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

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

15 **Abstract**

16 Impaired animal health causes both productivity and profitability losses on dairy farms,
17 resulting in inefficient use of inputs and increase in greenhouse gas (GHG) emissions
18 produced per unit of product (i.e. emissions intensity). Here, we used subclinical mastitis as
19 an exemplar to benchmark alternative scenarios against an economic optimum and adjusted
20 herd structure to estimate the GHG emissions intensity associated with varying levels of
21 disease. Five levels of somatic cell count (SCC) classes were considered namely 50,000 (i.e.
22 SCC50), 200,000, 400,000, 600,000 and 800,000 cells/milliliter (mL) of milk. The effects of
23 varying levels of SCC on milk yield reduction and consequential milk price penalties were
24 used in a dynamic programming (DP) model that maximizes the profit per cow, represented
25 as expected net present value, by choosing optimal animal replacement rates. The GHG
26 emissions intensities associated with different levels of SCC were then computed using a
27 farm-scale model (HolosNor). The total culling rates of both primiparous (PP) and
28 multiparous (MP) cows for the five levels of SCC scenarios estimated by the model varied
29 from a minimum of 30.9% to a maximum of 43.7%. The expected profit was the highest for
30 cows with SCC200 due to declining margin over feed, which influenced the DP model to cull
31 and replace more animals and generate higher profit under this scenario compared to SCC50.
32 The GHG emission intensities for the PP and MP cows with SCC50 were 1.01 kilogram (kg)
33 and 0.95 kg carbon dioxide equivalents (CO₂e) per kg fat and protein corrected milk (FPCM),
34 respectively, with the lowest emissions being achieved in SCC50. Our results show that there
35 is a potential to reduce the farm GHG emissions intensity by 3.7% if the milk quality was
36 improved through reducing the level of SCC to 50,000 cells/mL in relation to SCC level
37 800,000 cells/mL. It was concluded that preventing and/or controlling subclinical mastitis

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

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

44 1. Introduction

45 The dairy sector contributes approximately 40% of agricultural greenhouse gas (GHG¹)
46 emissions in Norway, producing around 1.9 million tonnes (t) of carbon dioxide equivalent
47 (CO₂e) emissions every year (Sandmo, 2014, Statistics Norway, 2016). The projected human
48 population growth and the increased demand for food production by at least 20% by the year
49 2030 in Norway are likely to result in increased GHG emissions from the agricultural sector.
50 Therefore, the Norwegian Ministry of Agriculture and Food requires reducing the agricultural
51 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 CO₂e: 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

52 (Climate and Pollution Agency, 2013). In order to meet the expected extra food production
53 and yet reduce the GHG emissions from dairy cows, minimum use of inputs is required for a
54 given level of milk output i.e. improved production efficiency (Place and Mitloehner, 2010).
55 Poor animal health and welfare conditions that often lead to clinical and subclinical diseases
56 may result in reduced production efficiency through increased mortality (Ersboll et al., 2003),
57 reduced milk yield (Bareille et al., 2003), reduced reproductive performance (Bennett et al.,
58 1999), and increased animal replacement rates (Weiske et al., 2006), all of which have the
59 potential to increase the GHG emissions produced per unit of product (i.e. emissions
60 intensity) (Place and Mitloehner, 2010). Therefore, it has been argued that if animal health
61 and welfare are improved, there is potential to reduce the intensity of GHG emissions and
62 increase productivity, increase farm income, reduce losses and therefore improve farm
63 profitability (Stott et al., 2010, Williams et al., 2013).

64 Bovine mastitis is an endemic disease of mammary glands and may be responsible for a
65 substantial proportion of the total production losses in dairy herds (Barkema et al., 2009). It
66 has also been recognized as one of the most intractable health conditions in cows (Skuce et
67 al., 2016), therefore an impediment to perform efficient and sustainable livestock production.
68 The losses associated with bovine mastitis include reduction in milk yield, discharge of
69 contaminated milk due to treatment with antibiotics, treatment losses and increases in
70 mortality and replacement rates (Geary et al., 2012). If the disease occurs in the form of
71 subclinical mastitis (SCM), no visible signs may be found in the udder or milk (IDF, 2011).
72 Milk from cows with SCM is characterized by increased lipolysis, proteolysis, rancidity and
73 bitterness (Ma et al., 2000) and reduction in milk yield (Halasa et al., 2009). The reduction in
74 milk yield and quality related to udder health are commonly calculated by somatic cell count
75 (SCC) (Bartlett et al., 1990). The International Dairy Federation (2013) reports that the level
76 of SCC in cows suffering from SCM is greater than 200,000 cells/milliliter (mL). Although

77 some studies reported that SCM causes increased SCC, impairs milk composition (Gonçalves
78 et al., 2016, Bobbo et al., 2017) and milk yield (Botaro et al., 2015), their impacts on the
79 environment have not been questioned widely. **Integrated modelling approaches combining**
80 **different models provide a thorough assessment of the livestock production systems studied**
81 **and facilitate the decision-making process (Özkan Gülzari et al., 2017).** In this study, we
82 aimed to assess the changes in GHG emissions intensity and economic performances
83 associated with raised SCC in relation to changes in milk yield, feed intake and replacement
84 rates. For this purpose, an optimization model along with a GHG calculating model
85 (HolosNor) were used. A dynamic programming (DP) model that maximizes the long-run
86 profit of a dairy herd by optimizing future culling and replacement decisions was used to
87 inform the GHG calculating model about the optimum composition of the herd in terms of
88 the age and production levels of the cows in herd under different SCC challenges.

