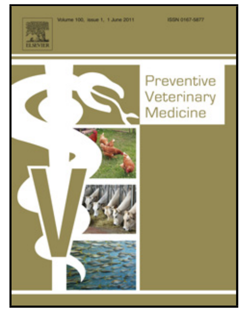
Accepted Manuscript



Title: Sow removal in commercial herds—Patterns and animal level factors in Finland

Authors: Paula Bergman, Yrj*ö* Tapio Gr*ö*hn, Päivi Rajala-Schultz, Anna-Maija Virtala, Claudio Oliviero, Olli Peltoniemi, Mari Heinonen

PII:	S0167-5877(17)30874-7
DOI:	https://doi.org/10.1016/j.prevetmed.2018.08.010
Reference:	PREVET 4518
To appear in:	*PREVET*
Received date:	8-1-2018
Revised date:	24-8-2018
Accepted date:	24-8-2018

Please cite this article as: Bergman P, Gr*ö*hn YT, Rajala-Schultz P, Virtala A-Maija, Oliviero C, Peltoniemi O, Heinonen M, Sow removal in commercial herds—Patterns and animal level factors in Finland, *Preventive Veterinary Medicine* (2018), https://doi.org/10.1016/j.prevetmed.2018.08.010

Sow removal in commercial herds – patterns and animal level factors in Finland

Paula Bergman*[a], Yrjö Tapio Gröhn[b], Päivi Rajala-Schultz [c], Anna-Maija Virtala[d], Claudio Oliviero[c], Olli Peltoniemi[c], Mari Heinonen[c]

[a]University of Helsinki, Faculty of Veterinary Medicine, Department of Production Animal Medicine,

P.O. Box 57, 00014 University of Helsinki, Finland

[b]Cornell University, College of Veterinary Medicine, Department of Population Medicine and Diagnostic Sciences, Section of Epidemiology, Ithaca, NY 14853

[c]University of Helsinki, Faculty of Veterinary Medicine, Department of Production Animal Medicine, Paroninkuja 20, 04920 Saarentaus, Finland

[d]University of Helsinki, Faculty of Veterinary Medicine, Department of Veterinary Biosciences, P.O. Box 66, 00014 University of Helsinki, Finland

*corresponding author

Paula Bergman

University of Helsinki, Faculty of Veterinary Medicine, Department of Production Animal Medicine,

P.O. Box 57, 00014 University of Helsinki, Finland

+358451133045

e-mail addresses: paula.bergman@helsinki.fi, ytg1@cornell.edu, paivi.rajala-schultz@helsinki.fi, anna-maija.virtala@helsinki.fi, claudio.oliviero@helsinki.fi, olli.peltoniemi@helsinki.fi, mari.heinonen@helsinki.fi

Highlights

- Description of recent sow productivity, removal patterns and factors affecting it
- Average sow productivity exceeded natural nursing abilities
- Removal patterns in the early parity cycles may reflect vague culling policies
- Early life performance affected removal especially in younger animals
- The protective effect of large litters increased with age

Sow removal

Abstract

This observational retrospective cohort study provides benchmarking information on recent sow productivity development in Finnish herds. It focuses on parity cycle specific trends in sow removal patterns, and especially on the role of litter performance (size and piglet survival) in sow removal. In addition, the generated models offer a tool for calculating sow removal risks in any period, which could be used in economic and other simulation models. The data used in the study pool information of sows starting the same parity cycle (1 through 8) over the enrollment period of July 1st, 2013 through June 30th, 2014 and followed until the end of the study period (December 31st, 2014), and their performance histories across their entire previous productive life. Out of 71,512 individual sow parity cycle observations from the first to the eighth, 15,128 ended up in removal. Average litter sizes exceeded 13 piglets born in total in all of the most recent farrowings. Yet, even larger litter sizes were favored by the implemented culling policies, as sows having medium and large early life litters had lower risks of removal compared to those with the smallest litters, particularly in younger animals. With regard to piglets born just prior to removal, the smallest litter sizes were associated with the greatest culling risk for sows of that particular parity. In addition, having more than one stillborn piglet in the first and second litter put the sow at higher risk of being removed in all but the last (sixth through eighth) of the studied parity cycles. Investigation of removal patterns revealed a negative linear relationship between parity count and the mean days from farrowing to removal. More specifically, the median (mean) times to removal varied across the parity cycles from 62 (72) in the first to 34 days in both the seventh and eighth (47 and 42, respectively). Moreover, one in every six sows was removed within the first and second parity cycle. The findings especially in the earliest cycles may be a reflection of removal decisions not made according to any clear and pre-determined policy, or of biological issues that prevent farmers from firmly adhering to their policy. Quantitative performance should be linked to overall system functionality and profitability while taking animal welfare into consideration in identifying opportunities to improve herd parity structure and future farm success.

Keywords: sow; performance; removal pattern; culling risk

Introduction

In piglet production, replacing sows is a major cost of operation and one of the most important management decisions for a producer to make as it is interrelated with numerous other factors that ultimately impact the system cost-efficiency (Dhuyvetter, 2000). Traditionally, culling has been referred to as either voluntary (removal for economic reasons) or involuntary (biological or forced reasons that are beyond the farmer’s control) (Fetrow et al., 2006). From an economic point of view, a particular sow should be kept in the herd as long as her expected profit for the next parity is higher than the per parity lifetime average return from a replacement gilt (Huirne et al., 1988; Dijkhuizen et al., 1989). Stalder et al. (2003) and Sasaki et al. (2012)

suggested that a sow needs to produce three litters to reach a positive net present value, whereas it has also been estimated that for profitable overall herd performance sows should be culled within parity cycles five through nine (Gruhot et al., 2017a) or be kept up to the eighth or ninth parity (Dhuyvetter, 2000). In contrast to financial perspectives, society's growing awareness of production animal welfare has drawn attention to reduced longevity and forced culls as they raise concern about animal well-being and sustainability.

An optimal herd profile is determined by numerous interacting factors, which can potentially vary over time (Dhuyvetter, 2000; Zimmerman, 2012a; Gruhot et al., 2017b). The overall herd culling rate is an accumulation of culling rates of all parities, which determine the herd parity distribution (Houška, 2009). Both the quantity and the quality of piglets produced per year are influenced by the parity distribution. With increasing culling rates the percentage of mated gilts inevitably increases, resulting in a larger proportion of gilt progeny of inferior performance and survivability (Klobasa et al., 1986; Hinkle, 2012; Mabry, 2016). The overall financial efficiency in pig herds decreases with increasing culling rates; as the average sow lifespan decreases, the number of piglets weaned per sow per year drops and the share of a sow in the cost per piglet increases (Lucia et al., 1999).

At herd level sow removal depends on a variety of biological and environmental factors. Different characteristics of sows, such as productivity, age at first farrowing, and stage within productive life, as well as living conditions and management practices within the farms, impact longevity (Le Cozler et al., 1998; Serenius and Stalder, 2007; Hoge and Bates, 2011; Sasaki et al., 2011; Iida and Koketsu, 2015; Engblom et al., 2016; Magnabosco et al., 2016).

Comparison between sow longevity studies is problematic due to differences in the time periods of interest, study populations, and statistical analyses used. Selection for hyperprolific sows is ongoing with a simultaneous change towards larger and more intensively managed units. However, at some point it will be uneconomical and unethical to expect sows to continue performing based on predominantly quantitative key production indicators. The main objective of this study was to scrutinize recent sow productivity and removal patterns by dam parity using lifetime records of animals in production from July 1st, 2013 to December 31st, 2014 in Finland. An additional objective was to calculate actual sow removal risks for further use as input values in economic and other simulation models.

