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Effects of extending dairy cow longevity by adjusted reproduction management decisions on partial net return and greenhouse gas emissions: A dynamic stochastic herd simulation study

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ABSTRACT

Prolonging dairy cattle longevity is regarded as one of the options to contribute to more sustainable milk production. Because failure to conceive is one of the main reasons for culling, this study investigates how adjustments in reproduction management affect partial net return at herd level and greenhouse gas emissions per unit of milk, using a dynamic stochastic simulation model. The effects of reproduction decisions that extend cattle longevity on milk yield, calving interval and pregnancy rate were derived from actual performance of Dutch commercial dairy cows over multiple lactations. The model simulated lactations, calving, and health status events of individual cows for herds of 100 cows. Scenarios evaluated differed in the maximum number of consecutive AI attempts (4, 5, or 6 services), or the production threshold (20, 15, or 10 kg of milk/d) at which cows that failed to conceive are culled (reproductive culling). Annual partial net return was computed from revenues of sold milk, calves, and slaughtered cows, and the costs from feed consumption, rearing replacement heifers, AI services, and treatment for clinical mastitis and lameness. Greenhouse gas emissions were computed for feed production, enteric fermentation, and manure management, and were expressed as total CO_2 equivalents (CO_2-eq). Average age at culling increased with an increased maximum number of AI services. This increase was larger when going from a maximum of 4 to 5 AI attempts (108 d) than from a maximum of 5 to 6 attempts (47 d). Similarly, the average age at culling increased from 1,968 to 2,040 and 2,132 d when the threshold for reproductive culling decreased from 20, to 15 and 10 kg of milk/d, respectively. Average annual partial net return increased by 1.1% from €165,850 per 100 cows at a maximum of 4 AI to €167,670 per 100 cows at a maximum of 6 AI, and increased by 4.3% from €161,210 per 100 cows at a reproductive culling threshold of 10 kg/d to €168,190 per 100 cows at a threshold of 20 kg/d. Greenhouse gas emissions decreased by 1.2% from 0.926 to 0.915 kg CO_2-eq per kg of fat- and protein-corrected milk (FPCM) with an increase in a maximum number of AI from 4 to 6 AI. Conversely, greenhouse gas emissions increased by 0.2% from 0.926 kg at a threshold of reproductive culling of 20 kg/d to 0.928 kg CO_2-eq/kg FPCM at a threshold of 10 kg/d. Although lowering the threshold for reproductive culling has the potential to extend cattle longevity more than increasing the maximum number of AI services, only the increase in AI services benefits a farm's partial net return, while reducing greenhouse gas emissions.

Key words: dairy cow longevity, reproduction management decisions, partial net return, greenhouse gas emissions

INTRODUCTION

On commercial dairy farms, failure to conceive is one of the primary reasons for culling cows, in addition to health disorders and low milk production (Dallago et al., 2021). Farmers' reproduction management involves decisions rules on the maximum number of AI attempts to get cows pregnant, as well as the production threshold below which cows that did not conceive after those maximum AI attempts are culled. Easing these reproduction management decision rules, will reduce reproductive culling and increase the average age at culling.

The average lifespan of a dairy cow in the Netherlands from birth to culling is around 5.8 yr, with a range of 4.9 to 7.1 yr across farms (Han et al., 2022), considerably shorter than the natural lifespan of dairy cows of approximately 20 yr (De Vries and Marcondes, 2020). In Dutch dairy farming systems, the vast majority of culled dairy cows are slaughtered for human consumption and replaced by on-farm-reared heifers. Prolonging the lifespan or longevity of dairy cattle could contribute to more sustainable milk production, from an economic and

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environmental, as well as a social perspective (Schuster et al., 2020; Han et al., 2022).

Extending cattle longevity through changes in reproductive decisions will inevitably affect farm profitability and greenhouse gas (GHG) emissions. A lower culling rate will reduce the demand for replacement heifers, reducing the associated rearing costs and GHG emissions. In addition, the milk yield of a herd might increase when longevity increases. Reduced reproductive culling increases the proportion of multiparous cows in a herd. Multiparous cows usually produce more milk than primiparous cows (Neave et al., 2017; Walter et al., 2022), resulting in a lower GHG emission per kilogram of milk produced. However, the increase in herd yield potential due to a higher proportion of multiparous cows may not offset the milk loss due to higher disease risk for older cows (Gussmann et al., 2019; Rilanto et al., 2020). In addition, more AI will directly increase AI costs, whereas a higher disease risk for older cows may increase treatment costs. The trade-offs between positive and negative effects of extending longevity on farm economic and environmental performance make it difficult to advise on optimal longevity.

The objective of this paper is to explore the effect of extending cattle longevity by assessing how different reproduction management decisions affect technical and economic results at herd level, and GHG emissions per unit of milk, using a dynamic stochastic simulation model.

