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Impact of subclinical mastitis on greenhouse gas emissions intensity and profitability of dairy cows in Norway

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Abstract

Impaired animal health causes both productivity and profitability losses on dairy farms, resulting in inefficient use of inputs and increase in greenhouse gas (GHG) emissions produced per unit of product (i.e. emissions intensity). Here, we used subclinical mastitis as an exemplar to benchmark alternative scenarios against an economic optimum and adjusted herd structure to estimate the GHG emissions intensity associated with varying levels of disease. Five levels of somatic cell count (SCC) classes were considered namely 50,000 (i.e. SCC50), 200,000, 400,000, 600,000 and 800,000 cells/milliliter (mL) of milk. The effects of varying levels of SCC on milk yield reduction and consequential milk price penalties were used in a dynamic programming (DP) model that maximizes the profit per cow, represented as expected net present value, by choosing optimal animal replacement rates. The GHG emissions intensities associated with different levels of SCC were then computed using a farm-scale model (HolosNor). The total culling rates of both primiparous (PP) and multiparous (MP) cows for the five levels of SCC scenarios estimated by the model varied from a minimum of 30.9% to a maximum of 43.7%. The expected profit was the highest for cows with SCC200 due to declining margin over feed, which influenced the DP model to cull and replace more animals and generate higher profit under this scenario compared to SCC50. The GHG emission intensities for the PP and MP cows with SCC50 were 1.01 kilogram (kg) and 0.95 kg carbon dioxide equivalents (CO_2e) per kg fat and protein corrected milk (FPCM), respectively, with the lowest emissions being achieved in SCC50. Our results show that there is a potential to reduce the farm GHG emissions intensity by 3.7% if the milk quality was improved through reducing the level of SCC to 50,000 cells/mL in relation to SCC level 800,000 cells/mL. It was concluded that preventing and/or controlling subclinical mastitis

consequently reduces the GHG emissions per unit of product on farm that results in improved profits for the farmers through reductions in milk losses, optimum culling rate and reduced feed and other variable costs. We suggest that further studies exploring the impact of a combination of diseases on emissions intensity in Norway are warranted.

Keywords: dairy cow, dynamic programming, greenhouse gas emissions intensity, profitability, subclinical mastitis, whole farm modelling.

1. Introduction

The dairy sector contributes approximately 40% of agricultural greenhouse gas (GHG[1]) emissions in Norway, producing around 1.9 million tonnes (t) of carbon dioxide equivalent (CO_2e) emissions every year (Sandmo, 2014, Statistics Norway, 2016). The projected human population growth and the increased demand for food production by at least 20% by the year 2030 in Norway are likely to result in increased GHG emissions from the agricultural sector. Therefore, the Norwegian Ministry of Agriculture and Food requires reducing the agricultural emissions by 20% from GHG emissions levels measured in the year 1990 by the year 2020

[1] Abbreviations: ARmilk: allocation ratio milk, BMR: beef milk ratio, CM: clinical mastitis, CW: carcass weight, DM: dry matter, DMI: dry matter intake, DP: dynamic programming, ENPV: expected net present value, FPCM: fat and protein corrected milk, GHG: greenhouse gas emissions, IPCC: Intergovernmental Panel on Climate Change, kg CO_2e: kilogram carbon dioxide equivalents, mL: milliliter, MJ: megajoules, MP: multiparous, NE: net energy, NEA: net energy for activity, NEL: net energy for lactation, NEM: net energy for maintenance, NEP: net energy for pregnancy, NOK: Norwegian krone, PP: primiparous, SCC: somatic cell count, SCM: subclinical mastitis

(Climate and Pollution Agency, 2013). In order to meet the expected extra food production and yet reduce the GHG emissions from dairy cows, minimum use of inputs is required for a given level of milk output i.e. improved production efficiency (Place and Mitloehner, 2010). Poor animal health and welfare conditions that often lead to clinical and subclinical diseases may result in reduced production efficiency through increased mortality (Ersboll et al., 2003), reduced milk yield (Bareille et al., 2003), reduced reproductive performance (Bennett et al., 1999), and increased animal replacement rates (Weiske et al., 2006), all of which have the potential to increase the GHG emissions produced per unit of product (i.e. emissions intensity) (Place and Mitloehner, 2010). Therefore, it has been argued that if animal health and welfare are improved, there is potential to reduce the intensity of GHG emissions and increase productivity, increase farm income, reduce losses and therefore improve farm profitability (Stott et al., 2010, Williams et al., 2013).

Bovine mastitis is an endemic disease of mammary glands and may be responsible for a substantial proportion of the total production losses in dairy herds (Barkema et al., 2009). It has also been recognized as one of the most intractable health conditions in cows (Skuce et al., 2016), therefore an impediment to perform efficient and sustainable livestock production. The losses associated with bovine mastitis include reduction in milk yield, discharge of contaminated milk due to treatment with antibiotics, treatment losses and increases in mortality and replacement rates (Geary et al., 2012). If the disease occurs in the form of subclinical mastitis (SCM), no visible signs may be found in the udder or milk (IDF, 2011). Milk from cows with SCM is characterized by increased lipolysis, proteolysis, rancidity and bitterness (Ma et al., 2000) and reduction in milk yield (Halasa et al., 2009). The reduction in milk yield and quality related to udder health are commonly calculated by somatic cell count (SCC) (Bartlett et al., 1990). The International Dairy Federation (2013) reports that the level of SCC in cows suffering from SCM is greater than 200,000 cells/milliliter (mL). Although some studies reported that SCM causes increased SCC, impairs milk composition (Gonçalves et al., 2016, Bobbo et al., 2017) and milk yield (Botaro et al., 2015), their impacts on the environment have not been questioned widely. Integrated modelling approaches combining different models provide a thorough assessment of the livestock production systems studied and facilitate the decision-making process (Özkan Gülzari et al., 2017). In this study, we aimed to assess the changes in GHG emissions intensity and economic performances associated with raised SCC in relation to changes in milk yield, feed intake and replacement rates. For this purpose, an optimization model along with a GHG calculating model (HolosNor) were used. A dynamic programming (DP) model that maximizes the long-run profit of a dairy herd by optimizing future culling and replacement decisions was used to inform the GHG calculating model about the optimum composition of the herd in terms of the age and production levels of the cows in herd under different SCC challenges.

2. Materials and methods

In this study, we combined two models, one DP model for replacement decisions, and one GHG model (HolosNor) to calculate the emissions associated with varying levels of SCC. Figure 1 shows the relationship between the two models, their input-output interactions, and the inputs that were estimated. Circle shapes refer to the model outputs while rectangular shapes describe the inputs. Optimum culling strategies, one of the outputs of DP, were used as an input in HolosNor. Most of the equations in both models were adapted from previously published papers (Stott et al., 2002 and Stott et al., 2005 for the DP model; and Bonesmo et al., 2013 for HolosNor model) and the parts where both models shared the same input to be representative for the Norwegian conditions; or used each other's input/output were deemed novel to the current study.

Figure 1 here

The DP model uses revenues from milk yield and sold calves as well as fixed costs of feed production and variable costs for cows in each parity and SCC category to estimate the profit. It then optimizes the keep or replacement decisions and determines the culling rates and therefore the proportion of animals in each parity and SCC categories that generate the maximum profit in the long term. The estimated proportion of animals in each parity and SCC categories are then used in the HolosNor model to calculate GHG emissions intensity. Following sections describe data, assumptions and details of the processes adapted in the DP and HolosNor models.

2.1. Herd characteristics and some key management data of the modelled farm

The modelled farm that comprises of individual dairy cows, except for milk production, concentrate intake and replacement rates, reflects an average Norwegian dairy farm based on the data originally reported by Bonesmo et al. (2013) from an inventory of 30 farms located all around Norway and those reported by TINE Advisory Services (2012; 2014) (Table 1). Input values for fuel and electricity consumption were as described by Bonesmo et al. (2013).