89 **2. Materials and methods**

90 In this study, we combined two models, one DP model for replacement decisions, and one
91 GHG model (HolosNor) to calculate the emissions associated with varying levels of SCC.
92 Figure 1 shows the relationship between the two models, their input-output interactions, and
93 the inputs that were estimated. Circle shapes refer to the model outputs while rectangular
94 shapes describe the inputs. Optimum culling strategies, one of the outputs of DP, were used as
95 an input in HolosNor. **Most of the equations in both models were adapted from previously**
96 **published papers (Stott et al., 2002 and Stott et al., 2005 for the DP model; and Bonesmo et al.,**
97 **2013 for HolosNor model)** and the parts where both models shared the same input to be
98 representative for the Norwegian conditions; or used each other's input/output were deemed
99 novel to the current study.

100 **Figure 1 here**

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

109 *2.1. Herd characteristics and some key management data of the modelled farm*

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

115 Table 1 here

116 *2.2. Inclusion of SCC levels in models*

117 Five scenarios of SCC levels in milk were defined. Cows with a SCC level of 50,000
118 cells/mL milk and below were considered uninfected (Laevens et al., 1997). Since
119 International Dairy Federation defines the level of SCC in milk of cows with SCM as above
120 200,000 cells/mL milk (IDF, 2013), we assumed that there was no reduction in milk
121 production in cows with SCC levels of 200,000 cells/mL milk and below (named as
122 “SCC50”) (see also Svendsen and Heringstad, 2006). Reductions in milk yield were
123 calculated for the following scenarios of SCC levels in milk (in SCC/mL milk): SCC levels at
124 200,000 cells (named as “SCC200”); SCC levels at 400,000 cells/mL (named as “SCC400”);

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

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

144 Milk yield of cows with SCC50 were provided by TINE Advisory Services and it reflects
145 years between 2009 and 2013 (TINE Advisory Services, 2014). For lactation numbers from
146 10 to 12, there were no data available after the year 2000. Therefore, we used an average milk
147 yield of data available for 1999 and 2000 for lactation 10 and above. The milk loss associated
148 with different levels of SCC was calculated using the mathematical formula used by TINE
149 Advisory Services based on Hortet et al. (1999) below (equation 1). Losses were calculated

150 as a percentage. Note that the milk loss associated with different SCC levels for lactation six
151 and onwards was calculated based on the assumption that the reduction remained constant
152 after lactation five. The formula reflects first lactation and equations for the 2nd, 3rd, 4th and
153 5th lactations can be found in the supplementary content:

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

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

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

167 For each of the SCC scenarios, a milk price was set. The current practice in Norway imposes
168 a price reduction of 0.30 NOK (NOK: Norwegian krone; 1 NOK equals 0.11 Euros as of the
169 3rd of October 2017) and 0.60 NOK/kg milk for bulk tank SCC levels of between 300,000
170 cells and 350,000 cells/mL and between 350,000 cells and 400,000 cells/mL, respectively.

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

183 2.3. *Dynamic Programming for replacement decisions*

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

196 [Table 2 here](#)

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

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

220 The key policy interest rate used by the central bank in Norway is currently at 0.5% (Norges
221 Bank, 2017). In this study, however, we used a discount rate of 3.5% recommended for long-
222 term projects and issues, under a declining schedule² of discount rate (Stott et al., 2002, Stott
223 et al., 2005). The purchase price of a heifer was considered to be 15,000 NOK (TINE
224 Advisory Services, Ås, personal communication) whereas the selling price of calves was
225 assumed to be 4,000 NOK (TINE Advisory Services, Ås, personal communication). The total
226 cost of fixed and non-feed variable costs was considered to be 2,800 NOK per cow (TINE
227 Advisory Services, Ås, personal communication).

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

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).

240 2.4. *Estimating GHG emissions intensity*

241 2.4.1. *Whole farm modelling* (HolosNor)

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

246 HolosNor is a tool for calculating the GHG emissions from combined dairy and beef
247 productions systems (Bonesmo et al., 2013; Özkan Gülzari et al., 2017) in Norway. It is
248 based on the Canadian HOLOS model (Little, 2008). It was modified to recognize Norwegian
249 conditions to consider enteric methane (CH₄), manure-derived CH₄, on-farm nitrous oxide
250 (N₂O) emissions from soils, off-farm N₂O emissions from leaching, run-off and volatilization
251 (indirect N₂O), on-farm carbon dioxide CO₂ emissions or C sequestration due to soil C
252 changes, CO₂ emissions from energy used on farm, and off-farm CO₂ and N₂O emissions due
253 to supply of feed inputs (Bonesmo et al., 2013). All emissions are expressed in CO₂e to
254 include the global warming potentials recommended by the Intergovernmental Panel on
255 Climate Change (IPCC) on a time horizon of 100 years as 25 kg of CO₂e/kg CH₄ and 298 kg
256 of CO₂e/kg N₂O (Forster et al., 2007). The emissions intensities are reported as kgCO₂e/kg
257 fat and protein corrected milk (FPCM) for milk and kgCO₂e/kg carcass weight (CW) sold for
258 meat.

