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# Production and environmental impact of dairy cattle production in Denmark 1900–2010

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ABSTRACT

Cattle production during the last century has changed dramatically in Western Europe, including Denmark, with a steady increase in production per animal and in herd and farm size. The effect of these changes on total production, herd efficiency, surplus of nitrogen (N) at herd and farm level and emission of greenhouse gases (GHG) per kg product has been evaluated for the Danish dairy cattle sector based on historic information. Typical farms representing the average situation for Danish dairy cattle farms and land required for feed supply was modeled for the situation in: (A) 1920 – representing a local-based production, (B) 1950 – representing a period with emerging mechanization and introduction of new technologies and a more global market, (C) 1980 – representing a period with heavy use of external resources like fertilizer and feed protein and (D) 2010 – today with focus on balancing production and risk of environmental damage. In A, B and C, other livestock such as pigs and hens also played a role, while the dairy farm in 2010 only had cattle. In 1920 and 1950 the farm was based on 7–8 dairy cows producing typically 1800–3400 kg energy-corrected milk (ECM) per cow annually and fed primarily on pasture and hay, only to a limited extent supplemented with imported protein. In 1980 the herd size had increased to 20 dairy cows producing 5000 kg ECM each, and feeding was with silage instead of hay, but still included grazing and there was a larger proportion of imported feed. In 2010 the herd had increased to 134 dairy cows producing 9000 kg ECM per cow and fed indoors all year. During this period net energy used for milk and meat in % of total intake and land use per 1000 kg of milk has steadily decreased as a consequence of higher milk yield per cow and higher yields of forage per ha. In opposition, the utilization of N in the herd, while increasing from 1920 to 1950 and to 2010 showed a drop in the 1980 system, where also the environmental N surplus per ha farmland was highest (40; 65; 226; 148 kg N per ha farmland in the respective periods). The lower N efficiency in 1980 also resulted in an increased GHG emission per kg milk than in the preceding and following periods (2.23; 1.38; 1.94; 1.20 kg $CO_2$-eq. per kg ECM in the respective periods). It is concluded that the biological and technical development has made it possible to reduce the environmental load of dairy production significantly, but that this requires a strong focus on nitrogen management at the farm level and production efficiency in the herd.



## 1. Introduction

Agricultural production reflects the increase in the global population and changes in consumer behavior. This has led to a relatively larger increase in the livestock sector compared to the total food production and this development is expected to continue, leading to a substantial increase in global farmland surpluses of nitrogen and phosphorus (Bouwman et al., 2013). Ruminants are less efficient than mono-gastric animals in converting feed energy and protein to food energy and protein. This leads to a higher waste production and risk of environmental pollution, including methane emission, and a higher land use.

Several papers have addressed this in a static time perspective based on the present situation, such as Lesschen et al. (2011) for European livestock, Gerber et al. (2011) for global dairy production and Nguyen et al. (2010) in a comparison of different beef systems in the EU, while only a few have looked at the development in a historical perspective. Hristov (2012) estimated that the emission of methane from past populations of wild ruminants would have been almost identical to the present emission of methane from wild animals and farmed animals in the US, while Capper et al. (2009) compared the US dairy production of 1944 with 2007 and

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estimated a reduction in the emission of greenhouse gases (GHG) of 37%, while in the same period milk production rose 59%. Capper (2011) found that US beef in 2007 produced 18% less manure than in 1977 and had reduced the emission of GHG per kg product by 16%. National evaluations of the environmental impact of agriculture in Denmark have estimated that since 1990 methane emissions have been reduced by 3%, while $N_2O$ emissions have been reduced by 32% (Nielsen et al., 2011). Vinther and Olsen (2013) estimated an average reduction in N surplus of 70 kg N per ha since 1990 for agricultural land in Denmark.

These changes reflect a combination of structural changes and political regulations of the sector as well as higher biological efficiency in the individual animal together with implementation of new technology and improved farm management. Evaluating the effect of these elements in a historical perspective can give insight into how efficiency may be improved and environmental impact from livestock reduced in the future.

The objective of this paper was to document how cattle production has changed in the last century with a steadily rising production per animal and increasing herd and farm size, and to quantify the effect of these changes on total production, herd efficiency, N surplus at herd and farm level and emission of greenhouse gases for the Danish dairy cattle sector based on available data from historical information.

