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Dairy cow longevity: Impact of animal health and farmers' investment decisions

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ABSTRACT

A dairy farmer's decision to cull or keep dairy cows is likely a complex decision based on animal health and farm management practices. The present paper investigated the relationship between cow longevity and animal health, and between longevity and farm investments, while controlling for farm-specific characteristics and animal management practices, by using Swedish dairy farm and production data for the period 2009 to 2018. We used the ordinary least square and unconditional quantile regression model to perform mean-based and heterogeneous-based analysis, respectively. Findings from the study indicate that, on average, animal health has a negative but insignificant effect on dairy herd longevity. This implies that culling is predominantly done for other reasons than poor health status. Investment in farm infrastructure has a positive and significant effect on dairy herd longevity. The investment in farm infrastructure creates room for new or superior recruitment heifers without the need to cull existing dairy cows. Production variables that prolong dairy cow longevity include higher milk yield and an extended calving interval. Findings from this study imply that the relatively short longevity of dairy cows in Sweden compared with some dairy producing countries is not a result of problems with health and welfare. Rather, dairy cow longevity in Sweden hinges on the farmers' investment decisions, farm-specific characteristics and animal management practices.

Key words: dairy cow longevity, animal health, farm investments, Sweden

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INTRODUCTION

The longevity of dairy cows has gained increased attention in recent years, largely due to the environmental (Zehetmeier et al., 2014; Bell et al., 2015; Bergeå et al., 2016; Grandl et al., 2019) and economic consequences (De Vries, 2017; Grandl et al., 2019; Dallago et al., 2021) associated with short longevity. The culling of dairy cows early on in the production cycle (i.e., before the cow is biologically old) is regarded as an unsustainable practice from both an economic (Vredenberg et al., 2021; Gambonini et al., 2022) and environmental (Axelsson, 2013) point of view. The concept of longevity has also been linked to animal welfare (Röcklinsberg et al., 2016). Given the growing concern for and awareness of the treatment of animals in modern agriculture (Ingenbleek and Immink, 2011; Lagerkvist and Hess, 2011; Thorslund et al., 2017), culling dairy cows at a young age raises animal welfare concerns. Short longevity and the practice of culling dairy cows at a young age signal that animals are not kept in such a way that they can function in production over an extended period of time (Röcklinsberg et al., 2016).

Culling of dairy cows is the act of removing cows from the herd. Culling decisions are usually influenced by intrinsic and extrinsic factors (Bergeå et al., 2016; Rostellato et al., 2021). Intrinsic factors that influence cow longevity include health, milk yield, and reproductive status (De Vries, 2013, 2017; Zehetmeier et al., 2014). Extrinsic factors influencing cow longevity include availability of replacement heifers, milk yield, land availability, and prices (Grandl et al., 2019; Adriaens et al., 2020; Rostellato et al., 2021). The reasons for culling dairy cows have received considerable attention in the scientific literature. Grandl et al. (2019) indicated that a large number of cows are removed from the herd early in lactation mainly because of metabolic health reasons. De Vries (2013) added that average cow longevity is based on extrinsic economic factors that are not related to the cow's health and performance.

Previous research has found that the amount of time a dairy cow stays in the herd is associated with the cow's welfare, farm economic outcome, and environmental impacts (Brickell and Wathes, 2011; Boulton et al., 2017). Previous research has also attempted to examine to what extent cow longevity affects farm economic outcomes. In the United States, De Vries (2013) found that when cows leave the herd early in lactation it costs the dairy farmer approximately €380 to €760 per cow, and this cost does not include milk losses. Culling cows early in the lactation (e.g., less than 60 DIM) leads to great economic losses (Lunak, 2020). In the UK and Denmark, studies have shown that a high proportion of income losses incurred by dairy farmers are linked to early culling of dairy cows (Orpin and Esslemont, 2010; Wright and Rusk, 2020). In Germany, Grandl et al. (2019) found that increasing dairy cow longevity improves the profitability of dairy farms.

A growing body of literature has focused on intrinsic, genetic, and trait factors (De Vries, 2013; Zehetmeier et al., 2014; Haile-Mariam and Pryce, 2015; Interbull, 2020); extrinsic factors (Grandl et al., 2019; Rostellato et al., 2021) to explain longevity. However, the longevity of dairy cows in the herd is determined by culling decisions made by the dairy farmer, which are based on a complex combination of different factors (De Vries, 2013, 2017). Although several factors related to the animal inform the decision to cull a dairy cow, the decision is likely to include an economic component relating to how many and which cows should be kept in the herd to maximize profit. In terms of production economics, one reason for not culling the oldest cows could be a recent farm expansion, whereby a farmer may need to retain all animals in the herd to fill the places. This suggests that the amount a farmer invests in the farm can influence longevity. A recent study by Reimus et al. (2020) supports the economic reasons for culling decisions. The study indicated that farmer characteristics and farm management practices can have a substantial effect on health and longevity. Furthermore, the authors suggested that good management practices, including investments in good housing, can lead to better animal health, welfare, and longevity. Still, no study to date has examined the relationship between investments made by the farmer and cow longevity. As a result, there is currently a limited understanding of how cow longevity is related to strategic decisions by the farmer regarding enlargements of the operation.

Furthermore, to the best of our knowledge, none of the previous studies mentioned above have examined causality between a farm's specific animal management practices and cow longevity. Instead, from a methodological point of view, most of the studies that have attempted to investigate culling decisions and methods to optimize longevity, as well as how these affect economic outcomes, have relied on computer-optimized models (De Vries, 2004; Cha et al., 2010; Nielsen et al., 2011). These computer-optimized models estimate profit per animal per year and assume that the profit is maximized for a fixed number of animals in the herd, without considering replacement heifers. In addition, these models do not account for time effects, given that the models are mostly set up for a specific time period or production season. Furthermore, the optimized models do not establish causality, and as a result, there is little information or no consensus on the causal link between farm-specific characteristics and animal management practices and cow longevity.

Accordingly, the aim of our study was to investigate whether there is a causal relationship between animal health, cow longevity, and farm investments, while controlling for farm-specific characteristics and animal management practices by using Swedish dairy farm and production data from 2009 to 2018. The farm-specific and animal management factors include milk yield, breed, type of housing and milking system, and production system (conventional vs. organic). Specifically, we first investigate to what extent animal health affects cow longevity. Second, we emphasize in particular the extent to which farms made investments to increase the size of their operation and to what extent the rate of culling is determined by farmers' choices to increase the number of places or to keep their operation at a constant size at a particular point in time. Furthermore, we differentiate between average estimated effects and the heterogeneous effects estimated by ordinary least square (**OLS**) and unconditional quantile regressions (**UQR**), respectively.

The scientific novelty of our study lies in its investigation of the mean and heterogeneous effects of how farmers' investment decisions, animal health, management practices (e.g., choice of breed, housing, and milking systems) and production characteristics (e.g., milk yield, herd size) affect cow longevity. An understanding of these determinants can simultaneously function to enhance herd health, welfare, and farm economic outcome. In addition, this study uses on-farm recording data and employs a rigorous econometric framework.