MATERIALS AND METHODS

This study used a modified version of the bio-economic simulation model by Kok et al. (2017), developed to stochastically simulate Dutch dairy herds of 100 cows to evaluate the effect of varying dry period lengths. The original model of Kok et al. (2017) simulated individual lactations and calving intervals, while accounting for culling, either for fertility reasons (reproductive culling) or for other reasons (i.e., general culling). Model output was defined by partial cash flow at the herd and GHG emissions per kilogram of fat- and protein-corrected milk (**FPCM**) production. To compute GHG emissions from "cradle to farm gate," a life cycle approach was applied, which also accounts for the production of meat from surplus calves and culled cows, assuming that it substituted other meat on the basis of edible product, thus avoiding additional GHG emissions from meat production elsewhere (Supplemental File S1, see Notes).

To evaluate the economic and environmental impact of alternative reproduction management strategies, the herd simulation model of Kok et al. (2017) was modified by accounting for (1) the timing and success of AI and the resulting calving interval, (2) the effect of clinical mastitis and lameness, (3) the adjustment of the probability of disease for the time present in the herd, (4) the milk production losses and discarded milk due to lameness and clinical mastitis, (5) the adjusted growth of first- and second-parity cows due to an increase in lactation length, and (6) the costs for AI and treatments for clinical mastitis or lameness (see Figure 1).

With the modified herd simulation model, the effects of alternative reproduction management decision rules were evaluated. In the default scenario, cows were inseminated a maximum of 4 times and culled if their milk yield dropped below a threshold of 15 kg/d. This default scenario was set to reflect typical reproduction management practices in Dutch dairy herds (Rutten et al., 2014). Alternative strategies were set by either increasing the maximum number of consecutive AI attempts per cow to 5 or 6 times or modifying the reproductive culling threshold (i.e., the threshold at which cows that failed to conceive are culled) to either 10 or 20 kg of milk/d.

A sensitivity analysis was conducted to evaluate the effect of variations in average milk production on financial performance of the herd, GHG emissions, and longevity, and the effect of changes in replacement heifer costs and milk prices on the financial performance of the herd.

The model was run for 500 herds of 100 cow places for each reproduction management strategy to obtain stable estimates for the average annual partial net return and GHG emission at herd level. Results are presented from yr 7 when cattle longevity estimates reach model equilibrium for adjusted reproduction management strategies. Details on the model updates and simulations are provided in the following sections.

Herd Simulation Model Modification

Reproduction. For each cow, the model randomly assigned several AI (1–6) until conception at the start of each lactation, based on the proportion of cows getting successful AI per parity (Table 1; Inchaisri et al., 2011). Subsequently, the length of the calving interval was determined by days between calving until conception and an assumed 280-d gestation period (Nogalski and Piwczyński, 2012; Table 1). Parity differences were estimated based on the mean proportion of successful AI from parity 1 as reference, and the relative differences in probability of successful AI between parities (Inchaisri et al., 2011).

Health Status. At the start of each lactation, each cow was stochastically assigned to 1 of 7 health events that could occur during the lactation (Figure 1): staying healthy, recovering from clinical mastitis, recovering from lameness, being culled because of clinical mastitis, being culled because of lameness, being culled because

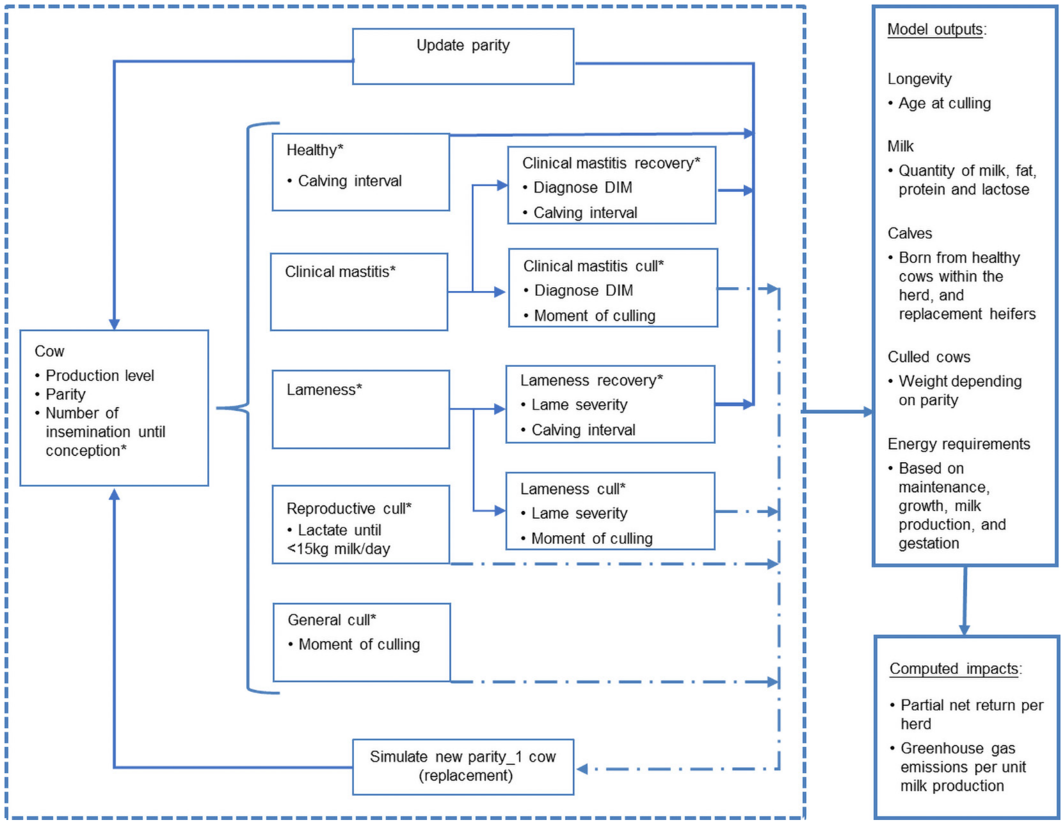

Figure 1. Schematic representation of the simulation model reflecting the processes at cow level per cow place. Stochastic events are marked with asterisks.

of failure to conceive, or being culled for other reasons (general culling).