## 2. Danish cattle production 1900–2010

The baseline data presented in this section, if no other references are given, are from national books of statistics (Danmarks Statistik, 1968, 1969) including data from 1900 until 1965, and thereafter updated annually, showing data for the year and for the last 10 years (Danmarks, 1971, 1981, 1991, 2001, and 2011).

The amount of milk delivered to the dairy industry increased from around 1700 Mkg at the start of the century until the 1930's, and has since then been around 5000 Mkg (Fig. 1). Production of beef meat increased until 1970, when the annual production was almost 300 Mkg, followed by a 50% reduction in the period 1970–2010 when beef production again reached the same level as in 1930. From Fig. 1 it can be seen that the number of dairy cows behind this production has been reduced from a maximum of 1.7 million heads in 1930 to less than a third, 568,000 heads, in 2010. Around 20% of the beef production in 2010 was from beef cattle, with 102,000 heads of beef cows producing 24 Mkg beef annually.

Farming structure has also changed over the last century. In 1950 there were dairy cattle on 89% of the farms in Denmark, with farms having an average of eight cows. In 1980 specialization had started and the proportion of farms with dairy cattle was reduced to 35%. This development continued, and in 2010 only 10% of Danish farms had dairy cattle, now with an average of 134 dairy cows per dairy farm. A similar trend for US dairy farming has been reported by Blayney (2002) for the period 1945–2000 and by March et al. (2014) for the British dairy industry since 1980.

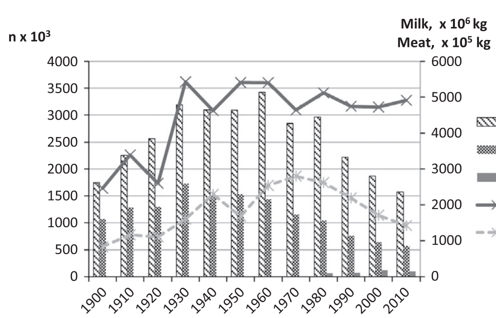


**Fig. 1.** Development since year 1900 in number of cattle (and dairy and beef cows) and the annual total production of milk and meat from cattle in Denmark.

The proportion of the different types of cattle (cows, heifers and bulls) within the dairy sector also changed during the century. In 1920 more than 60% of all dairy cattle were cows, and until 1950 more than half were dairy cows. This was due to the low profitability of beef production (Hansen and Livoni, 1959), which caused that more than one third of newborn calves to be either killed or slaughtered at a young age. This, together with a low reproduction rate and high mortality, resulted in a beef production of only 80 kg per cow and young stock (dairy production unit, DPU) in 1920 rising to 110 kg in 1950. In the following years there was a significant positive change in the economic conditions for beef farming, which together with improved reproduction increased the number of heads for slaughter and also the average weight at slaughter, leading to a maximum production in 1970–80 of 240 kg beef per DPU.

Productivity per animal has changed dramatically since 1900. Annual milk yield per cow, estimated as the amount delivered to the dairy, almost doubled in the first 70 years from 1900 to 1970, and more than doubled again in the last 40 year from 4000 kg in 1970 to almost 9000 kg in 2010 (Fig. 2). Fat concentration in the milk delivered to the dairy has increased steadily from 3.40% in 1900 to 4.43% in 1990, followed by a slight decrease to 4.30% fat in 2010. Regular data on protein concentration are only available since 1990, when the protein content was 3.38 – the same as today.

The development in milk and beef production has been influenced by a change in their genetic makeup, both between different types of breed and in genetic selection within breed. In the first part of the period Red Danish Cattle (RDM) (Andersen et al., 2003) was the dominating breed, representing more than 70% of the dairy cows, followed by 15–20% of the Danish Black and White (SDM) breed, and an increasing proportion of Jersey cows based on imported cows from the Island of Jersey at the start of the century (Johansen et al., 1963). The proportions of the breeds have changed over time due to large changes in the geographic location of the dairy cattle within Denmark in combination with different genetic developments for the different breeds, partly due to different opportunities for import of superior genes. The SDM cattle were mixed with the large global population of Holstein, increasing the popularity of this breed, so that in 1980 54% of the cows were SDM, only 22% RDM and 16% Jersey. In 2010, 72% of the dairy cattle were SDM (but had now changed the name to Danish Holstein due to the strong gene import), 13% were Jersey and only 7% were RDM (RYK, 2014), with an annual milk production of, respectively, 9518, 8492 and 8999 kg ECM (3.14 MJ/kg) per cow based on data from milk recordings. Østergaard and Neimann-Sørensen, 1989