This paper contributes to existing knowledge in the following ways: first, this study is the first to use long panel data on farm investments to examine the effect of investments in farm building on longevity of dairy cows. In this way, we highlight how farmers' strategies regarding dairy cow longevity can function to simultaneously enhance dairy herd welfare status. The study also contributes significant insights that are important for an informed discussion about ethical considerations linked to dairy cow longevity and to possible synergies or trade-offs between the wishes to keep animals for a long time for ethical reasons and consequences in terms of herd health and welfare. In addition, findings from this study contribute to the debate on wishes to keep animals in production for a long time to spread environmental burdens of raising heifers over a larger amount of total production, and how this relates to the herd health and welfare status. Finally, findings from the study contribute to dairy herd lifetime resilience, which is very relevant for the sustainability of the dairy industry.

MATERIALS AND METHODS

Data and Variable Description

The study used Swedish Dairy Cow Recording Scheme data from Växa Sverige and Farm Economic Survey (**FES**) from the Swedish Board of Agriculture for the years 2009 to 2018. The Swedish Dairy Cow Recording Scheme data contained detailed information on cow health variables, including the proportion of cows receiving veterinary treatment, mastitis, leg and hoof diseases, SCC, herd size, age at first calving (d), calving interval (mo), age at culling (d), number of cows culled, breed, milking system, and ECM were also included in this data set. The FES data contains variables such as investment in farm building, fixed and variable cost, system of production, milk and meat output, just to mention a few. The FES serves as a basis for Sweden's participation in the European Union Farm Accounting Data Network, which targets population farms containing at least 8 European size units (Hansson et al., 2013). Thus, FES data in Sweden target large farms. The 2 data sets were merged using unique identification numbers. Both data sets contained data from 2009 to 2018.

De Vries (2013) defined dairy cow longevity as the length of life of the dairy cow in the herd. Dairy cow longevity can be broken into the time before first calving and the time after first calving. In this study, dairy cow longevity was measured using the following 2 indicators: (1) productive lifespan of the cow, computed as the age at culling minus age at first calving, and (2) total lifespan (i.e., time from birth to culling). Farm management variables in the data set include breed of herd, type of housing, type of milking system, production system (conventional or organic), and investment costs (farm building). Figure 1 presents average milk yield per cow in the Nordic countries and shows that Sweden has high average milk yield per cow, relative to the other Nordic countries. There is an increasing trend in milk yield per cow in Sweden, Denmark, and Norway. From the year 2017, there has been a sharp increase in milk yield per cow in Sweden. Despite the high milk yield per cow, Sweden has short dairy herd longevity, and as such, there is the need to investigate what influences dairy farmers decision relating to how long herd stay in the dairy production system.

Empirical Framework

We applied OLS regression and quantile regression models. These models were selected because they allowed us to analyze both the mean and heterogeneous effects of animal health and farm investments on dairy cow longevity, while controlling for production and farm management characteristics. We started from the following baseline OLS regression functions:

$$Health_i = \alpha_0 + Invest_i\alpha_1 + Prod_i\alpha_2 + Mangmt_i\alpha_3 + Year_i\alpha_4 + \varepsilon_i, \quad [1]$$

where the variable $Health_i$ captures animal health proxied by the proportion of cows receiving veterinary treatment (Fall et al., 2008). Before this estimation, the variable, proportion of cows receiving veterinary treatment, was tested to see if the observed values were censored or not. The test revealed that the variable was uncensored, and OLS regression was therefore estimated instead of a censored regression (e.g., Tobit model), which established the relationship between variables when the dependent variable is censored. $Invest_i$ captures positive change in investment in farm buildings. $Prod_i$ is a vector of production variables milk yield, herd size, calving interval, age at first calving, and SCC. $Mangmt_i$ is a vector of farm management characteristics type of breed, type of housing, type of production system, and type of milking system. $Year_i$ refers to a vector of year dummies used for capturing the time-invariant and time-variant heterogeneities; α_0 is a constant; α_1, α_2, α_3, and α_4 are parameters to be estimated; and ε_i is an error term.

$$LGVT_i = \alpha_0 + \alpha_1 P\_Health_i + \alpha_2 Invest_i + \alpha_3 Prod_i + \alpha_4 Mangmt_i + \alpha_5 Year_i + \varepsilon_i, \quad [2]$$

where $LGVT_i$ denotes longevity measured using the following 2 indicators: (1) age at culling and (2) productive lifespan. P_Health is the predicted health variable from the Equation [1]. This predicted health variable was used to avoid endogeneity bias, which would have

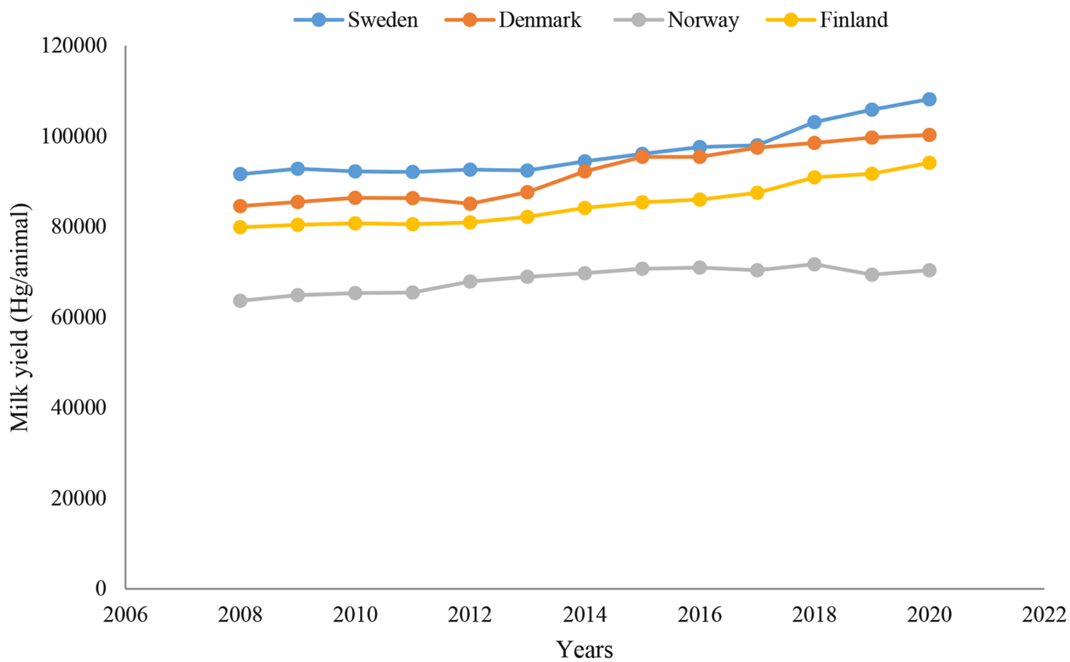

Figure 1. Average raw milk yield per cow in hectogram across Nordic countries. Denmark, Norway, and Finland values are from FAOSTAT (2022). Sweden values are from Växa Sverige (2020).

occurred if the actual values were used (Baltagi, 2011). Thus, the actual health variable could not be included directly in the Equation (2) because the proportion of cows receiving veterinary treatment correlates with some of the covariates in the equation (e.g., housing system, milking system). The rest of the variables were defined as above.