The probability of a cow remaining healthy was adjusted for the length of the calving interval.

Clinical mastitis was defined as an IMI causing visibly abnormal milk (e.g., color, fibrin clots), and lameness was defined as a case of poor locomotion (suboptimal mobility score 4 or 5 on a scale of 5).

The incidence rate of clinical mastitis varied with parity (Table 2) and stage of lactation (before or after 100 DIM). To capture the distribution of mastitis incidence within lactation, 60% of clinical mastitis cases were assumed to occur before 100 DIM and 40% between 101 to 307 DIM, based on the interval between calving to dry period from first successful AI (Steeneveld et al., 2008; Hertl et al., 2018). It was used to avoid mastitis occurring after the end of lactation. The moment of mastitis occurrence within these lactation periods was determined using a uniform distribution. Only cows with mastitis in the first 100 DIM were at risk of being culled for clinical mastitis 90 d after diagnosis. The probability of cows being culled due to clinical mastitis in each parity is stated in Table 2.

Similar to mastitis, the incidence rate of lameness varied with parity. It was calculated based on the odds ratio between multiparous and primiparous cows and the incidence rate in parity 1 (Alban, 1995; Enting et al., 1997; Table 2). Because the severity of lameness leads to varying degrees of milk loss, 80% of lameness cases was assumed to be mild and 20% to be severe (Randall et al., 2018). The probability of cows being culled due to lameness in each parity is stated in Table 2. The timing of culling due to lameness was determined using the data from the study of Edwardes et al. (2022).

The probability of reproductive culling varied with parity and the defined maximum number of AI (Table 2). In addition, more AI until conception resulted in a longer

Table 1. Proportion of conceptions per consecutive numbers of AI per parity and corresponding calving interval (CI), based on Inchaisri et al. (2011)

Consecutive numbers of AI	Parity 1–3	Parity 4	Parity 5+	CI (d)
1	0.45	0.44	0.41	363
2	0.23	0.23	0.23	398
3	0.13	0.13	0.14	439
4	0.07	0.07	0.08	476
5	0.04	0.04	0.04	510
6	0.02	0.02	0.03	544
Not pregnant	0.06	0.07	0.07	

Table 2. Incidence rates of clinical mastitis and lameness, and cull rates due to clinical mastitis, lameness, other reasons, and overall in each parity, based on the default reproduction management decision rules of a maximum of 4 AI and a reproductive culling production threshold of 15 kg of milk/d

Item	Parity 1	Parity 2	Parity 3	Parity 4	Parity 5+	Source
Clinical mastitis incidence	0.20	0.23	0.31	0.34	0.40	Lean et al., 2023
Lameness incidence	0.25	0.19	0.21	0.35	0.35	Alban, 1995, Enting et al., 1997
Lameness cull	0.02	0.02	0.03	0.05	0.06	Edwardes et al., 2022
Clinical mastitis cull	0.01	0.03	0.04	0.05	0.08	Bonestroo et al., 2023
Reproductive cull[1]	0.12	0.12	0.12	0.13	0.14	Inchaisri et al., 2011
Other general culling reasons	0.05	0.06	0.09	0.14	0.22	Rutten et al., 2014
Overall cull[2]	0.19	0.23	0.28	0.37	0.50	

[1]Based on maximal 4 AI services (default).

[2]Including culls for reproductive failure based on maximal 4 AI (default), clinical mastitis, lameness, and other general culling reasons.

calving interval. Cows were assigned to reproductive culling when they did not become pregnant within the maximum number of AI and when their milk production dropped below the defined threshold for reproductive culling.

To meet an overall cull rate in each parity, general culling remained in the model in addition to reproductive culling and culling for clinical mastitis and lameness. Its probability was fixed per parity (Table 2) to approximate the overall annual culling rate of 30% in Dutch dairy farms. General culling occurred at a certain fraction of completion of a cow's assigned calving interval, drawn from a distribution with a positive skew and a median fraction of 0.17 (β distribution with parameter a = 1.3, b = 5; Rutten et al., 2014).

A culled cow was replaced by a heifer that was assumed to calve at the age of 24 mo and enters the herd the following day.

