Department of Production Animal Medicine
University of Helsinki
Helsinki

SOW REMOVAL IN FINNISH COMMERCIAL HERDS: EPIDEMIOLOGICAL APPROACHES

Paula Susanna Bergman

ACADEMIC DISSERTATION

To be presented, with permission of the Faculty of Veterinary Medicine of the University of Helsinki, for public examination in room 104, Forest Sciences Building, on 20th November 2019, at 12 noon.

Helsinki 2019

Custos: **Prof. Olli Peltoniemi**
Department of Production Animal Medicine
Faculty of Veterinary Medicine
University of Helsinki

Supervised by: **Prof. Päivi Rajala-Schultz** (primary supervisor)
Department of Production Animal Medicine
Faculty of Veterinary Medicine
University of Helsinki

Adj. Prof. Claudio Oliviero
Department of Production Animal Medicine
Faculty of Veterinary Medicine
University of Helsinki

Adj. Prof. Anna-Maija Virtala
Department of Veterinary Biosciences
Faculty of Veterinary Medicine
University of Helsinki

Reviewers: **Prof. Yuzo Koketsu**
School of Agriculture
Meiji University
Kawasaki, Japan

Prof. Arvo Viltrop
Institute of Veterinary Medicine and Animal Sciences
Estonian University of Life Sciences
Tartu, Estonia

Opponent: **Prof. Elisabeth große Beilage**
University of Veterinary Medicine Hannover
Field station for Epidemiology
Bakum, Germany

ISBN 978-951-51-5589-4 (pbk.)
ISSN 2342-3161 (print)
ISBN 978-951-51-5590-0 (PDF)
ISSN 2342-317X (online)

Layout: Tinde Päivärinta/PSWFolders Oy/Ltd
Helsinki University Printing House
Helsinki 2019

ABSTRACT

In sow farms, animals are actively removed and replaced to maintain target efficiency levels, herd health status and a static herd size. Sow removal has a critical effect on pig farm functionality and profitability. Excessive removal decreases lifetime production and especially during periods of small profit margins, becomes burdensome. It is also recognized as a welfare issue.

The overall aim of this thesis was to investigate the current reality of piglet production in the rapidly changing Finnish production conditions with special emphasis on removal. The thesis is based on three individual studies which utilize diverse data from real commercial piglet producing farms. The types of data collected for each are different and the methods used reflect the differences.

We showed systematic and temporal differences in removal between individuals, parities, farms and replacement circumstances in Finland. The results also demonstrated the economic value of improved animal health and removal. We benchmarked national culling and mortality rates retrieved from mandatory registrations. Especially, the average on-farm mortality may be considered relatively high although the rates accorded with published literature. However, the large differences between farms and several farms succeeding in obtaining low levels of removal imply that it is conceivable to strive for and reach certain special targets. Unfortunately, we demonstrated that optimal lifetime of a sow is not a fixed number and as such, no generally applicable policy for replacing sows can be determined. Neither can excessive removal be improved by single improvements only, because of limited resource reserves and other shortages within the individual farm. However, a few factors were found to be linked with an increased risk for removal and higher removal levels in these studies: e.g. the smallest litter sizes and the number of stillborn piglets at the sow level, and features indicative of semi-intensive or intensive farming compared with a combination of environmental animal welfare indicators (mortality) and a non-intensified farming style (culling) at the farm level.

Traditional production approach of maximizing the net monetary income or quantitative measures in piglet production is likely to be changed in response to consumer's increasing concerns around animal well-being, environmental sustainability and one health. We introduced an empirical base that could be used to motivate debate on future development of piglet production systems and delivered useful evidence relevant for stakeholders to engage in and promote research into identification, monitoring and management of sow removal and health. It may be more motivating for Finnish piglet producers, herd advisors and the industry to have specified removal levels to work towards. Our study can also be considered valid for emphasizing awareness of multidisciplinary approaches in integrating accurate epidemiological livestock data into larger frameworks as well as identifying current bottlenecks in available data and modelling methodology.

ACKNOWLEDGEMENTS

The dissertation is entirely based on observational data from real commercial farms. Foremost, I want to show my respect and thank all the farmers for your effort and time.

This educational trip required skilful allocation of scarce finances and would not have been possible without the financial support from several funding bodies. The Ministry of Agriculture and Forestry, the University of Helsinki, the Emil Aaltonen Foundation, the Oiva Kuusisto Foundation, the Finnish Veterinary Foundation, the Finnish Foundation for Veterinary Research and Sianjalostuksen säätiö are thanked out of deepest gratitude.

I wish to thank my primary supervisor Prof. Päivi Rajala-Schultz and the responsible professor Prof. Olli Peltoniemi. I would like them to know that none of their efforts and contributions of time have gone unnoticed. The feedback provided by Adj. Prof. Anna-Maija Virtala and Adj. Prof. Claudio Oliviero is also acknowledged. The members of my thesis committee, Prof. Antti Sukura and Prof. Timo Soveri are deeply thanked for support, encouragement and fruitful conversations in general.

I cannot begin to express my gratitude to Prof. Yrjö Tapio Gröhn for offering me the opportunity of a research visit in his group. Without his confidence in me and continuous support, patience, motivation, and immense knowledge of science and life this dissertation would never have been written. He has enriched my world.

Prof. Mari Heinonen is acknowledged for providing me the opportunity to join the sow longevity project. Warm thanks are also dedicated to all my co-authors. Especially, I wish to thank Prof. Jarkko Niemi for his invaluable input and sharing his long experience in the field of modelling farm economics. Prof. Anna Valros is thanked for always pertinent, constructive comments, wide-ranging knowledge and great generosity.

I was privileged to have Prof. Yuzo Koketsu and Prof. Arvo Viltrop as the preliminary examiners. The discussions with Prof. Koketsu and his expertise in swine epidemiology and farm data analysis have been an important source of motivation for me since an early stage of the research project. Jonathan Robinson is thanked for the linguistic revision of the dissertation.

I also wish to thank Prof. Elisabeth große Beilage for agreeing to be my opponent at the public examination.

My special gratitude goes to my fellow PhD Leena Seppä-Lassila for all the support, encouragement and lending a sympathetic ear over the years.

