cow, milk from farms with yields of 9000 kg ECM or higher, scored better in terms of global warming potential (GWP). The milk from intensive farms scored more favourably also for terrestrial acidification (TA), fossil depletion (FD) and freshwater eutrophication (FE). However, this was not in all cases directly related to animal yield, but rather to lower burden from forage production. Production of high yields of energy-rich forage contributed substantially to the better scores on farms with higher-yielding animals. The ranking of farms according to score on agricultural land occupation (ALO) depended upon assumptions set for land use in the production of concentrate ingredients. When the Ecoinvent procedure of weighting according to the length of the cropping period was applied, milk and meat produced on diets with a high proportion of concentrates, scored better than milk and meat based on a diet dominated by forages. With regards to terrestrial ecotoxicity (TE), the score was mainly a function of the amount of concentrates fed per functional unit produced, and not of animal yield per se. Overall, the results indicated that an intensification of dairy production by means of higher yields per animal would contribute to more environment-friendly production. For GWP this was also the case when higher yields per head also resulted in higher milk yields and higher N inputs per area of land.

Highlights

- Environmental impacts from milk production were lowest on farms with high yield per animal
- High yields of energy-rich forage on intensive farms contributed to lower impacts
- The proportion of concentrates in the diet per se was not important for the global warming potential

Keywords: Animal yield, concentrate type, forage quality, LCA, milk production

1. Introduction

Food production represents a significant contribution to the global environmental burden, and impacts from ruminant husbandry are of special concern (e.g. Janzen, 2011; Lesschen et al., 2011). The relationship between the production intensity and the environmental impacts per unit of milk and beef produced has recently been widely analyzed and debated in the international scientific literature, mostly in terms of the global warming potential (GWP) of the production (e.g. Crosson et al., 2011; Hermansen and Kristensen, 2011; Weiss and Leip, 2012; Bellarby et al., 2013). When using the cowshed as the system boundary, high yields per animal and high feed efficiency lower the burden (per unit produce) from enteric methane production. However, expanding the boundaries to include also the feed production chains, may change the picture, since large emissions related to the production of energy- and protein-rich feed for the high yielding animals may undermine the benefits of high animal yields. Few recent studies of dairy production have included all processes and inputs to the forage production chain (Baldini et al., 2017).

In life cycle assessment (LCA) studies, emissions related to the production and acquisition of all major inputs in a production are normally accounted for, such as the feedstuffs used in dairy production. In LCA and other modelling work based on real farm data, the relation between GWP per unit milk and the production intensity, expressed as the average herd milk yield, appears, however, to be ambiguously negative. Gerber et al. (2011) and Vellinga et al. (2011) found no significant relationship above milk yields of 6000 - 7000 kg energy corrected milk (ECM) per year and head, and in the study of Bonesmo et al. (2013), the measures were not correlated at all. On the other hand, in a recent LCA of intensive dairy farms in Italy (Guerci et al., 2013), animal efficiency expressed as milk yield per cow and milk production per unit of dry matter (DM) intake, accounted for more than 80% of the variance in GWP in the population of farms. In their study, animal efficiency was clearly separated from farming intensity, expressing livestock units and amounts of milk produced per area farm land, nutrient balances, feed self-sufficiency and N-input from purchased feed. Farming intensity was, in contrast to animal efficiency, not significantly related to GWP. These findings were supported by a study of Dutch farms (Thomassen et al., 2009), in which the authors concluded that high annual milk production per cow and efficient use of feed per kg milk produced at moderate stocking density would be the best option for reducing GWP per kg milk.

The studies by Guerci et al. (l.c.) and Thomassen et al. (l.c.) also covered other impact categories as well as GWP. In brief, their findings showed that animal efficiency was significantly and negatively correlated to environmental acidification, eutrophication and both energy and land use per unit of milk, whereas farming intensity was positively correlated to the acidification and eutrophication burdens. None of these studies included the use of on-farm capital goods in the inventories, and they did not investigate or separate consequences of different forage production strategies as options for intensification.

In a previous LCA of combined dairy and beef production in Norway (Roer et al., 2013), we did include capital goods, and hypothesized that their inclusion would add to the environmental burden associated with the small-scale Norwegian production. The hypothesis was only correct for the toxicity indicators. Here, large (on a per unit produce base) investments in capital goods such as buildings, indoor mechanization and machinery accounted for more than 20% of the environmental burden of milk and meat production. By contrast, these investments accounted for less than 10% of the total impact for GWP, acidification and eutrophication. In terms of intensification, this study of Norwegian dairy farms appeared to support the findings for Italian and Dutch dairy farms, as moderate yields per animal and low forage yields (relative to N-fertilizer inputs) were identified as the two main bottlenecks for the environmental performance (i.e. they affected several impact categories negatively). However, the actual effects of increasing the level of intensity were not tested by Roer et al. (2013). The data gathered from this study did not allow for exploration of effects of intensity in forage production, although they revealed that forage production amounted to 50% or more of the environmental impact score for nine out of twelve investigated categories.

The intensity of Norwegian dairy production, expressed as yearly milk yield per cow has gradually increased over the last decade, to the present average of 7900 kg ECM (TINE rådgivning, 2014). In some herds with Norwegian Red cattle, average yields up to 12 000 kg ECM per cow (l.c.) are found and single cows have been reported to produce 16 000 kg per year, indicating that there is a genetic potential to increase milk yields on a national basis. Hence, a thorough study is required of the environmental effects of the observed intensification in Norway, which is similar to that found in most comparable countries. It is also of interest to explore and compare the effects of different production strategies, since higher animal yields may be obtained by a range of means, including different combinations of feed, concentrates and several other factors.

In the present study, we explore whether and how the intensification of Norwegian dairy production, in terms of higher animal yields, may contribute to more environmentally friendly production, using recently improved LCA methodology (Goedkoop et al., 2012). We have envisaged farms representing intensive production strategies in three regions of the country, and included all capital goods and machinery investments regarded as necessary in a cost-effective and modern production with a long indoor housing season. Further, we have constructed and analyzed scenario farms, which are either intensified or extensified through management principles and options that we regard as likely to be implemented under northern temperate conditions, with similar farm size and structure as that found in Norway. In all these comparisons, we have used as base case a medium/normal intensity level dairy farm envisaged and analyzed in the previous study (Roer et al., 2013).

2. Materials and methods

2.1. Case description

Three farms representing intensive combined milk and meat production were selected from a defined population for further inventory and analysis. The basis and procedure for the definition and selection process have been outlined in section 2.2. The farms were located in the counties Rogaland (‘southwest intensive’; SWI), Oppland (‘central southeast intensive’; CSEI) and Nord-Trøndelag (‘central intensive’; CI). Figures for farm and herd characteristics, inputs and outputs have been listed in Table 1, and a brief description of farming practice and feeding strategies follows below. Further details are available in the Supplementary material section. The medium intensity farm serving as base case (BC) in the present study was one out of three modelled farms that have previously been described in detail by Roer et al. (2013). BC was located in central Norway, and was representative for the population of combined milk and meat production farms in this region with forage as the only plant production. This population constituted about 30% of the total number of dairy farm units. For farm and herd size, the grant data base of the Norwegian Agricultural Agency (2010) supplied the source statistics. Figures from the Norwegian dairy cooperative (TINE), representing more than 90% of the dairy farm in the region, were used to establish animal yields, diet composition of the dairy herd, culling ratio and fertility. Table 1 contributes figures for farm and herd characteristics and inputs and outputs at BC, and section 2.4. outlines small modification of the assumption made in Roer et al. (2013).

Most of the forage at the intensive farms and at BC was harvested from leys dominated by perennial ryegrass and/or timothy and meadow fescue. Mown herbage was wilted before ensiling. At CI, all silage was preserved in round bales, whereas only 50% at CSEI and 33% at SWI. The rest was ensiled in tower silos. The average transport distances between fields and barns were 1, 2 and 3 km at SWI, CI and CSEI, respectively.

The manure produced by housed animals was spread on the farm fields, some of it on bare soil before reseeding, and the rest on established grass crops in spring and after succeeding cuts, except after the last cut.

The herds comprised freestall-housed dairy cows of the Norwegian Red breed and their offspring. Number of cows in the herds was expressed as cow-equivalents, i.e. the summarized number of cow days within/throughout a year, divided by 365. Each cow-equivalent produced 1.0 (CSEI) or 1.06 (CI, SWI) living calves (50% male) annually. At CI and SWI, all heifers were recruited to the dairy herd, whereas at CSEI 16% were slaughtered at an age of 20 months. All male offspring were housed on-farm for their entire lifetime.