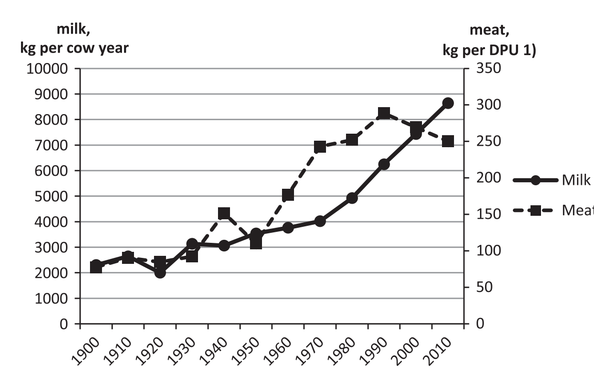


**Fig. 2.** Average production of milk and meat from dairy cattle since 1900 in Denmark, kg per DPU
(1) *DPU: One dairy cow including her offspring*).

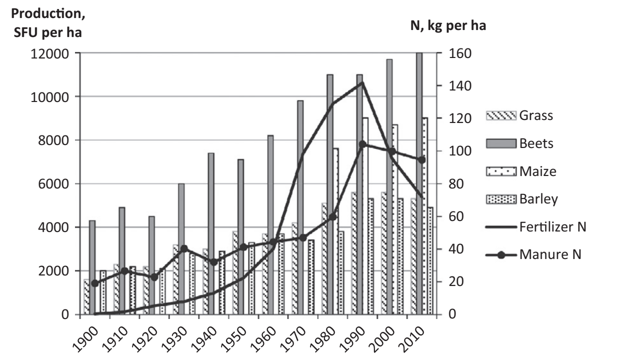


**Fig. 3.** Development since 1900 in production per ha of grass, beets, maize for silage and spring barley in Scandinavian feed unit (SFU) per ha and use of nitrogen from manure and fertilizer in kg N per ha as an average for the agricultural area at the dairy farm in Denmark.

estimated that 55% of the increased yield of Danish Holstein from 1965 to 1988 was due to genetic progress, while the remainder was due to feeding and management.

During the entire period, cattle feeding have been based on a large proportion of forage in the ration. In the early part of the century the dominating crop was grassland, utilized for grazing in a 6–7 month long season and for hay production for the indoor winter feeding period. The grassland was a combination of permanent pasture and grass in rotation with cereals and beets. The area with fodder beet, used for feeding during winter, increased from 10% of the area for roughage in 1900 to more than 30% in 1960–70. Later beets were replaced by maize wholecrop silage, and some small-grain cereals were also used as wholecrop silage.

The productivity was doubled in the period from 1900 to 1960 when measured as net energy (1 SFU = 7.89 MJ NE) production per ha for the different types of forage and for spring barley, which was the most commonly used cereal (Fig. 3). The productivity of the different forages in the entire period was highest for fodder beet. The proportion of permanent grassland increased from 30% of the total grassland area in 1900–1920 to almost half of the total area of grassland in 2010 due to a decrease in the total grassland area. This explains the stagnation in the productivity of grassland as the productivity of permanent grassland was only about 20% of that of grassland in rotation in 1980–2010 (Olesen, 1980; Pedersen, 2010; Kristensen, 2015).

The amount of N supplied per ha of agricultural land from manure and fertilizer increased in the period, especially from 1960 to 1990, followed by a marked reduction in the use of fertilizer N, while the amount of N supplied with manure only has been slightly reduced. This development has to a high degree been a result of an intensive political regulation of agriculture with the objective of reducing the environmental load, especially from the emission, leaching and run-off of nitrogen (Dalgaard et al., 2014).

## 3. Material and methods

The effect of the above described changes in production and the related environmental load have been quantified by defining four dairy farm prototypes representing four different periods

1920: When production was based on local resources together with an emerging import of feed protein.

1950: On the cusp of increasing the use of fertilizer, chemicals and introduction of mechanization.

1980: When production was the main focus without any major concern for the potential environmental load.

2010: Representing present production conditions as influenced by the different political regulations of agriculture to cope with the pressure on the environment from the intensification of agriculture.