I have also been fortunate to have numerous precious personal encounters. I would like to take this opportunity to thank these remarkable, passionate, knowledgeable, fascinating, engaged, inspirational, enthusiastic and friendly people worldwide for intellectual and moral support in a more or less chronological order: Kimmo Vehkalahti, Henri Karttunen, Kristian Lindqvist and Denis Haine, Ian Dohoo, Ulf Emanuelsson and Ane Nødtvedt, Henrik Stryhn, Julia Hertl, Lis Alban, Keith Howe, Hannu Sariola, Eeva Sievi and Liisa Uotila, Mette Bisgaard Petersen, the Ingrids Toftaker and Hunter Holmøy, Tariq Halasa, Kaare Græsbøll and Carsten Kirkeby. If I have forgotten someone, I apologize.

Parenting through a PhD coupled with moving abroad, twice, has had its challenges. My brother and friends Arja, Joanna, Maura and Minka, not to mention Mamu and Pepe, have offered unconditional support, which has made all the difference in these intensive years. I owe you a big thank you. Also, Marjo deserves honest words of appreciation. Thank you so much for the gift of your time. It created an opportunity for me to grow in ways I did not know were possible.

Experience has taught me that life can end in the blink of an eye creating unfillable voids of losses. In the end, all that matters are my loved ones: Heksu, Popi, Onnuska, Empsu. You have, more than would have ever been reasonable, struggled with and beside me. I thank you for putting it all into a perspective for me. To conclude, I hope to have modelled the art of working around obstacles, the importance of just getting things done and the mind-boggling joy of intellectual discovery for you, and that through vulnerably sharing my failures (or perceived failures) I have succeeded in truly inspiring you.

I may not always say it, but I really want you all to know, with every bit of my heart and soul that I am lucky, grateful, honoured and blessed to have you. I Love You!

Longyearbyen, October 2019

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I Bergman, P., Gröhn Y.T., Rajala-Schultz P., Virtala A-M., Oliviero C., Peltoniemi O. & Heinonen M. (2018) Sow removal in commercial herds: Patterns and animal level factors in Finland. *Preventive Veterinary Medicine*, 159, 30-39.

II Bergman P., Munsterhjelm C., Virtala A-M., Oliviero, C., Peltoniemi O., Valros A. & Heinonen M., (2019). Structural characterization of piglet producing farms and their removal patterns in Finland. *Porcine Health Management*, 5:12.

III 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. *Frontiers in Veterinary Science*, 4:181.

The publications are referred to in the text by their Roman numerals.

The author's contributions to the publications included in this thesis:

I PB was the main party responsible for the study, contributing to all its parts: PB outlined the research focus and the idea for the study, recruited the participants, collected the data, managed, processed and edited the data, wrote the codes in R and undertook data analysis, prepared the figures, interpreted the results and wrote the initial paper.

II PB was the main party responsible for the study, contributing to all its parts: PB outlined the research focus and the idea for the study, recruited the participants, collected the data, managed, processed and edited the data, wrote the macros in Excel and codes in R and undertook data analysis, prepared the figures, interpreted the results and wrote the initial paper.

III PB participated in the design of the study and outlining of the research focus, collected and processed primary on-farm sow level data and register data, was responsible for gathering information related to the veterinary aspects (diseases and their consequences), took part in the interpretation and utilization of sow health records, participated in the interpretation of the results and writing the paper, especially regarding introduction, diseases and discussion.

ABBREVIATIONS

HCA	hierarchical cluster analysis
MCA	multiple correspondence analysis
PDS/PPDS	postpartum dysgalactia syndrome
RR	risk ratio

1 INTRODUCTION

Finnish pork production chain in its entirety has been negatively affected for an exceptionally long time by very low profitability. Environmental, health, bioeconomy and agricultural policy agendas are shaping the Finnish food production system. Additionally, over the recent decades, sow health, fitness and well-being have received society's growing attention, owing to the change towards larger and more intensively managed units as well as the profound selection for highly reproductive traits (hyperprolific sows).

Producers have often reached a good understanding of their own production through a long history of trial and error. They are capable of making decisions based on the knowledge gathered over several years. However, problems are likely to arise in situations with too much uncertainty, changes and pressures, which are beyond their control.

Keeping farms alive is a shared concern for the entire industry and policy makers, in relation to secured, local, high quality food production and rural development. Sow and farm characteristics associated with both the economic and ethical relevance of production are becoming increasingly important yet are still poorly understood.

Finding ways to develop Finnish production towards sustainable, secure, animal- and environmentally friendly farming requires improved knowledge of animal husbandry to provide suitable tools for producers, farming advisers, government workers, policy makers and scientists. The search for such knowledge should be based on a holistic and systemic approach, covering both the biological characteristics of modern sow population, the living environments encompassing housing and management, and farm economics. Nevertheless, scientific studies on current Finnish sow husbandry have been scarce.

Sow removal is found to be an important aspect in pig farming and has a considerable impact on farm functionality and economic efficiency. It may also be linked to sow health and welfare. Replacement is one of the most complex decisions piglet producers make on an almost daily basis. This thesis project aims to describe some aspects contributing to a cost-efficient, sustainable, resilient and animal welfare-oriented piglet production with an optimal animal population with special emphasis on sow removal. Diverse data sources are integrated, and various epidemiological methods are implemented to investigate characteristics and determinants of removal (culling and mortality) among Finnish sows. We aim to identify favourable characteristics of sows and highlight salient aspects regarding housing systems and sow management that Finnish producers may utilize in the upcoming transition towards a surviving farm. We also demonstrate the economic and sow replacement implications of the most important production diseases.

In the following chapters of the thesis relevant literature including key aspects of Finnish pork production and its development is discussed, the aim and objectives are stated, the materials and methods are described, the main results are given and discussed. The report will end by giving conclusions of the research and future recommendations for both the producers and research.

2 REVIEW OF THE LITERATURE

The first part of this chapter introduces the main features of Finnish piglet production and farming systems in general. The second part describes the production cycle of a sow. The third part covers major aspects of and concepts underlying sow removal. In the fourth part, a brief introduction to decision-support systems and mathematical sow models is given.

2.1 Finnish pork production

The aim of Finnish food production is to produce high quality products competitively according to the principles of sustainability and economic efficiency while respecting humans, animals and environment (Ministry of Agriculture and Forestry, 2019; European Comission, 2018). Agriculture is a fundamental part of the national infrastructure: the industry not only provides food, financial returns and employment, but also contributes to sociocultural conditions in Finland. Local food production is, in addition, a crucially important element in national crisis management strategies.