Milk Production. Lactation curves were updated based on milk production recording data of 50 randomly selected Dutch herds collected by the Dutch Cooperative Cattle Improvement Organization CRV BV. Individual milk production (*MP*), in kilograms, of cow *i* in parity *j* at each DIM was calculated as

$$MP_{ij} = a_{ij} + b_{ij} \times DIM + c_{ij} \times exp(-k_{ij} \times DIM) + RPL_i \times ADY_j,$$

where RPL_i is the relative production level of cow *i*; *ADY* is the average daily yield based on 305-d yield (kg) milk of a cow in parity *j*; and a, b, c, and k model the shape of the lactation curve (Wilmink, 1987; Table 3). To reflect the natural variation in milk production from about 80% to 120% of the average milk production, and *RPL* was defined from a normal distribution with a mean of 0 and SD of 0.1. Average milk protein, fat, and lactose contents were calculated per parity class and used to parameterize the milk composition of the simulated lactation curves (Table 3). Time steps in the model were of variable length, starting, and ending when a cow calved or was culled, and when a calendar year started or ended, thus allowing aggregation of herd data per calendar year. Milk yield was computed per cow per time step, using the integral of the milk production function.

Clinical mastitis was assumed to result in a yield reduction of 5% for the remaining lactation period from diagnosis until dry-off or culling (Seegers et al., 2003). Moreover, milk was assumed to be discarded for 6 d following the diagnosis due to assumed treatment with antibiotics. Mild lameness was associated with a milk yield loss of 1.6% in total lactation yield, and severe lameness was associated with a milk yield loss of up to 6%, compared with the average yield in that lactation (O'Connor et al., 2023).

Energy Requirements and Feed Intake. Maintenance, milk production, gestation, and growth were included in

Table 3. Model inputs for individual lactation curves per parity[1]

Parity	ADY (kg)	a	b	c	k	Fat (%)	Protein (%)	Lactose (%)
1	23.5	25.75	−0.01468	−18.92	0.157	4.48	3.55	4.62
2	26.6	30.03	−0.02248	−25.01	0.2612	4.50	3.59	4.53
3	28.6	33.01	−0.02885	−28.85	0.2557	4.51	3.51	4.48
4	29.3	34.08	−0.0312	−32.15	0.2467	4.51	3.51	4.48
5+	28.5	32.4	−0.0256	−31.9	0.2718	4.51	3.51	4.48

[1]ADY = average daily yield based on 305-d milk yield; parameters a, b, c, and k of the Wilmink lactation curves; and fat, protein, and lactose content of the milk per parity class. Wilmink lactation curve: Yield = a + b × DIM + c × exp(−k × DIM).

Table 4. Parameters used to compute partial net return based on years 2019–2021

Parameter	Value (€)[1]	Source
Milk revenue[2] (per 100 kg of solids)		FrieslandCampina, 2022
Protein	580.5	
Fat	290.3	
Lactose	58.0	
Calves revenue (per animal)		Wageningen Economic Research, 2022
Female	21.2	
Male	68.0	
Slaughter value culled cows[3] (per kg of meat)	2.2	
Replacement heifer (per animal)	1,078	KWIN, 2022
Feed cost (per t DM)		KWIN, 2022
Summer ration	159	
Winter ration	192	
Artificial insemination (per service)	35	KWIN, 2022
Treatment cost (per case)		
Clinical mastitis	35	Lam et al., 2013
Mild lameness	0	Edwardes et al., 2022; O'Connor et al., 2023
Severe lameness	38	

[1]Average exchange rate 2021; €1 = USD 1.183.

[2]This results in €36.07/100 kg of milk, given average solids content (3.51% protein, 4.51% fat, and 4.48% lactose).

[3]Assumed dressing percentage 60% (KWIN, 2022).

the calculation of energy requirements (Kok et al., 2017, 2019). Subsequently, these requirements were used to compute feed intake of dairy cows, using a weighted average of fixed rations for the summer (170 d) and winter period (195 d). Roughage consisted of fresh grass (in summer only), grass silage, and maize silage and was supplemented with byproducts and concentrate.

GHG Emissions. A life cycle approach was used to assess the effect of altered reproduction management strategies on greenhouse gas emissions. Emissions of CO_2, methane, and nitrous oxide were computed for feed production, enteric fermentation, and manure management, and were expressed as total CO_2 equivalents (**CO_2-eq**). The model used a fixed value for GHG emissions per replacement heifer, which accounted for feed production, enteric fermentation, manure management, and mortality in the rearing phase, and computed GHG emissions of the dairy cows from simulation results using the same methodology (Kok et al., 2017). Total GHG emissions were expressed as CO_2-eq per kilogram of FPCM.

The CO_2-eq factors used in the original model (Kok et al., 2017) were updated to new Intergovernmental Panel on Climate Change (IPCC) values (100-yr time horizon; Forster et al., 2021). With this update, the GHG emissions related to the rearing of young stock in the current model were estimated to be 4,848 kg CO_2-eq per replacement heifer, and emissions related to feed production were 474 and 477 kg CO_2-eq/t DM for the summer and winter ration, respectively.

Partial Net Return. In accordance with a metric describing the economic performance of the simulated dairy farm from Kok et al. (2017), partial net return was estimated based on the modeled revenue from sold milk, calves, and slaughter-culled cows, and the costs from replacement heifer, feed, AI, and treatment for clinical mastitis and lameness per case. Only variable costs were considered (Table 4). The regular cost of labor provided by the farmer and housing costs were assumed to be fixed in the short term, implying that these cost items were not affected by changes in cow longevity. Partial net return was therefore calculated as

Partial net return = revenues (milk, calves, and slaughter-culled cows) − costs (replacement heifer, feed, AI, treatment cost of clinical mastitis and lameness).