Mixed concentrates were fed to all animal groups in addition to silage and pasture grazing. For simplification, we assumed that all diets were composed according to the 2013 recipes of Felleskjøpet Agri, Norway (Table 2). At BC, cows were fed FORMEL Favør 80® (F80), at CI and SWI they were fed FORMEL Energi Basis 90® (E90), and at CSEI they were fed FORMEL Energi Basis 80® (E80), whereas heifers and bulls received F80. Young calves were fed a total of 350 kg each of milk (produced on-farm) during the rearing period.

Milk withheld due to treatment with antibiotics against mastitis and that used for calf feeding and private consumption was subtracted in calculations of delivery at farm gate. Figures on health and fertility care formed basis for estimates of medicine consumption.

Each farm comprised two buildings - one for storing outdoor machinery and equipment, and one for housing the cattle, including a milking pit. At CI and SWI, the manure was stored in the cellar of the latter, and at CSEI in concrete pits. Indoor and outdoor equipment and machinery have been listed under Supplementary material.

2.2. Process data

The three farms were selected from the TINE Efficiency Control data base (EC 2010), in which information from the Norwegian dairy herd recording system (NDHR) is combined with accountancy data. The population was sorted according to region and intensity expressed as milk yield per farm area and yield per cow. Restrictions for the selection were that forage should be the only plant production, amounts of purchased or sold forages should be negligible, and finally, that the dairy herd and its offspring should comprise the only animal production at the farm. These restrictions were cross-checked with the grant database of the Norwegian Agricultural Agency (2010). Within each region, one farm was chosen from subgroups of 4-5 farms with high scores on both intensity variables.

After the selection, the farmers and local advisory services (TINE Rådgiving and Norsk Landbruksrådgiving) were interviewed about management practices and forage nutritional quality. Recent forage analyses were also available. In further computations, only the net energy requirements and consumptions (expressed as FEm, i.e. milk feed units, 1 FEm = 6.9 MJ net energy for lactation (NEL)) were taken into consideration, assuming that protein requirements were met. The Norwegian net energy evaluation system and calculation formula are outlined in Sundstøl and Ekern (1992).

The calculations of total consumption of different feedstuffs by the dairy herds were based on NDHR data for the actual farms, i.e. annual average net intake of concentrates, silage and pasture per cow on energy basis (unit FEm). In NDHR, feed intake data occur from monthly reported feeding plans. These plans predict silage intake from silage quality, animal performance and energy requirement, and concentrates are offered in amounts and qualities to meet the total energy and protein requirements of each cow individually. The reported concentrate consumption is regarded to be in close agreement with actual intake. During summer, pasture intake is calculated as a difference between total net energy requirements minus energy supplies from silage, concentrate and other feedstuffs, if fed. At the farms in the present study, the diets consisted of silage, mixed concentrates and pasture only. Diet composition for calves, heifers and bulls were based on feeding recommendations from TINE Rådgiving and Felleskjøpet AS and feeding standards for the respective ages and genders (Sundstøl and Ekern, 1992), as outlined in Roer et al. (2013). The bulls were kept indoors their entire lifetime, whereas the dairy herds were kept outdoors for a minimum of eight weeks. However, pasture contributed only to 3, 5 and 10% of the annual net energy intake at CI, CSEI and SWI respectively. At CI, the heifers were kept indoors all year through, whereas at SWI and CSEI they were on pasture from May until October, but with some additional feeding with silage and concentrates at CSEI.

Net energy yields from leys and pastures were estimated from the calculated consumption of silage and pasture by the herd. For preserved forage, losses amounting to 11% were added to the net yields to account for losses during preservation and storage (Randby et al., 2015). For the calculations of emissions from crop residues an additional moderate loss of 5% was assumed.

The consumption of drugs against mastitis and intestinal worms, as well as disinfectants were based on common practice as communicated by local vets and farmers, combined with data from NDHR. The consumption of detergents and mineral supplements were set according to recommendations given by the suppliers.

The type, size and construction costs of the buildings were adapted from www.innovasjonnorge.no/kufjos (accessed December 2012) after some modifications and by using a building cost indexes of 1.1. Costs of machinery related to the animal housing were collected from suppliers. Tractor lifetime was set to 15 years, which is somewhat longer than that suggested in Ecoinvent (12 years) (Nemecek et al., 2004), but more in accordance with current Norwegian practice. Lifetimes of other equipment were set according to Ecoinvent. The transport distances from the outer boundary were set to the shortest driving distance from the suppliers to the farm locations. The diesel requirement and consumption of lubrication oil for all field work processes were estimated as explained by Roer et al. (2013).

2.3. System boundaries, processes, functional units and allocations

The assessment covered most processes involved in dairy and meat production and the production of relevant inputs up to the farm gate (Fig. 1). It covered the production and acquisition of diesel and oil, fertilizer, lime, seeds, pesticides, fencing material, polyethylene and additives for silage production, detergents, medicines, sawdust, cow mattresses, concentrates and mineral supplements needed on the dairy farms, fieldwork processes, on-farm transport as well as animal feeding and management processes. We also included the production and acquisition of buildings, machinery and equipment. The acquisition included transport of all major inputs including healthcare services, but not small articles of consumption (e.g. polyethylene net and film, additives, detergents, mineral supplements).

The functional units were one kg ECM (with 4.2% fat, 3.4% protein and 4.7% lactose) and one kg slaughter carcass (calculated as liveweight × 0.5, with 20% protein) delivered at the farm gate. The dressing proportion of 0.5 (mean for cow and bull carcasses) was as according to Randby et al. (2010), Animalia (2011) and Animalia (2016).

Economic modelling was used to allocate impacts between milk, slaughter carcasses and manure, as described by Roer et al. (2013). We chose to use production prices, as prices are closely linked with net revenue, which again form the basis for most farmer choices. The environmental burdens for manure production and spreading were retained within the systems, since all manure was recycled within the farm.

Environmental impacts caused by fodder production were allocated between the husbandry (i.e. cows, bulls, heifers and calves) according to their relative fodder consumption. The housing was allocated analogously according to the space required, while mattresses, medicines and detergents were allocated on the basis of their use.

The milking and milk-cooling processes were assumed to consume 90% of the electricity used, while the remainder was allocated to non-milking activities. Environmental effects of milk wasted on-farm were allocated to milk delivered. Loss of preserved silage during storage and feeding were allocated between the husbandry groups according to their silage intake.

2.4. Scenario outlines

Six different scenarios were outlined, all with a total production of about 133 000 kg ECM year^{-1} delivered at the farm gate. The yearly total production was obtained under contrasting feeding regimes and corresponding differences in animal yields and numbers (Table 3). Small deviations to the production target were accepted in order to keep the number of cows realistic. The total production was thus the same as that of the base case selected for comparisons, which was the medium intensity farm located in central Norway inventoried and analyzed by Roer et al. (2013). A few small modifications were made to the base case, resulting in slightly altered outputs from the re-analysis of the base case inventory. The one surplus heifer was assumed slaughtered and included in the meat delivered from the farm rather than sold as livestock, and the environmental impacts attributed to grain used in concentrates were changed in accordance with a more recent LCA of Norwegian grain production (Korsaeth et al., 2014). Further, the amount of manure produced per head and year was increased according to more recent standards (Karlengen et al., 2012), and the amount of mineral fertilizer applied per ha was decreased correspondingly.

The 133 000 kg ECM was assumed to have been produced with low, medium or high milk yield per animal (Table 3). The yearly yield per head was allowed to vary according to feeding regimes that were developed by varying the proportion, and partly the type of concentrates in the diet and the energy concentration of preserved forage (feed energy units per kg DM). The feed intake (proportionally) from pastures and the quality of the pasture were kept constant and as in base case for all groups of animals.

All male calves from the dairy herd were always assumed to have been fed on the farm until they reached a carcass weight of 300 kg. In the scenario in which high energy silage was produced for high yielding dairy cows, growing bulls were finished at 16 months age (Table 3), whereas in all other cases male offspring were finished at 18 months.

By combining different forage energy concentrations and concentrate proportions in cow diets, and letting these factors influence crop and animal yields, ley renewal frequency and area demands (Table 3), we have explored the environmental impacts along intensity gradients in forage production, concentrate feeding and milk yield per animal. Parallel to the gradient in milk yield (6000 -7250 - 12000 kg ECM per cow and year) there was a gradient in feed efficiency from 1.3 via 1.4 to 1.6 kg ECM per milk feed unit (FEm). The management of the forage crop and the resulting yields have been outlined in Table 4, and were adapted from experience and from the results of previous research (Bakken et al., 2009; Flaten et al., 2015).