In recent years, pork consumption, production and markets have evolved markedly both globally and at the national level (Trienekens & Wognum, 2009; FAO, 2019; Niemi & Väre, 2019). Notwithstanding the recent changes, pork remains a key commodity in Finnish food production. The national pig population has fluctuated between 1,458,347 individuals (1997) housed in 6,155 farms to 1,088,988 (2018) in 1,027 farms (OSF, 2019). In terms of meat consumption, pork continues to rank first at 33.4 kg of the approximately 80 kg of meat consumed per capita annually (Niemi & Väre, 2019).

In 2018, there were about 20,000 young breeding females (<8 months of age) and 83,000 sows housed in 521 farms to produce piglets, representing almost 170 billion kg of pork produced (OSF, 2019; Niemi & Väre, 2019). This is approximately one half of all the meat produced in Finland and fundamentally corresponds to the national consumption of pork. However, there are both export and import markets representing annual amounts of approximately 20 and 30 billion kg of pork, respectively (Niemi & Väre, 2019).

Since Finland joined the European Union in 1995 the pork industry has been in serious decline (Fig.1), with almost nine in ten producers having given up piglet production (Niemi & Väre, 2019). Simultaneously, the number of sows has dropped by 45% from the peak of 190,000 in 1998 (Fig. 1). However, the number of piglets and finishers has remained approximately constant at around 500,000 (OSF, 2019).

The total number of active pig farms has declined, but the remaining farms have become larger (Marquer *et al.*, 2014; Kortesmaa *et al.*, 2017). Two decades ago, most piglet producers operated farms with fewer than 100 sows, whereas today most animals are kept in farms larger than 300 sows, suggesting an intensification of the sector (Table 1). The future development trend seems to be characterized by the concentration of production on a diminishing number of farms, which in turn are growing in size (Marquer *et al.*, 2014; Niemi & Väre, 2019). In large farms fixed costs are divided by a larger quantity of animals increasing productivity and aiming at reducing the average cost of production (Marquer *et al.*, 2014).

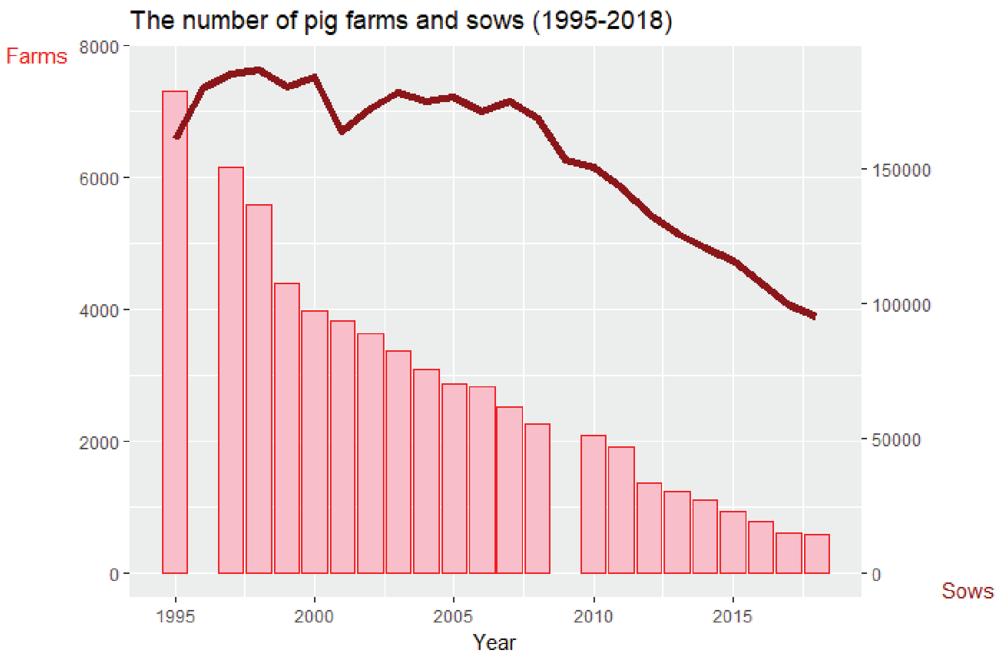

Figure 1 Change in the number of pig farms (bars) and sows (solid line) in Finland since 1995. Data source: Official statistics of Finland (*OSF*).

Table 1. The piglet producing farms classified based on the numbers of young breeding females (<8 Months) and sows in 2014. The median herd size was 72 and the average was 151 (SD 276) (provided by the Centre for ICT Services at the National Land Survey 13.4.2015)

Farm size	Number of farms	Number of females
1-50	283	7,585
51-100	207	15,159
101-200	129	17,977
201-300	62	15,170
301-500	34	12,918
501-800	22	14,079
801->	24	32,247
In total	761	115,135

Nevertheless, economic sustainability of pig production has become very sensitive: the future is unpredictable as prices fluctuate, production costs increase, disease pressures challenge the global market, and the interests of consumers and industry become conflicted. In addition, current pork production faces globalization, technological developments, constantly updated regulations, new emerging diseases and society's evolving social and cultural concerns about animal welfare, the environment, food quality and food safety (Trienekens & Wognum, 2009; European Comission 2017b; European Comission, 2018). The aim of agriculture may also be shifting from focusing on productivity to overall sustainability and diversification of rural functions (Steinfeld *et al.*, 2006; European Comission, 2018; FAO, 2018).

As a result, farmer management skills are challenged. In an effort to manage budgets and future insecurities, every element of agricultural production has to be subjected to careful scrutiny, optimizing resources and reducing expenditures in order to sustain the farm through difficult times. Sub-optimal management decisions may have long-term impacts not only on the survival or future functionality of the farm itself, but also on the entire production chain. The need for accurate information to support management is of paramount importance (Rodríguez *et al.*, 2014).

2.1.1 Production systems

In Finland, pigs are mainly kept indoors in specially designed buildings according to the guidelines of the World Organization for Animal Health (2019): good animal welfare requires disease prevention and veterinary treatment, appropriate shelter, management, nutrition, animal-friendly handling and humane slaughter.