Annual partial net returns were computed per herd of 100 dairy cows for different reproduction management decision rules. The revenues consisted of revenues obtained from milk production, surplus calves, and culled cows. Milk revenues were based on the Dutch payment system based on milk solids value (10:5:1 ratio of protein: fat:lactose) using the average Dutch prices from 2019 to 2021 (Table 4).

To estimate the revenues for surplus calf sales, it was assumed that 50% of the calves born was male and 50% was female. The number of female calves kept annually to be reared as a replacement heifer equaled 113.4% of the number of culled cows, to account for a 13.4% calf mortality rate during the rearing period. Female calves not needed for replacement, as well as all male calves, were sold at 2 wk of age, adjusted for 10% mortality.

The weight of slaughtered cows was estimated by assuming a dressing percentage of 60%. Calf values as well as slaughter value (Table 1) were based on the yearly values of 2019 to 2021 (Table 4).

Costs consisted of rearing costs of replacement heifers, feed costs, and costs for AI and for clinical mastitis and lameness treatment. Replacement heifer costs were based on the average market value of full-grown heifers over the period 2019 to 2021, while feed costs were calculated from Dutch feed prices per feed stuff during that same time period (Kok et al., 2019).

The cost of AI included both the price of semen and the costs of the AI procedure (KWIN, 2022). Each case of clinical mastitis was assumed to be treated with antibiotics. The applied treatment costs were derived from Dutch survey results from 2009 (Lam et al., 2013). For the treatment of lameness, this study differentiated between mild and severe cases; the treatment costs for mild lameness were negligible, and for severe cases, the cost per case was based on a weighted average treatment cost of multiple claw disorders. It was estimated by combining the cost for each type of claw disorder by its mean annual prevalence. These included sole ulcer and digital dermatitis, 2 of the most expensive disorders to treat (Edwardes et al., 2022; O'Connor et al., 2023).

Sensitivity Analysis

Milk revenue is the paramount component of farm partial net return. Variation in milk production could directly lead to changes in partial net return of a farm and affects GHG emission and culling decisions. As with milk yield, the milk price is directly associated with milk revenue. One of the benefits of extending cattle longevity is the reduced demand for replacement heifers. In the model, the market value of a replacement heifer is used to parametrize this cost. However, in the Netherlands, most heifers are reared on farm. Rearing these heifers involves considerable costs that can vary widely between farms depending on available resources. Therefore, a sensitivity analysis was conducted to capture the variation of those factors by evaluating the effect of production level, replacement heifer price, or milk price on the model's results.

To examine the effect of production level on model's results, the average daily milk production was adjusted by 1 SD to 22.75, 25.75, and 28.75 kg/d, respectively, for parity 1 to 3, parity 4, and parity 5 and greater (Table 3). The effect of milk price variation on the partial net return of a dairy farm was estimated by analyzing the highest and lowest prices of milk between 2019 and 2021. Relative to the default price setting (Table 4), the maximum price was 20% higher and the minimum price was 10% lower. Lowest replacement heifer price of €861 was based on the total variable costs per successfully home reared heifer, excluding the costs of own rearing labor and barn costs. In turn, the highest price of €1,567 was set on the total variable and fixed costs, where the fixed costs were valued by their full substitution (opportunity) value.

RESULTS

The technical, economic, and environmental results per herd of 100 cow places for all reproduction management strategies are presented in Table 5.

In the default scenario, based on a maximum of 4 attempts of AI and a milk yield drop below 15 kg as reproductive culling threshold, the average age at culling is 2,040 d, or about 5.6 yr. With an increase in the maximum number of AI, all technical variables except for the culling rate show an upward trend. The effect on the age at culling is larger when shifting from a maximum of 4 to 5 AI (108-d increase in age at culling) than from 5 to 6 AI (47-d increase). Decreasing the threshold for reproductive culling from a milk yield of 20 to 10 kg/d increased age at culling but decreased all other technical indicators of performance.

Partial net return increased with an increase in maximum number of AI, and decreased with less stringent thresholds of reproductive culling. Table 5 provides further insight into the effect of the various reproduction management decisions on components of the partial net return. Although revenues from milk and calves increased by 0.7% and 5.7%, respectively, with an increase of maximum number of AI from 4 to 6, meat revenue decreased by 11%. All costs, except for replacement costs, are also higher with an increased maximum number of AI, resulting in an overall increase in partial net return of 1.0%. With less stringent reproductive culling standards, all components of partial net return decrease, resulting in an overall decrease in partial net return of 4.0%. Within the strategy of increasing maximum number of AI, replacement costs are most strongly affected. As for changes in the reproductive culling threshold, milk revenues show the most prominent alterations among other economic components.

With increased maximum number of AI, the CO_2-eq per kilogram of FPCM decreased from 0.926 to 0.915 (Table 5). In terms of the environmental consequences, there is no difference in GHG emissions per kilogram of FPCM when the reproductive culling threshold is increased from 15 to 20 kg/d (Table 5).