A farm model was developed in Excel, including a model for herd structure, production and feed requirement. The area needed for fodder production from each type of crop and the requirements for N fertilizer for these was also included. The national production was calculated from the number of farms and production for each prototype and was compared to national annual statistical information (Danmarks Statistik, 1968, 1969, 1981, 2011) for livestock and crop production, imported feed and fertilizer as part of the model. In this way results obtained for each prototype could be interpreted as average values for cattle in Denmark for the respective years.

Each prototype was based on the average number of cattle (365 feeding days per year), partitioned into dairy cows, heifers and bulls, on farms with cattle. The cattle farms in the 1920 to 1980 period were different from the prototypes as most farms during this period were mixed livestock farms with a combination of dairy, pig and poultry. In 1920 and 1950 horses as draft power were included, calculated from the area of the prototype farms, assuming that the number of horses per ha on the cattle farm was identical to the average number of horses per ha in Denmark. All roughage and cereals were assumed produced on the farm, although the actual farm might have had some farm-gate exchange of cereals and roughage. During the entire period there was no or only little net export from Denmark of roughage and cereals, which means that the calculated area used for fodder production from the prototypes for each year was identical to the actual area used in Denmark.

Feed requirements for net energy (SFU) and crude protein, summed to annual totals for each group of animals, were calculated from defined and balanced feed rations formulated from handbooks (Larsen, 1941; Petersen-Dalum, 1943), registrations on commercial farms (Larsen, 1955; Hansen and Livoni, 1959; Østergaard and Hindhede, 1980; Kristensen, 2010), recommendations (Lund and Aaes, 2010) and research reports (Frederiksen, 1931; Steensberg et al., 1931; Nielsen, 1952; Larsen and Eskedahl, 1952; Østergaard and Neimann-Sørensen, 1989). Energy concentration (SFU per kg DM) and protein content (crude protein in DM) were adjusted for each year and type of feed based on some of the above given references and on feed tables (Andersen and Just, 1983; Møller et al., 2000). Use of additional mineral and vitamins to fulfill the requirements was not taken into account.

Change in sward composition, grassland management and fertilization increased the energy concentration in pasture from 0.71 SFU per kg DM in 1920 to 0.87 in 1980. Pasture protein concentration increased from 16% of DM in 1920 to 21% of DM in 1980, but then fell to 18% in 2010. The same trend was seen for conserved grass, but was even stronger with the shift from hay (0.52 SFU per kg DM in 1920) to silage (0.89 SFU per kg DM in 2010). The feed value for beets and cereals only changed marginally, while maize silage in 1980 had a lower energy content (0.75 SFU per kg DM) than in 2010 (0.88 SFU per kg DM). Feed requirement and ration formulation for horses were based on Jespersen et al. (1944).

The feed ration was adjusted to reflect the area and productivity of roughage at national level, and the levels of cereals and imported feed were balanced to meet the requirements for energy and protein, again reflecting the national level. This is a crucial part of the modeling as the statistical information is based on reported information of harvested amounts by farmers, which typically are higher than the requirements of the herd (Kristensen, 2015). For roughage the prototypes were balanced to the national level, within an acceptable difference between the harvested amount and the amount used in the herd of 10% in general, and 15% for grassland in 1920 and 1950 due to the higher proportion of pasture and hay compared to silage. For cereals a difference of 2% was accepted.

Manure excreted was calculated as the difference between N intake (protein/6.25) and the sum of N in milk (protein/6.38) and N in meat (0.026 kg N per kg live weight gain) (Poulsen et al., 2001). Type of manure system and handling of manure in the chain from animal to field was specified for each prototype (Bondorff and Petersen-Dalum, 1944; Danmarks Statistik, 1981; Nielsen et al., 2011). The proportion of net energy intake from grazing compared to total intake was used to allocate the total amount of N excreted to pasture and indoor excretion. All manure was applied to the farm area used for feed production for the cattle. The amount of N fertilizer applied per ha was for 1920 to 1980 set to the average national use of N in fertilizer per ha of agricultural land, and in 2010 calculated in accordance with the regulations taking into account type of crop and amount of manure N applied (Anonymous, 2012). In addition to N fertilizer, phosphorous and potassium were used, but this was not included in the modeling.