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

265 (NEM), activity (NEA), lactation (NEL) and pregnancy (NEP) were according to IPCC
266 (2006), and were previously described by Bonesmo et al. (2013) and the following procedure
267 was followed since we were required to calculate the area (and the amount) of grassland
268 necessary for silage making on farm because this was not an available input:

269 Total net energy requirement (sum of NEM, NEA, NEL and NEP) was converted to dry
270 matter (DM) by taking into account the energy density of the feeds used (i.e. NE per kg DM).
271 The NE/kg DM for concentrate, grass silage and pasture were 7.9, 5.9 and 6.9, respectively
272 according to Bonesmo et al. (2013). Concentrate intake **for milking cows** was an input and
273 was provided for different animal (PP and MP) and SCC categories (Table 3) (TINE
274 Advisory Services, Ås, personal communication). Annual consumptions of concentrate feed
275 of heifers and bulls were 263 kg and 1,258 kg DM/head, respectively (Bonesmo et al. 2013).
276 The total dry matter intake (DMI) of all animals was the sum of concentrate intake (DM) and
277 requirement of silage and pasture (DM), reflecting different proportions of concentrate, silage
278 and pasture in the ration. Subtracting the concentrate DMI from total DMI gave the total
279 expected silage and pasture DMI. Pasture constituted about 16% of total NE intake. Pasture
280 DMI was a function of pasture NE intake, its energy concentration and the time spent on
281 pasture (%). Expected silage DMI alone for the whole herd was then calculated by
282 multiplying the proportion of the silage in the total ration by (i) total expected DMI/head per
283 day; (ii) the number of animals; and (iii) the number of feeding days in each animal category.
284 Because the input required was the total farm silage production in fresh weights, the total
285 farm expected silage intake was divided by the DM content of silage (25%). The loss
286 associated with feeding the silage was accounted for as 10%. Once the total farm expected
287 net silage intake was calculated, area to grow the required amount of silage was calculated,
288 using the amount of silage produced per unit of area presented by Bonesmo et al. (2013)
289 (22,490 kg silage was produced per hectare (ha)) (Table 3). The reduction in total feed intake

290 due to reduced milk yield in all SCC scenarios was calculated by subtracting the feed intake
291 at each level of SCC from the feed intake of cows with SCC50.

292 Table 3 here

293 The ration, on DM basis, consisted of grass silage (37–38%), concentrates (barley and soya,
294 45-47%), and grazed grass (16%). The proportion of the concentrate in total DMI was
295 calculated by dividing the concentrate DMI by the total DMI. The proportion of the silage
296 DMI was calculated according to the equation 2 below used by Bonesmo et al. (2013):

$$297 \quad [(total\ DMI - concentrate\ DMI) \times (1 - time\ spent\ on\ pasture)] / total\ DMI \quad (2)$$

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

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

308 2.4.2. Allocation of emissions

309 The GHG emissions were partitioned between milk and meat according to the proportions of
310 feed resources consumed and as described by Bonesmo et al. (2013). The Norwegian dairy
311 production systems are combined dairy-beef systems where the practice is year round calving
312 with fattening of bulls on farm and average slaughter age is 18 months (Bonesmo et al.,

313 2013). The beef milk ratio (BMR) was calculated as the ratio between kg LW sold (all bulls
314 and the culled cows) and kg FPCM. Allocation ratio milk (AR_{milk}) was calculated by
315 dividing the proportion of the emissions allocated to milk production by the BMR according
316 to Bonesmo et al. (2013). Five BMR points for five AR of milk were calculated, reflecting
317 the five levels of SCC.

318 **3. Results**

319 *3.1. Reduction in milk yield and feed intake induced by elevated SCC levels*

320 Milk yield reduced as the level of SCC increased in all SCC scenarios between 0.4 kg and 0.9
321 kg FPCM/cow per day for the PP cows (4.3% higher in the SCC800 than in the SCC50), 1.2
322 kg and 2.4 kg FPCM/cow per day for the MP cows (10.3% higher in the SCC800 than in the
323 SCC50). The reduction in total feed intake (kg DM/cow per day) in relation to predicted SCC
324 induced change in milk yield (kg/cow per day) was between 1.4% (SCC200) and 2.8%
325 (SCC800) for the PP cows and 3.3% (SCC200) and 6.6% (SCC800) for the MP cows (Figure
326 2).

327 Figure 2 here

328 *3.2. Culling rates and ENPV*

329 The total culling rates for the SCC scenarios estimated by the DP model varied from a
330 minimum of 30.9% (SCC400) to a maximum of 43.7% (SCC800). The average longevity of
331 the herd with SCC50 was at 2.7 lactations. This reduced to 2.3 lactations under SCC200
332 scenario as a result of increased voluntary culling rate and therefore having increased
333 numbers of younger cows on the farm. The average longevity then increased again to 2.7
334 lactations for SCC400 scenario as the model reduced the optimum culling rate, implying
335 keeping cows longer on the farm in response to both lower milk yield and also lower milk

336 price due to higher SCC. As the SCC increased, implying also a greater milk price penalty,
337 average longevity of the herd reduced again to 2.5 and 2.3 under SCC600 and SCC800
338 scenarios, respectively, indicating more culling and replacement would maximize the profit
339 more than opting for lower culling rates and hence on average having younger animals in **the**
340 herd.

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

345 Figure 3 here

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

353 Table 4 here

354 3.3. *Sensitivity analysis*

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

359 **Figure 4 and Figure 5 here**

360 As it is expected, Figure 4 shows that the annual expected net margin per dairy cow is very
361 sensitive to the level of milk yield. The lowest annual milk yield of 2,570 (L/cow) that was
362 assumed for low producing cows, results in expected net margin of 1,167 NOK whereas the
363 highest annual milk yield of 11,863 (L/cow) that was assumed for high producing cows
364 results in an expected net margin of 44,844 NOK. Based on this result, in total 83% of the
365 uncertainty in expected net margin is due to such a variation around the milk yield. Milk
366 price was the second most influential input variable affecting the net margin, responsible for
367 15% of its uncertainty. The lowest and the highest assumed prices of 3.0 and 5.0 NOK/L
368 result in annual net margins of NOK 16,559 and NOK 34,873/cow, respectively. The
369 expected net margin, to some extent, was also sensitive to the feed costs accounting for 3.0%
370 of its variability. Figure 5 shows that the sensitivity of the expected annual net margin to five
371 other input parameters namely: calf sale value, cull cow value, heifer purchase cost, fixed
372 costs and the average longevity of cows in the herd. The DP model outputs were therefore
373 less sensitive to variations of these five mentioned input parameters.