Materials and Methods

Herds

The present study was a part of a larger project, where Finnish sow longevity was investigated in commercial herds (Niemi et al., 2017; Heinonen et al., 2018; Norring et al., 2018). Out of the 220 piglet producing farms of two major slaughterhouses in Finland a total of 46 farmers permitted the use of their farm data on breeding, productivity and longevity both at the animal and herd level for the project. After an extensive publicity campaign and being contacted in person, an additional 44 agreed to participate. The only inclusion criterion, in addition to the willingness of the farm manager to participate, was the use of WinPig herd management monitoring software (©2013 AgroSoft, Hietamaki, Finland). Based on the standardized performance summary statistics of WinPig from the participating farms the average herd size in 2014 was 342 sows (median 124, range 26-2726).

Data

Sow removal

Individual herd data files were exported as csv-files from WinPig.Net Agrosoft® and imported into the open source statistical software R-studio (Team, 2016). Records across the entire productive life of females in production between 1 July, 2013 and 31 December, 2014 (study period) were extracted. In principle, complete information for each animal included birth information, breeding, farrowing and weaning events and removal data, but there was marked variation between farms in the number of stored values. Generally, no recordings were registered on estrual events or pregnancy status, nor were reliable records on breed available.

Crude data quality checks were done for each herd dataset separately, which were thereafter merged to yield a dataset with 65,313 females. In total, 9,559 animals (14.7%) had not farrowed for the first time so they were excluded. Likewise, 1,601 sows (2.9%) with incomplete parity cycle records were excluded from the study. Also, 2,005 (3.6%) sows were excluded because of likely errors in dates of birth and first parturition (i.e. age at first farrowing less than 276 days or more than 555 days). Moreover, 92 (0.2%) records of sows were excluded if the total number of piglets born in a litter exceeded 26. The quality of the final dataset of 52,056 sows was assessed through preliminary descriptive analyses of the variables.

Cohort definition

Basically, we used the term parity to describe a sow by the number of completed farrowings as extrapolated to veterinary medicine from the Oxford medical dictionary (9th edition). In this study, our additional aim was to describe inter-parity removal characteristics. Thus, we supplemented the term parity with the term cycle (i.e. parity cycle) to refer both to the functional cyclicity of a sow's productive life, and to the number of days that pass after farrowing.

In order to document parity cycle specific productivity and the most recent patterns of removal, we included the maximum feasible number of parity cycles. Therefore, each cycle that had a record of a farrowing event between 1st July, 2013 and 30th June, 2014 (enrollment period) was included in the data set. To yield comparable follow up times, they were thereafter followed until 31st December, 2014 (end of the study period). To further differentiate the cycles, enable comparison between them and understand dynamics of sow removal according to parity number, cohorts 1 through 8 were formed based on the number of farrowings as opposed to age cohorts: All members of a parity number cohort shared a significant experience, namely started the same parity cycle, over the same period of time (Figure 1). Therefore, they all became at risk of progressing to their next farrowing, and subsequent parity cycle or removal, at the same point in time and production stage. For example, sows in cohort 5 all began their fifth parity cycle during the enrollment period, and if not removed, some of these sows also went on to start a further, the sixth, parity cycle (inclusion criteria for cohort 6).

After the actual start, i.e. farrowing, onwards cohort members were followed over time until the end date: a) the subsequent parturition, b) 180 days postpartum or c) removal, whichever occurred first. The choice of 180 day follow up was selected based on the observed data cycle length (95 percent quantile = 180 days). Baseline data on the relevant early life characteristics hypothesized to have effects on the individuals throughout their life course, i.e. considered as primary risk factors in our statistical analyses, were collected from existing records across the entire previous performance, linked with cohort follow up and outcome of interest, removal, and pooled together. In total, 17,379 eligible first farrowings, 13,605 second, 11,547 third, 9,783 fourth, 7,637 fifth, 5,700 sixth, 3,795 seventh, and 2,066 eighth farrowings occurred during the enrollment period. Furthermore, 1,467 of 9th or higher farrowings were omitted from the analysis due to low

numbers of records. Altogether, 71,512 parity cycles were included. The distribution of the cohorts is illustrated in Figure 2.

Further, to be able to take the time postpartum into account, the follow up time for each cohort member was divided into time intervals. The onset was set at farrowing (day 0) and the length of each interval was in total 20 (1-20 days). The removal indicator equaled 1 if the sow experienced the event (i.e. was removed from the herd) within the given time interval and 0 otherwise. The length of the period was chosen based on the phases of a sow parity cycle and to ensure convergence of statistical models.

Risk factor categories

Continuous performance measures were categorized using fixed percentiles or cut-points with clinical meaning. The numbers of animals in each of the generated categories with their definitions are shown in supplementary material (SM) Table T2. Of particular interest was to estimate the risk of removal based on early sow productive life, i.e. the first and second parturition, characteristics. Litter size was categorized into three categories using approximately 20th and 80th percentiles of the number of piglets born alive in the first, second and the most recent litter, namely the cohort specific one. Piglets born dead were grouped into three categories: none, one, or more than one stillborn piglet. The season of the first farrowing was categorized as winter (from October to March) and summer (from April to September), approximately according to the vernal and autumnal equinoxes. Four age categories were built on the basis of the quartiles of the first farrowing ages: 352 days old or younger, 353 to 369 days old, 370 to 386 days old and 387 days or older. In addition, lactation lengths of the first and second parity cycle were categorized as less than three weeks, 3-4 weeks and longer than four weeks.

Statistical Analyses

The cohort specific removal probability was presented as the percentage chance, *Prem,* for a sow being culled within a cohort *i* and calculated as follows:

$$Prem_i = \frac{n_i}{N_i} \times 100 \quad (1),$$

where *n* is the number of removed sows within the cohort and *N* is the total number of sows at the start in that cohort.

Crude removal risk, *R*, for a sow with a grouping characteristics c_k, within a cohort *i*, was calculated as follows:

$$R_{i,c_k} = \frac{n_{i,c_k}}{N_{i,c_k}} \quad (2),$$

where *n* is the number of removed sows within that cohort and *N* is the total number of sows at the start in that cohort. The proportion test (prop.test) was carried out to test the equality of proportions between the groups (Crawley, 2005). The study had a power of 80% (P=0.05) to detect a removal risk ratio ranging from 1.12 (cohort 7 and 8) to 1.16 (cohort 2) or greater between the subgroup of sows with a small first litter and that with a medium sized one. For the second litter sizes the lowest detectable levels ranged from 1.13 (cohorts 7 and 8) to 1.17 (cohorts 2, 4, 5 and 6) (epiR, Stevenson et al., 2018).

Poisson regression is generally used in the modeling of count data (Crawley, 2005). Its extension with a piecewise exponential model serves as an alternative approach to modeling survival data (Schukken et al.,

2010; Ospina et al., 2012; Elghafghuf et al., 2014). A more detailed description about model building and considerations is available in the SM.

The generalized linear mixed model procedure from the package lme4 (Bates et al., 2015) was used to provide a numerical estimate of the effects of sow performance factors on the risk of being removed across eight parity cycles. The form of the generalized linear model was

$$Ln\ (\mu) = \mathbf{X\beta} + \mathbf{Z\gamma}, \quad (3)$$

where μ is the expected probability that a removal event occurs in a given 20-d period of the parity cycle (given the sow survived through the previous one), β is the vector of regression coefficients corresponding to a fixed-effects matrix X, and γ is an unknown vector of random-effect parameters with matrix of herd indicators Z. A positive parameter value implies an increased risk of removal whereas a value below zero implies a decreased risk, i.e., the characteristics being protective relative to the baseline.