Table 1 here

2.2. Inclusion of SCC levels in models

Five scenarios of SCC levels in milk were defined. Cows with a SCC level of 50,000 cells/mL milk and below were considered uninfected (Laevens et al., 1997). Since International Dairy Federation defines the level of SCC in milk of cows with SCM as above 200,000 cells/mL milk (IDF, 2013), we assumed that there was no reduction in milk production in cows with SCC levels of 200,000 cells/mL milk and below (named as "SCC50") (see also Svendsen and Heringstad, 2006). Reductions in milk yield were calculated for the following scenarios of SCC levels in milk (in SCC/mL milk): SCC levels at 200,000 cells (named as "SCC200"); SCC levels at 400,000 cells/mL (named as "SCC400");

SCC levels at 600,000 (named as "SCC600"); and SCC levels at 800,000 cells/mL milk (named as "SCC800"). It was assumed that the average milk yields in Table 1 reflect a SCC level of less than 200,000 cells/ml (at the assumed fat and protein contents of milk of 4.12% and 3.40%, respectively). All levels of SCC were set at individual cow level, which was used to scale it up to herd level of 25 cows per farm. It is acknowledged that an individual cow's cell count varies from one milk recording to the next, and even from week to week as some cows recover and others become infected. Because we did not intend to cover the dynamics of the disease at an individual animal level, but instead meant to determine the overall possible financial and environmental impacts of the disease at herd level, it was deemed sufficient to set the SCC level at individual cow level.

Milk yield losses associated with different levels of SCC were calculated at single point level for each scenario e.g. milk losses associated with SCC200 scenario were calculated for SCC level of 200,000 cells/mL. Elevated SCC level of 200,000 cells/mL and above was assumed to be due to SCM. Possible cases of CM were not included in this analysis. Milk losses due to increased SCC were calculated by deducting the milk production of cows with elevated SCC levels from the milk production of cows with SCC50 during a 305-day lactation period. The amount of milk delivered on farm was assumed to be 93.3% of that produced (TINE Advisory Services, 2014) as the rest is assumed to be discharged due to use of antibiotics or used for feeding calves.

Milk yield of cows with SCC50 were provided by TINE Advisory Services and it reflects years between 2009 and 2013 (TINE Advisory Services, 2014). For lactation numbers from 10 to 12, there were no data available after the year 2000. Therefore, we used an average milk yield of data available for 1999 and 2000 for lactation 10 and above. The milk loss associated with different levels of SCC was calculated using the mathematical formula used by TINE Advisory Services based on Hortet et al. (1999) below (equation 1). Losses were calculated as a percentage. Note that the milk loss associated with different SCC levels for lactation six and onwards was calculated based on the assumption that the reduction remained constant after lactation five. The formula reflects first lactation and equations for the 2^{nd}, 3^{rd}, 4^{th} and 5^{th} lactations can be found in the supplementary content:

$$\text{The milk yield on each test day in lactation} = \text{Intercept } (15.3841) + (-0.0451) \times (\text{day in lactation}) + 2.3894 \times \ln(\text{day in lactation}) + (-0.0087) \times \ln(\text{SCC}) + (-0.002) \times \ln(\text{SCC}) \times (\text{day in lactation}) \quad (1)$$

Where; ln (SCC) refers to the SCC scenario (1,000 cells/mL) classes defined above and day in lactation was from day one to day 305 of lactation. It is the fixed effect of natural logarithm of SCC (x1000 cells/mL).

Inclusion of SCC in the DP and HolosNor models employed the assumption that the individual animals forming the herd are affected by SCM through the impacts on milk yield, feed intake and milk prices, all of which were defined for each individual SCC scenario. The DP model uses a single SCC scenario in each run and optimizes the profit by choosing the best culling regime under that SCC scenario. Similarly, in HolosNor, changes in feed intake and milk yield were defined at a single SCC level. The DP model then generates the proportion of animals in each parity (age) category that was used in HolosNor for GHG emission calculations, again defined at a single SCC level. Running the DP model for all the five SCC scenarios enabled us to compare the scenarios and their impact by using the same assumptions used in the same benchmarking tool (i.e. combined models).

For each of the SCC scenarios, a milk price was set. The current practice in Norway imposes a price reduction of 0.30 NOK (NOK: Norwegian krone; 1 NOK equals 0.11 Euros as of the 3^{rd} of October 2017) and 0.60 NOK/kg milk for bulk tank SCC levels of between 300,000 cells and 350,000 cells/mL and between 350,000 cells and 400,000 cells/mL, respectively.

Given that the milk losses were calculated for each cow, we assumed that milk prices applied at individual cow level as well. Although this assumption does not directly model the bulk tank and its related milk prices based on its SCC, the modelled individual cows and their proportion in the herd, reflected in combinations of various SCC levels and milk prices, indirectly construct a bulk tank representation. The milk prices of the SCC50 and SCC200 scenarios were set at 4.7 NOK/kg milk as the average milk price in years 2011 and 2012 (TINE Advisory Services, 2014). A modification to the current prices was made to reflect about a 10% reduction in market milk price in SCC400 and 15% reduction in market milk price in SCC600 and SCC800 scenarios. That is, the milk prices associated with SCC levels were 4.7 NOK/kg for SCC200; 4.3 NOK/kg milk for SCC400; and 4.0 NOK/kg milk for SCC600 and SCC800 scenarios. Lowering the SCC by feeding milk with high SCC to young stock and hence reducing the concentrate costs were not included in this study.

2.3. Dynamic Programming for replacement decisions

A DP model of the dairy cow replacement decision was used to establish the optimized culling strategy that consisted of voluntary and involuntary culling rates, leading to the long run steady-state herd structure in terms of the proportion of animals in lactations 1–12. The DP model has an annual time-frame meaning that the keep or replace decisions as well as all the financial revenues and costs occur on an annual basis. A lactation curve of daily milk yield from day 1 to day 305 of lactation (Formula 1) was used to calculate the annual milk yield under each SCC scenario. All culling due to low milk yield and cows with elevated SCC (all SCC scenarios), were considered voluntary and were decided by the DP model. All other conditions observed in the dataset such as lameness, CM, other diseases, teat injury, calving difficulty, bad udder and leakage, temperament issues and death due to other reasons were considered under the involuntary culling category and were used to estimate the involuntary culling probabilities that were used as input in the DP model (Table 2).

Table 2 here

Maximizing profit via optimum culling and replacement decisions could imply keeping animals for longer periods, and this is the reason why the lactation states of the model were extended up to 12 in the model.

The DP model was run using a version (Stott et al., 2005) of general purpose DP software (Kennedy, 1986). The average milk yield per lactation, probability of involuntary culling for cows with elevated SCC levels as well as financial figures such as fixed and non-feed variable costs, buying price of heifers and selling price of calves in Stott et al. (2005) were replaced by figures reflecting Norwegian practice. The objective of the DP was to maximize the expected net margin, i.e. the expected net present value (ENPV) of the margin of milk and calf sales over feed costs and net culling costs (other costs assumed fixed) expressed as an annuity, from a current lactating cow and all future cows over an infinite time horizon by making appropriate keep or replacement decisions. Using the milk yield in each parity and each SCC scenario, an optimal culling strategy, ENPVs and infinite state probabilities that reflect the herd structure in terms of proportion of animals in each lactation were generated. The initial involuntary culling rates that were used as input in the model for cows with low (SCC50) and high (SCC200 and above) levels of SCC were estimated from a dataset of the total number of culled cows and the main reasons of culling for lactation 1 to lactation 5 in Norwegian dairy herds (TINE Advisory Services, 2014). These figures were derived based on the actual data and considering the definition of the voluntary and involuntary culling rates used. As the data did not cover lactation 5 onwards, we assumed a fixed involuntary culling rate for lactation 5–12. These probabilities were used as input in the DP model. Probability of involuntary culling for cows with elevated SCC levels and values of culled cows under voluntary and involuntary culling categories are presented in Table 2.

The key policy interest rate used by the central bank in Norway is currently at 0.5% (Norges Bank, 2017). In this study, however, we used a discount rate of 3.5% recommended for long-term projects and issues, under a declining schedule[2] of discount rate (Stott et al., 2002, Stott et al., 2005). The purchase price of a heifer was considered to be 15,000 NOK (TINE Advisory Services, Ås, personal communication) whereas the selling price of calves was assumed to be 4,000 NOK (TINE Advisory Services, Ås, personal communication). The total cost of fixed and non-feed variable costs was considered to be 2,800 NOK per cow (TINE Advisory Services, Ås, personal communication).

A sensitivity analysis for the baseline scenario (i.e. SCC50) of the DP model was conducted to examine how sensitive the expected net margin (NOK/cow/year) estimated by the model was to variation and uncertainty of input parameters. To do this, minimum, base case and maximum values derived from our mentioned data sources were used for the following input parameters: milk yield, milk price, forage and concentrate consumption, calf sale, cull cow value, heifer purchase value, fixed costs and average longevity of cows. Ranges of input values used in the sensitivity analysis for SCC50 are presented in Table 1. The results of sensitivity analysis show how the model's output depends on ranges (i.e. minimum, base case and maximum values) that were specified by the data used for each of the model's input variables. Results are reported in tornado charts that show single-factor sensitivity analysis, i.e., for each output value, only one input value is changed from its base case value. The tornado charts then summarise eight separate single-factor sensitivity analyses.