374 3.4. The whole farm model (HolosNor)

375 3.4.1. Greenhouse gas emissions intensity

376 Emissions intensities for the PP and MP cows with SCC50 were 1.01 kg and 0.95 kg
377 CO₂e/kg FPCM, respectively. These figures increased by 3.3, 3.6 and 3.7% in the MP cows
378 with SCC400, SCC600 and SCC800, respectively compared to the MP cows with SCC50.
379 Emissions intensities for the PP and the MP cows with SCC50 for meat were 29.37 kg and
380 20.88 kg CO₂e/kg CW, respectively. The highest emissions intensities for meat were
381 observed in cows with SCC400 in both the PP and the MP cows; however the difference
382 between other SCC scenarios was not substantial.

383 Enteric CH₄ emissions per kg FPCM increased as the SCC level increased, up to 5% in the
384 SCC800 compared to SCC50 in the PP cows. In the MP cows, however, the increasing trend
385 was disrupted in SCC400, but reached 8% in SCC800 compared to SCC50. Similarly,
386 manure CH₄ emissions per kg FPCM also increased by SCC level in the PP and MP except
387 for the SCC400 in the MP where emissions decreased slightly. Direct and indirect N₂O
388 emissions intensity elevated as the SCC level increased being about 6% higher in the SCC800
389 than in the SCC50, with the exception of SCC400 which showed a similar trend to that of
390 SCC200 (about 2.1% higher than the SCC50) in the PP cows. In the MP cows, direct and
391 indirect N₂O emissions intensity reduced by about 1.7% in cows with SCC400, but increased
392 by 9.1% in cows with SCC800 compared SCC50. (Table 5).

393 Table 5 here

394 3.4.2. Allocation of emissions

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

399 4. Discussion

400 4.1. Reduction in milk yield

401 Based on the assumptions used in this study, calculated milk losses increased as the level of
402 SCC increased, reflecting the impact of disease on production. Hortet et al. (1999) reported
403 that if a reference value for SCC was set to 50,000 cells/mL, the reduction in milk yield may
404 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
405 cows, respectively. In our study, PP and MP cows with SCC200–SCC800 reduced the milk
406 yield between 0.4 kg and 0.9 kg/day; and 1.2 kg and 2.4 kg/day, respectively. The difference

407 for the MP cows in the current study and that by Hortet et al. (1999) can be due to genetic
408 potential of different breeds, in addition to that the milk yield of MP cows in the current study
409 was an average of 11 lactations after optimal culling compared to a single year lactation in
410 Hortet et al. (1999) who categorized the cows as 1st parity, 2nd parity and 3rd and above parity.
411 The milk reduction of MP cows with SCC200 (5.1%) was similar to that found by Bartlett et
412 al. (1990) (5%); however the reduction in milk yield increased (up to 10.3% in SCC800) as
413 the SCC level increased in the present study. Higher milk yield reduction in the MP cows
414 than the PP cows can be explained by the MP cows being exposed to infections more than the
415 PP cows, and the perpetual damage to udder cells in the MP cows (Bartlett et al., 1990). The
416 MP cows potentially require more energy for production reflecting that less energy is
417 available for maintenance and hence for recovery.

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

426 4.2. *Reduction in total feed intake in relation to change in SCC levels*

427 The total feed intake reduced as the SCC level increased (16.3 kg and 18.0 kg DM/cow per
428 day in the PP and the MP cows with SCC50, respectively compared to 15.9 kg and 16.8 kg
429 DM/cow per day in the PP and the MP cows with SCC800, respectively). The lowest silage
430 intake (5,089 kg and 5,976 kg for the PP and the MP cows, respectively) observed in cows
431 with SCC400 was probably due to the reduced number of young stock in SCC400 scenario

432 where the lowest culling rate was observed. It is important to note that the reduction in feed
433 intake in empirical studies cannot be attributed to increased levels of SCC only as mastitis
434 may be accompanied by other diseases (Seegers et al., 2003) in 65% of the cases, e.g. metritis
435 and other disorders (Zamet et al., 1979). In this study, we assumed that the reduction in milk
436 yield was due to the increased SCC (to expose the impacts of this condition) and the
437 reduction in total feed intake was therefore attributed to the reduced energy requirements to
438 produce a given level of milk. However, increased concentrate intake per kg of milk as the
439 SCC level increased in both PP and MP cows shows that cows with increased levels of SCC
440 may increase their energy requirement due to the production of immunological components
441 such as immunoglobulin G, other antibodies, and white blood cells. In our study,
442 maintenance NE requirement was a function of coefficient of maintenance requirement and
443 average live weight, both of which were not affected by the level of SCC. If elevated SCC
444 levels increase the maintenance energy requirement, then the feed consumption as well as
445 GHG emissions **intensity** may have been underestimated and ENPV may have been
446 overestimated in the cows with high SCC levels. Therefore, further studies are warranted to
447 identify the maintenance requirements of cows with elevated levels of SCC, **as well as the**
448 **changes in animal metabolism due to impaired health (see Özkan et al., 2016)**. This study,
449 however, **ad**opts a very conservative approach, reflecting that no published papers were
450 available to make assumptions on the increased maintenance requirements of cows with high
451 SCC levels. Based on the presented results of the sensitivity analysis, the ENPV of individual
452 healthy cows (i.e. SCC50) was relatively sensitive to variations of feed requirements and
453 subsequently the feeding costs, accounting for 3.0% of net margin's uncertainty. Reduction in
454 feed demand could increase the ENPV from NOK 32,125 **in the** base **scenario** to NOK
455 36,126 and increase of feed demand will decrease the ENPV to NOK 26,127. It is, therefore,
456 envisaged that any **potential** positive or negative effect of elevated SCC on feed requirements

457 may significantly affect the financial and environmental results estimated by our models.
458 However, in **absence** of scientific evidence and reliable data, this **has not been** quantitatively
459 included in such models.