Non-statistical considerations formed the basis for risk factor selection and retention criteria; the full model was built based on theoretical and practical knowledge, data availability and the factor´s significance in prior studies (Dohoo et al., 2009). The primary risk factors of interest, piglets born alive and dead in the first and second farrowing, and season and age at first farrowing were included in the models as fixed effects. The 20-day time period in parity cycle and additional risk factors, namely piglets born alive in the most recent, i.e. the cohort specific litter, and lactation length in the first and second parity cycles, were also included simultaneously in the models. First, a model for cohort 1 members, and thereafter corresponding models with relevant additional risk factors for every cohort (2- 8), were built separately. The number of risk factors had to be restricted and interaction terms excluded to maintain a feasible level of complexity with regard to model convergence. No specific offset was used in the models because the periods at risk were of the same length. Herd was included in the final models as a random effect.

The models were selected based on whether convergence could be attained, and further judged by looking at the Akaike's information criterion, and residual deviance/degrees of freedom.

Because such a short period was used as the unit of analysis, the distinction between risk and rate diminishes, so risk will be used throughout this paper. The generated models offer a tool for calculating the actual sow removal risks in any given period, and can generate estimates for any combination of characteristics of interest for further use in economic and other simulation models. For example, the risk of removing a sow during her third parity cycle, 35 days after farrowing (period 2), having farrowed at the age of 365 days for the first time in June and produced 13 piglets alive and zero stillborns in her first, 15 alive and 1 stillborn in her second and 14 piglets alive in her third litter and having nursed for an average time of 27 days both in the first and the second cycle, can be calculated by taking the exponential of the summation of the intercept and the parameter estimates of interest by the columns of the cohort 3 model (SM T4).

Results and discussion

General remarks

Our data provide an empirical base to inform debates of future piglet production system development. We show that the average litter sizes already routinely exceed what has been suggested to be the natural ability of individual sows to successfully rear the numbers born alive even when taking a certain amount of inevitable mortality into account (Andersen et al., 2011). Our results indicate that early life

performance of a sow predicts the length of her productive life, especially in younger animals. At the same time a considerable wastage of sows in early parity cycles with delayed removal decisions is confirmed.

Descriptive statistics of performance

The numbers of piglets born in total in each parity cycle and for each cohort separately are illustrated in Figure 3 (for a more detailed summary see SM T1). The litter sizes of the cohort members spanning their entire performance history until the cohort specific farrowing contributed to their group means. The summary can therefore be interpreted as a snapshot of productivity development both across recent time and across the productive life of sows in Finnish piglet production.

Litter sizes increased steadily up to the fourth litter and then slowly started to decline. The average first litter size increased by 0.8 piglets across the studied eight cohorts, i.e. approximately three and a half years as the cohort 8 members were starting their productive lives at that time. The litter sizes already exceeded 15 in the third farrowing apart from the most historical, i.e. cohort 8 farrowings, and considerable differences in productivity existed. Voluntary culling of sows prior to their fourth farrowing and replacing them with young animals of both poorer performance and lower reproductive fitness limits the productivity of the system (Hinkle, 2012; Engblom et al., 2016; Mabry, 2016). It is evident that by maintaining a herd age structure that retains mature sows allows individuals to reach peak performance.

The ongoing trend of increasing sow fertility is associated with weakened growth and development of embryos (Rekiel et al., 2014). Furthermore, within-litter variation in birth weights has been shown to be positively correlated with litter size and losses at birth with birth weight (Wolf et al. 2008). It is also worth keeping in mind that only a few western-breed sows have 14 to 16 well-positioned functional teats of suitable conformation, and breeding for greater teat numbers can have practical complications (Clayton et al., 1981; Baxter et al., 2013; Rutherford et al., 2013). From 1992 to 2012, the mean total number of teats increased from 14.4 to 14.6 in the Swedish Yorkshire pig (Chalkias et al., 2014). However, small and vulnerable piglets in larger litters would require special care and attention (Calderón Díaz et al., 2017), and for female piglets surviving longer, low birth weights have been shown to adversely affect both their productivity and longevity later on (Magnabosco et al., 2016). In concordance, Mabry (2016) recently indicated that birth weight equal to or above 1.4 kg should be set as a goal as it determines a piglet’s future performance and profit. Thus, selection on litter size should be actively accompanied by selection on birth-weight and mortality traits. Finally, Andersen et al. (2011) suggested based on their behavioral study that with regard to sibling competition, piglet survival and development, 10 to 11 piglets likely reflect the upper limit that the domestic sow is capable of properly caring for.

Thus, the observed litter sizes even with the losses due to unpreventable peripartum and preweaning mortality as well as litter size variation between parities, create an everyday challenge especially with regard to lactation management including nursing and fostering techniques (Baxter et al., 2013). Lund et al. (2002) stated that mothering abilities are seriously deteriorated by selecting on the number of born in total alone, and that not even cross-fostering is enough to maintain reasonable survival rates. Even without emphasizing sow selection based on sow productivity, the genetic refinement towards hyperprolific sows raises concerns for both piglets’ and nursing mothers’ wellbeing and farm economic efficiency (Rutherford et al., 2013).

Removal by cohorts

Sow removal

Of the cohort 1 sows, 16% [95% CI: 15.6; 16.7] failed to produce a second litter. Another 15% [14.3; 15.5] of sows were removed from cohort 2, and 17% [16.3; 17.6] of the cohort 3 sows did not farrow for the fourth time. Cohort specific percentage chances (%) for removal for cohorts 4- 8 were 19% [18.7; 20.3], 23% [22.0; 23.9], 29% [27.8; 30.1], 48% [46.1; 49.3] and 59% [56.8; 61.1], respectively.

The percentages of sows failing to have a second or third litter were in agreement with Andersson et al. (2016); even greater first parity removal percentages (exceeding 20%) have also been reported (Dagorn and Aumaitre, 1979; Dijkhuizen et al., 1989; Plà et al., 2003; Niemi et al., 2017). In addition to the net present value perspective, it has also been stated that a sow needs to produce three litters to recover her investment costs (Stalder et al., 2003; Sasaki et al., 2012). Applied to the present study, this suggests that less than 60% of the initiating gilt inventory are responsible for farms' profits. To maintain an ideal parity structure of a commercial herd, producers should aim to lose no more than 10% of the females per parity cycle (Mote et al., 2009), even though different aspects have also been introduced (Houška 2009). Better longevity and retaining sows as long as into their ninth farrowing increase the financial returns of piglet producing herds (Gruhot et al., 2017a).

Removal risks based on sow production performance

Litter size

The impacts of early life characteristics were first studied as crude risks of removal by the first and second litter size, season and age at first farrowing. The proportion test was used to determine whether the differences between two proportions were significant. Results with notations of significance are illustrated in SM F1-4. The understanding was further extended using a multivariable Poisson modelling approach, accounting for the effects of other risk factors and the herd. For ease of presentation, estimates for the explanatory variables and the different 20-d periods in the cycles are shown separately in Tables 1 and 2 for cohorts 1 and 8 (for other cohorts see SM T3-T8); all risk factors in both tables were included in the same models.

Crude removal risks for cohort 1 and 2 sows having had a small first litter were significantly greater than they were for sows with a medium or large first litter. In concordance, the model estimates (Table 1 for cohorts 1 and 8, SM T3-T8 for others) indicated that cohort 1 and 2 sows with a history of a medium or large first litter had a statistically significant survival advantage compared to the baseline (small litter size).

The impact of second litter size on crude removal risks was greater than that of the first litter size (SM F2). Sows within all but cohorts 7 and 8 having produced a small second litter were significantly more likely to be removed than sows with medium or large litters. Further, the model estimates indicated that both the medium-sized first and second litters had protective effects on removal for the members within the second and subsequent two cohorts. However, the largest effect was for cohort 2 members having produced 17 piglets or more: a sow with as high a productivity level as that was 0.58 [0.5; 0.68] times less likely to be removed than was a sow having farrowed a litter of 10 piglets or less (SM T3).