In general, three main piglet production systems can be distinguished. Farrow-to-finish production covers the entire production from breeding the sows to selling market hogs. Farrow-to-feeder farming involves producing piglets to be further reared by other producers on the finishing farms. These farms have a sow herd exclusively for breeding. Additionally, some farms are specialized in producing new breeding animals for these farms. Finisher or fattening farms only purchase pigs to be fed until they reach the market weight to be further processed into saleable pork and pork products.

Finnish agriculture has been based on traditional family farming (Kortesmaa *et al.*, 2017) and remains a predominantly family activity (European Comission, 2017a). However, the ongoing structural change from small-scale, mixed production systems towards more intensive, larger herds with genetically refined pig breeds is modifying the physical farming infrastructure and the daily strategies used to care for the animals and manage them (Rodríguez *et al.*, 2014). The quantitative production goals to raise more piglets per sow space unit accompanied with faster production cycles, and especially the desired high input/output ratios, require modern infrastructure, novel technologies, special health care and particular feeds (Baxter *et al.*, 2013; Koketsu *et al.*, 2017).

Despite the turbulent environment and challenges applying throughout the agricultural sector a diversity of farming practices still exists (European Comission, 2017b). Piglet producers differ by many characteristics, such as livestock assets, labour and cash availability, housing facilities, replacement animal management, biosecurity and herd health status, feeding regimen, animal handling and supervision and replacement orientations (Den Hartog *et al.*, 1993; Stalder *et al.*, 2004; Zurbrigg & Blackwell, 2006; Engblom *et al.*, 2007; Fitzgerald, 2009; Pukara, 2018). In particular, the rationale for the current condition of the farm and the course and ambition for future development determine the farm-specific logic in the particular objectives and strategies of a pig farmer (Kauppinen, 2013).

European Livestock Farming Systems (LFS) research has encouraged the dissemination of knowledge about the diversity of farming systems (Gibon *et al.*, 1999). Nevertheless, the multitude of current features across the rapidly evolving Finnish pork production sector has not been extensively described in the literature. To assess underlying risk factors for identified farm level problems and for modelling purposes, information on the whole range of farm typologies and livestock environments is needed (Stalder *et al.*, 2004; Serenius & Stalder, 2007; Engblom, 2008; Rushton, 2009). The challenges related to the heterogeneity of farms have also been recognized in the evaluation of animal welfare from a multifactorial point of view and overall guidelines such as those published by EFSA (EFSA, 2014).

The scarcity of detailed farm information is likely due to several factors. Observational field studies require data from a large number of representative herds. Such studies may be viewed as too subjective, and they are expensive to conduct and time-consuming to complete. In addition, data collection for such studies mainly utilizes questionnaires. Despite careful planning, imaginative design and validation, questionnaire-based approaches have their own limitations as they rely entirely on the cooperation and reliability of the participants (Boynton & Greenhalgh, 2004; Dohoo *et al.*, 2009b; Thrusfield *et al.*, 2018).

2.2 Sow production cycle

Breeding sows in commercial herds are managed through different stages as illustrated in Figure 2. A sow passes through these stages repeatedly until she is replaced by a new one that restarts the same cycle.

The productive life of a female breeding animal starts at breeding. Gilts are often kept in pens and sows to be mated in individual crates. Appropriate reproductive management is required to maximize production (King *et al.*, 1998; Merks *et al.*, 2000; Kaneko *et al.*, 2013). It is influenced by, *inter alia*, genetics, production systems, nutrition and the environment. Stimulation and detection of oestrus using boar contact is common. Normally, when heat is detected the sows and sufficiently mature gilts are mated mainly using artificial insemination or a natural service. Semen can be purchased or collected from the boars on the farm. Thereafter, appropriate housing and management are needed during early gestation to protect embryos and enable implantation. The majority of returns to oestrus occur during the first 3-6 weeks after service. Frequent monitoring of both mated and unmated females is highly recommended to minimize the costly non-productive days

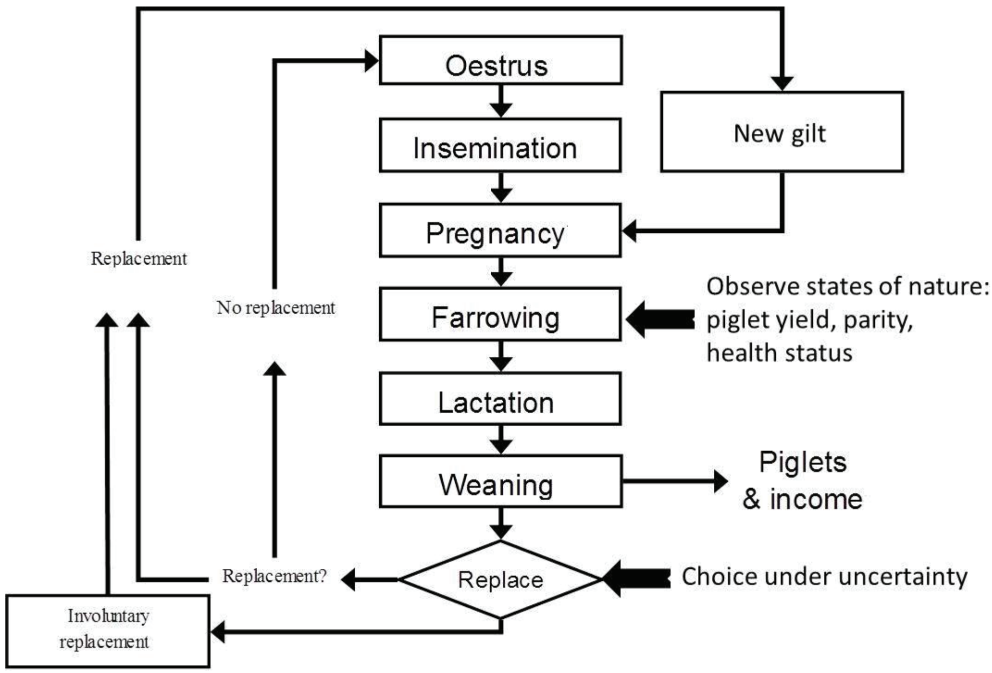

Figure 2 The production cycle of a sow (from Niemi et al, *Frontiers in Veterinary Science*, 4:181, 2017)

(King *et al.*, 1998; Sasaki & Koketsu, 2012; Tani *et al.*, 2016). To confirm pregnancy, real time ultrasound can be used 23-28 days after insemination. A negative result may lead to either re-mating according to the 3-week oestrus cycle (regular returns) or removal.