In Equation [2], α_1 captures the average (mean) effect of animal health on dairy cow longevity, which only illustrates a partial picture of the association between the 2 variables. Second, α_2 captures the average (mean) effect of investment in housing on dairy cow longevity. From a policy perspective, policymakers are more likely to be interested in understanding the influence of a program intervention (e.g., investment support for reconstruction of animal housing or support for extended hoof health care) on the distributions of animal health and welfare. Therefore, a quantile regression model should be further estimated to identify the heterogeneous relationship between health and investment variables on dairy cow longevity, as well as control variables.

Previous studies have applied both the conditional quantile regression (**CQR**) model (Mishra and Moss, 2013; Agyire-Tettey et al., 2018; Derbali et al., 2020) and UQR model (Mishra et al., 2015; Hernæs, 2020; Pérez-Rodríguez and Ledesma-Rodríguez, 2021). It should be noted here that differences exist between the CQR and UQR models. In particular, the CQR model offers a narrower interpretation of the effect of health and investments on longevity, because the estimated effect of a covariate is largely conditional on the selection of other variables (e.g., production, management) included in the model (Borah and Basu, 2013; Pérez-Rodríguez and Ledesma-Rodríguez, 2021). In contrast, the effect of health and investment variables in the UQR model estimates does not implicitly rely on the level of other conditional variables in the quantile models. The UQR model can estimate more reliable results, and thus, it is employed in the present study.

The UQR model is based on the concept of the recentered influence function (**RIF**; Firpo et al., 2009; Agyire-Tettey et al., 2018). The influence function (**IF**) assesses the effect of an individual observation on a distributional statistic, $v(F)$, such as the mean, median, or any quantiles, without having to recalculate that statistic. The IF can be defined as

$$IF\left[LGVT;v\left(F\right)\right]=\lim_{\varepsilon\to\infty}\left[\frac{v\left(1-\varepsilon\right)\cdot F+\varepsilon\delta_{LGVT}\right)-v\left(F\right)}{\varepsilon}\right],0\leq\varepsilon\leq1, \quad [3]$$

where F refers to the cumulative distribution function for dairy cow longevity, $LGVT$, and $\varepsilon\delta_{LGVT}$ represents a distribution that puts mass at the value $LGVT$. For the τth quantile of $LGVT$, the influence function can be written as

Table 1. Summary statistics of production, health, and investment variables[1]

Item	Mean	Median	SD	Minimum	Maximum
Production variable					
Number of cows per herd	88	63	95	10	1,335
Age at first calving (d)	856	835	94	689	1,644
Calving interval (mo)	13	13	1	11	23
Milk yield (kg ECM)	9,656	9,762	1,436	523	14,264
Age at culling (d)	1,884	1,853	267	1,114	3,769
Productive lifespan (d)	1,028	999	243	385	2,931
Number of culled cows per year	33	22	35	0	469
Health variable					
Veterinary treatment (proportion of cows, %)	24	20	18	1	100
Mastitis treatment (proportion of cows, %)	10	9	10	0	84
Hoof and leg treatment (proportion of cows, %)	2	0	4	0	46
BMSCC[2] (×1,000/mL milk)	244	234	84	60	713
Farm investment					
Farm building (SEK)[3]	2,692,089	1,224,094	4,014,146	1,144,164	4.45e+07
Investment (1 if farmer made investment in farm building, 0 otherwise	0.92	—	—	0	1

[1]Source: Sveriges Riksbank (https://www.riksbank.se/en-gb/statistics/search-interest--exchange-rates/annual-average-exchange-rates/?y=2022&m=5&s=Comma&f=y).

[2]Bulk milk SCC.

[3]Average exchange rate 2022 (€1: SEK10.46).

$$IF\left(LGVT;Q_\tau\right)=\left[\frac{\tau-I\left(LGVT\le Q_\tau\right)}{f_{LGVT}\left(Q_\tau\right)}\right], \qquad [4]$$

where Q_τ is the τth quantile of the unconditional distribution of $LGVT$, and the probability density function of $LGVT$ evaluated is represented by $f_{LGVT}(Q_\tau)$. $I(LGVT \le Q_\tau)$ indicates whether the observed value is less than or equal to Q_τ. The RIF is obtained by adding the relevant statistic (i.e., the quantiles) to its IF:

$$RIF\ (LGVT;\ Q_\tau\ ) = IF(LGVT;\ Q_\tau). \qquad [5]$$

In the present study, the UQR model estimates Equation [5] conditional on a vector of explanatory variables as follows (Firpo et al., 2009; Agyire-Tettey et al., 2018):

$$RIF\ (LGVT;\ Q_\tau\ ,\ F_{LGVT}) = \beta_0 + \beta_1 P\_Health_i$$
$$+\ \beta_2 Invest_i + \beta_0 Prod_i + \beta_4 Mangmt_i + \beta_5 Year_i + \mu_i, \qquad [6]$$

where $LGVT_i$ is the dependent variable, referring to longevity; Q_τ demotes the τth quantile of the dependent variable's cumulative distribution F_{LGVT}; the remaining variables are defined as above; β_0 is a constant; β_1 and β_2 are the parameters we are interested in, which is the unconditional marginal effect of health and investments; β_3, β_4, and β_5 are corresponding parameters to be estimated; and μ_i is an error term. The UQR estimates from Equation [6] have a similar interpretation as the coefficients from an OLS regression and are estimates of unconditional quantile marginal effects.

RESULTS

Descriptive Results

Table 1 presents the descriptive statistics of production, health, and investment variables. Milk yield in Swedish dairy cows has increased in recent decades because of improved genetics, feeding practices, and management (Växa Sverige, 2020). The average age at first calving in the Swedish data is about 28.5 mo. The results indicate that, on average, dairy cows are culled when they are 63 mo old.

In terms of productive life, we found that, on average, dairy cows are productive for 34 mo, with a median of 33 mo. Regarding the health variables, the results show that, on average, about 24% of the dairy cows in the herds receives veterinary treatment. The average bulk tank SCC observed in this study for the period from 2009 to 2018 was 244,000/mL milk, with a median of 234,000/mL.

To capture investment dynamics, in particular how a change in the level of investment affects cow longevity, we did not use the absolute values of the farm building in the empirical analysis. Changes in investment in farm infrastructure from the start year (t) to year ($t + n$) were computed and from this variable, a dummy variable was computed, taking on a value of 1 for farms with a positive change in investment in farm infrastructure and 0 for farms that did not make investments in farm infrastructure over the time period. The descriptive statistics show that the majority of the farms (92%) made investments in farm infrastructure. In terms of investment size, the results show that an average of SEK 2,692,089 (€257,616) was invested in farm infrastructure for the herd.

Table 2 presents the distributions of farm management characteristics. The majority of the dairy farms in the present study employed conventional production practices. Only about 16% of the dairy farms were certified by KRAV as organic producers. The percentage of organic producers does not differ significantly from the figure of 17% reported by the Swedish Board of Agriculture in 2018 (Swedish Board of Agriculture, 2019).