A lower milk yield level led to lower partial net returns, earlier culling, and higher GHG emissions. Similarly, a higher milk yield led to higher partial net returns, later culling, and lower GHG emissions (Table 6). In the default scenario of maximum 4 AI, 1-SD increase or decrease in average daily yield affected the partial net return by approximately a 14% increase or decrease,

Table 5. Technical, economic, and environmental simulation results per herd of 100 cows per year with a maximum of 4, 5, or 6 AI attempts per pregnancy (n = 500 herds per maximum number of AI) with default reproductive culling standard (15 kg of milk/d) and average milk production levels[1]

	Maximum number of AI			Subfertility culling standard		
Item	4	5	6	<20 kg/d	<15 kg/d	<10 kg/d
Technical indicators						
Number of calves	98 (5)	100 (5)	101 (5)	105 (5)	98 (5)	92 (6)
Age at culling (d)	2,040 (161)	2 148 (169)	2 195 (172)	1,968 (143)	2,040 (161)	2,132 (165)
FPCM delivered (kg/cow)	8,616 (105)	8,656 (111)	8,682 (110)	8,745 (99)	8,616 (105)	8,393 (131)
Annual cull rate	0.28 (0.05)	0.25 (0.05)	0.25 (0.05)	0.30 (0.05)	0.28 (0.05)	0.26 (0.05)
Mastitis incidence rate	31.0 (2.93)	31.4 (2.97)	31.4 (3.08)	32.0 (3.15)	31.0 (2.93)	30.0 (3.09)
Lameness incidence rate	30.3 (3.13)	30.2 (3.04)	30.4 (2.97)	31.3 (3.18)	30.3 (3.13)	29.1 (3.12)
Economic indicators (10^3 euros)						
Partial net return	165.83 (3.11)	167.11 (3.28)	167.65 (3.22)	168.17 (2.88)	165.83 (3.11)	161.19 (3.64)
Milk revenues	291.45 (3.53)	292.73 (3.71)	293.55 (3.7)	295.80 (3.33)	291.45 (3.53)	283.89 (4.39)
Meat revenues	23.51 (4.07)	21.5 (3.95)	20.84 (4.09)	24.76 (3.99)	23.51 (4.07)	21.74 (3.91)
Calf revenues	3.33 (0.18)	3.45 (0.16)	3.52 (0.17)	3.57 (0.15)	3.33 (0.18)	3.14 (0.19)
Feed costs	113.10 (0.92)	113.57 (0.96)	113.84 (0.96)	114.37 (0.85)	113.10 (0.92)	111.06 (1.18)
Replacement costs	30.08 (5.24)	27.47 (5.08)	26.62 (5.25)	31.87 (5.18)	30.08 (5.24)	27.77 (5.03)
AI cost	7.65 (0.66)	7.87 (0.68)	8.11 (0.71)	8.03 (0.65)	7.65 (0.66)	7.21 (0.66)
Mastitis treatment cost	1.05 (0.16)	1.08 (0.16)	1.10 (0.17)	1.09 (0.17)	1.05 (0.16)	0.99 (0.16)
Lameness treatment cost	0.58 (0.14)	0.58 (0.14)	0.59 (0.14)	0.59 (0.14)	0.58 (0.14)	0.55 (0.13)
Environmental indicator						
CO_2-eq (kg/kg of FPCM)	0.926 (0.014)	0.918 (0.014)	0.915 (0.014)	0.926 (0.013)	0.926 (0.014)	0.928 (0.015)

[1]Values presented as mean (SD).

respectively. The impact of 1-SD change on GHG emissions in the default scenario was relatively larger at the lower production level (+4.9%) than at the higher production levels (−4.0%). This contrasted with the effect on the age at culling, which decreased by 2.2% at the lower production level and increased with 3.7% at the higher production level.

The relative differences in partial net returns at alternative maximum AI increased with higher production levels, whereas the relative differences between culling age and GHG emissions decreased. Independent of the number of AI services, the partial net return altered proportionally with the relative changes in milk price and heifer price.

DISCUSSION

In recent years, research has been conducted to identify measures that enable a reduction of GHG emissions from dairy production, such as adjustments in feed ratios (e.g., Schils et al., 2006), feeding systems (O'Brien et al., 2010), the use of feed additives (Place and Mitloehner, 2010), manure management (Petersen et al., 2013), and breeding (e.g., de Haas et al., 2021; Richardson et al.,

Table 6. Absolute changes within the default scenario (maximum of 4 AI) and relative changes with a maximum of 5 or 6 services compared with the default scenario in average partial net return, GHG emission, and age at culling (d) for a variation in milk production level of 1 SD, a minimum and maximum price of replacement heifer and milk, given a reproduction strategy based on a maximum of 4, 5, and 6 inseminations (n = 500 herds)

	Partial net return (€/herd per year)			GHG (kg CO_2-eq/kg FPCM)			Age at culling (d)		
Parameter	Default (4 AI)[1]	5 AI (% change)	6 AI (% change)	Default (4 AI)[1]	5 AI (% change)	6 AI (% change)	Default (4 AI)[1]	5 AI (% change)	6 AI (% change)
Default	165,828	0.7	1.1	0.926	−0.9	−1.2	2,040	5.3	7.6
Production level									
−SD[2]	142,305	0.3	0.6	0.971	−0.7	−1.1	1,996	4.7	8.5
+SD	188,813	0.7	1.3	0.889	−0.6	−0.9	2,115	3.0	4.8
Replacement heifer price									
Minimum	171,883	0.4	0.7						
Maximum	152,183	1.6	2.2						
Milk price									
Minimum	136,104	0.8	1.2						
Maximum	226,478	0.7	1.0						

[1]Refers to the default setting of a subfertility reproductive culling standard of 15 kg/d milk yield.