Sows go through gestation in groups of different sizes and must have space to move freely according to legislation (Animal Welfare Act 247/1996: Government Decree 15.12.2012/629, 2012). Appropriate feeding and general gestation management are needed to ensure sufficient nutrition to support the pregnancy, and also until the third parity the growth of the dam (Yang *et al.*, 1989; Rutherford *et al.*, 2013). There is variation in pregnancy length, but the majority of sows farrow between 114 and 116 days after conception. Approximately a week before the expected farrowing, most pregnant sows are moved into individual farrowing crates.

Constant monitoring and special care are required during the peripartum period. As a polytocous species, pigs produce many offspring at a single birth. In each farrowing on average 10-17 piglets are born but litter sizes up to 20-26 piglets are possible for hyperprolific lines (Andersson *et al.*, 2016; Gruhot, 2017b; Tani *et al.*, 2018; Hasan *et al.*, 2019). Birth weight markedly influences piglet survival (Ferrari *et al.*, 2014; Feldpausch *et al.*, 2019). On average, at birth piglets weigh approximately 1.4-1.5kg, but the genetically induced increase in litter size has been shown to be linked with a decrease in the mean piglet weight and an increase in the within litter variability of birth weight (Wolf *et al.*, 2008; Feldpausch *et al.*, 2019). A target weight of at least 1 kg has been recommended to improve piglet survival and future performance (Mabry, 2016).

The period after farrowing is termed the lactation period. The average daily feed intake affects herd productivity through litter and subsequent reproductive performance (Yang *et al.*, 1989; Koketsu *et al.*, 1997; Tantasuparuk *et al.*, 2001; Hoving *et al.*, 2010). The piglets remain with a sow to be nursed for at least the legislated 28 days (Animal Welfare Act 247/1996: Government decree 15.12.2012/629, 2012). A considerably longer lactation period is often not practised in commercial production for several economic and productivity reasons. Piglets are weaned, either removing the sow from the pen or removing both, and further reared in the nursery department. Some of the best female piglets may be kept as future replacements for the sows, i.e. they may constitute the farm's own gilt pool.

After weaning, the sows are taken to the breeding unit to start the cycle from the beginning. In commercial piglet production the desired aim is to produce as many litters per sow a year as possible (Koketsu *et al.*, 2017). Thus, each sow repeats the cycle on average 2.3-2.4 times a year (Wolf *et al.*, 2008). They should show oestrus within a couple of days after weaning and mated successfully to maximize production (Koketsu *et al.*, 2017).

2.3 Sow removal

Sow removal refers to the replacement step in the production cycle. Animals are actively removed and replaced to maintain target efficiency levels and a static herd size. Average annual removal rates have climbed to levels approaching 50% and large variation among farms has been reported (D'allaire *et al.*, 1987; Dijkhuizen *et al.*, 1989; Stein *et al.*, 1990; Rodriguez-Zas *et al.*, 2003; Engblom *et al.*, 2007; Masaka et al., 2014)

Sow removal has an important effect on pig farm functionality and profitability. The replacement females either have to be reared as an own internal pool of gilts or purchased externally from a breeder supplier. Assets for purchase, labour, feed and housing facilities for gilt development, acclimation and teaching are required (Stalder *et al.*, 2003). In addition, if replacement animals are purchased from other farms, the risk for introducing diseases increases (Koketsu, 2000).

Combined high voluntary and involuntary removal rates result in the need for more breeding gilts, distort the herd parity structure and harm herd performance (Houška, 2009). Especially during periods of small profit margins, excessive removal becomes burdensome (Rodriguez-Zas *et al.*, 2003; Rodriguez-Zas, 2006; Sasaki *et al.*, 2012; Gruhot *et al.*, 2017a). In addition to being an economic concern, excessive removal is also recognized as a welfare issue (OIE, 2019). Thus, understanding sow removal is a critical component of farm success, but because of its complexity, managing sow retention optimally represents an ongoing challenge.

2.3.1 Quantifying and reporting removal

Despite the general goal towards optimized removal, and recent development of comprehensive animal databases, our ability to evaluate and monitor removal is relatively poor due to absence of an accepted set of standards. Several measures are used to demonstrate the flow of animals at the herd level: removal, culling, mortality and replacement rate, herd turnover, percent gilts in the herd, average parity or the frequency distribution of parity of the culled females, and average number of piglets weaned per female per lifetime (Stein *et al.*, 1990; King *et al.*, 1998; Koketsu *et al.*, 1999; Houška, 2009; Balogh *et al.*, 2015; Wang *et al.*, 2019). Culling and mortality rates may also confusingly be used to describe the risk of these events (Dohoo *et al.*, 2009a). Moreover, it is worth pointing out that the scrutiny is further complicated by existence of several sow-level measures of longevity, such as the litter, parity or production cycle number at removal (Hoge & Bates, 2011; Hoving, 2012), the length of life, the herd life, the sow welfare productive lifetime (SWPL) and sow economically productive lifetime (SEPL) (Fitzgerald, 2009), lifetime prolificacy (Hoge & Bates, 2011; Sasaki et al., 2011; Ek-Mex *et al.*, 2015) and stayability (Serenius *et al.*, 2006; Knauer *et al.*, 2010; Hoge & Bates, 2011).

Not only does the definition of removal vary throughout the literature, but there are also different means used to compute the figure (D'allaire *et al.*, 1987). From an epidemiological point of view, Fetrow et al (2006) and Dohoo et al (2009a) have considered removal and mortality, respectively, as specific events or incidents. Therefore, they have emphasized the use of culling/mortality incidence rate as the most ideal way to measure removal. To compute the extent of culling the number of culled individuals over a specified time period should be divided by the population at risk of being culled over the same period. A simple count of the sows that have been culled would be a straightforward measurement. This would also be an understandable basis for the numerator, assuming that the removals are correctly specified, most preferably excluding the number of deaths and reporting them separately. To standardize the figure, a denominator encompassing the population at risk and specifying the time frame would be needed. The specified time is typically a year but could be another period of interest (Stein *et al.*, 1990; Sasaki & Koketsu, 2008a; Jensen *et al.*, 2012).