Emission of greenhouse gases (GHG) was estimated using a life cycle assessment (LCA) with farm gate as the system border, including emission from imported feed, fertilizer and use of energy on the farm. Carbon sequestration due to crop production on the farm in Denmark and a potential effect of imported feed on emission due to global land use change were not included. The emission at farm gate was estimated in $CO_2$ eq., by converting 1 kg $CH_4$ to 24 $CO_2$ eq. and 1 kg $N_2O$ to 298 kg $CO_2$ eq., and allocated to the two products (kg ECM and kg live weight gain) based on the standard net energy requirement (0.4 SFU per kg ECM and 4 SFU per kg live weight gain). The emissions factors are based on the present recommendation by IPCC (2006) Tier 3 approach using specific figures for Denmark (Mikkelsen et al., 2006) and the farm balance method documented by Kristensen et al. (2011), with some correction in earlier periods for changes in technology, composition of feed intake, etc. (Table 1).

**Table 1**
Assumptions used for estimation of N and greenhouse gases at farm gate from dairy cattle production in Denmark from 1920 to 2010.

| Year | 1920 | 1950 | 1980 | 2010 | Note |
|---|---|---|---|---|---|
| **$CH_4$**-enteric | | | | | |
| Gross energy, MJ/kg DMI | 18.4 | 18.3 | 18.6 | 19.1 | (1) |
| EF | 0.071 | 0.071 | 0.067 | 0.060 | (2) |
| **$CH_4$** – manure | | | | | |
| DOM, % DMI | 69 | 72 | 76 | 78 | (1) |
| Ash, % of DMI | 10 | 9 | 8 | 7 | (1) |
| Horses, kg $CH_4$ per year per head | 25 | 25 | | | |
| **Manure system**, % of N excreted | | | | | |
| Solid manure | 38 | 41 | 32 | 9 | |
| Liquid | 10 | 20 | 18 | 5 | |
| Slurry | | | 28 | 78 | |
| Grazing | 38 | 34 | 16 | 8 | |
| Lost before storage | 14 | 5 | 4 | 0 | (3) |
| **$NH_3$–N losses,** % of N excreted, (stable + storage + application) | | | | | |
| Solid manure | 20 | 20 | 20 | 20 | |
| Liquid | 35 | 25 | 12 | 9 | |
| Slurry | | | 29 | 15 | |
| Grazing | 7 | 7 | 7 | 7 | |
| Fertilizer | 2 | 2 | 2 | 2 | |
| **Fixation**, kg N per ha grassland | 44 | 86 | 66 | 83 | (4) |
| **Import** | | | | | |
| Energy, kg $CO_2$ per kg ECM | 0 | 0.018 | 0.177 | 0.140 | (5) |
| Fertilizer, kg $CO_2$ per kg N | 8.60 | 8.60 | 5.60 | 5.44 | |
| Feed import (soybean meal) | | | | | |
| -$CO_2$ eq., kg per SFU | 0.998 | 0.855 | 0.701 | 0.536 | (6) |
| -Area, $m^2$ per SFU | 3.89 | 3.89 | 2.19 | 1.36 | |

(1) Calculated from composition of annual feed ration; (2) IPCC (2006) adjusted for effect of sugar and starch (Danfær and Weisbjerg, 2006); (3) Proportion of N lost due to poor storage facilities (Bondorff and Petersen-Dalum, 1944; Olsen, 1954; Olsen, 1955) – not included in manure loss and application; (4) Based on farm registration of proportion of legumes (Kristensen, 1944; Kristensen and Kristensen, 1992) and principles for estimation of fixation (Kristensen and Kristensen, 1992); (5) For 2010 from Kristensen et al. (2011) and for earlier periods based on statistical data on energy in the agricultural sector as well as higher emission due to use of coal instead of gas; (6) For 2010 from Dalgaard et al. (2008) and for later periods corrected for productivity in soya (FAO data) and extra energy of 10% per 30 year in processing and transport.

## 4. Result and discussion

Herd size and structure was almost identical in 1920 and 1950 with 7–8 cows and heifers for replacement (Table 2). Males were divided equally into calves for slaughter and bulls for breeding purposes in 1920 and 1950, as the use of artificial insemination was in its infancy in 1950. Later in 1980 the proportion of heifers increased, which together with a reduced age at first calving enabled a higher replacement rate of the cows from 25% in 1920 to 40–42% in 1980 and 2010. In 1980 and 2010 males were bull calves for slaughter at 400–425 kg live weight.

In 1920 and 1950, respectively, 52 and 44% of the dry matter intake (DMI) was from grassland, while this was reduced to 26% in 2010. In 1920 and 1950 the average intake and production was highest during summer, which means that the grassland was mainly (more than 70% of production) used for grazing. The proportions of cereals and concentrate were below 20% of DMI in 1920–1950 and increased to 30% in 2010.