2.5. Emission estimation

Methane emissions from enteric fermentation were estimated according to a Tier 3 methodology (Volden and Nes, 2006). This is based on figures for gross energy intake and a methane conversion rate, with parameters depending upon lactation yield and the proportion of concentrates in the diet. For the replacement heifers and slaughter bulls, the estimates depend on their age and carcass weight.

The methane emissions from manure were estimated in accordance with the Norwegian default IPCC Tier 2 method (IPCC, 2006; Statistics Norway, 2010), and the daily manure, N and P production for dairy cattle was calculated according to Karlengen et al. (2012). Direct nitrous oxide emissions were calculated from the N content in manure (stored, spread or dropped from grazing animals), N applied in fertilizers and N in crop residues according to the methods in The Norwegian Emission Inventory (Statistics Norway, 2010). For the N applied in fertilizers, we used an emission factor of 0.010 kg N_2O-N kg^{-1} N in accordance with the IPCC standard (IPCC, 2006). Nitrous oxide emissions from biological N fixation were assumed to be negligible (IPCC, 2006). Indirect nitrous oxide emissions originate from the re-deposited N lost through volatilization, leaching or runoff. N volatilization from mineral N fertilizer was set in accordance to IPCC-standard (IPCC, 2006). Annual indirect nitrous oxide emission from atmospheric deposition of N to soil and water surfaces was calculated in accordance with IPCC standards, i.e. multiplication of the N volatilized (mineral fertilizer and manure) by the default N_2O emission factor of 0.01 kg N_2O per kg N volatilized (IPCC, 2006). N loss through leaching and runoff was estimated as 18% of N applied (Statistics Norway, 2010) in fertilizer and manure corrected for the volatilized N loss. The annual indirect N_2O emission through the water pathways was then calculated in accordance with IPCC standards, using the default N_2O emission factor of 0.0075 kg N_2O-N per kg N lost (IPCC, 2006). Although waterway N losses depend not only on applied N, but also on soil and meteorological conditions, we did not differentiate between the three regions. The justification for this was that N-leaching affects mainly the environmental indicator marine eutrophication, which was not evaluated in this study. The effects of N-leaching on GWP, through indirect N_2O emissions, are only marginal.

Soil organic C changes were assumed to be negligible both for the permanent pastures and in total including the years between renovations of leys. It was assumed that liming was performed after breaking of leys, but the average annual CO_2 emissions were calculated in accordance with IPCC (2006), i.e. as if the annual lime requirement was added each year.

For diesel combustion, emissions of 2.64 kg CO_2 per liter were adopted (National Energy Foundation, 2010).

A total P loss from the farm of 1.75 kg P ha^{-1} yr^{-1} in CI and 1.5 kg P ha^{-1} yr^{-1} in SWI and CSEI were set on the basis of results from several field experiments and monitoring series (Hauken et al., 2012). All P loss was assumed to be in the form of phosphate.

The acidification compounds accounted for are ammonia volatilized from manure (35% of total N applied) (Statistics Norway, 2010) and applied mineral fertilizers (2% of total N as NH_3-N; Bouwman et al., 1997), nitrogen oxide from mineral fertilizer (IPCC, 2006) and NO_X emission from on-farm diesel combustion (Li and McLaughlin, 2006).

For occupation of agricultural land (ALO), the area covered by different forage crops was not weighted according to the length of the cropping season. This is also true for the land occupation of Norwegian grain products (wheat, barley, oat) in concentrates (Korsaeth et al., 2014). To explore the effects of this deviation from the procedure implemented for annual crops in Ecoinvent, scores on ALO were calculated with and without weightings for the two concentrate types F80 and E90 (Table 2).

2.6. Implementations

The LCA approach was carried out using the Matlab software (version R2013b). The ReCiPe method (Goedkoop et al., 2012) was used for the impact assessment. Results for six impact categories have been presented here. These are global warming potential (GWP), terrestrial acidification (TA), agricultural land occupation (ALO), fossil depletion (FD), terrestrial ecotoxicity (TE) and freshwater eutrophication (FE). GWP is here equivalent to the impact category climate change (abbreviated CC) in the description of the ReCiPe method (Goedkoop et al., 2012).

Information for the production of agriculture machinery, tractors, diesel, oil, lime, pesticides, seeds, detergents, sawdust, phosphorus and potassium in mineral fertilizer, as well as data for transportation was taken from the LCA-database Ecoinvent (Nemecek et al., 2004). The production of sawdust was modified in that its impact on ALO was not included in this study. The input output database EXIOPOL (2011) was used for the production of buildings, medicines and indoor machinery. Data for the processing and manufacturing of the concentrates used were collected from the supplier (Felleskjøpet), whereas production of their ingredients was based on Ecoinvent and recent studies of Norwegian grain production (Korsaeth et al., 2014). The system boundaries for ingredients gathered from Ecoinvent and for grain produced in Norway differed. In the studies of Korsaeth et al. (l.c.), soil organic carbon mineralization, production and application of pesticides and production of machinery and building were taken into account (Fig. 1). These wide system boundaries were applied for Norwegian grain in all analyses with milk and meat as functional units in the present study. However, the consequences of excluding these processes and narrowing the system boundaries were explored in additional analyses of environmental impacts from concentrate production, with feed energy as functional unit.

Finally, production of the nitrogen component of mineral fertilizer was included in the inventory, based upon Best Available Technique, Yara and Ecoinvent (Davis and Haglund, 1999; EFMA, 2000; Nemecek et al., 2004; Yara, 2011).

3. Results

For the functional units 1 kg ECM and 1 kg carcass weight, total impacts for the categories Global warming potential (GWP), Agricultural land occupation (ALO), Fossil depletion (FD), Terrestrial acidification (TA), Terrestrial ecotoxicity (TE) and Freshwater eutrophication (FE) have been assigned to the sub-processes concentrate production, on-farm forage production (including field emissions), direct emissions from cattle and other inputs representing production of buildings, machinery, medicines, detergents and related transportation (Figs. 2-4). For the functional unit FEm (milk feed unit) in concentrates (two types × two system boundaries), impacts have been assigned to the different ingredients, whereas impacts related to forage (three levels of net energy concentration) have been assigned to buildings/machinery, manure, mineral fertilizer, on-farm driving, field emissions and land use and other inputs (silage additives, polyethylene) (Fig. 5).

3.1. Real farms

At the three inventoried intensive farms (SWI, CI and CSEI), milk was produced with overall lower environmental impacts than at the medium intensive base case, with exception for TE. For this category the score was 13% higher for CSEI than for the base case (Fig. 2). Meat attained lower scores at the intensive farms for the categories GWP, ALO, FD and FE, and lowest at SWI, where bulls were slaughtered at the youngest age (Table 1, Fig. 3). TA was higher at CI and CSEI than in the base case (Fig. 3)

The relative contribution from different processes varied between impact categories. For TA, ALO, FD and FE, forage production (and related field emissions) accounted for most of the impact, whereas methane emissions from cattle, contributed most (40-50%) to the GWP, both for milk and meat (carcass) production (Figs 2-3). No principal differences between the medium intensity farm and the more intensive ones appeared with regard to relative contributions from different processes. The absolute and relative environmental burdens from concentrates were closely related to the concentrate proportion of the diet (Table 1, Figs 2-3), and not to the intensity per se.

3.2. Scenario farms

3.2.1. Effects of concentrate proportion in the diet - constant forage quality

In the first two scenarios (A and B), concentrate type, forage quality and animal yield were kept the same as in the base case (F80, 0.85 FEm kg DM^{-1}, 7250 kg ECM cow^{-1}), but with the concentrate proportion in the diet changed from 40% (base case) to either 25% (case A) or 55% (case B). Relative to the base case, differences in score on milk GWP, ALO and FD were small or negligible (Fig. 4). For B, the indicators TA and FE were 4 and 6% lower than at base case, respectively, whereas for TE the score was 34% higher. The low concentrate proportion case (A), represented an improvement relative to base case for the score on indicator TE, whereas the environmental loads for the other indicators (TA, FD and FE) were marginally higher (Fig. 4).

3.2.2. Effects of forage quality and animal yield – constant proportion of concentrates

In the two scenarios C and F, the proportion of concentrates in the diet was kept as in the base case (40%) (Table 3), but the level of forage energy concentration (forage quality) was changed from medium (base case, 0.85 FEm kg DM^{-1}) to either low (case C, 0.80 FEm kg DM^{-1}) or high (case F, 0.95 FEm kg DM^{-1}). This change was made to affect the yearly milk yield also, which changed from medium to either low (case C, 6000 kg cow^{-1}) or high (case F, 12000 kg cow^{-1}) (Table 3). Comparing scenario C and F with the base case, the scores were highest overall in case C and lowest in case F (Fig. 4).