Our findings suggest that medium and large early-life litters significantly decrease the risk of removal compared to the smallest litters. They are consistent with others that have reported a positive association between early life productivity and measures of longevity and lifetime performance, either directly or indirectly. However, this relationship seems to be population dependent, as in Japanese and South European herds young sows with large litter sizes seem to have the best potential (Iida and Koketsu, 2015; Iida et al.,

2015), but in Sweden medium-sized first and second litters have been the most advantageous (Andersson et al., 2016). Breed or management differences between countries may account for these contrasting findings.

Furthermore, the model estimates showed that the size of the litter produced within the most recent, i.e. cohort specific farrowing, has a strong effect on the probability of being removed within each cohort (Table 1 for cohorts 1 and 8, SM T3-T8 for others). This was seen particularly for the largest litter sizes as they decreased the risk even more than the medium sized litters did compared to the small litter sizes. The greatest effect appeared among the cohort 5 members: a sow with a large fifth litter was 0.37 [0.31; 0.43] times less likely to be removed in that parity cycle than a sow with a small fifth litter (SM T6). Accordingly, Engblom et al. (2008) and Yazdi et al. (2000) reported an increased removal hazard for sows farrowing small litters. The greater protective effect of the largest litters was seen especially in the cohort 5-7 sows indicating that it is less tolerable for sows in higher order parities to perform below the average. Most of the planned removal attributable to low productivity occurs in higher parities (Dijkhuizen et al., 1989; Lucia Jr et al., 2000; Engblom et al., 2007; Mote et al., 2009).

Moreover, the number of stillborn piglets was clearly associated with removal risk in several cohorts. Two or more dead piglets in the first farrowing made a cohort 1 sow 1.50 [1.37; 1.64] times more likely to be removed than a sow with solely viable piglets (Table 1). A similar effect was observed for stillborn piglets in the second litter (SM T3).

Season and age at first farrowing

Seasonal crude risks implied a slight survival advantage for cohort 1 sows starting their productive lives from October to March, but the opposite was seen for cohort 4 sows (SM F3). As a whole, no clearly interpretable overall pattern of a seasonal effect on the risk of removal with respect to first farrowing was seen in our data or in the Swedish population (Andersson et al., 2016).

Age at first farrowing affected removal. Sows within cohorts 1-3 farrowing for the first time at older ages had a higher risk of removal (SM F4). The models illustrated the same phenomena in the lower order cohorts. The greatest effect was within cohort 2, where an old first parturient was 1.43 [1.24; 1.66] times more likely to be removed than a sow having had her first litter at a young age (SM T3). The model estimates did not show any clear differences between the age groups in the higher four of the studied cohorts.

These findings are in agreement with those of several authors who have stated that associations with younger ages at first farrowing and longer lifespan exist (Serenius and Stalder, 2007; Hoge and Bates, 2011). Gilts reaching puberty at an earlier age, and thereafter being mated at a younger age, had improved performance or longevity in the studies of Yazdi et al. (2000) and Engblom et al. (2008) as well. In the survival analysis for reproductive failures, older age at first farrowing increased the removal hazard considerably (Engblom et al., 2008).

Removal patterns within parity cycles

Parity cycle specific removal patterns during the 180 days after farrowing are presented in Figure 4. From 71,512 initiated cohort follow ups from 1 to 8, in total 15,128 ended up in removal. With a higher order cohort number the mean time to removal shortened. The median (mean, [95% CI)) time from farrowing to exit was 41 days (62, [61; 63]), but varied across cohorts from 62 (74, [72; 76]) in the first to 34 in both the seventh and eighth (47, [45; 49] and 42, [40; 44], respectively).

Sow removal

Within three days after every farrowing, an average of 2.8% [2.5; 3.1] of the removed sows exited the herds, the proportion varying from 1.3 [0.9; 2.0] to 5.3% [4.3; 6.6] within different cohorts. This phenomenon most likely reflects the increased disease incidence at farrowing and is in agreement with the higher risk of mortality reported around the peripartum period (Engblom et al., 2008).

Yet, the pattern of overall removal emerging from these data is slightly unexpected, since a marked proportion of the removed sows were removed already during the first 28 days after farrowing, which is the normal and legislated nursing period in Finland. In total 3,732 animals were removed ((3,732/15,128) *100=24.7% [24.0; 25.4]) within the first four weeks after farrowing, varying from 21.5 [20.0; 23.0] to 29.2% [27.0; 31.4] within different cohorts. Altogether 4,157 (27.5% [26.7; 28.2]) of all removals took place from days 28 to 42 postpartum, with a steady increase from 15.3% [14.0; 16.6] within cohort 1 to 45.1% [42.3; 48.0] within cohort 8. A considerable number of removals, 1,203 (8.0% [7.5; 8.4]), still occurred from days 56 to 70 in all of the cohort follow ups; for the cohort 1 sows the proportion exceeded 10% (10.5 [9.4; 11.8]). Even later than 70 days after farrowing some sows exited their herds in all cohorts, in which period removals attributable to reproductive disorders have been shown to take place (Engblom et al., 2008). Sows bred but not pregnant are finally removed from the herd as they never farrow even after a long interval has passed since the last farrowing.

The shorter median time (34 days) from farrowing to removal for the cohort 7 and 8 sows is likely a reflection of conscious and determined decision-making around or shortly after weaning, whereas the 62 days for the cohort 1 sows is not. Removals of all but the cohort 1 sows seem to concentrate around day 30 postpartum (Figure 4). Engblom et al. (2008) also showed that the risk of being removed was greatest after weaning compared to other times in the cycle. The cohort 1 information likely partly mirrors the prevalence of reproductive issues ranging from e.g. poor gilt overall management, detection of heat and returns both in gilts and after the first weaning and impairments in mating strategies, and the association between long weaning-to-removal intervals caused by the difficulty in diagnosing and controlling them (Dijkhuizen et al., 1989; Lucia Jr et al., 2000; Engblom et al., 2007). In addition, culls for locomotion problems have tended to be more common for low-parity females (Dijkhuizen et al., 1989; Lucia Jr et al., 2000; Engblom et al., 2007), but despite their painful nature are generally not easy to recognize early (Zimmerman, 2012b).

Data and model considerations

In the present study some advantages and disadvantages arose as a result of how the materials and methodology were chosen, which should be taken into account when interpreting the results.

Data

The data used in this observational retrospective cohort study were generated by individual farm personnel for their own purposes and this naturally affected the consistency of the recordings between herds. On the other hand, using secondary data like these, a representative number of sow observations originating from herds differing in size, management and housing could be collected across the country, and results therefore represent the field conditions. Herd recording data should be valued as a good resource by both farmers and researchers.

Model

Sow removal

Generalized linear mixed models with a Poisson error distribution using periodically split data are appropriate for estimating the risk of an event. However, the sizes of the datasets increase dramatically with the dichotomous approach. Models converged only by keeping the number of risk factors limited. Furthermore, underdispersion occurred, which refers to occurrence of less variance in the data than predicted by a statistical model (Kokonendji, 2014; Sellers and Morris, 2017). Even with the limitations, the estimates in Poisson regression models are still consistent, albeit, inefficient. The approach is more conservative; in particular, statistical inference with regard to standard errors has to be made cautiously as they are biased upwards leading to the rejection of fewer null hypotheses (Ferrari and Comelli, 2016).

Conclusions

Early judgement and decision making are necessary for producers to plan removals of low parity sows, but removal of young sows should not impede the overall production of the herd. The number of piglets born alive is undeniably a key trait to detect prolific sows at an early stage as has been studied previously. However, increasing litter sizes pose challenges for sow and piglet well-being, and may jeopardize piglet growth, development and health. Furthermore, large litters are known to require special management interventions and skilled stockmanship. Moreover, unplanned or forced culling of young sows continues to be a worrying phenomenon in itself and should be further investigated and controlled for as it reduces the scope for objective culling. A sound culling policy across and within all parity cycles is an integral part of herd management and predetermined recommendations about replacing young animals due to low productivity should be implemented with caution. Otherwise, the early culling of sows hurts herd age structure, prevents individuals from reaching peak performance, reduces longevity and adversely affects the overall productivity.