The protein intake was restricted in 1920 and 1950 by a lower protein concentration in the roughage than later in the period and in 1950 also due to problems with import of protein feedstuffs following the Second World War. In the following 30 years the import of N in fertilizer increased, leading to a higher concentration of protein in the roughage. This, together with an economically favorable use of imported high protein feedstuffs (Hansen and Livoni, 1959), reduced the herd N efficiency to 16% in 1980 despite the increasing milk and meat production per animal. A combination of increased costs of protein compared to energy, a better understanding of optimal protein supply by changing from the digestible crude protein system to the AAT/PBV system in feed planning (Hvelplund et al., 1987) and the political regulations on manure storage and fertilizer use (Dalgaard et al., 2014) have

**Table 2**
Herd structure, land use, annual livestock production, feed intake and gross efficiency for prototypes of Danish dairy farms representing the last four decades.

| **Year** | **1920** | **1950** | **1980** | **2010** |
|---|---|---|---|---|
| *Herd size, no (avg. weight kg)* | | | | |
| Dairy cows | 7 (430) | 8 (470) | 20 (520) | 134 (585) |
| Heifers | 5 (218) | 6 (239) | 22 (263) | 126 (286) |
| Bulls produced | 2 (125) | 2 (134) | 12 (220) | 55 (233) |
| *Land use, ha* | | | | |
| Cereals | 1.6 | 1.7 | 6.2 | 26.8 |
| Forage | 7.1 | 6.3 | 13.2 | 136.7 |
| *Production* | | | | |
| Milk yield, kg ECM per cow | 1804 | 3435 | 5058 | 8994 |
| Live weight gain, kg per DPU[a] | 152 | 200 | 457 | 422 |
| Feed intake, SFU per DPU | 3425 | 4481 | 7191 | 9237 |
| DMI, kg per DPU | 4604 | 5522 | 8101 | 9983 |
| Protein, kg crude protein per DPU | 655 | 757 | 1456 | 1569 |
| Energy concentration, SFU per kg DMI | 0.74 | 0.81 | 0.89 | 0.93 |
| Protein concentration, % in DMI | 14.2 | 13.7 | 18.0 | 15.7 |
| *Efficiency* | | | | |
| Energy[b], % | 39 | 49 | 54 | 57 |
| Protein[c], % | 12 | 19 | 16 | 23 |
| Milk, kg ECM per ha in DK | 1443 | 3435 | 5109 | 7372 |
| Milk, kg ECM per ha total | 1289 | 3095 | 3692 | 5956 |

[a] DPU: one dairy cow including her offspring (heifers and bull calves).
[b] Standard energy used for milk and meat in percent of total energy intake.
[c] Protein in milk and meat produced in percent of protein in intake.

reduced the protein concentration in the ration to 15.7% of DM in 2010. In combination with the steadily increasing milk yield, these changes have improved protein efficiency since 1980 to 23% herd N efficiency in 2010.

The net energy intake of the cows in 1920, 1950, 1980 and 2010 out of total net energy intake per DPU was 70%, 72%, 60% and 73%, respectively, and of this energy intake the cows used 58%, 46%, 36% and 25% for maintenance. The lower proportion of net energy used for maintenance is due to the diluting effect of the higher milk yield, despite a lower feed efficiency with an increased feeding level (Østergaard and Neimann-Sørensen, 1989; Volden, 2011). The same trend is seen at herd level (Table 2) where an increasing part of the energy intake is used for production, milk and meat, but is less pronounced due to the change in herd structure with an increasing proportion of young stock.

The generally increasing productivity both in the herd and in crop production have significantly increased the amount of milk produced per ha of land used for fodder production, with almost five times more milk produced per ha in 2010 than in 1920. The largest improvement has taken place in the last 30 years, with 2264 kg additional milk per ha from 1980 to 2010 compared to an additional 1806 kg between 1920 and 1950 and only 597 kg between 1950 and 1980. Capper et al. (2009) estimated an improved productivity from 590 kg milk per ha in 1944 to more than 6000 kg in 2007 based on data from US dairy farming.