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[2] Declining schedule of discount rate refers to "a discount rate applied today to benefits and costs occurring in future years declines with maturity: the rate used today to discount benefits from year 200 to year 100 is lower than the rate used to discount benefits in year 100 to the present" (Arrow et al., 2013).

2.4. Estimating GHG emissions intensity

2.4.1. Whole farm modelling (HolosNor)

Once the alternative optimum replacement rates were obtained for each scenario from the DP model based on the increased levels of SCC inducing reduction in milk yield, net margin and milk prices, as well as changes in the replacement rates, HolosNor was used to calculate the changes in the GHG emissions intensity.

HolosNor is a tool for calculating the GHG emissions from combined dairy and beef productions systems (Bonesmo et al., 2013; Özkan Gülzari et al., 2017) in Norway. It is based on the Canadian HOLOS model (Little, 2008). It was modified to recognize Norwegian conditions to consider enteric methane (CH_4), manure-derived CH_4, on-farm nitrous oxide (N_2O) emissions from soils, off-farm N_2O emissions from leaching, run-off and volatilization (indirect N_2O), on-farm carbon dioxide CO_2 emissions or C sequestration due to soil C changes, CO_2 emissions from energy used on farm, and off-farm CO_2 and N_2O emissions due to supply of feed inputs (Bonesmo et al., 2013). All emissions are expressed in CO_2e to include the global warming potentials recommended by the Intergovernmental Panel on Climate Change (IPCC) on a time horizon of 100 years as 25 kg of CO_2e/kg CH_4 and 298 kg of CO_2e/kg N_2O (Forster et al., 2007). The emissions intensities are reported as kgCO_2e/kg fat and protein corrected milk (FPCM) for milk and kgCO_2e/kg carcass weight (CW) sold for meat.

The model and the farm data published by Bonesmo et al. (2013) were the basis for our calculations except for the following: Concentrate intake of lactating cows (TINE Advisory Services, Ås, personal communication); Replacement decisions (output of the DP model); and Milk losses (formula used by TINE Advisory Services based on Hortet et al. (1999)). The following procedure was followed to run the model: The principles used to calculate the net energy (NE) requirements (in mega joules (MJ)) of all animals consisting of maintenance

(NEM), activity (NEA), lactation (NEL) and pregnancy (NEP) were according to IPCC (2006), and were previously described by Bonesmo et al. (2013) and the following procedure was followed since we were required to calculate the area (and the amount) of grassland necessary for silage making on farm because this was not an available input:

Total net energy requirement (sum of NEM, NEA, NEL and NEP) was converted to dry matter (DM) by taking into account the energy density of the feeds used (i.e. NE per kg DM). The NE/kg DM for concentrate, grass silage and pasture were 7.9, 5.9 and 6.9, respectively according to Bonesmo et al. (2013). Concentrate intake for milking cows was an input and was provided for different animal (PP and MP) and SCC categories (Table 3) (TINE Advisory Services, Ås, personal communication). Annual consumptions of concentrate feed of heifers and bulls were 263 kg and 1,258 kg DM/head, respectively (Bonesmo et al. 2013). The total dry matter intake (DMI) of all animals was the sum of concentrate intake (DM) and requirement of silage and pasture (DM), reflecting different proportions of concentrate, silage and pasture in the ration. Subtracting the concentrate DMI from total DMI gave the total expected silage and pasture DMI. Pasture constituted about 16% of total NE intake. Pasture DMI was a function of pasture NE intake, its energy concentration and the time spent on pasture (%). Expected silage DMI alone for the whole herd was then calculated by multiplying the proportion of the silage in the total ration by (i) total expected DMI/head per day; (ii) the number of animals; and (iii) the number of feeding days in each animal category. Because the input required was the total farm silage production in fresh weights, the total farm expected silage intake was divided by the DM content of silage (25%). The loss associated with feeding the silage was accounted for as 10%. Once the total farm expected net silage intake was calculated, area to grow the required amount of silage was calculated, using the amount of silage produced per unit of area presented by Bonesmo et al. (2013) (22,490 kg silage was produced per hectare (ha)) (Table 3). The reduction in total feed intake due to reduced milk yield in all SCC scenarios was calculated by subtracting the feed intake at each level of SCC from the feed intake of cows with SCC50.

Table 3 here

The ration, on DM basis, consisted of grass silage (37–38%), concentrates (barley and soya, 45-47%), and grazed grass (16%). The proportion of the concentrate in total DMI was calculated by dividing the concentrate DMI by the total DMI. The proportion of the silage DMI was calculated according to the equation 2 below used by Bonesmo et al. (2013):

$$[(\text{total DMI} - \text{concentrate DMI}) \times (1 - \text{time spent on pasture})] / \text{total DMI} \quad (2)$$

Where time spent on pasture was set to 30% for cows and 17% for heifers according to Bonesmo et al. (2013) and it was the % of the days in a year when the animals had access to pasture.

The proportion of the grazed grass in the total DMI was computed by subtracting the total proportions of concentrate and silage intake from value 1 (i.e. 1 − % concentrate − % grass silage). No cereal crops were grown on farm. The amount of nitrogen (N) fertilizer applied to the silage area was 100 kg N/ha. About 1.4 ha of farm area was allocated for only grazing, and cows were also assumed to graze on area where silage was made to fulfill the required proportion of grass intake. Energy used to produce pesticides in all scenarios was 40 MJ/ha (Bonesmo et al., 2013).

2.4.2. Allocation of emissions

The GHG emissions were partitioned between milk and meat according to the proportions of feed resources consumed and as described by Bonesmo et al. (2013). The Norwegian dairy production systems are combined dairy-beef systems where the practice is year round calving with fattening of bulls on farm and average slaughter age is 18 months (Bonesmo et al., 2013). The beef milk ratio (BMR) was calculated as the ratio between kg LW sold (all bulls and the culled cows) and kg FPCM. Allocation ratio milk (AR_{milk}) was calculated by dividing the proportion of the emissions allocated to milk production by the BMR according to Bonesmo et al. (2013). Five BMR points for five AR of milk were calculated, reflecting the five levels of SCC.

3. Results

3.1. Reduction in milk yield and feed intake induced by elevated SCC levels

Milk yield reduced as the level of SCC increased in all SCC scenarios between 0.4 kg and 0.9 kg FPCM/cow per day for the PP cows (4.3% higher in the SCC800 than in the SCC50), 1.2 kg and 2.4 kg FPCM/cow per day for the MP cows (10.3% higher in the SCC800 than in the SCC50). The reduction in total feed intake (kg DM/cow per day) in relation to predicted SCC induced change in milk yield (kg/cow per day) was between 1.4% (SCC200) and 2.8% (SCC800) for the PP cows and 3.3% (SCC200) and 6.6% (SCC800) for the MP cows (Figure 2).

Figure 2 here

3.2. Culling rates and ENPV

The total culling rates for the SCC scenarios estimated by the DP model varied from a minimum of 30.9% (SCC400) to a maximum of 43.7% (SCC800). The average longevity of the herd with SCC50 was at 2.7 lactations. This reduced to 2.3 lactations under SCC200 scenario as a result of increased voluntary culling rate and therefore having increased numbers of younger cows on the farm. The average longevity then increased again to 2.7 lactations for SCC400 scenario as the model reduced the optimum culling rate, implying keeping cows longer on the farm in response to both lower milk yield and also lower milk price due to higher SCC. As the SCC increased, implying also a greater milk price penalty, average longevity of the herd reduced again to 2.5 and 2.3 under SCC600 and SCC800 scenarios, respectively, indicating more culling and replacement would maximize the profit more than opting for lower culling rates and hence on average having younger animals in the herd.

The long-run state probabilities generated by the DP model indicate the proportion of the animals in the herd in each lactation number (i.e. state) and the stable herd composition that will arise if the optimum culling regime is followed (Figure 3). This herd composition provides a convenient benchmark for comparison between SCM scenarios.