In terms of milking systems, the tiestall milking system is the most popular, used by 51% of the dairy farms, followed by automatic milking systems (**AMS**) and milking parlors. The rotary system is the least common system. Half of the dairy farms had tiestalls, and this is consistent with the use of a tiestall milking system. The remaining farms had freestall housing systems: 34% had insulated housing and 15% had noninsulated housing. In terms of breed, 39% of the farms had a herd with cross breeding between the Swedish Red and the Swedish Holstein, which together constituted more than 50% of the herd.

In Table 3, the correlations between health and longevity variables are presented. The proportion of cows receiving veterinary treatment was positive and significantly correlated with the proportion of cows treated for mastitis, as well as with the proportion of cows with hoof and leg disorders. Moreover, the proportion of treatments for hoof and leg disorders was positively and significantly correlated with the proportion of mastitis treatment. Culling age and productive lifespan were highly correlated. Milk yield is positively correlated with share of cows with veterinary, mastitis, and hoof and leg treatments, but negatively correlated with SCC, productive life span, and culling age.

In addition, bulk tank SCC was correlated with culling age, whereas the proportion of cows receiving veterinary treatments had no significant correlation with productive life or culling age. It is important to note that these results do not show cause-and-effect relationships. Hence, in the next section, we present OLS and UQR results to show how the different covariates affect health and longevity variables.

Table 2. Summary statistics (number and percentage of farms) of farm management variables

Variable	No. of farms	Percentage
Production system		
Conventional	1,842	84
Certified organic by KRAV[1]	347	16
Milking system		
Automatic milking system	627	29
Milking parlor	436	20
Rotary	34	1
Tiestall milking	1,092	50
Housing type		
Freestall housing, noninsulated	337	15
Freestall housing, insulated	745	34
Tiestall	1,107	51
Breed[2]		
1 = SR (SR ≥ 80%)	468	21
2 = SH (SH ≥ 80%)	548	25
3 = SR + SH ≥ 50%	844	39
4 = Other breeds	329	15

[1]KRAV is the main Swedish organization that develops and maintains regulations for ecological sustainable agriculture. KRAV is the Swedish organic market's private label.

[2]SR = Swedish Red; SH = Swedish Holstein. The numbers indicate the proportion of the breeds in the entire herd.

Average Effects of Farm-Specific Characteristics and Animal Management Practices on Animal Health and Productive Lifespan of Dairy Cows

Table 4 presents the empirical results of the mean-based analysis of the effects of farm-specific characteristics and animal management practices on dairy cow health using the OLS regression model. The results show that the proportion of cows receiving veterinary treatments increases by 0.002 percentage units for 1 kg of ECM increase in herd average milk yield. On the other hand, for one increase in bulk milk SCC (**BMSCC**; i.e., for an increase of 1,000 cells/mL), the

Table 3. Correlation of health and longevity variables

Variable	Veterinary treatment	Mastitis treatment	Hoof and leg treatment	BMSCC[1]	Productive lifespan	Culling age	Milk yield
Veterinary treatment	1						
Mastitis treatment	0.84**	1					
Hoof and leg treatment	0.51**	0.29**	1				
BMSCC	−0.13	−0.08	−0.08	1			
Productive lifespan	−0.05	−0.05	−0.03	0.07	1		
Culling age	−0.05	−0.04	−0.04	0.13**	0.94**	1	
Milk yield	0.16**	0.11**	0.11**	−0.19**	−0.23**	−0.16**	1

[1]BMSCC = bulk milk SCC.

** indicates statistical significance at 5% level.

Table 4. Effects of farm-specific and animal management characteristics on dairy herd health ordinary least square estimates; dependent variable is proportion of herd with veterinary treatment[1]

Variable	Coefficient	R. SE	*t*-statistic	*P*-value
Constant	26.51***	9.92	2.67	0.01
Production indicator				
Milk yield (kg ECM)	0.00***	0.00	7.53	<0.001
Calving interval (mo)	−0.05	0.36	−0.13	0.90
Age at first calving (d)	−0.00	0.00	−0.16	0.87
BMSCC (×1,000 cells/mL)	−0.03***	0.01	−3.75	<0.001
Herd size (no. of cows)	0.01	0.01	1.55	0.12
Production system (reference: conventional)				
Certified organic (KRAV)	−9.57**	4.46	−2.15	0.03
Breed [reference: SR (SR ≥ 80%)]				
SH (SH ≥ 80%)	0.17	1.20	0.14	0.89
SR + SH ≥ 50%	−0.75	1.03	−0.73	0.47
Other_breed	−1.28	1.29	−1.00	0.32
Housing type (reference: freestall housing, noninsulated)				
Freestall housing, insulated	−4.81***	1.42	−3.39	<0.001
Tiestall	−7.35	4.96	−1.48	0.14
Milking system (reference: tiestall)				
Automatic milking system	8.34**	4.04	−2.06	0.04
Milking parlor	−9.29**	3.96	−2.34	0.02
Rotary	3.54	4.46	−0.79	0.43
Production system and milking system				
Conven_tiestall milking	−7.38***	2.86	−2.58	0.01
Conven_parlor	−3.53	4.99	−0.71	0.48
Conven_AMS	−1.81	2.38	−0.76	0.45
Organic_tiestall milking	9.67**	4.25	2.28	0.03
Organic_parlor	10.73**	5.19	2.07	0.04
Year effects (reference: 2009)				
2010	−5.90**	2.46	−2.40	0.02
2011	−7.32***	2.46	−2.97	<0.001
2012	−8.65***	2.41	−3.59	<0.001
2013	−4.01***	1.39	−2.88	<0.001
2014	−8.52***	2.29	−3.72	<0.001
2015	−11.28***	2.27	−4.98	<0.001
2016	−14.15***	2.20	−6.43	<0.001
2017	−12.96***	2.22	−5.85	<0.001
2018	−12.73***	2.23	−5.72	<0.001
Number of observations		2,189		
Adjusted R^2		0.56		
F-statistic		9.40***		
Mean variance inflation factor		4.00		

[1]R. SE = robust standard error; BMSCC = bulk milk somatic cell count; SR = Swedish Red; SH = Swedish Holstein.

*** and ** show significance at 1% and 5% levels, respectively.

proportion of cows receiving veterinary treatment decreased by 0.02 percentage units, and having organic production, compared with conventional, reduced the proportion by about 10 percentage units.

In terms of housing type, the results show that insulated freestall housing reduces the proportion of cows receiving veterinary treatment, compared with noninsulated freestall housing. This finding suggests that the use of AMS increases the proportion of veterinary treatment by 8, relative to a tiestall system. On the other hand, the use of milking parlors reduces the proportion of veterinary treatment by 9, relative to tiestall system.

The results show that herds raised using conventional systems with tiestall milking have a low proportion of veterinary treatment. On the other hand, herds kept on organic systems with tiestall and parlor milking have a high proportion of cows receiving veterinary treatment. Compared with 2009, veterinary cases among Swedish dairy herds have been declining from 2010 to 2018 and this may explain the declining proportion of veterinary treatments in the present study.