Nitrogen turnover on the dairy farms in Table 3 included the area needed for feed production – also that for horses – in order to make the comparison between years as fair as possible. Compared to the figures in Table 2, feed requirements for horses needed for the dairy production added 2.1 ha in 1920 and 1.3 ha in 1950 to the land used for fodder production. N from legume fixation is an important part of the N input; therefore, in addition to import of N with feed and fertilizer, the amount of N fixation by legumes was added (Table 3), accounting for more than 50% of the total input to the farm in 1920 and 1950. Almost half of the input in 1980 was from N fertilizer, while the largest input in 2010 was from N in imported feed. The N in milk as a proportion of N in total products (milk+meat) increased from 66% in 1920 to 81% in 2010.

The farm surplus of N (farm gate import plus fixation minus export) increased from 40 kg N per ha in 1920 to a maximum of 226 kg N per ha in 1980 followed by a reduction to 148 kg N per ha in 2010. The N efficiency was highest in 2010 with 24% of total input converted to milk and meat. Nielsen and Kristensen (2005) also found a significant decrease in N surplus on dairy farms from 1997 to 2003 on conventional dairy farms in Denmark, as did Nevens et al. (2006) for intensive dairy farms in Belgium and Vellinga et al. (2011) for the Netherlands. The N surplus from livestock farming estimated at global level was almost four times higher in 2010 than in 1950 due to a larger increase in livestock population in other parts of the world than Europe and a slower increase in productivity (Bouwman et al., 2013).

Farm N surplus is an indicator of N losses from the farm if the soil N pool is stable. The potential pathways for losses are runoff from storage, emission as $NH_3$–N or $N_2O$ during indoor handling of manure, during storage or during application to the fields or N leaching from the soil to groundwater (Dalgaard et al., 2014). It is outside the scope of this paper to address more specifically the losses over time, but two types of losses – runoff from housing and storage and $NH_3$–N emission – which are closely related to the development in livestock farming have been estimated. Runoff due to lack of proper facilities was estimated to be equal to 6 to 9 kg N per ha, but the effect was typically related to much smaller areas near cattle sheds creating severe hot spots with N running into streams or leaching into the groundwater. Emission of $NH_3$–N increased significantly from 1950 to 1980 in kg N, but the proportion of the surplus lost as $NH_3$ emission was reduced from 25% in 1950 to 18% in 1980 and to 16% in 2010, where the total loss as $NH_3$–N had been reduced to 24 kg per ha.

Addressing the N surplus per kg milk, without correcting for the change in the ratio of milk to meat produced in the period, shows that N surplus in 2010 was at the lowest level (20 g N per kg ECM) and that it was more than twice that figure (44 g) in 1980. Also for $NH_3$ emission, 2010 was the year with the lowest emission (3 g $NH_3$–N per kg ECM) compared to the second-lowest (4 g) in 1950 and much lower than the 8 g in 1980.

Estimation of emission of GHG based on the LCA showed that methane was the largest source of the total emission at farm gate in all years (Table 4), but the proportion was reduced from 61% in 1920 to 45% in 1980, and rose again to 52% in 2010. The recent rise was caused by a higher methane emission from manure at the expense of the $N_2O$ emission due to the change from farmyard manure towards slurry and lower direct and indirect emissions from N manure due to the lower N input and higher N-efficiency at farm level (Table 3). Gerber et al. (2011) compared emissions at national level between a large numbers of countries and identified the same effect of increased milk yield on the proportion of GHG from methane as well as a reduction in emission per kg milk. The $CO_2$ emission in 2010 from the use of energy on the farm accounted for 12% of the total emission, which is higher than the 9% in 1980 and also higher than the contribution from horses in 1920, which was 8%.

**Table 3**
Nitrogen turnover for prototypes of Danish dairy farms representing the last four decades, annual figures, kg N per ha.

| Year | 1920[a] | 1950[a] | 1980 | 2010 |
|---|---|---|---|---|
| Fertilizer | 5 | 22 | 129 | 74 |
| Fixation | 29 | 48 | 33 | 42 |
| Feed import | 15 | 15 | 103 | 80 |
| Total input | 49 | 85 | 266 | 196 |
| Milk | 6 | 15 | 27 | 39 |
| Meat | 3 | 5 | 12 | 9 |
| Total output | 9 | 20 | 39 | 48 |
| Surplus (farm balance) | 40 | 65 | 226 | 148 |
| *Efficiency, %* | *18* | *23* | *15* | *24* |
| $NH_3$–N emission | 10 | 16 | 41 | 24 |
| Runoff from storage | 6 | 6 | 9 | 0 |

[a] Including horses.