Figure 3 here

The highest ENPV observed was related to the SCC200 scenario (using a milk price of 4.7 NOK/kg) that was 5% higher than the ENPV of cows with SCC50. In the case of SCC200, the model suggests a higher culling rate than SCC50 (41.2% versus 38.3%) that is caused by the reduction in milk yield due to higher SCC. The highest culling rate observed was related to SCC800 (43.7%), but the estimated ENPV for this scenario was the second lowest. The lowest ENPV belonged to cows with SCC400 and when a milk price of 4.3 NOK/kg was used. We present the outputs of the DP for culling rates and ENPVs in Table 4 below.

Table 4 here

3.3. Sensitivity analysis

A sensitivity analysis for the baseline scenario (i.e. SCC50) of the DP model was performed to show how sensitive the expected net margin (NOK/cow/year) is to variation and uncertainty of input parameters. Results are presented in two graphs related to i) highly influential input variables (Figure 4); and ii) less influential input variables (Figure 5).

Figure 4 and Figure 5 here

As it is expected, Figure 4 shows that the annual expected net margin per dairy cow is very sensitive to the level of milk yield. The lowest annual milk yield of 2,570 (L/cow) that was assumed for low producing cows, results in expected net margin of 1,167 NOK whereas the highest annual milk yield of 11,863 (L/cow) that was assumed for high producing cows results in an expected net margin of 44,844 NOK. Based on this result, in total 83% of the uncertainty in expected net margin is due to such a variation around the milk yield. Milk price was the second most influential input variable affecting the net margin, responsible for 15% of its uncertainty. The lowest and the highest assumed prices of 3.0 and 5.0 NOK/L result in annual net margins of NOK 16,559 and NOK 34,873/cow, respectively. The expected net margin, to some extent, was also sensitive to the feed costs accounting for 3.0% of its variability. Figure 5 shows that the sensitivity of the expected annual net margin to five other input parameters namely: calf sale value, cull cow value, heifer purchase cost, fixed costs and the average longevity of cows in the herd. The DP model outputs were therefore less sensitive to variations of these five mentioned input parameters.

3.4. The whole farm model (HolosNor)

3.4.1. Greenhouse gas emissions intensity

Emissions intensities for the PP and MP cows with SCC50 were 1.01 kg and 0.95 kg CO_2e/kg FPCM, respectively. These figures increased by 3.3, 3.6 and 3.7% in the MP cows with SCC400, SCC600 and SCC800, respectively compared to the MP cows with SCC50. Emissions intensities for the PP and the MP cows with SCC50 for meat were 29.37 kg and 20.88 kg CO_2e/kg CW, respectively. The highest emissions intensities for meat were observed in cows with SCC400 in both the PP and the MP cows; however the difference between other SCC scenarios was not substantial.

Enteric CH_4 emissions per kg FPCM increased as the SCC level increased, up to 5% in the SCC800 compared to SCC50 in the PP cows. In the MP cows, however, the increasing trend was disrupted in SCC400, but reached 8% in SCC800 compared to SCC50. Similarly, manure CH_4 emissions per kg FPCM also increased by SCC level in the PP and MP except for the SCC400 in the MP where emissions decreased slightly. Direct and indirect N_2O emissions intensity elevated as the SCC level increased being about 6% higher in the SCC800 than in the SCC50, with the exception of SCC400 which showed a similar trend to that of SCC200 (about 2.1% higher than the SCC50) in the PP cows. In the MP cows, direct and indirect N_2O emissions intensity reduced by about 1.7% in cows with SCC400, but increased by 9.1% in cows with SCC800 compared SCC50. (Table 5).

Table 5 here

3.4.2. Allocation of emissions

The BMR was between 0.074 and 0.079 in the PP, and between 0.074 and 0.083 in the MP. Emissions were allocated to milk (ARmilk) at a higher ratios in the PP cows (88.3%) than the MP cows (76.7%) and the ARmilk was the highest in the SCC50 scenario for the PP cows, in the SCC400 scenario for the MP cows.

4. Discussion

4.1. Reduction in milk yield

Based on the assumptions used in this study, calculated milk losses increased as the level of SCC increased, reflecting the impact of disease on production. Hortet et al. (1999) reported that if a reference value for SCC was set to 50,000 cells/mL, the reduction in milk yield may be up to 1.09 and 1.13 kg/day for a SCC level of 600,000 cells/mL in the PP and the MP cows, respectively. In our study, PP and MP cows with SCC200–SCC800 reduced the milk yield between 0.4 kg and 0.9 kg/day; and 1.2 kg and 2.4 kg/day, respectively. The difference for the MP cows in the current study and that by Hortet et al. (1999) can be due to genetic potential of different breeds, in addition to that the milk yield of MP cows in the current study was an average of 11 lactations after optimal culling compared to a single year lactation in Hortet et al. (1999) who categorized the cows as 1st parity, 2nd parity and 3rd and above parity. The milk reduction of MP cows with SCC200 (5.1%) was similar to that found by Bartlett et al. (1990) (5%); however the reduction in milk yield increased (up to 10.3% in SCC800) as the SCC level increased in the present study. Higher milk yield reduction in the MP cows than the PP cows can be explained by the MP cows being exposed to infections more than the PP cows, and the perpetual damage to udder cells in the MP cows (Bartlett et al., 1990). The MP cows potentially require more energy for production reflecting that less energy is available for maintenance and hence for recovery.

We considered that the SCC level above 200,000 cells/mL were due to subclinical mastitis. This is because while CM can be detected by clinical symptoms such as swelling, heat and hardness in the udder or watery appearance of milk with flakes, clots or pus, SCM may remain undetected unless identified through the change in SCC level. Further, the clinical signs in the case of CM may underpin the decisions made for voluntary culling, reflecting a greater voluntary culling in the CM than in the SCM. Moreover, only yield and price impacts associated with SCM were considered in this study because in the case of CM, a range of symptoms, impacts and control decisions are involved, which were not included in this study.

4.2. Reduction in total feed intake in relation to change in SCC levels

The total feed intake reduced as the SCC level increased (16.3 kg and 18.0 kg DM/cow per day in the PP and the MP cows with SCC50, respectively compared to 15.9 kg and 16.8 kg DM/cow per day in the PP and the MP cows with SCC800, respectively). The lowest silage intake (5,089 kg and 5,976 kg for the PP and the MP cows, respectively) observed in cows with SCC400 was probably due to the reduced number of young stock in SCC400 scenario where the lowest culling rate was observed. It is important to note that the reduction in feed intake in empirical studies cannot be attributed to increased levels of SCC only as mastitis may be accompanied by other diseases (Seegers et al., 2003) in 65% of the cases, e.g. metritis and other disorders (Zamet et al., 1979). In this study, we assumed that the reduction in milk yield was due to the increased SCC (to expose the impacts of this condition) and the reduction in total feed intake was therefore attributed to the reduced energy requirements to produce a given level of milk. However, increased concentrate intake per kg of milk as the SCC level increased in both PP and MP cows shows that cows with increased levels of SCC may increase their energy requirement due to the production of immunological components such as immunoglobulin G, other antibodies, and white blood cells. In our study, maintenance NE requirement was a function of coefficient of maintenance requirement and average live weight, both of which were not affected by the level of SCC. If elevated SCC levels increase the maintenance energy requirement, then the feed consumption as well as GHG emissions intensity may have been underestimated and ENPV may have been overestimated in the cows with high SCC levels. Therefore, further studies are warranted to identify the maintenance requirements of cows with elevated levels of SCC, as well as the changes in animal metabolism due to impaired health (see Özkan et al., 2016). This study, however, adopts a very conservative approach, reflecting that no published papers were available to make assumptions on the increased maintenance requirements of cows with high SCC levels. Based on the presented results of the sensitivity analysis, the ENPV of individual healthy cows (i.e. SCC50) was relatively sensitive to variations of feed requirements and subsequently the feeding costs, accounting for 3.0% of net margin's uncertainty. Reduction in feed demand could increase the EPNV from NOK 32,125 in the base scenario to NOK 36,126 and increase of feed demand will decrease the ENPV to NOK 26,127. It is, therefore, envisaged that any potential positive or negative effect of elevated SCC on feed requirements may significantly affect the financial and environmental results estimated by our models. However, in absence of scientific evidence and reliable data, this has not been quantitatively included in such models.