Table 5 presents the average effects of animal health, investments, farm-specific characteristics, and animal management variables on average productive lifespan. The results show that the average productive lifespan of dairy cows increases by about 39 d when a farm makes investments to increase the size of farm buildings.

Among the production variables, the results show that the average effect of a single unit increase in ECM milk yield equates to an increase in productive lifespan

Table 5. Average effects of animal health, investment, farm-specific, and animal management variables on productive lifespan; dependent variable is productive lifespan of dairy herd[1]

Variable	Coefficient	R. SE	*t*-statistic	*P*-value
Health[2]	−0.08	0.30	−0.28	0.78
Investment	38.86**	16.75	2.32	0.02
Control variable				
Production indicator				
Milk yield	0.02***	0.00	4.73	<0.001
Calving interval	37.19***	5.75	6.47	<0.001
Age at first calving	−0.09	0.07	−1.15	0.25
BMSCC, ×1,000 cells/mL	0.18**	0.07	2.41	0.02
Herd size	0.06	0.06	0.98	0.33
Production system (reference: conventional)				
Certified organic (KRAV)	−74.39	62.68	−1.19	0.24
Breed [reference: SR (SR ≥ 80%)]				
SH (SH ≥ 80%)	−21.79	16.05	−1.36	0.18
SR + SH ≥ 50%	−2.96	14.65	−0.20	0.84
Other_breed	5.93	20.88	0.28	0.78
Housing type (reference: freestall housing, noninsulated)				
Freestall housing, insulated	−7.57	15.77	−0.48	0.63
Tiestall	−44.73	57.68	−0.78	0.44
Milking system (reference: tiestall)				
AMS	−18.98	31.30	−0.61	0.54
Milking parlor	10.13	30.99	0.33	0.74
Rotary	69.54**	34.19	2.03	0.04
Production system and milking system				
Conven_tiestall milking	−13.14	43.14	−0.30	0.76
Conven_AMS	−8.94	29.45	−0.30	0.76
Conven_parlor	32.65	51.94	−0.63	0.53
Organic_tiestall milking	35.59	64.39	0.55	0.58
Organic_parlor	82.66	58.71	1.41	0.16
Year effects (reference: 2009)				
2010	8.65	27.69	0.31	0.76
2011	12.41	27.07	0.46	0.65
2012	22.32	28.00	0.80	0.43
2013	16.83	26.70	0.63	0.53
2014	41.63	26.22	1.59	0.11
2015	72.28***	26.56	2.72	0.01
2016	73.66***	27.84	2.65	0.01
2017	67.42**	26.86	2.51	0.01
2018	85.97***	28.49	3.02	<0.001
Constant	705.31***	130.20	5.42	<0.001
Number of observations		2,188		
Adjusted R^2		0.62		
F-statistic		6.13***		
Mean variance inflation factor		4		

[1]R. SE = robust standard error; BMSCC = bulk milk somatic cell count; SR = Swedish Red; SH = Swedish Holstein.

[2]Health is the predicted proportion of the herd with veterinary treatment from the ordinary least square estimation of farm-specific and animal management characteristics on animal health (Equation 1).

*** and ** show significance at 1% and 5% levels, respectively.

of 0.021 d. This implies that dairy cows with high milk yields remain in the herd longer. The results also show that a one-month increase in average calving interval on herd level leads to an increase in average productive lifespan on herd level of 37 d. The model showed that the average productive lifespan was higher in herds with higher BMSCC. Farmers do not cull the chronic infected cows, and hence, they will have a higher BMSCC. This finding is contrary to Samoré et al. (2003), who found high SCC to be associated with a high rate of culling. An increased productive lifespan was seen in herds with rotary systems compared with herds with tiestall milking systems. The results show that that the average productive lifespan of cows in Swedish dairy herds increased substantially from 2015 to 2018.

The estimates of animal health, investments, farm-specific characteristics, and animal management variables on age at culling are provided in Appendix Tables A1 and A2. The results obtained do not differ from the results presented in Table 5, and in the interest of brevity, we will not discuss the results with age at culling as a dependent variable. The test statistics for variance inflation factor showed no severe multicollinearity problem in the covariates.

Table 6. Descriptive statistics of the productive life, age at culling, veterinary treatment, and investment per quantile

Variable	Observation	Mean	SD	Minimum	Maximum
25th quantile					
Productive life (d)	548	785.15	101.61	388.50	1,006.67
Age at culling (d)	548	1,595.08	93.80	1,114.00	1,713.22
Veterinary treatment (%)	548	25.98	18.64	0	93.07
Investment	548	0.89	0.31	0	1
50th quantile					
Productive life (d)	547	942.23	74.89	631.40	1,110.29
Age at culling (d)	547	1,780.79	39.84	1,713.55	1,852.52
Veterinary treatment (%)	547	23.75	17.88	0	100
Investment	547	0.92	0.28	0	1
75th quantile					
Productive life (d)	547	1,068.83	87.56	550.73	1,288.21
Age at culling (d)	547	1,927.31	44.69	1,852.97	2,012.26
Veterinary treatment (%)	547	23.51	18.18	0	100
Investment	547	0.91	0.29	0	1
95th quantile					
Productive life (d)	547	1,316.64	249.30	384.50	2,930.67
Age at culling (d)	547	2,233.70	233.49	2,013.08	3,768.67
Veterinary treatment (%)	547	22.69	18.42	0	100
Investment	547	0.92	0.27	0	1

Heterogeneous Effects of Farm-Specific Characteristics and Animal Management Practices on Productive Lifespan of Dairy (UQR Estimates)

In this section, we present the UQR results. Before the discussion of the empirical results, we present the quantile statistics of productive lifespan, culling age, proportion receiving veterinary treatment, and investments (see Table 6). The unconditional regression results present some interesting findings. To begin with, the results in Table 7 show that the health variable (proportion receiving veterinary treatment), which was insignificant in the pooled sample (see Table 5), is statistically significant and negative in the 25th quantile. This result suggests that productive lifespan of dairy herds reduces as the proportion of veterinary treatments increases at the lower quantile (25th), where the average productive lifespan of a dairy cow is about 785 d, with a standard deviation of 102 d.

Another interesting result relates to investments in farm infrastructure. The results show that investments in farm buildings prolongs the productive lifespan of the dairy herd. This effect is realized only in the 75th quantile, where the average productive lifespan is about 1,069 d, with a standard deviation of 86 d.

The estimated effects of milk yield monotonically increase from the lowest (25th) to the highest (95th) quantile. This result indicates that across the quantiles, an incremental increase in milk yield prolongs the productive lifespan of dairy cows (cows with high milk yield are kept in the herd). Similarly, the results show that calving interval is significantly positive across the 4 quantiles. The estimated effects continually increase from the 25th to 75th quantile. The estimated effect of age at first calving is significant and negative only in the lowest quantile (25th). This calving interval had no significant effect in the mean-based results presented in Table 5.