[2]SD = adjustment of average daily yield by 1 SD to 22.75, 25.75, and 28.75 kg/d, respectively, for parities 1–3, 4, and 5 and greater (see Table 3).

2021). Moreover, some studies focused on the effect of improved health and reproduction on GHG emissions (Özkan Gülzari et al., 2018; Mostert et al., 2018a,b, 2019; MacLeod et al., 2018; Kok et al., 2017, 2019). One of the motivations behind these health and reproduction studies is the exploration of the impact of improved management on the culling rate of dairy cows and, consequently, their longevity, which is closely associated with GHG emissions (De Vries and Marcondes, 2020; Schuster et al., 2020).

There is a large variation in replacement rates among farms (Mohd Nor et al., 2015; Han et al., 2022), partly leading to considerable differences in GHG emissions across farms (Kristensen et al., 2011). Given the suboptimal replacement decisions commonly made by farmers (Mohd Nor et al., 2015), along with the substantial costs (Mohd Nor et al., 2012) and GHG emissions associated with the heifer rearing process (Schuster et al., 2020), we hypothesized that by adjusting the replacement rate, farmers could simultaneously reduce GHG emissions and enhance profitability, while taking into consideration that the age of cows is associated with disease incidence (e.g., O'Connor et al., 2019; Lean et al., 2023).

We explored the marginal effect of extending longevity of dairy cows (thus reducing replacement rate) on a typical Dutch farm by changing reproduction management decision rules (i.e., increasing AI attempts or lowering yield threshold for reproductive culling). The developed dynamic stochastic simulation model included these rules for reproductive culling, and simulated culling due to clinical mastitis, lameness or other reasons (i.e., general culling). By including parity as a risk factor for occurrence of mastitis and lameness, we were able to correct for the negative effects of an older herd on disease occurrence.

In the default scenario with a maximum of 4 inseminations and a minimum milk production of 15 kg/d as the reproductive culling threshold, the average age at culling was 2,040 d (5.6 yr). This corresponds reasonably well to the average of 5.9 yr reported in an empirical study using census data of Dutch dairy farms (Han et al., 2022). The GHG emissions under this default situation were 0.926 kg CO_2-eq/kg of FPCM. This estimation is relatively low compared with estimates of GHG emissions published in a recent review (Singaravadivelan et al., 2023), in which estimates varied from 0.92 to 13.8 kg CO_2-eq/kg FPCM. However, the estimate is in line with estimates for relatively intensive dairy production systems, such as in Eastern Canada (0.92 kg CO_2-eq/kg of FPCM; Mc Geough et al., 2012), the United States (0.46–0.69 kg CO_2-eq/kg of milk; Rotz et al., 2010), the Netherlands (1.4 kg CO_2-eq/kg of FPCM; Thomassen et al., 2008), and Europe in general (1.3 kg CO_2-eq/kg of FPCM; Lesschen et al., 2011). However, please note that comparing these studies is challenging due to variations in timing and the use of different emission factors for converting methane (CH_4) and nitrous oxide (N_2O) emissions to CO_2-eq to estimate the global warming potential.

When comparing the default scenario with a situation allowing for AI services up to a maximum of 5 or 6 services, cattle longevity increased with 108 and 155 d, respectively. This increase in longevity was associated with a reduction in the culling rate from 0.28 to 0.25, and resulted in a decrease of GHG emissions of 0.008 (0.9%) and 0.011 (1.2%) kg CO_2-eq/kg of FPCM produced, respectively. These changes were caused by a slightly increased milk production per cow per year, lowering the GHG emissions per kilogram of milk (e.g., Grandl et al., 2016), in combination with a reduction in the number of required replacement heifers, which reduced the GHG emissions from heifer rearing. Partial net returns increased by €13 and €18 per cow per year, respectively, for a maximum of 5 or 6 AI services, mainly due to lower costs for rearing replacement heifers. The milk production per cow per year was slightly higher despite longer lactation lengths (Panthi et al., 2017), due to a higher average parity (Bokkers et al., 2014). In a study based on the lifetime performance data of 30 individual dairy cows, Grandl et al. (2019) also showed that the lifetime GHG emissions of dairy cows decreased with longer productive lifetime. In their study, the GHG emissions leveled out to approximately 1.1 kg CO_2-eq/kg of FPCM around a productive lifetime of 1,600 d, whereas the net returns per cow increased and leveled out to approximately €0.17/kg of FPCM. A productive lifetime of 1,600 d is a longevity of ~2,360 d (assuming a first calving age of 760 d), about 6 yr and 6 mo, which is above the current average Dutch longevity.