Biological performance should be linked to overall system functionality and profitability while taking into consideration animal welfare in identifying opportunities to control herd parity structure, improve future farm success and maximize long term profits.

Funding

This work was supported by the Ministry of Agriculture and Forestry in Finland (Dnro 1807/312/2012). The project has received funding also from the Finnish Slaughterhouse Industry. The first author is also grateful for the financial support from the Emil Aaltonen Foundation.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements

Leena Seppä-Lassila is thanked for fruitful discussions. Dennis Haine is thanked for his inspiring attitude and helpful consultations. The authors are grateful to the swine producers and the slaughterhouses Atria and HKScan for their cooperation, and Agrosoft® personnel both in Denmark and in Finland for their technical assistance. Special thanks go to all developers of the open source statistical software R, RStudio and its packages which were used in this study.

References

Andersen, I.L., Naevdal, E., Boe, K.E., 2011. Maternal investment, sibling competition, and offspring survival with increasing litter size and parity in pigs (Sus scrofa). Behav. Ecol. Sociobiol. 65, 1159-1167.

Andersson, E., Frössling, J., Engblom, L., Algers, B., Gunnarsson, S., 2016. Impact of litter size on sow stayability in Swedish commercial piglet producing herds. Acta Vet. Scand. 58, 1-9.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using {lme4}. J. Stat. Softw. 67, 1-48.

Baxter, E.M., Rutherford, K.M.D., D'Eath, R.B., Arnott, G., Turner, S.P., Sandøe, P., 2013. The welfare implications of large litter size in the domestic pig II: management factors. Anim. Welf. 22, 219-238.

Calderón Díaz, J.A., Boyle, L.A., Diana, A., Leonard, F.C., Moriarty, J.P., McElroy, M.C., McGettrick, S., Kelliher, D., García Manzanilla, E., 2017. Early life indicators predict mortality, illness, reduced welfare and carcass characteristics in finisher pigs. Prev. Vet. Med. 146, 94-102.

Chalkias, H., Ekman, E., Lundeheim, N., Rydhmer, L., Jacobson, M., 2014. Inverted teats (Mammillae invertitae) in gilts—Effect on piglet survival and growth rate. J. Anim. Sci 92, 2587-2594.

Clayton, G., Powell, J., & Hiley, P., 1981. Inheritance of teat number and teat inversion in pigs. Anim. Sci. 33, 299-304.

Crawley, M., 2005. Statistics, an introduction using R. Wiley Chichester.

Dagorn, J., Aumaitre, A., 1979. Sow culling: Reasons for and effect on productivity. Livest. Prod. Sci. 6, 167-177.

Dhuyvetter, K., 2000. What does attrition cost and what is it worth to reduce? In, Retrieved from the University of Minnesota Digital Conservancy.

Dijkhuizen, A.A., Krabbenborg, R.M.M., Huirne, R.B.M., 1989. Sow replacement: A comparison of farmers' actual decisions and model recommendations. Livest. Prod. Sci. 23, 207-218.

Dohoo, I., Martin, S., Stryhn, H., 2009. Veterinary Epidemiologic Research. VER Inc Prince Edward Island, Canada: Charlottetown, 2009.

Elghafghuf, A., Stryhn, H., Waldner, C., 2014. A cross-classified and multiple membership Cox model applied to calf mortality data. Prev. Vet. Med. 115, 29-38.

Engblom, L., Calderon Diaz, J.A., Nikkila, M., Gray, K., Harms, P., Fix, J., Tsuruta, S., Mabry, J., Stalder, K., 2016. Genetic analysis of sow longevity and sow lifetime reproductive traits using censored data. J. Anim. Breed Genet., 138-144.

Engblom, L., Lundeheim, N., Dalin, A.-M., Andersson, K., 2007. Sow removal in Swedish commercial herds. Livest. Sci. 106, 76-86.

Engblom, L., Lundeheim, N., Strandberg, E., del P. Schneider, M., Dalin, A.-M., Andersson, K., 2008. Factors affecting length of productive life in Swedish commercial sows1. J. Anim. Sci. 86, 432-441.

Ferrari, A., Comelli, M., 2016. A comparison of methods for the analysis of binomial clustered outcomes in behavioral research. J. Neurosci. Methods 274, 131-140.

Fetrow, J., Nordlund, K.V., Norman, H.D., 2006. Invited Review: Culling: Nomenclature, Definitions, and Recommendations. J. Dairy Sci. 89, 1896-1905.

Gruhot, T., Calderon Diaz, J., J Baas, T., C Dhuyvetter, K., L Schulz, L., Stalder, K., 2017a. An economic analysis of sow retention in a United States breed-to-wean system. J. Swine Health Prod. 25, 238-246.

Gruhot, T.R., Calderón Díaz, J.A., Baas, T.J., Stalder, K.J., 2017b. Using first and second parity number born alive information to estimate later reproductive performance in sows. . Livest. Sci. 196, 22-27.

Heinonen M., Bergman P., Fredriksson-Ahomaa M., Virtala A-M., Munsterhjelm C., Valros A., Oliviero C., Peltoniemi O., Hälli O., 2018, Sow mortality is associated with meat inspection findings. Livest.Sci.208, 90-95.

Hinkle, E.E., 2012. The effect of dam parity on progeny growth performance, passive immunity, and gastrointestinal microbiota. PhD Thesis. Animal Science Department. University of Nebraska, Nebraska, Lincoln, NE.

Hoge, M.D., Bates, R.O., 2011. Developmental factors that influence sow longevity. J. Anim. Sci. 89, 1238-1245.

Houška, L., 2009. The relationship between culling rate, herd structure and production efficiency in a pig nucleus herd. Czech. J. Animal Sci. 54, 365-375.

Huirne, R.B.M., Hendriks, T.H.B., Dijkhuizen, A.A., Giesen, G.W.J., 1988. The economic optimisation of sow replacement decisions by stochastic dynamic programming. J. Agric. Econ. 39, 426-438.

Iida, R., Koketsu, Y., 2015. Number of pigs born alive in parity 1 sows associated with lifetime performance and removal hazard in high- or low-performing herds in Japan. Prev. Vet. Med. 121, 108-114.

Iida, R., Piñeiro, C., Koketsu, Y., 2015. High lifetime and reproductive performance of sows on southern European Union commercial farms can be predicted by high numbers of pigs born alive in parity one. J. Anim. Sci. 93, 2501-2508.

Klobasa, F., Butler, J.E., Werhahn, E., Habe, F., 1986. Maternal-neonatal immunoregulation in swine. II. Influence of multiparity on de novo immunoglobulin synthesis by piglets. Vet. Immunol. Immunopathol. 11, 149-159.

Kokonendji, C.C., 2014. Over-and Underdispersion Models. Methods and Applications of Statistics in Clinical Trials. John Wiley & Sons, Inc., 506-526.

Le Cozler, Y., Dagorn, J., Lindberg, J.E., Aumaître, A., Dourmad, J.Y., 1998. Effect of age at first farrowing and herd management on long-term productivity of sows. Livest. Prod. Sci. 53, 135-142.

Lucia Jr, T., Dial, G.D., Marsh, W.E., 2000. Lifetime reproductive performance in female pigs having distinct reasons for removal. Livest. Prod. Sci. 63, 213-222.

Lucia, T., Dial, G.D., Marsh, W.E., 1999. Estimation of lifetime productivity of female swine. J. Am. Vet. Med. Assoc. 214, 1056-1059.