The BMSCC, which was significant in the mean-based analysis, is found to be significant and positive only in the lower (25th) and median (50th) quantiles, indicating that higher BMSCC at the lower and median quantiles prolongs the lifespan of the herd. In herds with prolong lifespan, famers keep cows with high SCC and hence, the higher BMSCC. The estimated effect of herd size on productive life is statistically significant and positive only in the lowest quantile, suggesting that higher herd size at the lower quantile prolongs the productive lifespan of dairy herd. This variable was not significant in the mean-based results presented in Table 5.

In terms of breed, we found that the effect of having at least 80% Swedish Holstein on the productive life of dairy cows is significant and negative in the median and 75th quantiles, compared with herds with at least 80% Swedish Red. This means that the productive life of dairy herds dominated by Swedish Holstein cows reduces in the median and 75th quantiles, where the average productive life is about 942 and 1,069 d, respectively. In addition, the heterogeneous results show that the estimated effect of insulated freestall housing, compared with noninsulated freestall housing, on the productive life of dairy cows was negative and significant only in the median quantile. In terms of year fixed effects, the results indicate that the productive life of dairy cows in the lowest quantile (25th) increased from

Table 7. Heterogeneous effects of animal health, investment, and farm management variables on productive life of dairy cows; dependent variable is productive lifespan of dairy herd[1]

Variable	25th quantile	50th quantile	75th quantile	95th quantile
Health	−0.72** (0.33)	−0.14 (0.29)	−0.01 (0.39)	0.03 (1.01)
Investment	11.41 (20.52)	9.91 (18.56)	43.26** (20.09)	88.19 (68.56)
Control variable				
Production indicator				
Milk yield	0.01** (0.00)	0.01*** (0.00)	0.02*** (0.01)	0.06*** (0.02)
Calving interval	30.37*** (5.59)	33.13*** (5.06)	46.96*** (6.56)	31.28** (17.67)
Age at first calving	−0.16** (0.07)	−0.04 (0.06)	0.01 (0.08)	0.01 (0.22)
BMSCC, ×1,000 cells/mL	0.29*** (0.07)	0.25*** (0.07)	0.11 (0.09)	−0.12 (0.25)
Herd size	0.28*** (0.09)	0.04 (0.08)	0.07 (0.11)	−0.03 (0.31)
Production system (reference: conventional)				
Certified organic (KRAV)	−56.83 (78.55)	−75.28 (71.07)	−42.78 (92.26)	169.69 (262.51)
Breed [reference: SR (SR ≥ 80%)]				
SH (SH ≥ 80%)	−15.59 (18.43)	−28.60** (15.68)	−47.18** (21.65)	23.01 (61.59)
SR + SH ≥ 50%	7.46 (15.88)	−5.85 (14.37)	−14.85 (18.65)	58.67 (53.08)
Other_breed	2.18 (20.79)	−17.25 (18.81)	17.44 (24.42)	48.73 (69.49)
Housing type (reference: freestall housing, noninsulated)				
Freestall housing, insulated	17.04 (21.48)	−37.76* (19.44)	−3.51 (25.23)	17.64 (71.79)
Tiestall	3.00 (71.22)	−33.66 (64.43)	8.27 (83.64)	74.83 (237.99)
Milking system (reference: tie stall)				
AMS	10.01 (61.76)	−37.92 (55.88)	56.68 (72.54)	101.06 (206.39)
Milking parlor	44.35 (61.16)	13.69 (55.33)	80.53 (71.83)	117.07 (204.37)
Rotary	81.66 (67.73)	27.42 (61.28)	121.96 (79.55)	343.80 (226.34)
Production system and milking system				
Conven_tiestall milking	−15.19 (52.62)	0.73 (47.60)	22.88 (61.80)	41.88 (175.83)
Conven_AMS	18.98 (40.02)	18.00 (36.21)	−31.23 (47.00)	−9.39 (133.74)
Conven_parlor	−28.79 (68.63)	−35.26 (62.09)	22.09 (80.60)	73.66 (229.33)
Organic_tiestall milking	81.05 (73.46)	21.95 (68.67)	10.15 (89.14)	−162.98 (253.64)
Organic_parlor	−0.87 (75.90)	93.19 (66.46)	47.26 (86.27)	−126.53 (245.48)
Year effect				
2010	25.71 (32.73)	−16.35 (29.62)	−34.02 (38.44)	67.33 (109.39)
2011	10.28 (31.95)	−6.07 (28.91)	2.51 (37.53)	33.12 (106.78)
2012	3.65 (31.01)	−2.78 (28.06)	1.05 (36.42)	98.89 (103.63)
2013	18.22 (30.39)	0.14 (27.49)	−12.47 (35.67)	47.59 (101.57)
2014	38.29 (30.06)	21.26 (27.19)	30.53 (35.30)	64.64 (100.44)
2015	48.87 (30.36)	50.24** (25.46)	52.46 (35.65)	141.95 (101.45)
2016	55.54** (28.35)	49.42** (23.46)	44.35 (35.65)	127.90 (101.43)
2017	34.78*** (10.82)	71.81*** (27.88)	40.111 (36.20)	144.92 (102.99)
2018	56.04** (28.89)	77.01*** (27.94)	68.79** (33.27)	109.99 (103.21)
Constant	543.69*** (143.33)	89.87*** (129.68)	566.46*** (168.34)	1,070.29** (478.98)
Observation	2,188	2,188	2,188	2,188
Pseudo R^2	0.24	0.21	0.26	0.25

[1]BMSCC = bulk milk somatic cell count; SR = Swedish Red; SH = Swedish Holstein.
***, **, * show significance at 1%, 5%, and 10% levels, respectively.

2016 to 2018. In the median quantile, the results indicate that productive life of dairy cows increased from 2015 to 2018.

DISCUSSION

In this paper, we investigated how herd animal health and farm investment decision relate to dairy cow longevity on the herd level, while controlling for farm-specific characteristics and animal management practices. This study builds on previous literature that has investigated the relationship between longevity and intrinsic (i.e., genetics and traits) factors (Zehetmeier et al., 2014; Haile-Mariam and Pryce, 2015; De Vries, 2017) and the extrinsic reasons for culling dairy cows, such as availability of replacement heifers, land availability, and prices (Bergeå et al., 2016; Grandl et al., 2019; Gambonini et al., 2022). This paper is one of the first to establish the extent to which a farms' decision to invest in farm infrastructure affects cow longevity. Thus, we examined the extent to which dairy cow longevity is affected by the farmers' decision to increase the number of places or keep the dairy operation at a constant size at a particular point in time. Similar to Ahlman et al. (2011), De Vries (2017), and Rostellato et al. (2021), cow longevity was considered using length of productive life and age at culling. These variables were continuous and allowed us to examine the average and heterogeneous effects of the variables of interest and the control variables.