3.2.3. Effects of substituting low forage quality with high concentrate proportion

In scenario D, the concentrate proportion was increased (to 50%) to compensate for low forage energy concentration, whereas in case E it was reduced (to 35%) at high energy concentration. In both cases, animal yield was kept constant (medium, as in the base case).

The effects of substituting low forage quality by a higher concentrate proportion (case D) and *vice versa* (case E), followed the same pattern as when comparing effects of changes in concentrate proportion with constant forage quality (case A versus case B), but the differences in environmental impacts were slightly smaller. The largest difference between cases D and E was observed for TE, as it was also for cases A and B. The score on TE is thus mainly a function of the amount of concentrate fed per functional unit produced, being highest in case D (and B). For the indicators TA, FD, FE, the scores were highest in cases where the forage proportion was high; i.e. in case E (and A). For GWP there were hardly any differences, and for ALO, the score was lower at the low concentrate proportion case E than it was in case D.

3.3. Feed types

When interpreting the impact scores for medium (0.85 FEm kg DM^{-1}), low (0.80 FEm kg DM^{-1}) and high (0.95 FEm kg DM^{-1}) energy forages presented in Figure 5, it is important to be aware that they were influenced by the characteristics of the whole system within which they were produced, and not only by processes directly related to forage production. Although the total milk production and yield per animal were the same, the proportion of concentrate used in the animal diets differed between the farms base case, D and E, where the three forage types were produced. The environmental burden with animal origin (e.g. emissions from spread manure) allocated to forage production became therefore higher per unit forage field area and forage energy, as the proportion of concentrate increased.

Most of the environmental impact caused by forage production was related to on-farm emissions and operations (Fig. 5). One exception was FD, where buildings+machinery, purchased mineral fertilizer and other inputs to the system, accounted for more than 70% of the impact.

There were small differences between the forage types in total impact per energy unit. Regarding GWP, the rank in score from medium to low to high energy forage was related to differences in field emissions (Fig. 5), which again had their origin in the level of N-fertilization per harvested energy yield (Table 4). For TA, which mainly expresses the acidifying effect of ammonia evaporating from manure, the emissions per unit were highest for low energy forage. In system D, producing low energy forage, the proportion of concentrate in the diet was as high as 50%, and as explained in the section above, the lower demand and production of forage, led to more impact per produced forage unit.

The score for forages on ALO mirrored the energy yield per unit of farmland, and the lowest impact was for the high energy forage with the highest energy yields (Table 4). For FD, the total score was about the same, but the various sub-processes contributed differently (Fig. 5), very much reflecting inputs and investments per unit forage energy produced. For instance, the impact related to mineral fertilizer production was highest for high energy forage at the highest rate of fertilization (Table 4), and the impact related to machinery and buildings was highest within system D where least forage was produced. TE was negligible for the production of all forage types. For FE, the main contribution was from field emissions/land use, and for the three types of forage the ranking was medium>low>high energy, as for yield level (Table 4).

The environmental burden from production of concentrates was lower than for forages for the impact categories TA and FE, and higher for TE, irrespective of system boundaries (Fig. 5). For GWP, ALO and FD, the ranking was dependent upon the type of concentrate and/or the system boundaries for concentrate ingredient production. The GWP was lower for the concentrate type F80 with the highest proportion of grain produced in Norway (73% w/w, versus 37% in E90), and it was also marginally lower than for forages, even when soil organic carbon mineralization and production of machinery, buildings and pesticides were included (wide system boundaries). The score on ALO was higher for E90 than for F80 because yields of soy were lower than yields of Norwegian grain (Fig. 5, Table 2). When land occupation in grain production was not adjusted according to the length of the cropping period (part of whole year), F80 scored higher on ALO than did both E90 and forages.

System boundaries were also important for the score on FD. With wide boundaries, the FD per energy feed unit was as high as or higher for concentrates than for forages. For TE, rape

meal and seeds contributed much more to the score than did any other ingredient (Fig. 5, Table 2), and the proportion of this feed source in the concentrate (8% and 2% rape meal, and 3% and 5% rape seed, in F80 and E90, respectively) determined the total impact. For the impact category FE, a higher proportion of soya beans in E90 than in F80 (9% versus 24%) was the explanation for the higher score per energy unit in the former (Fig. 5, Table 2).

4. Discussion

Achieving higher animal yields than medium and low levels appeared to reduce the environmental impacts from milk production in five out of the six evaluated categories. For GWP, this was the case when higher milk yields were obtained by using either a high forage energy concentration (SWI, scenario F) or a high proportion of concentrates in the diet (CSEI), and also when higher yields per head resulted in higher milk yields and higher nitrogen inputs per area land. These results were not in agreement with the findings of a previous study on Norwegian milk production (Bonesmo et al., 2013), in which no correlation between GWP per unit milk and animal yield was found. In their study, methane emissions from cattle were calculated according to Tier 2, and emissions per kg fat and protein corrected milk (FPCM, almost equal to ECM) were obviously lower both in absolute and relative terms than in our study where Tier 3 methodology has been implemented. Animal yield was therefore relatively more important for the final GWP with our approach.

At medium (base case) animal milk yield, the diet composition seemed to be of minor importance for the score on GWP, although the methane conversion rate in the rumen was allowed to be influenced by proportion of concentrates in the diet, according to Volden and Nes (2006). In this regard, it should, however, be taken into consideration that at medium forage energy concentration, an increase of concentrate proportion in the diet would have allowed an increase in animal yield as well. When assuming no change in animal yield, the upstream burden from concentrate production nearly equalled that from forage production when carbon mineralization in soil during grain cropping was taken into account (i.e. with wide system boundaries).

Further, the on-farm environmental burden of animal origin (e.g. manure on and in soils), would be about the same in absolute terms, irrespective of feed ration. The higher proportion of concentrates (produced off-farm) in the diet, the higher were the rates of manure application and N deposition on farmland used for forage production within the system. These facts and findings illustrate that alternative strategies for farming practices (e.g. forage production) should always be investigated in a whole-system context with fully developed soil-plant-animal cycles. The scenario methodology developed and applied in the study also allowed a comparison of different strategies without confounding of climatic and edaphic factors that often occur when a descriptive approach based on real farm data is applied.

For the categories TA, FD and FE, the relationship between animal yield and impact score was ambiguous. Regarding the real farms, the milk from the South-West farm (SWI), had a lower score than CI (with equal yield per cow). The farming intensity, expressed as milk yield per area unit, was substantially higher at SWI than at either the base case or CI and CSEI. On the basis of the studies by Guerci et al. (2013) and Thomassen et al. (2009), the acidification and eutrophication burden (here TA and FE) from the practice and production at SWI could therefore be expected to be highest. What kept the score lower was the higher level of forage yields at SWI (in both DM and energy units).

For the scenario farms, the milk scores on TA, FD and FE were lowest at the farm with the highest animal yield, which also represented the highest farming intensity and attained the highest feed energy yields per field area unit.

The ranking of farms according to score on ALO was not the same as for GWP, TA, FD and FE. Forage yields per area unit was of course important, as was also the amount and composition of the concentrates fed to animals. In Norway, the short growing season never allows more than one grain crop to be grown per year, and we did not find it relevant to weight the area occupation by such crops according to their actual growing period. Milk and meat based on concentrates with a high proportion of barley, oats and wheat of Norwegian origin, thus fared less well in the assessment than those based on imported products inventoried in Ecoinvent. For the concentrate type F80 (fed to cows in base case and scenario cases A-D), ALO per unit feed energy was halved if Ecoinvent principles were applied also for Norwegian grains. The striking effect of different calculation practices should also be considered when consequences of forage-based versus more concentrate based diets are evaluated.

In the previous LCA of combined milk and meat production on Norwegian farms with medium animal yield (Roer et al., 2013), it was concluded that Norwegian products had high scores on most impact categories compared to products from other European countries. This was irrespective of the wide system boundaries that were applied. Low yields in animal and forage production, especially relative to nitrogen inputs to the system, were assigned as weak points. The intensifications from medium level that have been explored through construction of scenario farms in the present study, would result in reductions in environmental burden, at least for GWP. The inventories of real farms with high animal yields confirmed this. For the other indicators, high animal yields sustained by high yields of energy-rich forage, seemed to cause improvements relative to the base case, also at higher rates of N fertilization, higher farming intensity and higher cow replacement rates.