Lund, M., Puonti, M., Rydhmer, L., & Jensen, J., 2002. Relationship between litter size and perinatal and pre-weaning survival in pigs. Animal Science, 74(2), 217-222. doi:10.1017/S1357729800052383

Mabry, J., 2016. How to Deal with Success in Genetic Improvement. In, 24th International Pig Veterinary Society Congress 8th European Symposium of Porcine Health Management, 64-72.

Magnabosco, D., Bernardi, M.L., Wentz, I., Cunha, E.C.P., Bortolozzo, F.P., 2016. Low birth weight affects lifetime productive performance and longevity of female swine. Livest. Sci. 184, 119-125.

Martin, E. (2015). (Ed.), Concise Medical Dictionary.: Oxford University Press.

Mote B., Mabry J., Stalder K., Rothschild M.F., 2009. Evaluation of current reasons for removal of sows from commercial farms. PAS 25, 1-7.

Niemi, J.K., Bergman, P., Ovaska, S., Sevón-Aimonen, M.-L., Heinonen, M., 2017. Modeling the costs of postpartum dysgalactia syndrome and locomotory disorders on sow productivity and replacement. Front. Vet. Sci. 4.

Norring M., Valros A., Bergman P., Marchant-Forde J., Heinonen M., 2018. Body condition, live weight and success in agonistic encounters in mixed parity groups of sows dring gestation. Anim. (in press).

Ospina, P.A., Nydam, D.V., DiCiccio, T.J., 2012. Technical note: The risk ratio, an alternative to the odds ratio for estimating the association between multiple risk factors and a dichotomous outcome. J.Dairy. Sci. 95, 2576-2584.

Plà, L.M., Pomar, C., Pomar, J., 2003. A Markov decision sow model representing the productive lifespan of herd sows. Agric. Syst. 76, 253-272.

Rekiel, A., Więcek, J., Batorska, M., Kulisiewicz, J., 2014. Effect of sow prolificacy and nutrition on preand postnatal growth of progeny – a review. Ann. Anim. Sci. 14, 3-15.

Rutherford, K.M.D., Baxter, E.M., D'Eath, R.B., Turner, S.P., Arnott, G., Roehe, R., Ask, B., Sandoe, P., Moustsen, V.A., Thorup, F., Edwards, S.A., Berg, P., Lawrence, A.B., 2013. The welfare implications of large litter size in the domestic pig I: biological factors. Anim. Welf. 22, 199-218.

Sasaki, Y., McTaggart, I., Koketsu, Y., 2012. Assessment of lifetime economic returns of sows by parity of culled sows in commercial breeding herds. J. Vet. Epidemiol. 16, 37-45.

Sasaki, Y., Saito, H., Shimomura, A., Koketsu, Y., 2011. Consecutive reproductive performance after parity 2 and lifetime performance in sows that had reduced pigs born alive from parity 1 to 2 in Japanese commercial herds. Livest. Sci. 139, 252-257.

Schukken, Y.H., Bar, D., Hertl, J., Gröhn, Y.T., 2010. Correlated time to event data: Modeling repeated clinical mastitis data from dairy cattle in New York State. Prev. Vet. Med. 97, 150-156.

Sellers, K.F., Morris, D.S., 2017. Underdispersion models: Models that are "under the radar". Commun. Stat. Theory Methods 46, 1-12.

Serenius, T., Stalder, K.J., 2007. Length of productive life of crossbred sows is affected by farm management, leg conformation, sow's own prolificacy, sow's origin parity and genetics. Animal 1, 745-750.

Stalder, K.J., Lacy, R.C., Cross, T.L., Conatser, G.E., 2003. Financial impact of average parity of culled females in a breed-to-wean swine operation using replacement gilt net present value analysis. J. Swine Health Prod. 11, 69-74.

Stevenson M, Nunes T, Heuer C, Marshall J, Sanchez J, Thornton R, Reiczigel J, Robison-Cox J, Sebastiani P, Solymos P, Yoshida K, Firestone S. , 2018. Tools for the analysis of epidemiological dataR package version 0.9-96 https://rdrr.io/cran/epiR/ 2018

Team, R., 2016. RStudio: Integrated Development Environment for R_. RStudio,Inc., Boston,MA.

Wolf J., Žáková E., Groeneveld E., 2008.Within-litter variation of birth weight in hyperprolific Czech Large White sows and its relation to litter size traits, stillborn piglets and losses until weaning. Livest. Sci. 115: 2-3, 195-205.

Yazdi, M.H., Rydhmer, L., Ringmar-Cederberg, E., Lundeheim, N., Johansson, K., 2000. Genetic study of longevity in Swedish Landrace sows. Livest. Prod. Sci. 63, 255-264.

Zimmerman, J.J., 2012a. Diseases of swine: Longevity in breeding animals. Wiley-Blackwell, 50-59.

Zimmerman, J.J., 2012b. Diseases of swine: Nervous and locomotor systems. Wiley-Blackwell, 294-328.

Figure 1

Schematic illustration of the data. PC*n* refers to parity cycle *n* (1 through 8). The grey sows (between the vertical dashed lines) demonstrate the parity cycles that commenced during the enrollment period (1st July, 2013 to 30th June, 2014). Cohort *n* refers to the group of sows starting the same parity cycle *n* (1 through 8) over this enrollment period. Cohorts were followed until the end of the study period (31st December, 2014). Baseline data on risk factors were collected from existing parity cycle records across the performance before enrollment period (sows in white), linked with cohort *n* follow up and outcome of interest, removal, and pooled together. The decreasing size of sows illustrates the population attrition after previous parity cycle.

Figure 2

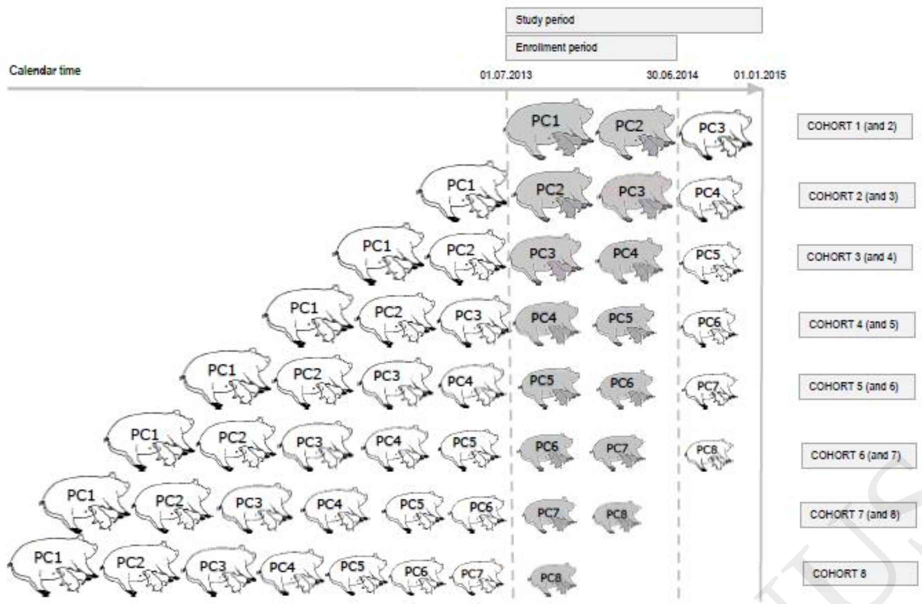
Percentage distribution of the study cohorts. Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) over the enrollment period of 1st July, 2013 through 30th June, 2014 and followed until the end of the study period (31st December, 2014).