4.3. Culling rates and ENPV

The total voluntary culling rates estimated by the DP model in this study (9.7% in the SCC50 and up to about 16% in cows with SCC800) were influenced by the change in milk yield with parity and SCC according to equation 1. The total (both PP and MP) culling rates were also influenced by involuntary culling rates that were due to reasons other than elevated SCC and associated milk production. By focusing on SCM only, we ensured that the culling decisions were made only for SCM (not because of the clinical signs in the CM, for example). However, there is scope for identifying other diseases which may have greater impact on GHG emissions (Özkan et al., 2016). The voluntary culling rates of 12.8% and 6.9% in the SCC200 and SCC600, respectively with milk prices of 4.7 NOK and 4.00 NOK/kg milk, correspond with the voluntary culling rates of 7.1% in a mastitis-infected herd and 11.2% for cows with yield loss, presented by Stott et al. (2002).

It is important to stress that based on the sensitivity analysis, the ENPV was mainly driven by milk yield and milk and feed market prices and therefore if, for example, the average milk yield of a dairy farm or milk prices were higher than those reported here, higher culling rates may be expected. On the contrary, a low ENPV may also be caused by reduced milk yield and/or milk market prices. Results also show that variations and uncertainty of other input parameters including calf sale value, heifer purchase value, cull cow value, fixed costs of feed production and longevity of individual cows have less influence on ENPV than yield, milk and feed prices. Based on the outcome of the sensitivity analysis, it was concluded that the presented models and results are robust and encompass uncertainty around the input variables. The main reason is that the uncertainty of the most influential variables namely milk yield, milk price and forage and concentrate consumption, were included in the five SCC scenarios examined. In other words, effect of SCM on milk yield, possible consequences on milk price and margin over feed were assessed under the five SCC scenarios. However, it should be noted that each of these single input parameters is only one of the elements that may increase the culling rate. Eventually, it is the net financial value (e.g. meat price for culled cows, price/cost of replaced heifer, milk production costs and milk price) which determines the optimal culling rate. Although it was shown that the profit of suckler cow systems were sensitive to culled cow meat prices (Vosough Ahmadi et al., 2016), presented results show that this is not the case for the combined dairy and beef systems where milk prices compose of a higher proportion of the income. Declining margin over feed of SCC200 compared with SCC50 scenario (average margin over feed of 29,615 versus 31,787 NOK/cow per year, respectively) and reduced milk yield as a result of SCM but receiving the same milk price as the cows with SCC50, influenced the DP model to cull and replace more animals under this scenario than SCC50. Further decreases in milk yield and fall in margin over feed, but also this time penalized milk prices under SCC400, led the DP model to reduce the voluntary culling rates to compensate for the losses. Imposing an increased rate of penalty to the milk price of SCC600 and SCC800 scenarios in addition to the further yield losses and further reduced margin over feed, forced the DP to cull and replace more animals to compensate for the loss and maximize the ENPV. It should be noted that the DP model does not account for impact of culling on SCM spread in the herd.

4.4. Greenhouse gas emissions intensity

The emissions intensities of 1.01 kg and 0.95 kg CO_2/kg FPCM for the PP and the MP cows with SCC50 were close to those reported by Bonesmo et al. (2013), Jayasundara and Wagner-Riddle (2014) and Williams et al. (2013). An extensive discussion on the emissions intensities was previously reported by Bonesmo et al. (2013), however in the study conducted by Williams et al. (2013), a healthy cow produced 7,875 kg milk which was 12% higher than the milk yield of a cow with SCC50 (7,021 kg) in the MP cows in this study. Note that the lowest level of SCC defined in this study (50,000 cells/mL) may be considered as the level of SCC of a healthy cow, however we avoided the use of "healthy" in this study since there are controversial definitions of a healthy cow as far as the SCC level is concerned. The GHG emissions intensity calculated using HolosNor in this study represent on-farm emissions in Norway. Therefore variations are expected if the emissions are calculated at a larger scale or the IPCC Tier 2 approach has been modified to reflect the country-specific conditions (as in Jayasundara and Wagner-Riddle (2014)) or the nature of the systems compared (e.g. the combined dairy and beef systems as opposed to the specialised systems in Williams et al. (2013)).

There are only a few studies showing the relationship between health status of dairy cows and the GHG emissions intensity (Elliott et al., 2014; MacLeod et al., 2017; Skuce et al., 2016). For example, Elliott et al. (2014) reported that if the health status of the cows were improved by 50%, the reduction in the emissions would be about 669 kilo t CO_2e, equal to 5% of the UK's dairy emissions. Very few studies reported the impact of elevated levels of SCC on GHG emissions at an individual animal or herd level. Reductions in GHG emissions intensity in healthy cows have previously been based on the input-use efficiency (Hospido and Sonesson, 2005) because the healthy cows were found to be more efficient converters of feed as they use more of their energy for milking and less of it for maintenance (Tyrrell and Moe, 1975). The lowest GHG emissions intensity found in this study in the cows with SCC50 could be discussed for the two parameters: milk yield and feed intake. The cows with SCC50 consumed the highest DM and produced the highest milk yield as oppose to the cows with elevated levels of SCC where the reductions in feed intake and milk yield were proportional.

In this study, we only compared the milk yield losses due to increased SCC levels and no account was given to other milk losses e.g. wasted or discarded milk (as opposed to that presented by Hospido and Sonesson (2005)). Given that mastitis may increase the emissions intensity by up to 7–8% (Williams et al., 2013), and up to 3.3, 3.6 and 3.7% for the MP cows with SCC levels of 400,000, 600,000 and 800,000 cells/mL milk, respectively in our study, combatting this disease can be perceived, as well as the other diseases that result in a reduction in feed intake and feed utilization efficiency, as a strategy to reduce the on-farm GHG emissions intensity from dairying. Further studies may focus on evaluating the prevention strategies from SCM and their impacts on GHG emissions. This is not to prioritize SCM over any disease as it is used only as an exemplar in the present study. In practice, lower levels of SCC may be achieved by incorporating the calculation of GHG emissions intensity into a penalty or reward system both to improve animal health and to create awareness of the impact of ill-health on farm GHG emissions among farmers, farm advisors and policy makers. Based on the results shown here, it is likely that preventing and/or controlling subclinical mastitis consequently reduces the GHG emissions intensity on farm that results in improved profits for the farmers through reductions in milk losses, optimum culling rate and reduced feed and other variable costs.

Lower emissions intensities for meat (kg CO_2e/kg CW) (varying between 24.44 kg and 30.01 kg CO_2e/kg CW for the PP cows and between 20.88 kg and 22.46 kg CO_2e/kg CW for the MP cows) in this study than that reported by Pradère (2014) (32 kg CO_2e/kg CW) may be due to that the current study results reflect combined dairy and beef systems and not specialized beef systems. The PP cows produced higher emissions per kg CW than the MP cows, reflecting the lower culling rate in the PP cows, and therefore a lower mass of meat leaving the farm. In general, the number of cows slaughtered would be expected to be fewer in the herds with lower culling rate than the herds with higher culling rates, thereby increasing the emissions intensity due to more surplus calves not used for replacement (Hospido and Sonesson, 2005). Although a current trend in dairy farming is to increase a cow's lifetime and consequently rear less calves in Europe, high meat prices in Norway appear to encourage farmers to keep the young stock and reduce the number of lactations. However, from an environmental point of view, farms with more young stock are likely to emit higher emissions intensity than those with fewer young stock because young stock do not contribute to milk production.

The approaches taken in individual models and in combining the model results warrant further discussion. The use of DP allowed us to eliminate the avoidable losses (McInerney et al., 1992) associated with sub-optimal replacement that would otherwise be present had we compared different SCC scenarios under the same fixed set of assumptions. Optimal replacement was used as a proxy for the optimal set of potential/alternative prevention and control investments that can be adopted to minimize the financial impact of SCM at the assumed level of SCC applied to each scenario. In other words, future investments in any potential intervention could be compared with the benefits from implementing the optimum culling rate estimated by the DP model. Examples of the potential prevention and control measures were given by Yalcin et al (1999) that include: pre-milking udder-preparation methods; post-milking teat disinfection; the use of dry-cow therapy and a regular milking-machine test.

Obtaining the replacement rates from the DP model to be used in HolosNor enabled us to demonstrate that a win-win situation for both maximizing profit and minimizing environmental consequences is achievable by optimum management of subclinical mastitis at herd level. The DP model tests alternative SCCs fairly in terms of the physical and financial assumptions we made that reflect the real Norwegian situation. However, the results do not aim to provide a representation of current practice. We have modelled the 'rational farmer' as well as the herd under these circumstances as he/she would respond to these drivers to minimize the financial damage SCC does to the herd. We, therefore, have a framework that allows us to compare the herds on the same basis were the circumstances to change. Therefore, we do not intend to rank diseases by their importance nor would we aim to mimic the current practice as the DP model considers the whole life cycle of an animal as opposed to a real life situation where only current status of an animal would facilitate the decision-making process. Instead, by using the DP and combining it with HolosNor, we are proposing a standardized way to assess the impact of animal diseases on GHG emissions intensity that others could adopt so results would be comparable.