Regarding investment in farm infrastructure, the findings of the present study demonstrate that dairy cow longevity is significantly linked to changes in investments made by the farmer, namely, to increase farm building space and the number of places for dairy cows. The heterogeneous effect results show that the stage of productive life at which the farmer makes changes in farm infrastructure is crucial to cow longevity. This finding is in line with the Asset Replacement Theory (Hartman and Tan, 2014), which says that replacing assets is an important decision that every producer faces, and that the replacement decision is usually driven by increasing operating and maintenance costs associated with existing assets or improvements of existing assets in the market. In applying this basic economic theory to dairy cow longevity and the replacement of heifers, the best time to replace existing dairy cows would be determined by comparing the marginal revenue from the existing cows with the anticipated returns from replacement heifers (De Vries, 2017; Vredenberg et al., 2021; Gambonini et al., 2022). Thus, the optimal time to replace existing cows will be the point where the annuity value of the cow falls below the maximum annuity value the farmer can attain from the replacement heifer. However, with an investment in farm infrastructure, there will be additional space for the replacement heifers, and the farmer will not have to cull old cows that are still productive. In the absence of investment in farm buildings, farmers would have to cull old cows to make room for new recruitment heifers, or they would have to bring in fewer recruitment animals. De Vries and Marcondes (2020), who argued that without space for new heifers, farmers would decide to cull existing cows to make space for new heifers, support this assertion.

On average, animal health, proxied by the proportion of cows receiving veterinary treatment, negatively and insignificantly correlates with herd longevity. This finding is supported by the study by Fall et al. (2008), who also found no significant relationship between the length of productive life and the proportion of the herd receiving veterinary treatment in Sweden. However, heterogeneous findings from this study show that an increase in disease in the early stages of the herd's productive life (26 mo) significantly reduces longevity. For instance, primiparous cows with severe disease in early lactation are culled. This is in accordance with De Vries and Mercondes (2020) who opined that health problems are major drivers of culling at a young age.

Among the control variables, increase in herd average milk yield significantly prolongs average herd longevity, and this positive relationship increases monotonically along all the 4 heterogeneous quantiles examined. This is supported by Rostellato et al. (2021) who found that dairy farmers are more likely to cull herds with low output even if they had good health characteristics. Haile-Mariam and Pryce (2015) found that increases in milk yield reduced culling in dairy cows in Australia. Longer calving interval prolongs herd longevity, and this is in line with the findings of Do et al. (2013), who found calving interval and age at first calving to exert a positive effect on the longevity of Korean Holstein cows. Similarly, Remmik et al. (2020) found a longer calving interval to be positively associated with a higher productive life among dairy cows, also reducing the probability of early culling. The BMSCC was positively associated with cow longevity, on average, and this is contrary to the findings of Samoré et al. (2003), who found high SCC to be associated with a high rate of culling. However, our heterogeneous findings showed that high BMSCC was positively associated with cow longevity in herds in the lower to medium quantiles of longevity. It is worth mentioning that it is not SCC per se that positively influences longevity, rather older cows have higher SCC. However, the disparity in the level of significance of SCC is in line with the Fuerst-Waltl et al. (2004), who found inconsistent results for SCC across different parities.

Increasing the age at first calving in a herd reduces the longevity of cows at an early stage of their productive life. This finding is consistent with a Swedish study by Hultgren and Svensson (2009), who found that a Swedish dairy herd with an age at first calving of 27 to 28 mo to be 1.1 times more likely to have a shorter length of productive life relative to cows with an age at first calving younger than 25 mo. This could be attributed to an increased risk of complications at calving for older heifers as they become fatter. Sherwin et al. (2016) found a positive relationship between age at first calving and the length of productive life for cows in the United Kingdom.

On average, the dominating breed of the herd had no significant effect on the length of productive life, and this is contrary to findings by Garcia-Peniche et al. (2006), who reported differences in survival probabilities between Holstein, Brown Swiss, and Jersey cows in the United States. However, Garcia-Peniche et al. (2006) support the heterogeneous findings relating to the negative relationship between Holstein herds and a herd average longevity around 31 to 36 mo. The authors found Holstein herds to have a lower longevity compared with Brown Swiss or Jersey breeds.

In terms of animal health, this study shows that high milk yield is positively associated with the proportion of cows receiving veterinary treatment, whereas high SCC is negatively associated with the proportion of cows receiving veterinary treatment. Existing studies by Cinar et al. (2015) found that the somatic cell count is negatively correlated with milk yield. Yalçın et al. (2000) and Król et al. (2010) indicated that a high SCC is positively associated with milk losses and milk quality. Thus, existing studies show that SCC affects milk output. Contrary to studies by Sutherland et al. (2013), Weller and Bowling (2000), and Rutherford et al. (2009), the present study showed that in herds with organic production, the proportion of cows with veterinary treatment was lower compared with herds with conventional system. The proportion of cows with veterinary treatments was lower in herds with an insulated freestall housing compared with herds with a noninsulated freestall housing. We do not know why that differs and will not make any speculation on that. More research is needed to clarify that association.

Moreover, in herds with milking parlors compared with tiestalls, the proportion of the herd with veterinary treatment was reduced. Earlier findings by van den Borne et al. (2021) and Frössling et al. (2017) indicated that AMS leads to poorer teat and udder health relative to conventional milking systems, such as the milking parlor. The positive correlation between the use of AMS and the proportion of the herd receiving veterinary treatment is not supported by earlier studies by Neijenhuis et al. (2004) and Zecconi et al. (2004) found no significant change in udder health in cows with AMS. It is important to note that this study considered the proportion of the herd treated for all diseases, including udder diseases.

From an empirical point of view, the UQL gave us the opportunity to better comprehend and assess the sole effects of animal health and farm investment on longevity, regardless of the effects of other control variables (Mishra et al., 2015). Indeed, the findings from this study suggest that the effect of animal health and farm investments on longevity varies significantly across quantiles.

The implication of these findings is that the short longevity of dairy herd in Sweden relative to other dairy producing countries is not a result of problems with health and welfare. Rather, dairy cow longevity in Sweden hinges on the farmers' investment, farm-specific characteristics, and animal management decisions. Thus, productive lifespan of dairy herd is largely based on the dairy farmer's decision-making.

With the societal concern of farm animal welfare and environmental sustainability, it is probable that the society will require higher longevity of dairy herd in accordance with life expectancy. Our findings point out that higher longevity can be attained through investment in farm building to accommodate recruiting heifers as well as herd management. Extending the productive life of dairy herd could enhance environmental sustainability as well as building a resilient dairy sector using farm management and decision support.

CONCLUSIONS

Based on our findings, the following conclusions are drawn: first, investment in farm infrastructure prolongs dairy cow longevity in Sweden. The investment in farm buildings creates room for new or superior recruitment heifers, without the need to cull already existing dairy cows. This means that the culling decision is indeed a strategic decision related to investment choices made at the farms. Second, in Swedish dairy herds, there is no association between proportion of unhealthy cows in the herd reflected as the proportion receiving veterinary treatment and the average length of productive life of the cows. Animal health, on average, does not have a significant effect on the longevity of a dairy herd in Sweden, and culling is predominantly done for other reasons than poor health. In addition, production variables that were associated with higher dairy herd longevity include higher milk yield and long calving interval. Prolonged age at first calving reduces the longevity of the herd. The findings further show that the productive lifespan of dairy herds in Sweden started increasing significantly from 2015 to the present day.