460 4.3. *Culling rates and ENPV*

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

472 It is important to stress that based on the sensitivity analysis, the ENPV was mainly driven by
473 milk yield and milk and feed market prices and therefore if, for example, the average milk
474 yield of a dairy farm or milk prices were higher than those reported here, higher culling rates
475 may be expected. On the contrary, a low ENPV may also be caused by reduced milk yield
476 and/or milk market prices. Results also show that variations and uncertainty of other input
477 parameters including calf sale value, heifer purchase value, cull cow value, fixed costs **of**
478 **feed production** and longevity of individual cows have less influence on ENPV than yield,
479 milk and feed prices. **Based on the outcome of the sensitivity analysis, it was concluded that**
480 **the presented models and results are robust and encompass uncertainty around the input**
481 **variables. The main reason is that the uncertainty of the most influential variables namely**

482 milk yield, milk price and forage and concentrate consumption, were included in the five
483 SCC scenarios examined. In other words, effect of SCM on milk yield, possible
484 consequences on milk price and margin over feed were assessed under the five SCC
485 scenarios. However, it should be noted that each of these single input parameters is only one
486 of the elements that may increase the culling rate. Eventually, it is the net financial value (e.g.
487 meat price for culled cows, price/cost of replaced heifer, milk production costs and milk
488 price) which determines the optimal culling rate. Although it was shown that the profit of
489 suckler cow systems were sensitive to culled cow meat prices (Vosough Ahmadi et al., 2016),
490 presented results show that this is not the case for the combined dairy and beef systems where
491 milk prices compose of a higher proportion of the income. Declining margin over feed of
492 SCC200 compared with SCC50 scenario (average margin over feed of 29,615 versus 31,787
493 NOK/cow per year, respectively) and reduced milk yield as a result of SCM but receiving the
494 same milk price as the cows with SCC50, influenced the DP model to cull and replace more
495 animals under this scenario than SCC50. Further decreases in milk yield and fall in margin
496 over feed, but also this time penalized milk prices under SCC400, led the DP model to reduce
497 the voluntary culling rates to compensate for the losses. Imposing an increased rate of penalty
498 to the milk price of SCC600 and SCC800 scenarios in addition to the further yield losses and
499 further reduced margin over feed, forced the DP to cull and replace more animals to
500 compensate for the loss and maximize the ENPV. It should be noted that the DP model does
501 not account for impact of culling on SCM spread in the herd.

502 4.4. Greenhouse gas emissions intensity

503 The emissions intensities of 1.01 kg and 0.95 kg CO₂/kg FPCM for the PP and the MP cows
504 with SCC50 were close to those reported by Bonesmo et al. (2013), Jayasundara and Wagner-
505 Riddle (2014) and Williams et al. (2013). An extensive discussion on the emissions
506 intensities was previously reported by Bonesmo et al. (2013), however in the study conducted

507 by Williams et al. (2013), a healthy cow produced 7,875 kg milk which was 12% higher than
508 the milk yield of a cow with SCC50 (7,021 kg) in the MP cows in this study. Note that the
509 lowest level of SCC defined in this study (50,000 cells/mL) may be considered as the level of
510 SCC of a healthy cow, however we avoided the use of “healthy” in this study since there are
511 controversial definitions of a healthy cow as far as the SCC level is concerned. The GHG
512 emissions intensity calculated using HolosNor in this study represent on-farm emissions in
513 Norway. Therefore variations are expected if the emissions are calculated at a larger scale or
514 the IPCC Tier 2 approach has been modified to reflect the country-specific conditions (as in
515 Jayasundara and Wagner-Riddle (2014)) or the nature of the systems compared (e.g. the
516 combined dairy and beef systems as opposed to the specialised systems in Williams et al.
517 (2013)).

518 There are only a few studies showing the relationship between health status of dairy cows and
519 the GHG emissions intensity (Elliott et al., 2014; MacLeod et al., 2017; Skuce et al., 2016).
520 For example, Elliott et al. (2014) reported that if the health status of the cows were improved
521 by 50%, the reduction in the emissions would be about 669 kilo t CO₂e, equal to 5% of the
522 UK’s dairy emissions. Very few studies reported the impact of elevated levels of SCC on
523 GHG emissions at an individual animal or herd level. Reductions in GHG emissions intensity
524 in healthy cows have previously been based on the input-use efficiency (Hospido and
525 Sonesson, 2005) because the healthy cows were found to be more efficient converters of feed
526 as they use more of their energy for milking and less of it for maintenance (Tyrrell and Moe,
527 1975). The lowest GHG emissions intensity found in this study in the cows with SCC50
528 could be discussed for the two parameters: milk yield and feed intake. The cows with SCC50
529 consumed the highest DM and produced the highest milk yield as oppose to the cows with
530 elevated levels of SCC where the reductions in feed intake and milk yield were proportional.