5. Conclusions

In this study, by using the DP model to calculate the replacement rates and ENPV in relation to varying levels of SCC, and integrating the outputs of the DP to the GHG model HolosNor, we present an attempt in combining two models to demonstrate the expected impact of SCM on replacement rates, ENPV and GHG emissions intensity. Combining HolosNor with the DP results ensures that the rationale behind the replacement decisions is solid and justified, given that the relationships between animal-related inputs and management decisions are complex and require comprehensive modelling. We concluded that there is a potential to reduce the total farm emissions intensity by 3.7% if the milk quality was improved through reducing the level of SCC to 50,000 cells/mL in relation to SCC level 800,000 cells/mL. We, however, acknowledge that this may be an underestimation as SCM is usually accompanied by other diseases. Based on the presented results, it is concluded that preventing and/or controlling SCM consequently reduces the GHG emissions per unit of production on farm, which results in improved profits for the farmers through reductions in milk losses, optimum culling rate and reduced feed and other variable costs. We suggest that further studies exploring the impact of a combination of diseases on GHG emissions intensity in Norway are warranted.

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Supplementary content

The milk losses associated with increased SCC in the second (equation 3), third (equation 4), fourth (equation 5) and fifth (equation 6) lactations were calculated according to the equations below (Hortet et al., 1999):

$$\text{The milk yield on an actual day in lactation} = \text{Intercept } (22.1919) + (-0.0534) \times (\text{day in lactation}) + 2.1395 \times \ln(\text{day in lactation}) + (-0.0061) \times \ln(\text{SCC}) + (-0.0044) \times \ln(\text{SCC}) \times (\text{day in lactation}) \quad (3)$$

$$\text{The milk yield on an actual day in lactation} = \text{Intercept } (23.3835) + (-0.0606) \times (\text{day in lactation}) + 2.5301 \times \ln(\text{day in lactation}) + (-0.0119) \times \ln(\text{SCC}) + (-0.005) \times \ln(\text{SCC}) \times (\text{day in lactation}) \quad (4)$$

$$\text{The milk yield on an actual day in lactation} = \text{Intercept } (23.8389) + (-0.0657) \times (\text{day in lactation}) + 2.8911 \times \ln(\text{day in lactation}) + (-0.1405) \times \ln(\text{SCC}) + (-0.0053) \times \ln(\text{SCC}) \times (\text{day in lactation}) \quad (5)$$

$$\text{The milk yield on an actual day in lactation} = \text{Intercept } (23.3551) + (-0.0656) \times (\text{day in lactation}) + 2.9135 \times \ln(\text{day in lactation}) + (-0.0667) \times \ln(\text{SCC}) + (-0.0053) \times \ln(\text{SCC}) \times (\text{day in lactation}) \quad (6)$$

Where; ln (SCC) refers to the SCC scenario (cells/mL) classes defined above and day in lactation was from day one to day 305 of lactation.

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Table 1. Data on herd size, production and biophysical parameters used to run the modelled farm

Parameter	Base case value[1] (minimum-maximum)	Unit	Reference
Herd size	25	cow equivalents[2]/year	TINE Advisory Services (2014) and Bonesmo et al. (2013)
Average milk yield for PP[3] cows	6,169	kg/cow per year	TINE Advisory Services (2014)
Average milk yield for MP[4] cows	7,021	kg/cow per year	TINE Advisory Services (2014)
Cows' average live weight	512 (PP cows) 539 (MP cows)	kg/head	Bonesmo et al. (2013)
Carcass weight of culled cows and calculated carcass weight of sold live animals	263	kg/head	TINE Advisory Services (2012)
Ratio of the number of slaughtered bulls and cows	0.76	head/year	Bonesmo et al. (2013)
Bulls' live weight at slaughtering	586	kg/head	TINE Advisory Services (2012)
Bulls' average slaughter age	17.6	months	TINE Advisory Services (2012)

Average milk yield (all cows)	6,595 (2,570-11,860)	kg/cow per year	TINE Advisory Services (2014) and authors' assumption
Milk price	4.7 (3-5)	NOK/L	TINE Advisory Services (2014)
Forage and concentrate costs	9,000 (5,000-13,000)	NOK/cow/year	TINE Advisory Services (2014) and Stott et al (2005)
Calf sale	4,000 (3,000-8,000)	NOK/calf sold	TINE Advisory Services (2014) and authors' assumption
Heifer purchase	15,500 (13,000-18,000)	NOK/purchased heifer	TINE Advisory Services (personal communication)
Cull cow value	12,500 (9,000-15,000)	NOK/cull cow	TINE Advisory Services (personal communication)
Fixed costs of producing feed	2,800 (2000-3,500)	NOK/cow per year	TINE Advisory Services (2014)

[1]Base case value; figures in parenthesis present minimum and maximum values respectively that were used in the sensitivity analysis. Ranges were derived from the references when available or are authors' assumptions.

[2]Weighted number of livestock in relation to the number of feeding days per year

[3]PP: Primiparous cows refer to cows that are in their first lactation

[4]MP: Multiparous cows refer to cows that are in their second or above lactations

Table 2. Value of culled cow (NOK) for both voluntary and involuntary culling and probability of involuntary replacement for cows with somatic cell count (SCC) level of 50,000 cells/mL and above for different lactation numbers (parity)

Lactation number[1]	Value of cull cow (NOK)[2] for both voluntary and involuntary culling	Probability of involuntary culling	
		Cows with SCC level of 50,000 cells/mL	Cows with elevated SCC levels
1	12,500	0.156	0.170
2	12,500	0.193	0.229
3	13,500	0.257	0.309
4	13,500	0.324	0.389
5−12	13,500	0.270	0.390

[1]The dataset did not include data on probability of involuntary culling for lactation beyond year 5. Therefore figures for lactation 5 were used for years 5-12. These figures were directly calculated from the dataset based on the reasons of culling included in the definition of involuntary culling. As such, the variations observed in these figures (e.g. probability of involuntary culling increases for cows with SCC50 from lactation 1 to lactation 4 and then drops for lactation 5) are attributed to the recorded data.

[2]NOK: Norwegian krone

Table 3. Concentrate intake, estimated silage requirement and area allocated for making silage for cows with elevated levels of somatic cell count (SCC). SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk and above

	Concentrate intake (kg dry matter (DM)/cow per year)	Estimated silage requirement[3] (kg DM/head-kg fresh weight/head[4])	Total silage area (hectare)	Concentrate consumption (kg DM/kg FPCM)
SCC50 PP[1]	2,312	5,164-20,654	23	0.375
SCC200 PP	2,305	5,153-20,612	23	0.382
SCC400 PP	2,299	5,089-20,355	23	0.385
SCC600 PP	2,287	5,102-20,407	23	0.386
SCC800 PP	2,295	5,225-20,901	23	0.389
SCC50 MP[2]	2,493	6,407-25,626	28	0.355
SCC200 MP	2,442	6,374-25,497	28	0.367
SCC400 MP	2,413	5,976-23,905	27	0.373
SCC600 MP	2,401	6,101-24,405	27	0.377

SCC800 MP	2,384	6,245-24,979	28	0.379

[1]PP: Primiparous cows refer to cows that are in their first lactation

[2]MP: Multiparous cows refer to cows that are in their second or above lactations

[3]Includes milking cows, dry cows, first lactating cows, heifers younger and older than 1 year old, bulls younger and older than 1 year old (finishing)

[4]Includes 10% loss associated with feeding the silage

Table 4. The output of the dynamic programming (DP) model for culling rates and estimated net present value (ENPV) for cows with elevated levels of somatic cell count (SCC). SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk and above

	SCC50 (4.7 NOK/kg)	SCC200 (4.7 NOK/kg)	SCC400 (4.30 NOK/kg)	SCC600 (4.00 NOK/kg)	SCC800 (4.00 NOK/kg)
Proportion of PP cows culled in total cows[1] (%)	6.7	7.8	6.6	7.1	11.2
Proportion of MP cows culled in total cows[2] (%)	31.6	33.4	24.3	28.4	32.5
Total culling for all cows (%)	38.3	41.2	30.9	35.5	43.7
Voluntary culling rate (%)[3]	9.7	12.8	2.4	6.9	15.9
Involuntary culling rate (%)[4]	28.6	28.4	28.5	28.6	27.9
Average longevity (lactation)	2.7	2.3	2.7	2.5	2.3
ENPV (NOK[5]/year)	32,125	33,760	26,079	27,053	26,762