Parallel to the ongoing increases in animal yield in milk production in Norway, changes occur in farm size and structure, leading to more land rental, increases in transport distances of manure and forage and, in some instances, sub-optimal agronomic practices and poorer nutrient use efficiency in plant production. The present study has not addressed these issues and their side-effects because they are not within the scope of exploring effects of intensification per se. The authors are still aware that they should be taken into consideration when agricultural policies and future regulations of dairy farming are developed.

In the debate over the sustainability of intensive dairy farming, it has also been argued that high animal yields cause fertility problems and result thereby in less efficient production. In a study by Ødegård (2011), herds with high fertility scores had actually higher milk yields compared to those with low fertility scores. Consequently, in our scenario development, we found no reason to differentiate between farms and yield levels with regard to this measure.

5. Conclusions

Our results indicated that an intensification of Norwegian dairy production by means of higher yields per animal would contribute to more environment-friendly production. For GWP this was also the case when higher yields per head resulted in higher milk yields and higher N inputs per area of land, irrespective of the composition of diets and forage production strategies.

Also for impact categories TA, FD and FE, the milk from farms with high-yielding animals scored more favourably. This was not in all cases directly related to animal yield, rather to a lower burden from forage production. Production of high yields of energy-rich forage contributed substantially to the lower scores on impact categories at farms with high compared to lower yielding animals.

At a medium level of milk yield, the diet composition was of minor importance for the GWP score. The upstream burden from concentrate production nearly equalled that from forage production when carbon mineralization in the soil during off-farm grain cropping was taken into account. Furthermore, the on-farm environmental burden of animal origin (e.g. emissions related to manure on and in soils), was about the same in absolute terms, irrespective of feed ration. The higher proportion of concentrates (produced off-farm) in the diet, the higher were the rates of manure application and N deposition on farmland needed for forage production within the system. These results and relationships illustrate how important it is to interpret LCA results with an eye to the allocation principles chosen, and to investigate alternative strategies for farming practices in a whole system context with fully developed soil-plant-animal loops.

Conflict of interest statement

No actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations.

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Table 1 Farm and herd characteristics and yearly inputs, intermediary products and outputs for a base case farm (BC) and three intensively managed dairy farms in southwest (SWI) central (CI), central southeast (CSEI) Norway.

	BC	SWI	CSEI	CI
Farm size and management				
Arable land (ha)	22.5	26.0	48.5	30.0
Permanent pastures (ha)	2.0	5.9	10.5	0
Dairy cows (cow-equivalents)	20	32	50	32
Cow replacement rate (%)	45	50	42[a]	53
Age at slaughter, bulls (months)	18	16	17	18
Number of cuts per year on leys (units)	2	4	2	2/3
Ley renewal interval (years)	5	5	4/13	4
DM content of wilted grass and silage (%)	26	35	30	30
Net energy content of silage (FEm kg DM^{-1})	0.85	0.92	0.84	0.89
Pasture, dairy cows (% of total energy intake)	12.5	10	3	5
Pasture, heifers (% of total energy intake)	34	42	39	0
ECM yield (kg $cow\text{-}equivalent^{-1}$)	7250	9000	8700	9000
ECM yield (kg ha^{-1})[b]	6440	11080	8970	9600
Inputs				
Mineral fertilizer on (all) arable land (kg N ha^{-1})	140	177	119	160
Mineral fertilizer on perm. pastures (kg N ha^{-1})	0	37	25	-
Diesel in forage production (litres)	3380	4760	8220	6370
Concentrates, cows (% of total energy intake)	39	36	48	42
Concentrates, heifers (% of total energy intake)	19	20	22	25
Concentrates, bulls (% of total energy intake)	40	45	44	40
Electricity (kWh)	26000	34000	123000	34000
Intermediate products				
DM yield, arable land (kg ha^{-1})[c]	6300	7940	6440	7650
DM yield, permanent pastures (kg ha^{-1})	2500	4000	2800	-
Stored manure (tonnes)[d]	855	2496	2397	1723
Outputs				
ECM delivered to dairy plant (kg)[e]	133000	265800	401500	265100
Cow carcasses delivered to slaughter plant (units)	9	16	21	17
Cow carcass weight (kg $carcass^{-1}$)	270	270	270	270
Bull carcasses delivered to slaughter plant (units)	10	16	25	17
Bull carcass weight (kg $carcass^{-1}$)	300	300	310	300
Heifer carcasses deliv. to slaughter plant (units)	1	0	4	0
Heifer carcass weight (kg $carcass^{-1}$)	270	-	230	-

DM: Dry matter, FEm: Milk feed units, net energy value according to the Norwegian net energy evaluation system for ruminants (Ekern and Sundstøl, 1992), ECM: Energy corrected milk.

[a] Four heifers slaughtered at the age of 20 months each year have not been accounted for here

[b] Gross milk production per area of arable land

[c] Average for annual ryegrass and perennial crops in years of establishment and later years of ley

[d] With 6.5% DM at BC, CI and CSEI, and with 4% DM at SWI

[e] Milk fed to calves and withheld due to antibiotics treatments has been subtracted

Table 4. Management of perennial leys (year of establishment not included) for production of forage with low, medium and high feed energy concentrations fed in scenario cases.

	Feed energy concentration in forage		
	Low	Medium	High
No of cuts (year $^{-1}$)	2	2	4
Phenological stage of timothy at 1st cut	Heading	Early heading	Stem elongation
Renewal interval (years)	6	5	4
N-fertilization (kg ha^{-1} year^{-1}), manure included	212	202	260
DM yield (kg ha^{-1} year^{-1})	7100	6300	6130
Feed energy concentration (FEm kg DM^{-1})	0.80	0.85	0.95
Feed energy yield (FEm ha^{-1} year^{-1})	5720	5360	5730

Table 2. Proportion (weight/weight) and scores on impact categories for ingredients in concentrates F80 (0.97 FEm kg^{-1}), E80 (1.03 FEm kg^{-1}) and E90 (1.03 FEm kg^{-1}) fed to the herds of real and scenario farms.

Ingredient	Concentrates			Environmental impact per kg ingredient					
	F80	E80	E90	GWP1)	TA1)	ALO2)	FD1)	TE1)	FE1)
				kg CO_2-Eq	kg SO_2-Eq × 10^{-3}	m^2	kg oil-Eq × 10^{-2}	kg 1,4-DCB-Eq × 10^{-3}	kg P-Eq × 10^{-4}
Norwegian barley	0.40	0.60	0.30	0.48/0.75	6.07/6.45	0.77/2.64	6.08/9.15	1.41/1.42	1.59/2.07
Norwegian oat	0.28	0.00	0.00	0.43/0.66	5.41/5.72	0.71/2.33	5.33/7.89	0.45/0.46	0.48/0.88
Norwegian wheat	0.05	0.00	0.07	0.51/0.81	6.67/7.03	0.88/2.57	6.22/9.03	1.78/1.79	0.37/0.81
Rapeseed meal	0.08	0.04	0.02	0.58	4.39	1.10	9.81	118.25	2.66
Rapeseed	0.03	0.06	0.05	0.92	13.92	2.92	12.73	109.39	3.21
Soymeal, extracted	0.09	0.18	0.24	1.30	4.71	1.63	6.81	4.22	4.04
Maize	0.00	0.00	0.15	0.43	4.03	0.72	8.23	5.17	2.47
Other ingredients	0.07	0.12	0.17						

1) For grains produced in Norway, with narrow / wide system boundaries, respectively

2) For grains produced in Norway, weighted / not weighted according to length of cropping period, respectively

Table 3. Farm and herd characteristics and yearly inputs, intermediary products and outputs for six scenario for feed ration, animal and crop yield on a dairy farm in central Norway.