Figure 3

Average litter sizes as piglets born in total by cohort as a function of the stage of productive life. Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) over the enrollment period of 1st July, 2013 through 30th June, 2014 and followed until the end of the study period (31st December, 2014), and stage of productive life is defined as the number of completed parity cycles before the start of the study period 1st July, 2013 and the first subsequent cycle thereafter. The horizontal dotted line represents the overall average litter size.

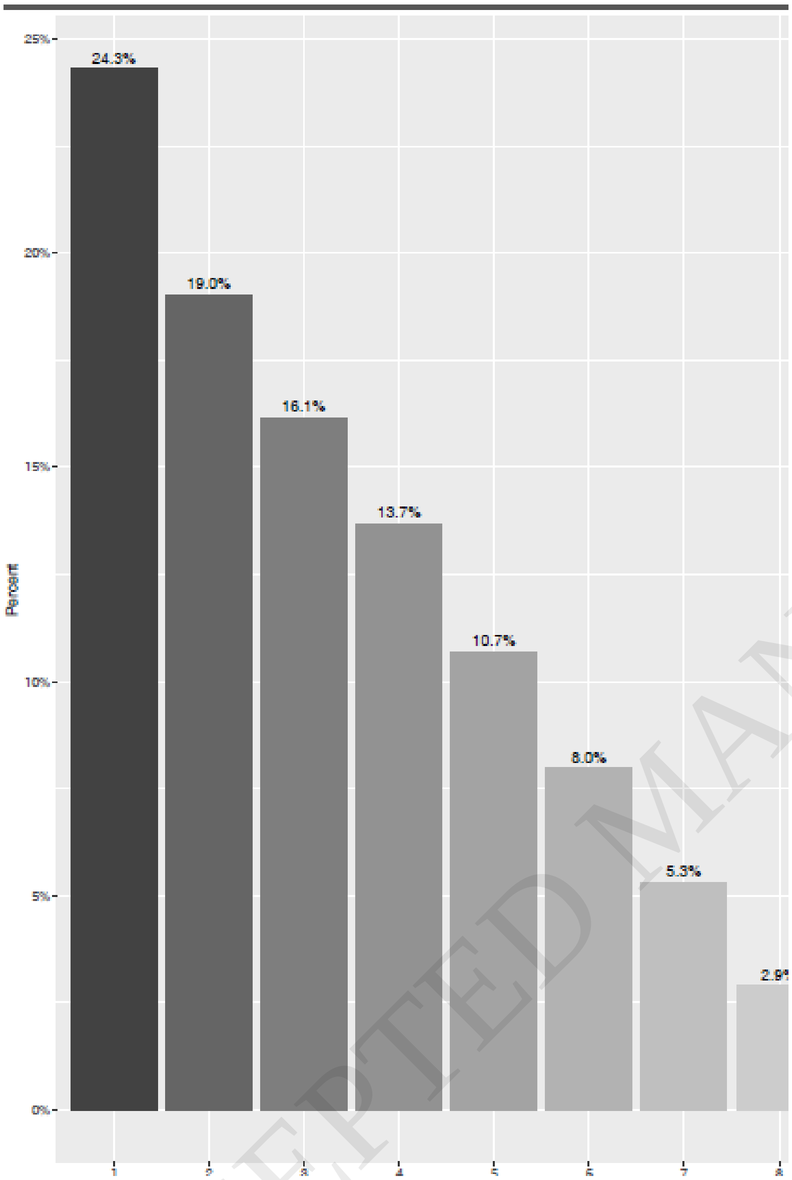
Figure 4

Removal profiles presented as days from the last farrowing to removal by cohort. The cohort number is situated in the top left corner of each graph. Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) over the enrollment period of 1st July, 2013 through 30th June, 2014 and followed until the end of the study period (31st December, 2014). Percentage was calculated as (removals occurring in a time step/ all removals) x100.

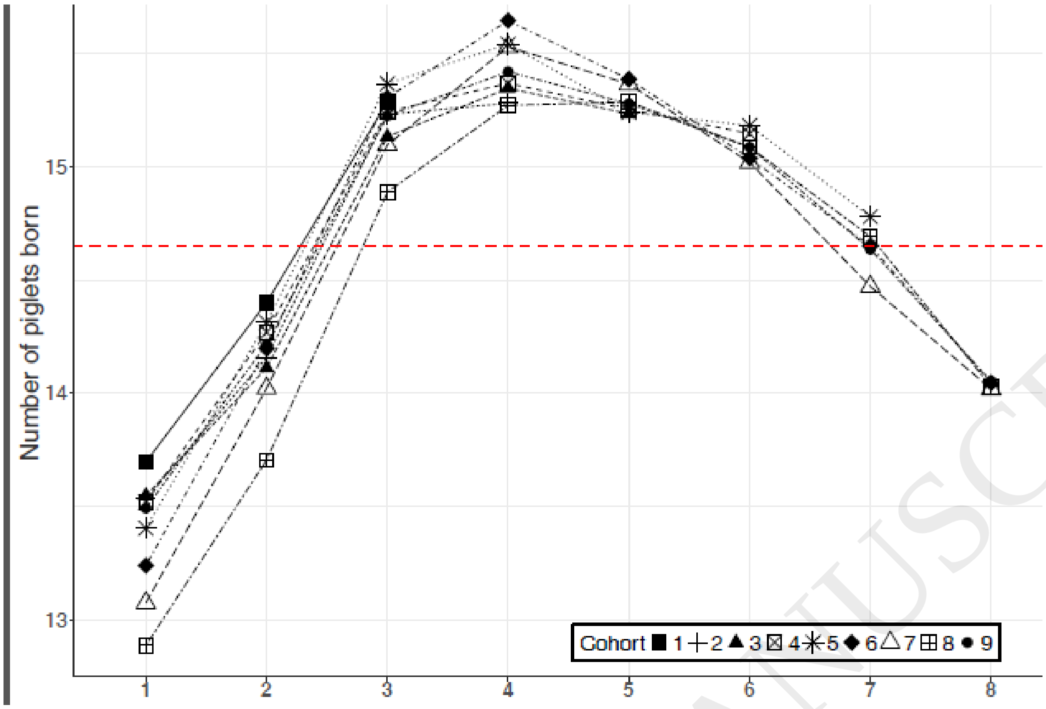


Study period
Enrollment period
Calendar time
01.07.2013
30.06.2014
01.01.2015
COHORT 1 (and 2)
COHORT 2 (and 3)
COHORT 3 (and 4)
COHORT 4 (and 5)
COHORT 5 (and 6)
COHORT 6 (and 7)
COHORT 7 (and 8)
COHORT 8