[1]PP: Primiparous cows refer to cows that are in their first lactation. This rate was used as the proportion of the PP cows culled

[2]MP: Multiparous cows refer to cows that are in their second or above lactations. This rate was used as the proportion of the MP cows culled

[3]All culling due to low milk yield, poor reproduction performance and cows with elevated SCC (all SCC scenarios) were considered voluntary

[4]All other categories such as lameness, clinical mastitis, other diseases, teat injury, calving difficulty, bad udder and leakage, temperament issues and death due to other reasons were used to estimate the involuntary culling rates

[5]NOK: Norwegian krone

Table 5. Emissions intensity, methane (CH_4) emissions from enteric fermentation and manure, direct and indirect nitrous oxide (N_2O) emissions per kg of fat and protein corrected milk (FPCM) for cows with elevated levels of somatic cell count (SCC). SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk& above

Emissions	Emissions intensity		Enteric CH_4	Manure CH_4	Direct N_2O from fertilizers, manure and residues	Indirect N_2O from volatilisation and leaching
Unit	kg CO_2e/kg FPCM[1]	kg CO_2e/kg CW[2]	kg CO_2e/kg FPCM			
SCC50 PP[3]	1.01	29.37	0.644	0.120	0.178	0.055
SCC200 PP	1.01	27.75	0.656	0.122	0.182	0.056
SCC400 PP	1.02	30.01	0.656	0.122	0.182	0.056
SCC600 PP	1.02	29.12	0.661	0.123	0.183	0.057
SCC800 PP	1.02	24.44	0.676	0.126	0.189	0.058
SCC50 MP[4]	0.95	20.88	0.676	0.126	0.192	0.059
SCC200 MP	0.97	21.10	0.705	0.132	0.201	0.062
SCC400 MP	0.98	22.46	0.689	0.129	0.195	0.060

SCC600 MP	0.98	21.99	0.710	0.133	0.202	0.062
SCC800 MP	0.98	21.61	0.730	0.136	0.209	0.064

[1]FPCM: Fat protein corrected milk

[2]CW: Carcass weight

[3]PP: Primiparous cows refer to cows that are in their first lactation

[4]MP: Multiparous cows refer to cows that are in their second or above lactations

Figure captions

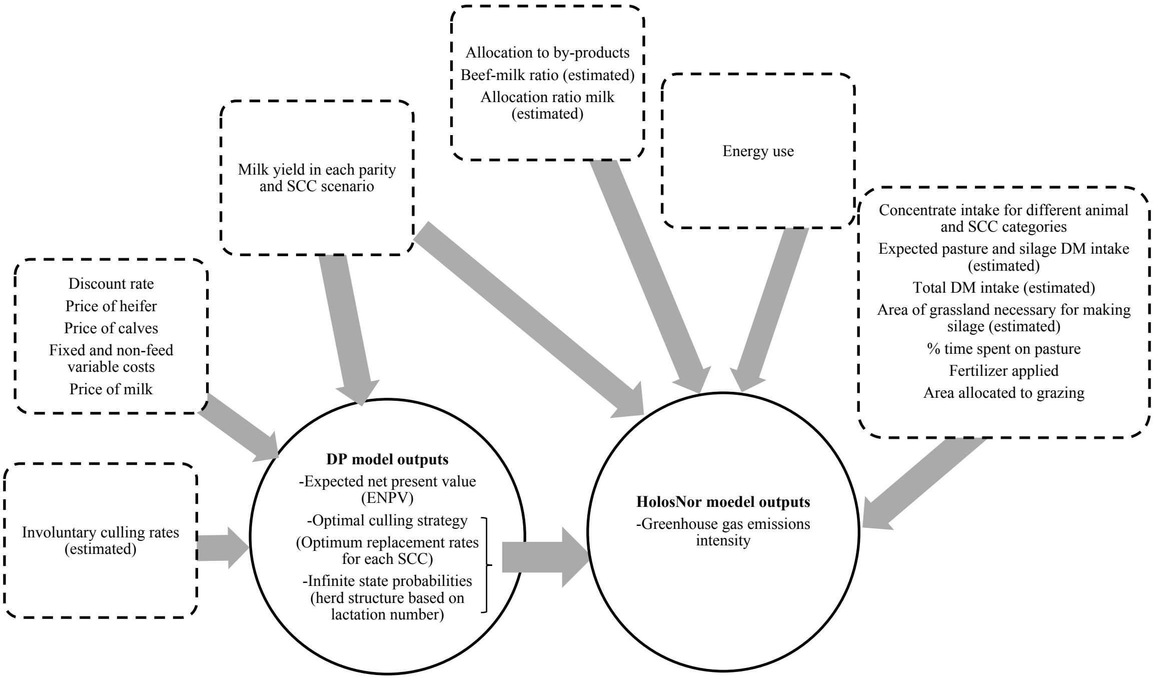
Figure 1. Schematic view of the two models used. Dashed framed boxes indicate the input parameters in each model and the solid framed circles indicate the output of each model. Note that the optimum culling rates and herd structure in terms of proportion of each lactation group were the two outputs of the DP model that were used as input in HolosNor model.

Figure 2. Effect of somatic cell count (SCC) on milk yield (kg fat protein corrected milk FPCM/cow per day; grey shaded area) and feed intake (kg dry matter (DM)/cow per day; black shaded area) for the primiparous (PP) (left) and the multiparous (MP) (right) cows. SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk and above

Figure 3. Age structure (proportion of animals in various age groups in the herd) predicted in the long term by the optimum replacement strategies determined by the dynamic programming method for cows with elevated levels of somatic cell count (SCC). SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk and above.

Figure 4. Sensitivity of the expected annual net margin per cow to the range of variations (i.e. minimum, base case and maximum values) of the three most influential input parameters used in the DP model. Values specified on the bars represent the ranges that were tested.

Figure 5. Sensitivity of the expected annual net margin per cow to the range of variations (i.e. minimum, base case and maximum values) of the five input parameters used in the DP model. Values specified on the bars represent the ranges that were tested.



Allocation to by-products
Beef-milk ratio (estimated)
Allocation ratio milk (estimated)
Energy use
Milk yield in each parity and SCC scenario
Concentrate intake for different animal and SCC categories
Expected pasture and silage DM intake (estimated)
Total DM intake (estimated)
Area of grassland necessary for making silage (estimated)
% time spent on pasture
Fertilizer applied
Area allocated to grazing
Discount rate
Price of heifer
Price of calves
Fixed and non-feed variable costs
Price of milk
Involuntary culling rates (estimated)
DP model outputs
-Expected net present value (ENPV)
-Optimal culling strategy
(Optimum replacement rates for each SCC)
-Infinite state probabilities (herd structure based on lactation number)
HolosNor moedel outputs
-Greenhouse gas emissions intensity

Figure 1

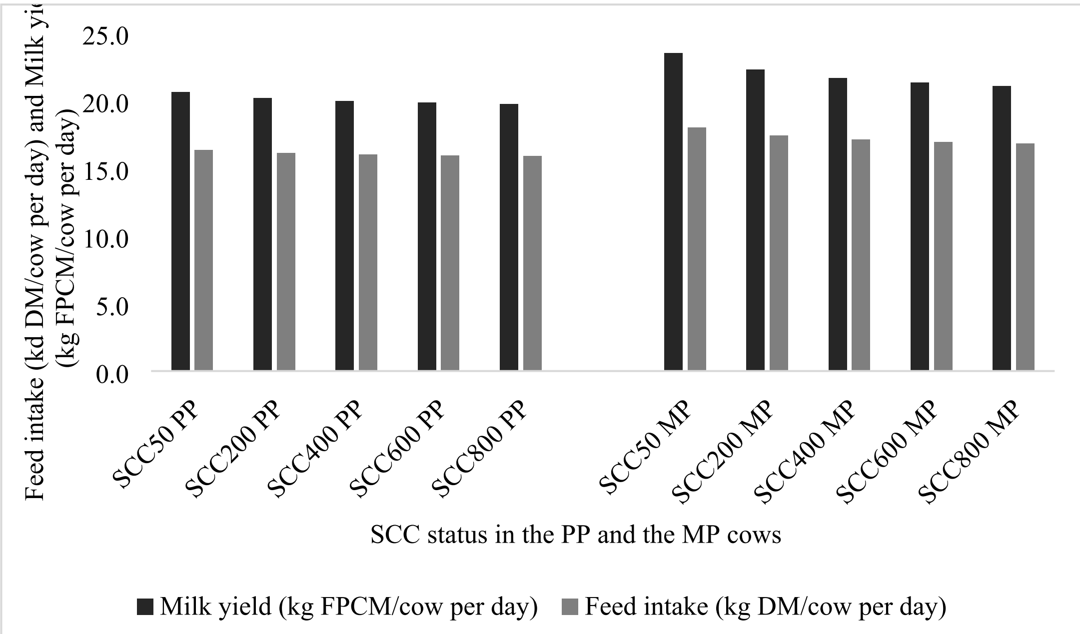

Feed intake (kd DM/cow per day) and Milk yi
(kg FPCM/cow per day)
25.0
20.0
15.0
10.0
5.0
0.0
SCC50 PP
SCC200 PP
SCC400 PP
SCC600 PP
SCC800 PP
SCC50 MP
SCC200 MP
SCC400 MP
SCC600 MP
SCC800 MP
SCC status in the PP and the MP cows
Milk yield (kg FPCM/cow per day)
Feed intake (kg DM/cow per day)