Scenario: Forage energy concentration[a]:	Base case medium	A medium	B medium	C low	D low	E high	F high
Concentrate proportion/type[b] in cow diet:	40%, F80	25%, F80	55%, F80	40%, F80	50%, F80	35%, E90	40%, E90
Farm size and management							
Arable land (ha)	22.5	25.5	18.5	23.5	18.5	21.6	15.4
Permanent pastures (ha)	2.0	2.0	2.5	2.5	2.5	2.5	2.0
Dairy cows (cow-equivalents)	20	20	20	24	20	20	12
Number of cuts per year	2	2	2	2	2	4	4
Ley renewal interval (year)	5	5	5	6	6	4	4
Age at slaughter, bulls (months)	18	18	18	18	18	18	16
ECM yield (kg cow-equivalent^{-1})	7250	7250	7250	6000	7250	7250	12000
ECM yield (kg ha^{-1} arable land)	6440	5690	7840	6130	7840	6710	9340
Inputs							
Mineral fertilizer, arable land (kg N ha^{-1})	140	145	131	144	139	176	176
Mineral fertilizer, permanent pastures (kg N ha^{-1})	0	0	0	0	0	0	0
Diesel in forage production (litres)	3380	3890	2750	3740	2920	3470	2480
Concentrates, cows (% of total energy intake)	39	25	55	39	50	35	39
Concentrates, heifers all ages (% of total energy intake)	19	19	19	19	19	19	19
Concentrates, bulls all ages (% of total energy intake)	40	40	40	47	40	40	47
Electricity (kWh)	26000	26000	26000	26000	26000	26000	26000
Intermediate products							
DM yield, arable land (kg ha^{-1})	6300	6300	6300	7100	7100	6125	6125
DM yield, permanent pastures (kg ha^{-1})	2500	2500	2500	2500	2500	2500	2500
Stored manure (tonnes, 6.5% DM)	855	855	855	973	855	855	609
Outputs							
ECM delivered to dairy plant (kg)	133000	133000	133000	130600	133000	133000	134800
Cow and heifer carcasses delivered to slaughter plant	10	10	10	12	10	10	6
Bull carcasses delivered to slaughter plant	10	10	10	12	10	10	6

DM: Dry matter, FEm: Milk feed units, net energy value according to the Norwegian net energy evaluation system for ruminants (Ekern and Sundstøl, 1992), ECM: Energy corrected milk. [a] Low=0.80, medium=0.85, high=0.95 FEm kg DM^{-1}. [b] For composition of concentrates, confer Table 2.

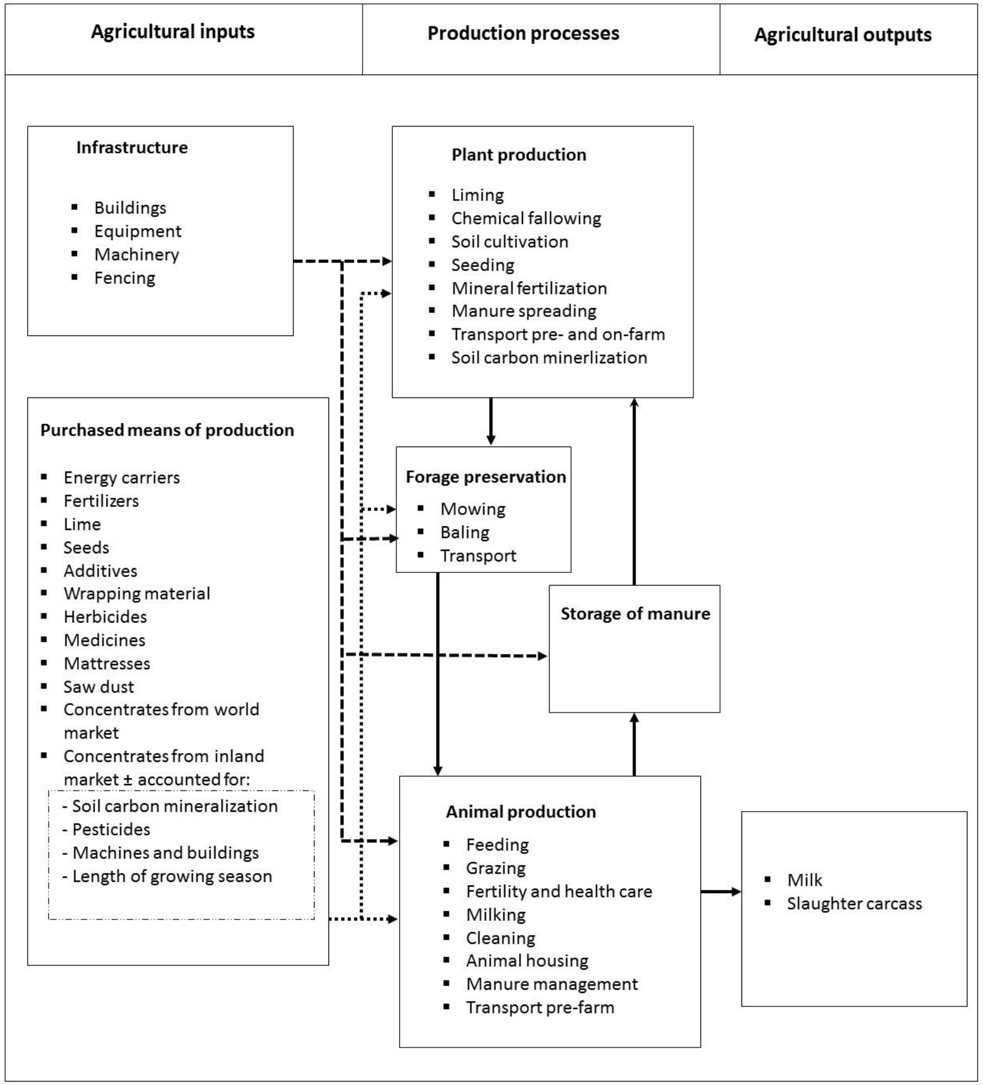
Agricultural inputs
Production processes
Agricultural outputs
Infrastructure
Buildings
Equipment
Machinery
Fencing
Plant production
Liming
Chemical fallowing
Soil cultivation
Seeding
Mineral fertilization
Manure spreading
Transport pre- and on-farm
Soil carbon minerlization
Purchased means of production
Energy carriers
Fertilizers
Lime
Seeds
Additives
Wrapping material
Herbicides
Medicines
Mattresses
Saw dust
Concentrates from world market
Concentrates from inland market ± accounted for:
- Soil carbon mineralization
- Pesticides
- Machines and buildings
- Length of growing season
Forage preservation
Mowing
Baling
Transport
Storage of manure
Animal production
Feeding
Grazing
Fertility and health care
Milking
Cleaning
Animal housing
Manure management
Transport pre-farm
Milk
Slaughter carcass

Figure 1

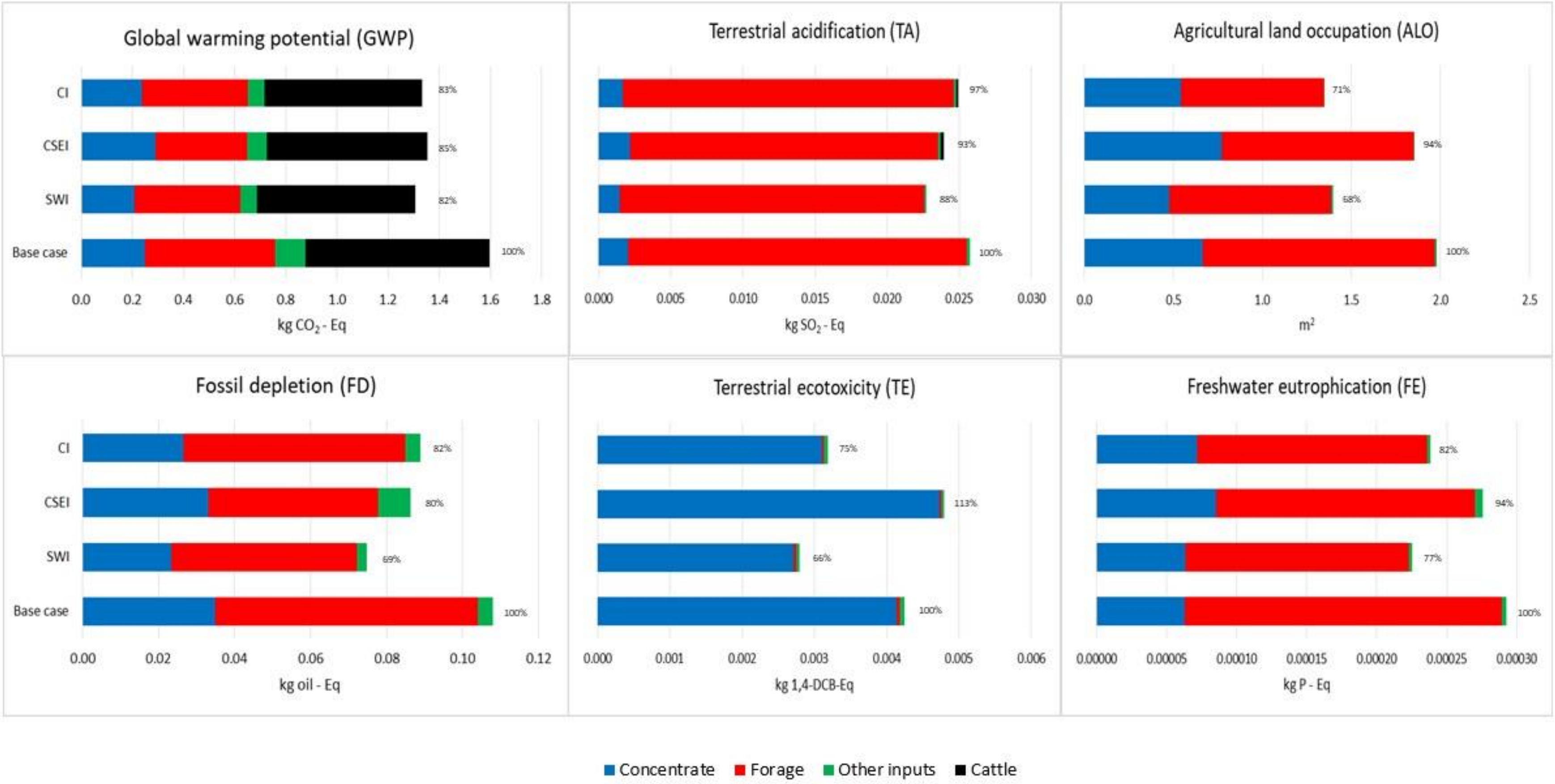
Global warming potential (GWP)
CI
CSEI
SWI
Base case
83%
85%
82%
100%
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
kg CO_2 - Eq
Terrestrial acidification (TA)
97%
93%
88%
100%
0.000 0.005 0.010 0.015 0.020 0.025 0.030
kg SO_2 - Eq
Agricultural land occupation (ALO)
71%
94%
68%
100%
0.0 0.5 1.0 1.5 2.0 2.5
m^2
Fossil depletion (FD)
CI
CSEI
SWI
Base case
82%
80%
69%
100%
0.00 0.02 0.04 0.06 0.08 0.10 0.12
kg oil - Eq
Terrestrial ecotoxicity (TE)
75%
113%
66%
100%
0.000 0.001 0.002 0.003 0.004 0.005 0.006
kg 1,4-DCB-Eq
Freshwater eutrophication (FE)
82%
94%
77%
100%
0.00000 0.00005 0.00010 0.00015 0.00020 0.00025 0.00030
kg P - Eq
Concentrate
Forage
Other inputs
Cattle