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

548 Lower emissions intensities for meat (kg CO₂e/kg CW) (varying between 24.44 kg and 30.01
549 kg CO₂e/kg CW for the PP cows and between 20.88 kg and 22.46 kg CO₂e/kg CW for the
550 MP cows) in this study than that reported by Pradère (2014) (32 kg CO₂e/kg CW) may be due
551 to that the current study results reflect combined dairy and beef systems and not specialized
552 beef systems. The PP cows produced higher emissions per kg CW than the MP cows,
553 reflecting the lower culling rate in the PP cows, and therefore a lower mass of meat leaving
554 the farm. In general, the number of cows slaughtered would be expected to be fewer in the
555 herds with lower culling rate than the herds with higher culling rates, thereby increasing the

556 emissions **intensity** due to more surplus calves not used for replacement (Hospido and
557 Sonesson, 2005). Although a current trend in dairy farming is to increase a cow's lifetime and
558 consequently rear less calves in Europe, high meat prices in Norway **appear to** encourage
559 farmers to keep the young stock and reduce the number of lactations. However, from an
560 environmental point of view, farms with more young stock are likely to emit higher
561 emissions **intensity** than those with fewer young stock because young stock do not contribute
562 to milk production.

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

575 Obtaining the replacement rates from the DP model to be used in HolosNor enabled us to
576 demonstrate that a win-win situation for both maximizing profit and minimizing
577 environmental consequences is achievable by optimum management of subclinical mastitis at
578 herd level. The DP model tests alternative SCCs fairly in terms of the physical and financial
579 assumptions we made that reflect the real Norwegian situation. However, the results do not
580 aim to provide a representation of current practice. We have modelled the 'rational farmer' as

581 well as the herd under these circumstances as he/she would respond to these drivers to
582 minimize the financial damage SCC does to the herd. We, therefore, have a framework that
583 allows us to compare the herds on the same basis were the circumstances to change.
584 Therefore, we do not intend to rank diseases by their importance nor would we aim to mimic
585 the current practice as the DP model considers the whole life cycle of an animal as opposed
586 to a real life situation where only current status of an animal would facilitate the decision-
587 making process. Instead, by using the DP and combining it with HolosNor, we are proposing
588 a standardized way to assess the impact of animal diseases on GHG emissions intensity that
589 others could adopt so results would be comparable.

590 **5. Conclusions**

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

604 and reduced feed and other variable costs. We suggest that further studies exploring the
605 impact of a combination of diseases on GHG emissions intensity in Norway are warranted.

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616 **Supplementary content**

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

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

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

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

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

620 Where; $\ln(\text{SCC})$ refers to the SCC scenario (cells/mL) classes defined above and day in
621 lactation was from day one to day 305 of lactation.

622

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777 **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)

778 ¹Base case value; figures in parenthesis present minimum and maximum values respectively that were used in the sensitivity analysis. Ranges

779 were derived from the references when available or are authors' assumptions.

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

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

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

783 **Table 2.** Value of culled cow (NOK) for both voluntary and involuntary culling and probability of involuntary replacement for cows with
 784 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

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

789 ²NOK: Norwegian krone

790 **Table 3.** Concentrate intake, estimated silage requirement and area allocated for making silage for cows with elevated levels of somatic cell
791 count (SCC). SCC50: SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between 200,000 cells and 400,000
792 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;
793 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
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794 ¹PP: Primiparous cows refer to cows that are in their first lactation

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

796 ³Includes milking cows, dry cows, first lactating cows, heifers younger and older than 1 year old, bulls younger and older than 1 year old

797 (finishing)

798 ⁴Includes 10% loss associated with feeding the silage

800 **Table 4.** The output of the dynamic programming (DP) model for culling rates and estimated net present value (ENPV) for cows with elevated
801 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
802 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
803 800,000 cells/mL; and SCC800: SCC levels of 800,000 cells/mL milk and above

	SCC50	SCC200	SCC400	SCC600	SCC800
	(4.7 NOK/kg)	(4.7 NOK/kg)	(4.30 NOK/kg)	(4.00 NOK/kg)	(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

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

805 ²MP: 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

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

807 ⁴All other categories such as lameness, clinical mastitis, other diseases, teat injury, calving difficulty, bad udder and leakage, temperament issues

808 and death due to other reasons were used to estimate the involuntary culling rates

809 ⁵NOK: Norwegian krone

810

811 **Table 5.** Emissions intensity, methane (CH₄) emissions from enteric fermentation and manure, direct and indirect nitrous oxide (N₂O) emissions
812 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
813 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
814 600,000 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	Manure	Direct N ₂ O from fertilizers,	Indirect N ₂ O from
	kg CO ₂ e/kg	kg CO ₂ e/kg	CH ₄	CH ₄	manure and residues	volatilisation and leaching
Unit	FPCM ¹	CW ²	kg CO ₂ e/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