Figure 2

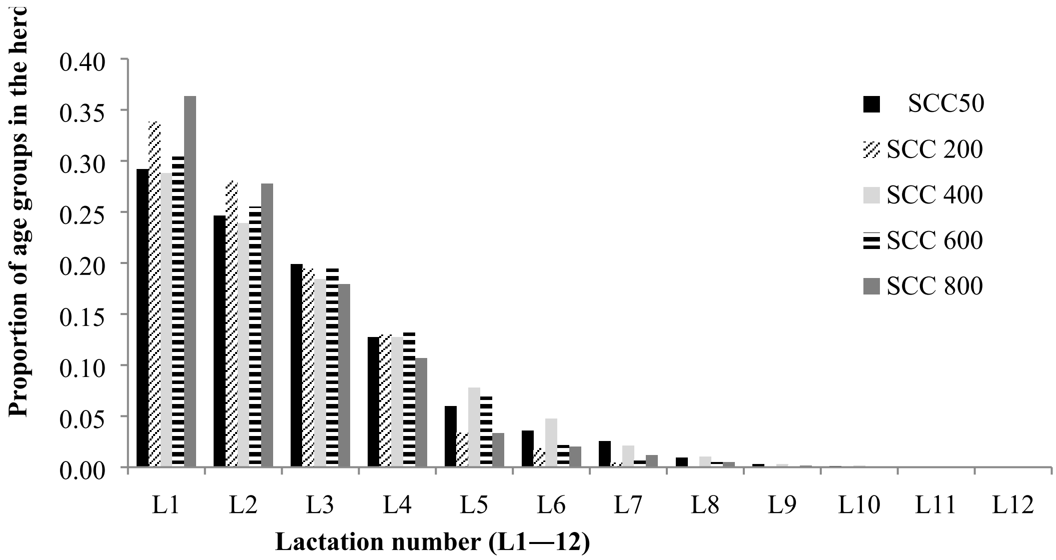

Proportion of age groups in the her
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
SCC50
SCC 200
SCC 400
SCC 600
SCC 800
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
L12
Lactation number (L1—12)

Figure 3

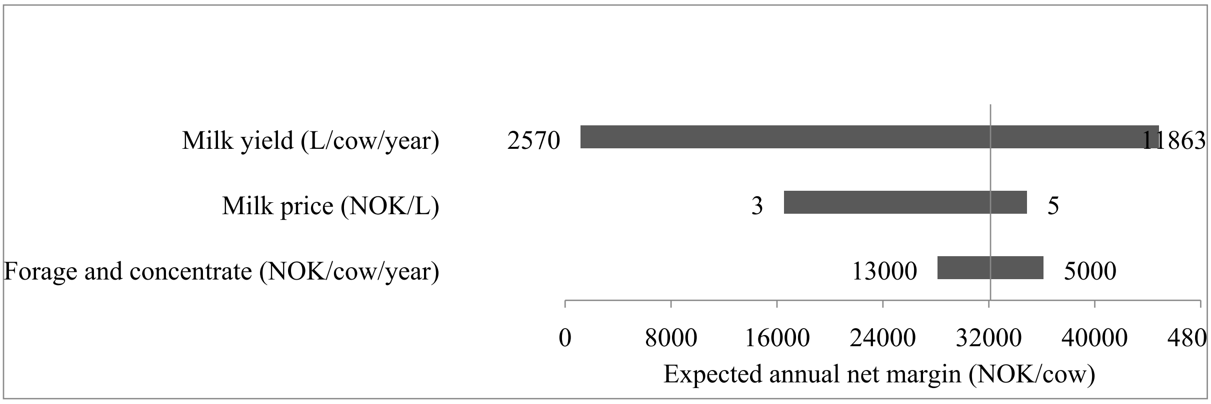

Milk yield (L/cow/year)
2570
11863
Milk price (NOK/L)
3
5
Forage and concentrate (NOK/cow/year)
13000
5000
0
8000
16000
24000
32000
40000
480
Expected annual net margin (NOK/cow)

Figure 4

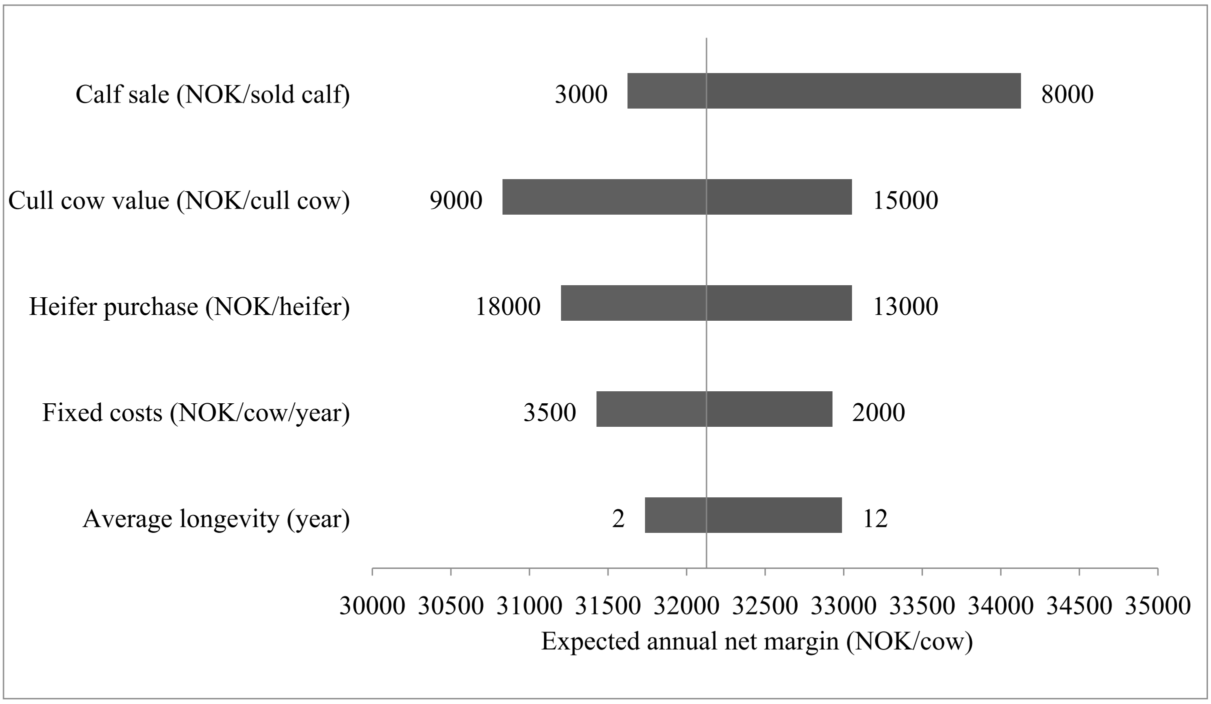

Calf sale (NOK/sold calf)
Cull cow value (NOK/cull cow)
Heifer purchase (NOK/heifer)
Fixed costs (NOK/cow/year)
Average longevity (year)
3000
8000
9000
15000
18000
13000
3500
2000
2
12
30000
30500
31000
31500
32000
32500
33000
33500
34000
34500
35000
Expected annual net margin (NOK/cow)

Figure 5