The most confusing term in the formula is 'the population at risk'. It may be a cohort, i.e. a group determined by a common characteristic, a whole herd according to the farmer either including the gilts and young breeding animals or not, the herd management programme-based figure or a herd size retrieved from an official register. Females may also be counted in annual sow farrowings (D'allaire *et al.*, 1987). Several practical problems occur as there is a constant flow of animals and current herd management systems tend to use different terms to describe herd size, e.g. the definition of a gilt may differ, as would the register-keeping for them. Moreover, several previous research efforts have not measured breeding female inventories either at all or not by parity. Instead, they have reported reason-specific and parity-specific removal using proportions among all the removed females (Stein *et al.*, 1990; Chagnon *et al.*, 1991; Zhao *et al.*, 2015; Wang *et al.*, 2019).

Quantifying the extent of removal appropriately and consistently would be beneficial not only for an internal analysis of individual farms but also for improving the clarity of discussion, providing means for comparisons and screening potential problem herds. Before an international consensus for reporting removal is created, interpretations, comparisons and conclusions among populations, countries and studies must be treated with caution.

2.3.2 Culling

Literally, culling refers to the reduction of an animal population by selective slaughter (Stevenson, 2010), but may also be used to define numerous reasons for an animal to leave the herd: sale, slaughter, unassisted death or euthanasia (Fetrow *et al.*, 2006). Traditionally, culling has been further categorized as voluntary, i.e. removal for economic reasons, and involuntary, i.e. biological or forced reasons mostly beyond the farmer's control (Fetrow et al., 2006). Studies have shown that throughout the years and across populations the main proportion of all removals has been of an unplanned nature (Stein *et al.*, 1990; Boyle *et al.*, 1998; Lucia Jr *et al.*, 2000; Engblom *et al.*, 2007; Zhao *et al.*, 2015; Wang *et al.*, 2019). Therefore, these subdivisions are not useful for management purposes.

The essential prerequisite for an internal farm-specific analysis is well managed, motivated record-keeping. A clear and concise distinction between different destinations (e.g. slaughter, spontaneous death, euthanasia) should be emphasized to improve clarity of the removal records and further interpretation of the summaries (Fetrow et al., 2006).

At an individual animal level, culling means identifying and removing a sow without sufficient merit or fitness compared to the herd average. If she is better than the average sow, she is allowed to remain in the herd, otherwise she is replaced with another, younger female considered to have superior future productivity. At the same time, each of these decisions should consider that an optimum parity profile of productive sows will be maintained (Koketsu, 2005; Koketsu, 2007a; Houška, 2009). The most appropriate time to classify sows systematically and select the ones to be culled is at weaning in order to minimize the unnecessary costs (Engblom *et al.*, 2008b; Tani *et al.*, 2018). Both gilts and sows increase the number of non-productive days before being removed from the herd when they are found not to be pregnant (King *et al.*, 1998). These culling intervals account for a considerable proportion of overall non-productive days influencing the herd reproductive performance and economic efficiency (Koketsu, 2005).

The overall herd culling rate is an accumulation of culling rates of all parities which determine the herd parity distribution (Houška, 2009). A report published from Sweden on a selected sample of farms with good record-keeping skills described annual culling proportions expressed as percentage of sows in production ranging from 27.9 to 56.8% and averaging 42.2% (Engblom *et al.*, 2007). Likewise, a convenience sample of farms in Canada had culling rates ranging from 23 to 50% (Anil *et al.*, 2005b). In a Japanese study focusing on mortality, other culls (culled, euthanized, transferred and unrecorded removals) were differentiated from death, yielding an annualized culling rate of 33.8% (Sasaki & Koketsu, 2008a). In an investigation on commercial pig removal practices, as opposed to those on research farms, one Zimbabwean herd was associated with an average culling rate of approximately 45% (Masaka et al., 2014). In a large Spanish study, the annual culling rate was shown to be 44% (Tani *et al.*, 2018). A recent study from China on culling reasons described the study farms as having average culling rates, potentially on-farm deaths included, of between 30 and 40% (Wang *et al.*, 2019). In each case referred to above, care must be exercised in interpreting or comparing the values.

Reason-specific and parity-specific removal has been described in several studies. Culling strategies and perception of longevity are strongly influenced by views within the industry as a whole and the state of knowledge. Moreover, the decision-making varies over time, season, country, herd, parity number and stage of the production cycle (Dijkhuizen *et al.*, 1989; Tarrés *et al.*, 2006; Anil *et al.*, 2008; Engblom *et al.*, 2008b; De Jong *et al.*, 2014; Balogh *et al.*, 2015; Zhao *et al.*, 2015; Wang *et al.*, 2019). Despite the wide variation, a general pattern across studies is evident in which reproductive failure represents the most common reason (Dagorn & Aumaitre, 1979; D'allaire *et al.*, 1987; Dijkhuizen *et al.*, 1989; Stein *et al.*, 1990; Engblom *et al.*, 2007; Segura-Correa *et al.*, 2011; De Jong *et al.*, 2014; Zhao *et al.*, 2015; Tani *et al.*, 2018). The other major reasons include locomotor problems, inadequate performance and old age (Stein *et al.*, 1990; Engblom *et al.*, 2007; Segura-Correa *et al.*, 2011; De Jong *et al.*, 2014; Wang *et al.*, 2019). Moreover, a large proportion of young breeding females is culled at first farrowing or even before that (Lucia Jr *et al.*, 2000; Knauer, 2011; Masaka et al., 2014; Zhao *et al.*, 2015; Tani *et al.*, 2018).

Ideally, the core of removals should be in selected culls based on a predetermined set of replacement criteria. Culling guidelines should not only include the selection measures but also the timing for gilts and sows (Lucia Jr *et al.*, 2000; Sasaki & Koketsu, 2012). Failure to have or follow appropriate culling policy will result in an increase in unplanned removals. High levels of involuntary culling or mortality reduce the possibilities to follow the culling policy and stick to the targets (Engblom, 2008; Masaka et al., 2014). They create extra costs, reduce production efficiency, disturb the workflow, may require extra facilities for isolation and are a potential reflection of unnecessary suffering due to underlying diseases or management problems. Improving the quality of life of animals through better health and welfare will result in longer living sows and higher lifetime productivity, but can also make the production more socio-culturally accepted (Fraser *et al.*, 1997; Sørensen & Fraser, 2010; Boogaard *et al.*, 2011).