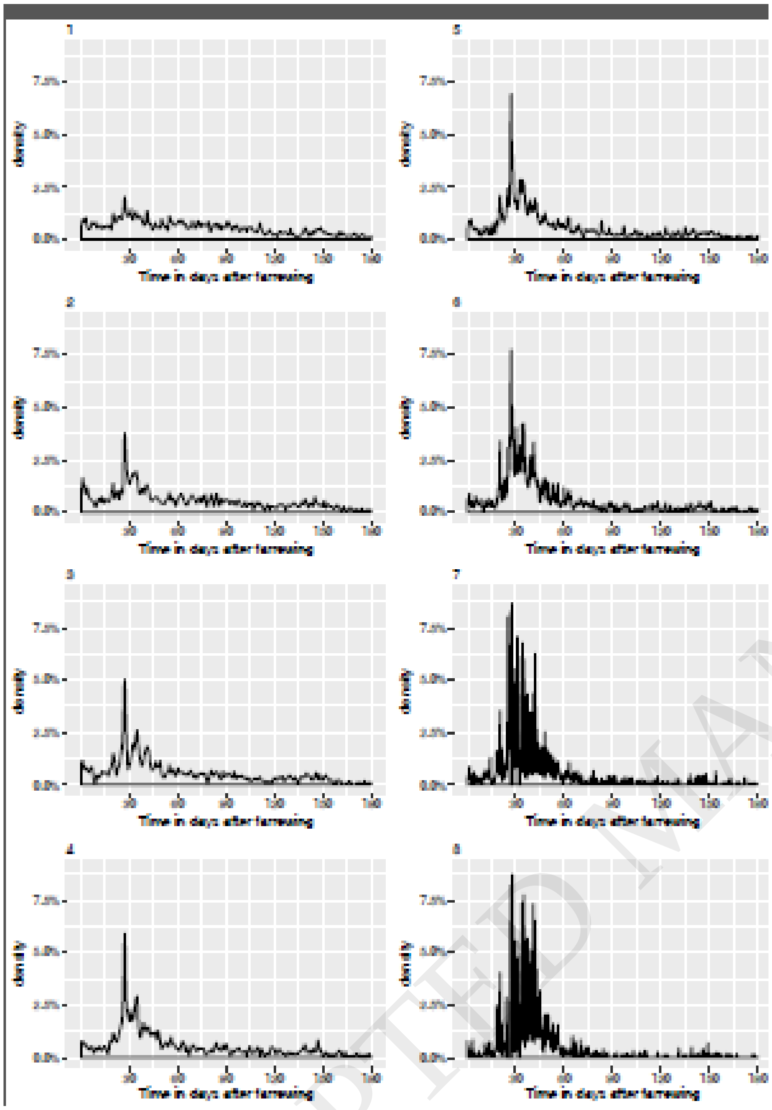
Sow removal



Sow removal



Sow removal



Sow removal

Tables

Table 1.

Parameter estimates and exponentiated effects of the performance characteristics, season and age at first farrowing and lactation length on removal for cohorts 1 (n_{sows}=17,379, $n_{periods}$=129,770) and 8 (n_{sows}=2,066, $n_{periods}$=9,965). Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) between 1st July, 2013 and 30th June, 2014 (enrollment period), and followed until 31st December, 2014 (end of the study period). Risk factors in tables 1 and 2 were included in the same models.

		Sow being removed			
		Cohort 1		Cohort 8	
Parameter	Level	β(SE)[1]	exp(β) (95% CI)	β(SE)	exp(β) (95% CI)
Age at first farrowing (days)	<353	Ref.	-	Ref.	-
	353-369	0.036 (0.059)	1.04[3] [0.92;1.16]	-0.003 (0.082)	1.00 0.85;1.17]
	370-386	0.091 (0.061)	1.10 [0.97;1.23]	0.024 (0.093)	1.02 [0.85;1.23]
	>386	0.275***(0.058)	**1.32 [1.17;1.48]**	-0.051 (0.100)	0.95[0.78;1.15]
Season at first farrowing	April-September	Ref.	-	Ref.	-
	October-March	-0.198***(0.038)	**0.82 [0.76;0.88]**	-0.004 (0.059)	1[0.89;1.13]
1.Litter size[2]	0-10	Ref.	-	Ref.	-
	11-15	-0.304***(0.045)	**0.74 (0.68;0.81]**	0.063 (0.075)	1.07[0.92;1.2]
	16-26	-0.341***(0.060)	**0.71 (0.63;0.80]**	0.132 (0.113)	1.14[0.91;1.42]
1. Litter stillborn	0	Ref.	-	Ref.	-
	1	0.057 (0.047)	1.06 (0.97;1.16]	-0.061 (0.071)	0.94[0.82;1.08]
	>1	0.407***(0.046)	**1.50 (1.37;1.64]**	0.031 (0.083)	1.03[0.88;1.21]
1.Lactation length (days)	<22	Ref.	-	Ref.	-
	21-28	NA	-	0.032 (0.091)	1.03[0.86;1.23]
	>28	NA	-	0.009 (0.107)	1.01[0.82;1.24]
2.Litter size	<11	Ref.	-	Ref.	-
	11-16	NA	-	-0.024 (0.079)	0.98[0.84;1.10]
	>16	NA	-	-0.040 (0.114)	0.96[0.77;1.20]
2.Litter stillborn	0	Ref.	-	Ref.	-
	1	NA	-	0.011 (0.070)	1.01[0.88;1.16]
	>1	NA	-	0.099 (0.084)	1.1[0.94;1.30]
2.Lactation length	<22	Ref.	-	Ref.	-
	21-28	NA	-	-0.019 (0.107)	0.98[0.8;1.21]
	>28	NA	-	-0.050 (0.122)	0.95[0.75;1.21]
8.Litter size	<10	Ref.	-	Ref.	-
	10-15	NA	-	-0.439***(0.075)	**0.64[0.56;0.75]**
	>15	NA	-	-0.532***(0.100)	**0.59[0.48;0.71]**
Constant		3.894***(0.089)		3.904***(0.089)	
Random effects		0.138 (0.372)		0.621 (0.788)	
Observations		129,770		9,965	
Deviance		26,205		5,598	
Df.resid.		129,752		9,937	
Log Likelihood		- 13,084		-2,779	
Akaike Inf		26,205		5,654	
Bayesian Inf		26,381		5,856	

Sow removal

[1]Estimates were obtained from a generalized mixed model with a Poisson distribution and random herd effect
All cohorts were analyzed separately. For details on cohorts from two to seven, see supplementary material.
[2]Litter sizes refer to numbers of piglets born alive
[3]The rate ratio is calculated as exp (0.036) = 1.04
NA = not applicable; the factor was not in the particular model
$^{*}P < 0.1$ $^{**}P < 0.01$ $^{***}P < 0.001$
Bold type indicates significance at alpha=0.05 level

Sow removal

Table 2

Parameter estimates and their exponentiated effects for the 20-d periods during the first 180 days postpartum for cohorts 1 (n_{sows}=17,379, $n_{periods}$=129,770) and 8 (n_{sows}=2,066, $n_{periods}$=9,965). Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) between 1st July, 2013 and 30th June, 2014 (enrollment period), and followed until 31st December, 2014 (end of the study period). Risk factors in tables 1 and 2 were included in the same models.

		Sow being removed			
		Cohort 1		Cohort 8	
Parameter	Level	β(SE)[1]	exp(β) (95% CI)	β(SE)	exp(β) (95% CI)
20 day interval in the parity cycle	0-20	Ref.	-	Ref.	-
	21-40	0.444***(0.065)	**1.56[2] [1.37;1.78]**	2.178***(0.112)	**8.83[7.09;11.00]**
	41-60	0.085***(0.072)	1.09[0.95;1.25]	2.113***(0.125)	**8.27[6.48;10.56]**
	61-80	0.063***(0.073)	1.07[0.92;1.23]	0.880***(0.180)	**2.41[1.69;3.43]**
	81-100	-0.069***(0.076)	0.93[0.8;1.08]	-0.387***(0.299)	0.68[[0.38;1.22]
	101-120	-0.400***(0.084)	**0.67[0.57;0.79]**	-0.292(0.290)	0.75[0.42;1.32]
	121-140	-0.793***(0.097)	**0.45[0.37;0.55]**	-0.345(0.299)	0.71[0.39;1.27]
	141-160	-0.628***(0.093)	**0.53[0.44;0.64]**	0.049(0.261)	1.05[0.63;1.75]
	161-180	1.246***(0.085)	**3.48[2.94;4.11]**	2.041***(0.259)	**7.7[4.63;12.79]**
Observations		129,770		9,965	

[1]Estimates were obtained from a generalized mixed model with a Poisson distribution and random herd effect;

[2]The rate is calculated as exp (0.444) = 1.56

All cohorts were analyzed separately. For details on cohorts two to seven, see supplementary material.

$^{*}P < 0.1$ $^{**}P < 0.01$ $^{***}P < 0.001$

Bold type indicates that the confidence interval (CI) does not include one