Figure 2

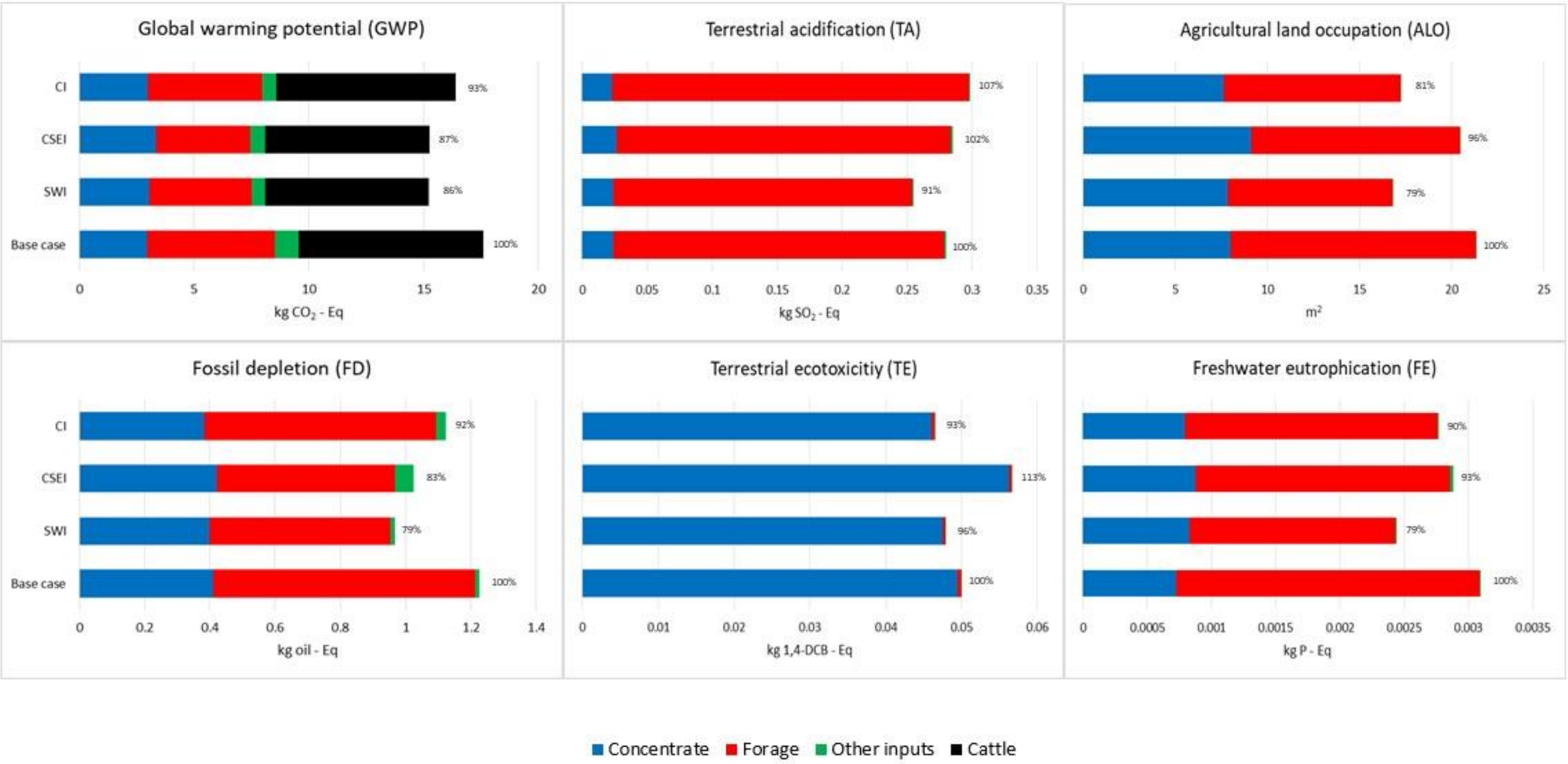
Global warming potential (GWP)
CI
CSEI
SWI
Base case
93%
87%
86%
100%
0
5
10
15
20
kg CO2 - Eq
Terrestrial acidification (TA)
107%
102%
91%
100%
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
kg SO2 - Eq
Agricultural land occupation (ALO)
81%
96%
79%
100%
0
5
10
15
20
25
m2
Fossil depletion (FD)
CI
CSEI
SWI
Base case
92%
83%
79%
100%
0
0.2
0.4
0.6
0.8
1
1.2
1.4
kg oil - Eq
Terrestrial ecotoxicitiy (TE)
93%
113%
96%
100%
0
0.01
0.02
0.03
0.04
0.05
0.06
kg 1,4-DCB - Eq
Freshwater eutrophication (FE)
90%
93%
79%
100%
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
kg P - Eq
Concentrate
Forage
Other inputs
Cattle