In our study we did not account for reduced genetic progress as a consequence of the increased calving intervals, which might have had an impact on the economic returns. However, this effect is not expected to be large (Schuster et al., 2020). Moreover, in studies aimed at genetic progress, it was concluded that the genetic progress in sires is not fast enough to warrant a high culling rate (De Vries, 2015), and consequently, a reduced longevity.

When changing the reproductive culling rules of cows that failed to conceive (under the default setting of maximum 4 AI services) from a production threshold of 20 kg of milk/d to 10 kg of milk/d, the age at culling increased on average with 164 d. This change was associated with a reduction in culling rate of 0.04. Interestingly, in these scenarios, increased longevity was not associated with reduced GHG emissions. Moreover, when an improved longevity is reached by relaxing the reproductive culling rules on milk yield, the partial net returns reduced. Relaxing the threshold from 20 kg of milk/d to 10 kg of milk/d resulted in €69/cow per year lower partial net returns. The cost savings on replacement heifers did not outweigh the reduction in milk returns as a result of a lower milk production per year.

In this research, we explicitly modeled the effect of increased longevity on the disease occurrence. At the end, the incidence of mastitis and lameness was hardly affected by any of the evaluated longevity changes. The increased probability of production diseases because of older cows, was more or less compensated by the reduced number of transition cows as a result of the increased calving interval.

In our results, we observed a decreasing marginal effect when altering the rules for the maximum number of inseminations, comparable with the results of Grandl et al. (2019). The age at culling increased by 108 d when changing the maximum from 4 to 5 inseminations, whereas changing the maximum number from 5 to 6 inseminations yielded only a 47-d increase. This discrepancy arises from a decline in the proportion of cows conceiving at each insemination attempt. Approximately 4% of all primiparous cows conceived at the fifth insemination attempt, compared with only 2% at the sixth attempt. Moreover, extending the maximum number of inseminations leads to a longer calving interval, eventually reducing milk production per cow per year. This reduction negatively affects both GHG emissions and farmers' income, suggesting an optimum number of inseminations, which most likely depends on the milk yield of the cow (e.g., Inchaisri et al., 2011; Stangaferro et al., 2018; Kok et al., 2019).

In this study, we wanted to study the marginal effect of changes in longevity in dairy cows using a modeling approach. The association between dairy cattle longevity and profitability has also been studied using empirical data. Although Adamie et al. (2023) showed a clear association between longevity and economic performance, this finding was not supported by the research conducted by Han et al. (2022) and Vredenberg et al. (2021). Establishing clear associations with empirical data poses challenges due to the presence of data noise (i.e., farm profitability is influenced by many other farm characteristics that may not always be possible to adjust for (Vredenberg et al., 2021). Therefore, we used a modeling approach allowing us to alter management variables while maintaining all other factors constant.

We modeled farmers' commonly used decision rules of thumb for determining when to cease inseminating cows (i.e., adhering to a maximum of 4 inseminations) and when to cull nonpregnant cows (i.e., when daily milk yield drops 15 kg/d). It is clear that the use of these straightforward decision rules is not optimal, which is not a novel observation. In the past, much research has been carried out on optimizing insemination and culling decisions, and specific metrics have been proposed to support these decisions, such as retention pay-off value and insemination value (e.g., Groenendaal et al., 2004; De Vries, 2006; Cabrera 2010). These metrics are, however, based upon the assumption of unlimited availability of replacement heifers, which in the Dutch systems is not the case. Culling decisions are restricted by the number of available heifers at herd level, which is a result of the decision (made more than 2 yr earlier) to keep and rear calves as replacement heifers (Mohd Nor et al., 2015; De Vries and Marcondes, 2020). Moreover, systemic barriers, as a consequence of the production system and the prevailing ideas about replacement decisions, may also prevent an increase in productive lifetime (Rödiger and Home, 2023). In practice, farmers tend to stick to the rules of thumb that have proven useful in the past (Kulkarni et al., 2023). A lack of practical decision tools for farmers to optimize the number of calves to be reared may hamper more rational decisions regarding reproduction and culling (De Vries and Marcondes, 2020).

Our results demonstrate that increased longevity by adjusted reproduction management decisions can benefit both farmers' income and GHG emissions. Moreover, it is not longevity itself that leads to a change in environmental and economic efficiency, but rather the method by which this extension of longevity is achieved. In contrast to merely adjusting the decision rule for the timing of reproductive culling, increasing AI attempts can enhance the sustainability of dairy farming from both economic and environmental perspectives.

CONCLUSIONS

The study shows that cattle longevity in the Netherlands can be extended by up to 5.5 mo by altering reproduction management decision rules in terms of the maximum number of AI services (from 4 to 6 attempts) or the production threshold after which a cow that failed to conceive was culled (from 20 to 10 kg of milk/d). Although lower reproductive culling thresholds have the potential to extend cattle longevity more than increasing the maximum number of AI services, only the latter increases a farm's partial net return while reducing greenhouse gas emissions.

NOTES

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Nonstandard abbreviations used: CO_2-eq = CO_2 equivalents; FPCM = fat- and protein-corrected milk.

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