2.3.3 Mortality

On-farm mortality includes sows that die spontaneously, but also the ones euthanized due to trauma or untreatable disease, considered unsuitable for entering the food chain or unfit to be transported are often included in the figure (Engblom *et al.*, 2008a). Each of these losses represents a failure: all forced removals of sows create economic losses for the farmer and are an implication of inefficient use of animal resources (Koketsu, 2000). In addition, morbidity and mortality are indicators of insufficient freedom from pain, injury or disease, and thus raise welfare concerns (Barnett *et al.*, 2001; Welfare Quality®, 2009).

There seems to be no collective agreement as to what might be considered a natural, normal or accepted level of mortality in sow herds. A review of studies reveals relatively large variation, and yet again, due to lack of accepted standards, the results must be interpreted with caution. A rather old study reported as low a death rate as 3.3% in Canada, however with a range from 0 to 9.2% (Chagnon *et al.*, 1991). A large mortality study in the USA two decades ago estimated an annual mortality risk for breeding females to average 5.7% (Koketsu, 2000). Several studies have been conducted at the individual animal level considering only those removed. North American herds for which there was high quality record-keeping were assessed using such an approach and reported that 7.4% of all those removed had died (Lucia Jr *et al.*, 2000).

Notwithstanding the societal concern regarding livestock mortality, current figures for sow herds in different countries to monitor development have not been reported widely (Deen & Xue, 1999; Koketsu, 2000). Crude three month death rates ranging from 0 to 8% for gestating and 0 to 25% for lactating sows in Danish herds have been described (Jensen *et al.*, 2012). Another Danish study estimated the annual mortality to average 12.7% and range from 5.2 to as high as 34.4% (Knage-Rasmussen *et al.*, 2015). The Swedish removal study with detailed and controlled record-keeping could separate euthanasia and death rates, which were 5.2% and 2.1%, respectively (Engblom *et al.*, 2007). Japanese studies reported annualized mortality rates of 3.9 (the euthanized ones not included) (Sasaki & Koketsu, 2008a) and 8.9% (Iida & Koketsu, 2014). Death accounted for 15.6%, 16% and 8.2% of all removals in studies with a limited number of herds from Zimbabwe, Hungary and China, respectively (Masaka et al., 2014; Balogh *et al.*, 2015; Zhao *et al.*, 2015).

Published literature on the specific, confirmed causes of mortality is scarce. A potential diagnosis may be estimated through information from the farmer, but only a postmortem examination can provide a more precise diagnosis (Engblom *et al.*, 2008a). Similarly to those for culling, supposed or suggested causes of sow death and reasons for euthanasia are numerous, varying between parities (Anil *et al.*, 2005b; Kirk *et al.*, 2005; Engblom *et al.*, 2008a), stage of the production cycle (Chagnon *et al.*, 1991; Sanz *et al.*, 2007; Wang *et al.*, 2019), management routines and housing (Christensen *et al.*, 1995; Abiven *et al.*, 1998; Jensen *et al.*, 2012), season (Chagnon *et al.*, 1991; Iida & Koketsu, 2014), populations and countries. Among sows found dead, heart failure and pathologies involving the abdominal organs, especially torsions, ruptures and perforations were the most frequently mentioned causes (Chagnon *et al.*, 1991; D'allaire *et al.*, 1991; Kirk *et al.*, 2005). In contrast, locomotor related problems were reported to constitute a dominant factor determining euthanasia (Christensen *et al.*, 1995; Kirk *et al.*, 2005; Sanz *et al.*, 2007; Engblom *et al.*, 2008a).

Farms differ in the performance level, housing conditions, quality of management, feeding regimen and water availability, biosecurity measures and timing of treatment in cases of signs of discomfort and disease in sows. Populations differ in their genetics and herds in their age structure. Different thresholds and strategies for euthanasia affect the mortality rate and may partly explain herd variations. A better awareness of on-farm mortality and knowledge of the confirmed, farm-specific causes of mortality would be essential when tailoring practical improvements to enhance animal well-being and the farm economy.

2.3.4 Determinants of optimal removal

Sow longevity, i.e. the length of time that a sow remains in the herd plays an important role in the productivity and profitability of piglet production. Therefore, previous research has focused on a wide variety of aspects on sow removal. They all share the aim of improving commercial herd management by producing knowledge to determine optimal culling policies. Yet the specific objectives, designs, study populations and methods of assessment have varied considerably across studies. All interrelated determinants of removal form a complex, at least three level, hierarchical, network (sow, herd, region/country) in which deficits in one can be compensated for by better abilities in the others. Besides, the entity is further modified by the dynamic forces beyond the farmer's control that manipulate herd level replacement strategies such as global markets and production costs, availability of replacement gilts or infectious disease outbreaks.

To guide culling decisions at the individual animal level, many factors have been found to affect the risk of removal. The studies defining what might influence longevity and overall lifetime performance have focused on a wide range of variables thought to be prognostic of better potential. Partly conflicting evidence has been presented. Sow characteristics stated to be predictive for better longevity in some populations may not be predictive in others. Additionally, the relationships between these factors of interest and wellbeing of the sow and resulting litter have hardly been examined.