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Appendix Table A1. Effects of animal health, investment, farm-specific, and animal management on age at culling; dependent variable is total lifespan[1]

Variable	Coefficient	R. SE	*t*-statistic	*P*-value
Health	−0.07	0.30	−0.25	0.78
Investment	38.63**	16.05	2.41	0.02
Production indicator				
Milk yield (kg ECM)	0.02***	0.00	4.73	0.00
Calving interval (mo)	37.29***	5.75	6.49	0.00
Age at first calving (mo)	0.82***	0.07	11.01	0.00
BMSCC, ×1,000 cells/mL	0.28**	0.07	3.72	0.00
Herd size (no. of cows)	0.06	0.06	0.98	0.33
Production system (reference: conventional)				
Certified organic (KRAV)	−74.39	62.68	−1.19	0.24
Breed [reference: SR (SR ≥ 80%)]				
SH (SH ≥ 80%)	−21.79	16.05	−1.36	0.18
SR + SH ≥ 50%	−2.96	14.65	−0.20	0.84
Other_breed	5.93	20.88	0.28	0.78
Housing type (reference: freestall housing, noninsulated)				
Freestall housing, insulated	−7.57	15.77	−0.48	0.63
Tiestall	−44.73	57.68	−0.78	0.44
Milking system (reference: tiestall)				
AMS	−18.98	31.30	−0.61	0.54
Milking parlor	10.130	30.99	0.33	0.74
Rotary	69.54***	26.19	2.65	0.06
Production system and milking system				
Conven_tiestall milking	−13.14	43.14	−0.30	0.76
Conven_AMS	−8.94	29.45	−0.30	0.76
Conven_parlor	−32.65	51.94	−0.63	0.53
Organic_tiestall milking	35.59	64.40	0.55	0.58
Organic_parlor	82.66	58.71	1.41	0.16
Year effects (reference: 2009)				
2010	8.65	27.69	0.31	0.76
2011	12.41	27.07	0.46	0.65
2012	22.32	28.00	0.80	0.43
2013	16.83	26.70	0.63	0.53
2014	41.63	26.22	1.59	0.11
2015	72.384***	26.56	2.79	0.01
2016	73.76***	27.84	2.65	0.01
2017	67.52**	26.86	2.51	0.01
2018	85.87***	28.50	3.01	0.00
Constant	701.31***	130.20	5.39	0.00
Observation		2,188		
Adjusted R^2		0.24		
F-statistic		18.56***		

[1]R. SE = robust standard error; BMSCC = bulk milk somatic cell count; SR = Swedish Red; SH = Swedish Holstein.

*** and ** show significance at 1% and 5% levels respectively; dependent variable is age at culling.

APPENDIX

Appendix Table A2. Heterogeneous effects of animal health, investment and farm management variables on age at culling; dependent variable is total lifespan[1]

Variable	25th quantile	50th quantile	75th quantile	95th quantile
Health	−0.74*** (0.32)	−0.15 (0.30)	−0.01 (0.39)	0.056 (1.10)
Investment	11.41 (20.52)	9.91 (18.56)	44.51** (22.10)	88.19 (68.56)
Control variable				
Production indicator				
Milk yield (kg ECM)	0.02** (0.00)	0.01*** (0.00)	0.03*** (0.01)	0.06*** (0.02)
Calving interval (mo)	30.38*** (5.57)	33.14*** (5.04)	46.98*** (6.54)	31.28* (17.67)
Age at first calving (mo)	0.84*** (0.067)	0.96*** (0.06)	1.01*** (0.08)	1.014*** (0.22)
BMSCC (×1,000 cells/mL)	0.30*** (0.07)	0.26*** (0.07)	0.11 (0.09)	−0.12 (0.25)
Herd size (no. of cows)	0.29*** (0.08)	0.04 (0.08)	0.07 (0.11)	−0.03 (0.31)
Production system (reference: conventional)				
Certified organic (KRAV)	−56.83 (78.55)	−75.28 (71.07)	−42.78 (92.26)	169.69 (262.51)
Breed [reference: SR (SR ≥ 80%)]				
SH (SH ≥ 80%)	−15.59 (18.43)	−28.60** (14.68)	−47.18** (21.65)	23.01 (61.59)
SR+SH ≥ 50%	7.46 (15.88)	−5.85 (14.37)	−14.85 (18.65)	58.67 (53.08)
Other_breed	2.18 (20.80)	−17.25 (18.81)	17.44 (24.42)	48.73 (69.49)
Housing type (reference: freestall housing, noninsulated)				
Loose housing, insulated	17.04 (21.48)	−37.76** (17.44)	−3.507 (25.230)	17.64 (71.79)
Tiestall	3.00 (71.22)	−33.66 (64.43)	8.272 (83.643)	74.83 (38.99)
Milking system (reference: tiestall)				
AMS	10.01 (61.76)	−37.92 (55.88)	56.68 (72.54)	101.06 (206.39)
Milking parlor	44.35 (61.16)	13.69 (55.33)	80.53 (71.83)	117.07 (204.37)
Rotary	81.66 (67.73)	27.42 (61.28)	121.955 (79.55)	343.80 (226.34)
Production system and milking system				
Conven_tiestall milking	−15.19 (52.62)	10.73 (47.60)	22.88 (61.80)	41.88 (75.83)
Conven_AMS	18.98 (40.02)	18.00 (36.21)	−31.23 (47.00)	−9.39 (13.73)
Conven_parlor	−28.80 (68.63)	−35.26 (62.09)	22.09 (80.60)	73.66 (39.33)
Organic_tiestall milking	−0.87 (5.90)	21.95 (68.67)	10.15 (89.14)	−162.98 (253.64)
Organic_parlor	81.05 (73.46)	93.19 (66.46)	47.26 (86.27)	−126.53 (245.48)
Year effects (reference: 2009)				
2010	25.71 (32.73)	−16.35 (29.62)	−34.02 (38.44)	67.32 (49.39)
2011	10.28 (31.95)	−6.07 (8.91)	2.51 (3.53)	33.12 (26.78)
2012	3.65 (3.01)	2.78 (2.06)	1.051 (3.42)	98.89 (103.63)
2013	18.22 (30.39)	0.14 (2.49)	−12.47 (35.70)	47.59 (31.57)
2014	38.30 (30.06)	21.26 (27.19)	30.53 (35.30)	64.64 (40.44)
2015	48.87** (28.36)	50.24** (23.46)	52.46 (35.65)	141.95 (101.45)
2016	55.54** (28.35)	49.42** (24.46)	44.35 (35.65)	127.91 (101.43)
2017	34.78*** (10.8)	71.81*** (27.88)	40.11 (36.20)	144.92 (102.99)
2018	56.037** (28.89)	77.01*** (27.94)	68.798** (31.27)	109.99 (103.21)
Constant	543.79*** (143.36)	689.88*** (129.68)	565.32*** (168.35)	1,071.29** (478.97)
Observation	2,188	2,188	2,188	2,188
Pseudo R^2	0.27	0.38	0.16	0.22

[1]BMSCC = bulk milk somatic cell count; SR = Swedish Red; SH = Swedish Holstein.

***, **, * show significance at 1%, 5%, and 10% levels, respectively. Values in parentheses are standard errors.