815 ¹FPCM: Fat protein corrected milk

816 ²CW: Carcass weight

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

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

819 **Figure captions**

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

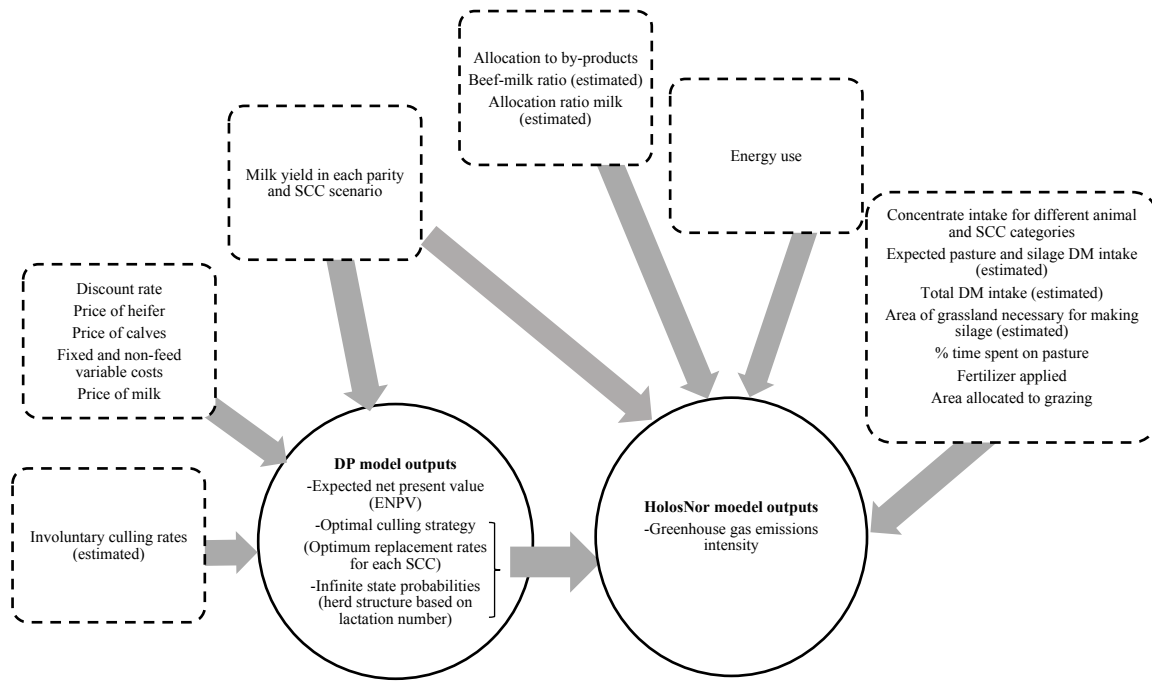
824 **Figure 2.** Effect of somatic cell count (SCC) on milk yield (kg fat protein corrected milk
825 FPCM/cow per day; grey shaded area) and feed intake (kg dry matter (DM)/cow per day;
826 black shaded area) for the primiparous (PP) (left) and the multiparous (MP) (right) cows.
827 SCC50: SCC levels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

831 **Figure 3.** Age structure (proportion of animals in various age groups in the herd) predicted in
832 the long term by the optimum replacement strategies determined by the dynamic
833 programming method for cows with elevated levels of somatic cell count (SCC). SCC50:
834 SCC levels between 50,000 cells and 200,000 cells/mL; SCC200: SCC levels between
835 200,000 cells and 400,000 cells/mL; SCC400: SCC levels between 400,000 cells and 600,000
836 cells/mL; SCC600: SCC level between 600,000 cells and 800,000 cells/mL; and SCC800:
837 SCC levels of 800,000 cells/mL milk and above.

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

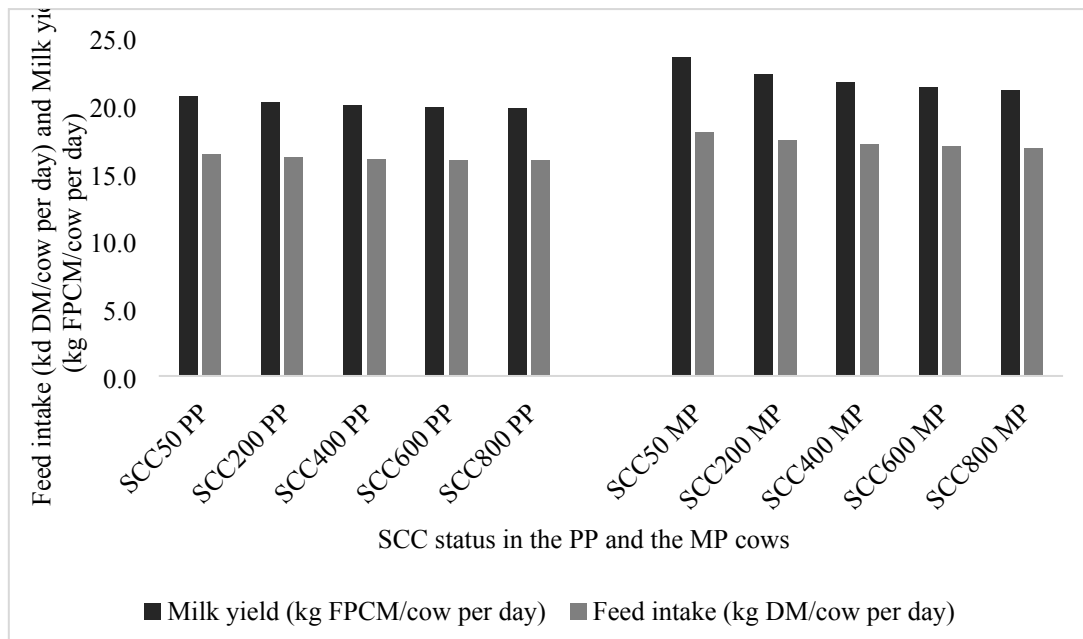
841 **Figure 5.** Sensitivity of the expected annual net margin per cow to the range of variations
842 (i.e. minimum, base case and maximum values) of the five input parameters used in the DP
843 model. Values specified on the bars represent the ranges that were tested.