Figure 3

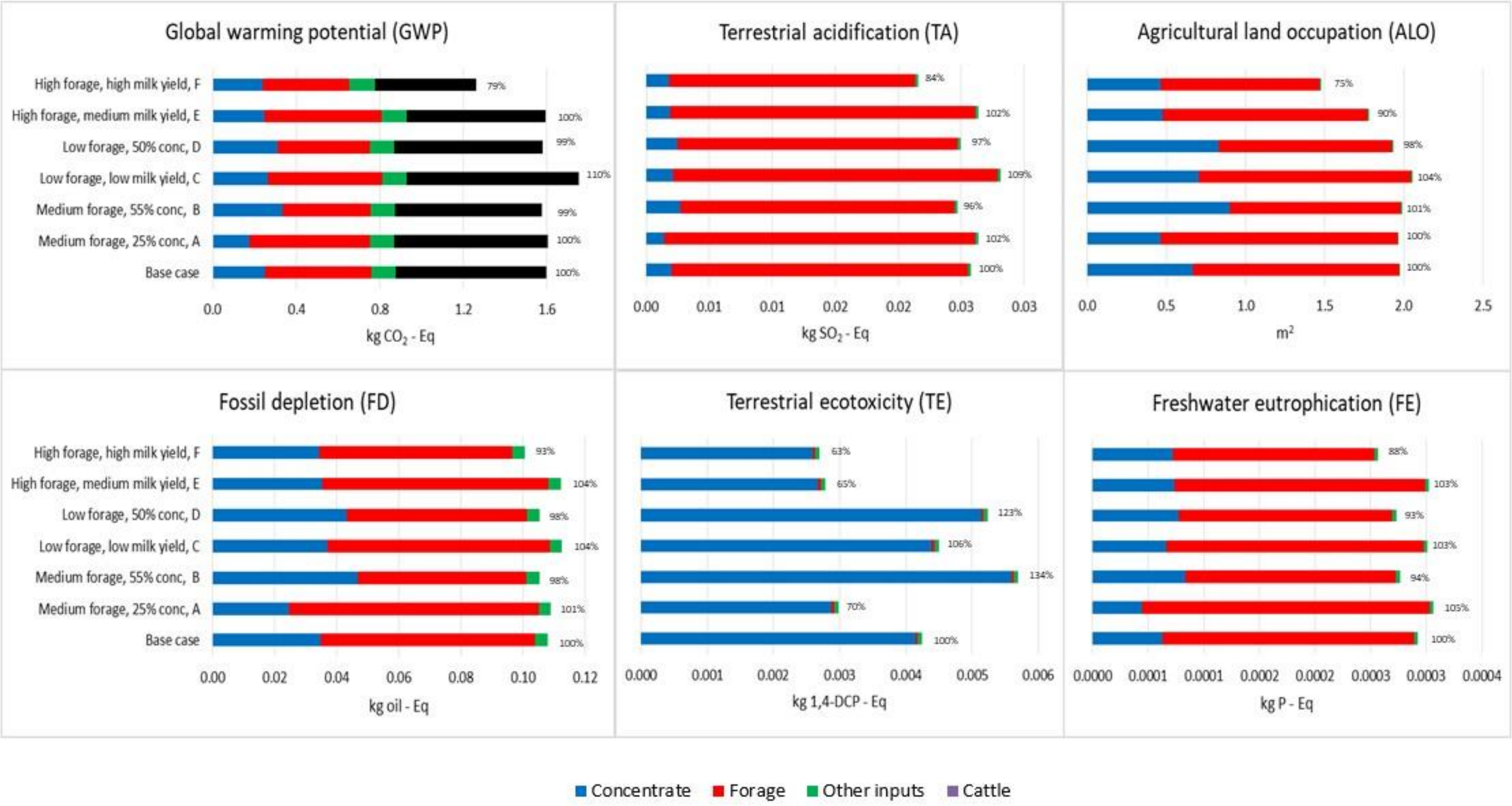
Global warming potential (GWP)
High forage, high milk yield, F
High forage, medium milk yield, E
Low forage, 50% conc, D
Low forage, low milk yield, C
Medium forage, 55% conc, B
Medium forage, 25% conc, A
Base case
79%
100%
99%
110%
99%
100%
100%
0.0
0.4
0.8
1.2
1.6
kg CO₂ - Eq
Terrestrial acidification (TA)
84%
102%
97%
109%
96%
102%
100%
0.00
0.01
0.01
0.02
0.02
0.03
0.03
kg SO₂ - Eq
Agricultural land occupation (ALO)
75%
90%
98%
104%
101%
100%
100%
0.0
0.5
1.0
1.5
2.0
2.5
m²
Fossil depletion (FD)
High forage, high milk yield, F
High forage, medium milk yield, E
Low forage, 50% conc, D
Low forage, low milk yield, C
Medium forage, 55% conc, B
Medium forage, 25% conc, A
Base case
93%
104%
98%
104%
98%
101%
100%
0.00
0.02
0.04
0.06
0.08
0.10
0.12
kg oil - Eq
Terrestrial ecotoxicity (TE)
63%
65%
123%
106%
134%
70%
100%
0.000
0.001
0.002
0.003
0.004
0.005
0.006
kg 1,4-DCP - Eq
Freshwater eutrophication (FE)
88%
103%
93%
103%
94%
105%
100%
0.0000
0.0001
0.0001
0.0002
0.0002
0.0003
0.0003
0.0004
kg P - Eq
Concentrate
Forage
Other inputs
Cattle

Figure 4

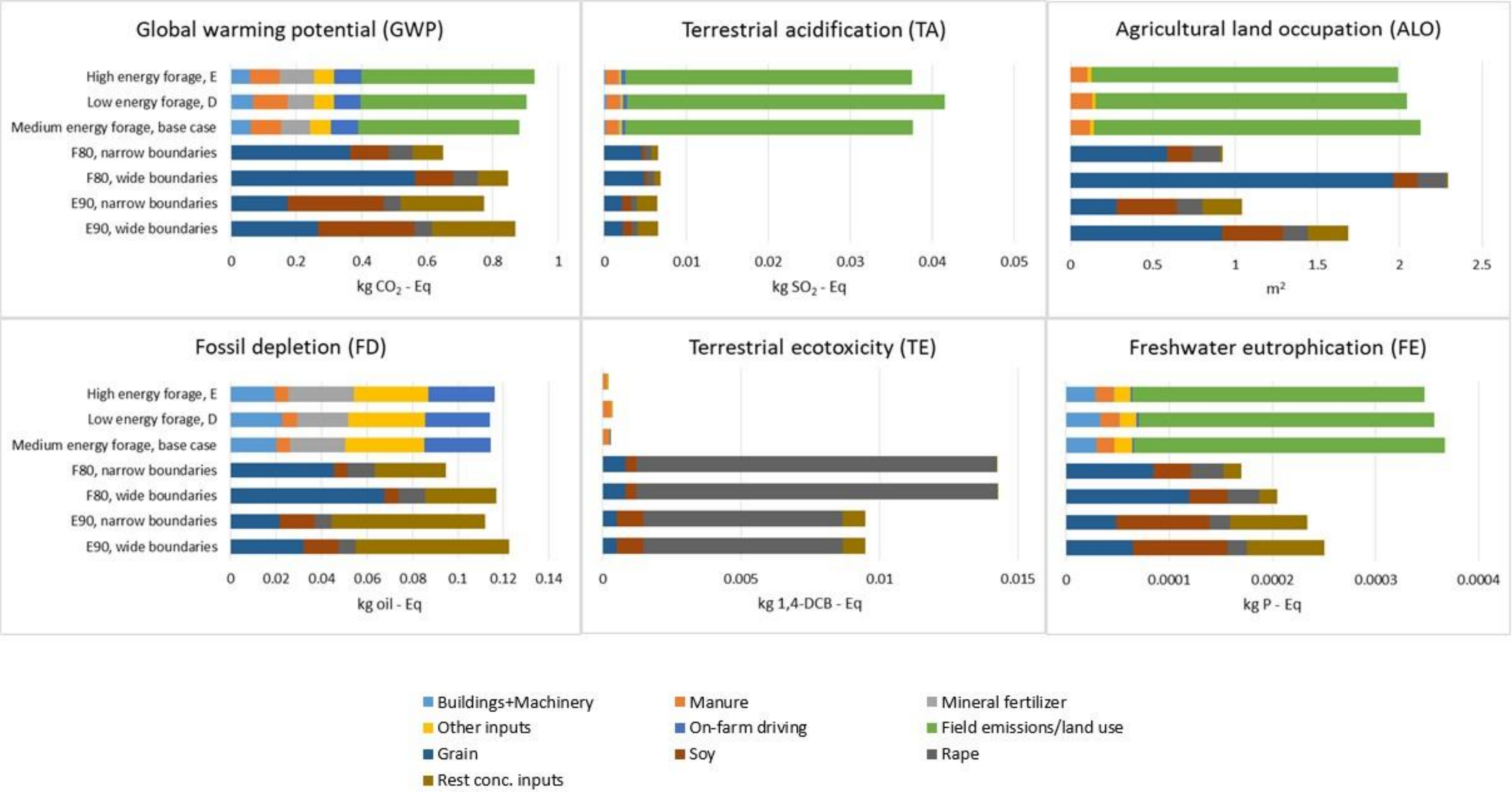
Global warming potential (GWP)
Terrestrial acidification (TA)
Agricultural land occupation (ALO)
Fossil depletion (FD)
Terrestrial ecotoxicity (TE)
Freshwater eutrophication (FE)
High energy forage, E
Low energy forage, D
Medium energy forage, base case
F80, narrow boundaries
F80, wide boundaries
E90, narrow boundaries
E90, wide boundaries
0 0.2 0.4 0.6 0.8 1
kg CO_2 - Eq
0 0.01 0.02 0.03 0.04 0.05
kg SO_2 - Eq
0 0.5 1 1.5 2 2.5
m^2
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
kg oil - Eq
0 0.005 0.01 0.015
kg 1,4-DCB - Eq
0 0.0001 0.0002 0.0003 0.0004
kg P - Eq
Buildings+Machinery
Manure
Mineral fertilizer
Other inputs
On-farm driving
Field emissions/land use
Grain
Soy
Rape
Rest conc. inputs

Figure 5