**Table 4**
Emission of greenhouse gases from four prototypes of Danish dairy farms representing the last four decades, annual figures.

| Year | | 1920 | 1950 | 1980 | 2010 |
|---|---|---|---|---|---|
| Kg $CO_2$ e per DPU[a] | | | | | |
| $CH_4$ enteric | | 2626 | 3090 | 4217 | 4979 |
| $CH_4$ manure | | 46 | 54 | 225 | 631 |
| $N_2O$–N directly | | 755 | 874 | 2016 | 1811 |
| – indirectly from $NH_3$ | | 60 | 74 | 185 | 137 |
| – from leaching | | | | | |
| | | 91 | 125 | 354 | 309 |
| Feed import | | 392 | 246 | 1220 | 1149 |
| Fertilizer import | | 54 | 190 | 702 | 487 |
| Fossil energy | | 0 | 62 | 900 | 1259 |
| Horses | | 369 | 373 | | |
| Total per farm | | 4392 | 5088 | 9830 | 10761 |
| Per produced unit | Kg $CO_2$ eq. per kg ECM | 2.23 | 1.38 | 1.94 | 1.20 |
| After allocation[b] | Kg $CO_2$ eq. per kg ECM | 1.27 | 0.92 | 1.02 | 0.81 |
| | Kg $CO_2$ eq. per kg meat[c] | 25.4 | 18.0 | 20.4 | 16.3 |

[a] DPU: one dairy cow including her offspring (heifers and bull calves).
[b] Allocation based on net energy per kg ECM (0.4 SFU) and per kg live weight gain (4 SFU).
[c] Meat 50% of live weight.

The emission per DPU increased over time, although less so from 1980 to 2010 than from 1950 to 1980. The lower increase between 1980 and 2010 was mainly due to a decrease in the contribution from N turnover ($N_2O$ and fertilizer). The lowest emission, when comparing per kg ECM before allocation between milk and meat, was in 2010 with a reduction of 38% from 1980 to 2010, while the emission in 2010 was only 15% lower than in 1950. Capper et al. (2009) looked at US dairy production in 1944 and 2007 and estimated that there had been a reduction from 3.74 to 1.45 kg $CO_2$ eq. per kg ECM, which was related to an increased milk yield from 2032 to 8559 kg ECM per cow, similar to the change from 1920 to 2010 in Denmark (Table 2). Vellinga et al. (2011) based on the national inventory estimated a reduction in $CH_4$ emission per kg ECM by 13% and an increase per cow by 17% from 1990 to 2010.

Based on the net energy intake utilized for either milk or meat production 54%, 63%, 53% and 68% was allocated to milk and the rest to meat in 1920, 1950, 1980 and 2010, respectively. Emission from both milk and meat was lowest in 2010 at 0.81 kg $CO_2$ eq. per kg ECM and 16.3 kg $CO_2$ eq. per kg meat. Verge et al. (2008), although a not directly comparable study, reported a similar reduction from 1981 to 2001 in emission from beef production as the reduction we estimated from 1980 to 2010 per kg meat.

Typically, the farm emission is 85–90% of the total emission in the chain from field to consumer based on the present use of energy for transport and processing at the dairy plant or slaughterhouse (Van Middelaar et al., 2011; Thoma et al., 2013; Mogensen et al., 2014). The proportion from farm gate onwards might have been lower back in time as the industry and consumption had a more local base, but not of a size that would change the ranking of the environmental impact per produced unit over time.

## 5. Implications and conclusions

In a report dealing with the EU dairy sector after the end of the quota system it was stated that “Milk production will tend to be more concentrated in larger and more efficient farms, as it has been the case in the recent years. However, growth in production in the vulnerable areas is likely to be restrained by environmental limitations. Environmental constraints are thus regarded as one of the main challenges for the years to come” (Anonymous, 2013). Our results indicate that growth are possible without increasing the environmental load in terms of $NH_3$ and greenhouse gases, which are the two major constrains in relation to milk production in EU.

In the period from 1950 to 2010 total national milk production in Denmark has remained almost static, while the N surplus from dairy cattle farms in 2010 was reduced by 45% compared to the maximum surplus in 1980 and emission of $NH_3$ in the same period has been reduced by 59%.

Emission of GHG in 2010 was reduced by 40% compared to 1980, but $CH_4$ only 31% due to change in slurry system. These changes has been driven by a combination of increased milk yield per cow, higher feed conversion at herd level and higher utilization of manure, together with a reduction in use of fertilizer, leading to an increased N efficiency at farm level.

## Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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