844



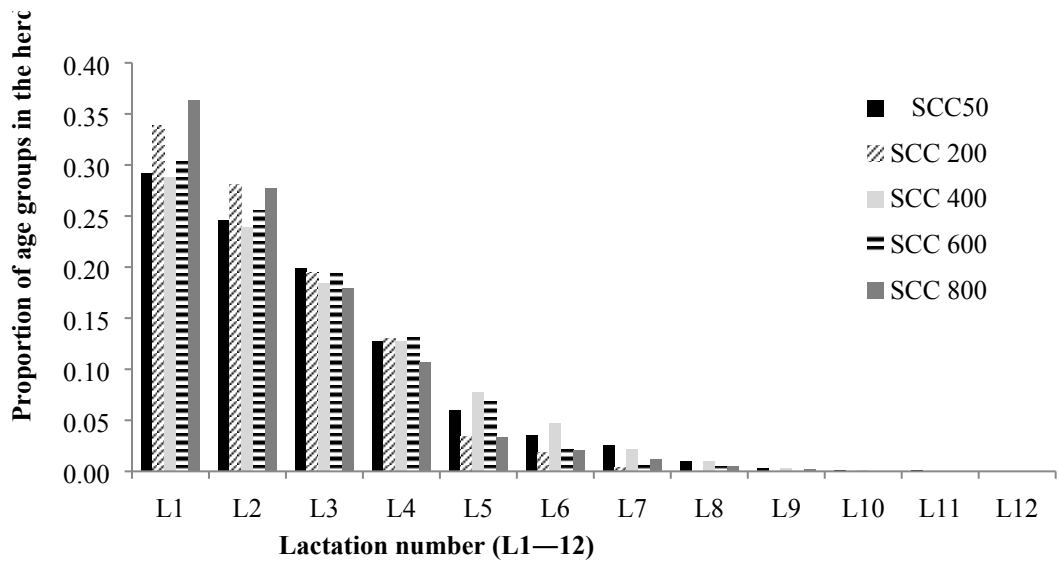
845

846 **Figure 1**



847

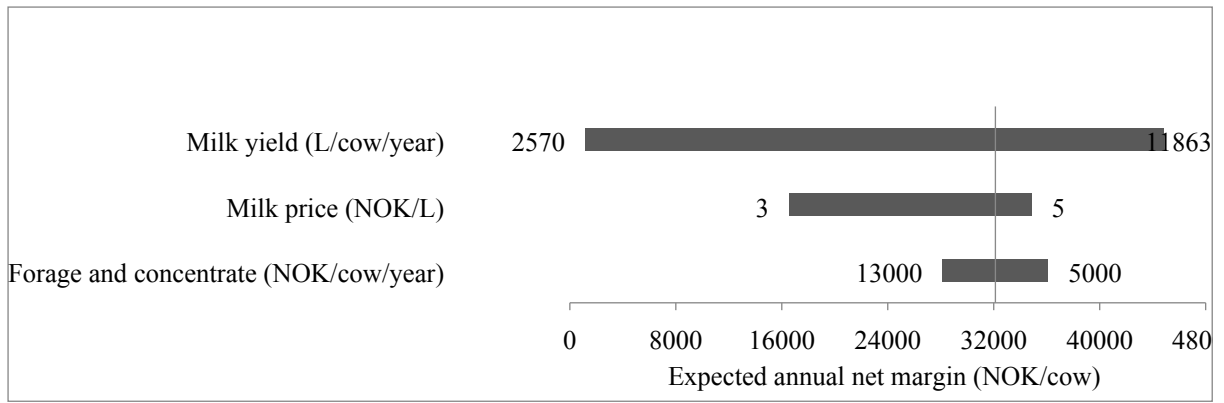
848 **Figure 2**



849

850 **Figure 3**

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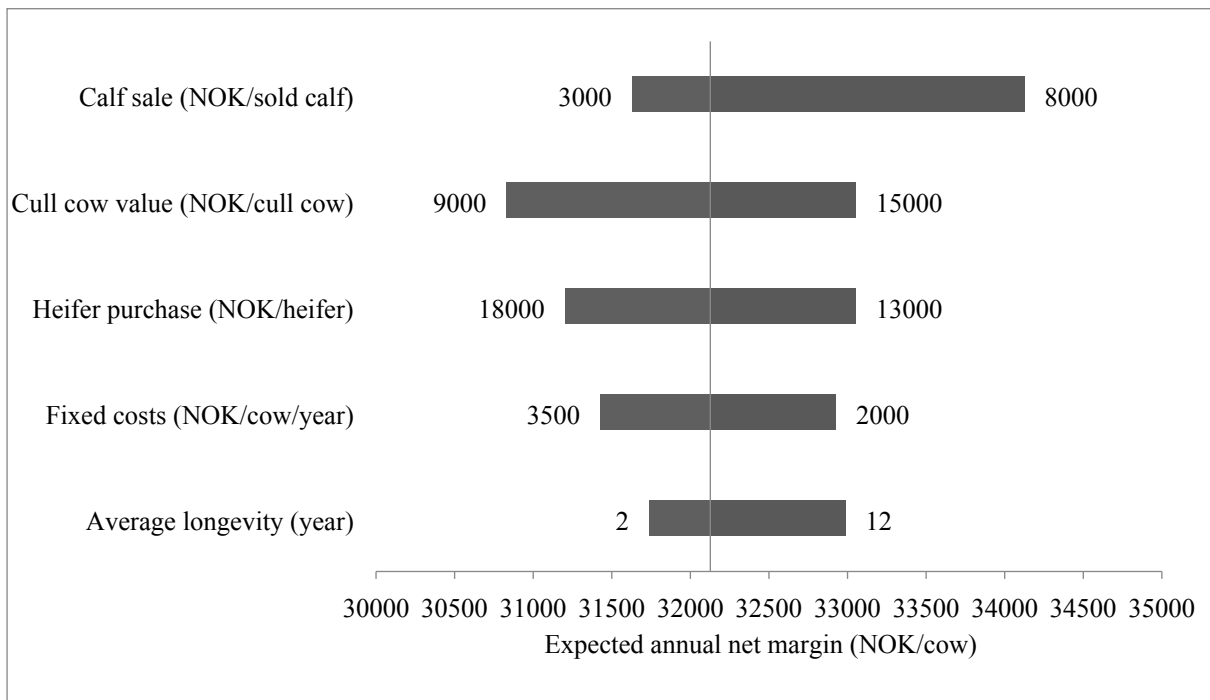


852

853 **Figure 4**

854

855



856

857 **Figure 5**

858