Breeding values for longevity traits have been widely assessed. Most studies have indicated that sufficient genetic variation exists for effective selection (Yazdi *et al.*, 2000; Serenius & Stalder, 2004; Arango, 2005; Serenius & Stalder, 2006; Serenius & Stalder, 2007; Engblom *et al.*, 2009; Mote, 2009; Knauer *et al.*, 2010). It has also been suggested that by selecting for improved longevity, even differences as great as approximately one parity between the worst and the best lines, may be successful (Rodriguez-Zas *et al.*, 2003). Gilts starting their productive life at younger ages have been shown to have improved survivability (Serenius & Stalder, 2007; Engblom *et al.*, 2008b). Further, their lifetime performance has been reported to be better compared with those farrowing at older ages for the first time (Le Cozler *et al.*, 1998; Sasaki & Koketsu, 2008b; Hoge & Bates, 2011). A sow's risk of removal has also been reported to be influenced by her performance, such as the number of piglets born within parities (Serenius & Stalder, 2007; Engblom *et al.*, 2008b; Hoge & Bates, 2011; Sasaki *et al.*, 2011; Iida & Koketsu, 2015; Iida *et al.*, 2015; Engblom *et al.*, 2016). The effects of the first and second litter sizes separately or combined have been studied because it would be profitable to be able to identify superior individuals during the early stages of the productive life to maximize performance and longevity. In particular, an increased removal hazard has been found to be associated with small litters (Brandt, 1999; Yazdi *et al.*, 2000; Ek-Mex *et al.*, 2015; Tani *et al.*, 2018). However, the most advantageous number of piglets seems to be population dependent (Iida & Koketsu, 2015; Iida *et al.*, 2015; Andersson *et al.*, 2016). Fewer stillborn piglets have also tended to decrease the risk of removal (Hoge & Bates, 2011). Reproductive fitness, such as weaning to first mating intervals affect the number of non-productive days in the herd and have also been linked to removal and lifetime performance (Yatabe *et al.*, 2019). Moreover, the association between the preweaning litter characteristics and environment of breeding females and their later life have also been studied. However, partly conflicting evidence of the overall impact have been reported (Tummaruk *et al.*, 2001; Serenius & Stalder, 2007; Hoge & Bates, 2011; Vallet *et al.*, 2016).

Herd level factors can modify sow-level outcomes independently of the sow's characteristics. Due to the multitude of current features of animal husbandry, problems, and especially the underlying risk factors or their combinations, become difficult to identify and control (Den Hartog *et al.*, 1993; Zurbrigg & Blackwell, 2006; Spoolder *et al.*, 2009).

Thus far, the impact of housing facilities, management routines or other farm level factors, such as farm × year combination, herd size, performance level or reproductive efficiency, have mainly been investigated as separate effects in studies identifying risk factors for the most important causes of premature removal or quantifying direct risks for a sow to leave the herd (Gjein & Larssen, 1995; Abiven *et al.*, 1998; Morris *et al.*, 1998; Koketsu, 2000; Koketsu, 2007a; Serenius & Stalder, 2007; Engblom *et al.*, 2008b; Sasaki & Koketsu, 2008a; Pluym *et al.*, 2011; Jensen *et al.*, 2012; Cador *et al.*, 2014).

It has been suggested that a larger herd size may have a particular effect on mortality (Christensen *et al.*, 1995; Koketsu, 2000). It may be associated with working time allocated per animal and partly with human-animal relationship. These may also jointly affect husbandry practices, including health control and treatment in a number of ways (Hemsworth *et al.*, 1994; Koketsu, 2000; EFSA, 2007). However, the opposite was also reported based on a Japanese study (Sasaki & Koketsu, 2008a), and also a lack of any association between herd size and death occurrence has also been observed (Jensen *et al.*, 2012; Iida & Koketsu, 2014). Further research is needed to improve the knowledge on how workload, caretaker skills and sow removal are interrelated.

Culling frequencies for reproductive reasons have consistently been shown to be high. In addition to genetics and age, farm level factors such as nutrition, breeding management and culling policy on repeat breeders are linked to the number of unnecessary culls for a variety of reproduction related causes (D'allaire *et al.*, 1987; Dijkhuizen *et al.*, 1989; Dalin *et al.*, 1997; Lucia Jr *et al.*, 2000; Engblom, 2008; Engblom *et al.*, 2008b).

Premature removal for locomotory disorders, both through slaughter and euthanasia, is common (Heinonen *et al.*, 2013). Leg and claw problems and lameness are all known contributors to impaired health and welfare (Boyle *et al.*, 1998; Kirk *et al.*, 2005; Anil *et al.*, 2008; Engblom *et al.*, 2008a; Anil *et al.*, 2009; Pluym *et al.*, 2011). The frequencies range widely, which may partly be due to poor selection for structural soundness. With good reasoning it may also be assumed that farm level factors or factor combinations influence removal through influencing locomotor soundness (Engblom *et al.*, 2008a; Engblom *et al.*, 2008b). Increasing the proportion of concrete slatted floor (Heinonen *et al.*, 2006; Zurbrigg & Blackwell, 2006; Cador *et al.*, 2014), poor floor hygiene and restricted space (Gjein & Larssen, 1995; Cador *et al.*, 2014; Pluym *et al.*, 2017), larger group sizes and higher workload (Cador *et al.*, 2014) have all been identified as risk factors for locomotor disorders.

Aggression is a recognized disadvantage of group housing of gestating sows (Maes *et al.*, 2016). While the degree of aggressive encounters does not directly associate with a sow removal problem, it may associate with lameness, traumatic injuries, dirtiness, stress, reduced feed intake and other negative effects of aggression (Razdan *et al.*, 2004; Engblom, 2008). A combination of housing factors and management routines affects the frequency, duration, intensity and consequences of fighting (Anil *et al.*, 2005a; Zurbrigg & Blackwell, 2006; Spoolder *et al.*, 2009). However, these interrelationships and especially the potential link between aggression and removal is not well-studied (Stalder *et al.*, 2004; Fitzgerald, 2009).

The effects of otherwise harsh housing conditions may be modified by provision of enrichment material. Bedding, rooting and nesting materials facilitate natural behavioural needs, and especially with other animal friendly initiatives and proper management, influence animal welfare, health and presumably performance (Tuyttens, 2005; EFSA, 2007; Spoolder *et al.*, 2009; Spoolder *et al.*, 2011; Yun *et al.*, 2013; Munsterhjelm *et al.*, 2015). They may also improve longevity indirectly, through better welfare, potentially lowering morbidity and mortality.

2.4 Computerized decision-making support

Decision-making in the traditional sense can be seen as the interface between the evaluation of a situation, the choice of action or a combination of the two. Ideally, the decision maker must be completely informed about all possible alternatives and their instant and long-term consequences. Preferably, it should be possible to rank the alternatives such that across all possibilities the one maximizing the decision outcome can be identified (Sauter, 2011).

We are experiencing a data revolution: substantial amounts of data are being generated passively and actively on a daily basis (Wolfert *et al.*, 2017). Structured collections of data such as detailed animal-related records on farms enter databases. However, databases are only of limited value. They need to be converted into information in order to be useful (Thrusfield & Christley, 2018). All databases with a consistent, coordinated set of modules for collecting, storing, processing, optimizing, analysing and valuing data can be considered to be information systems (Ratzan, 2004). Further, extensions of such information systems generate decision support systems. Operations research deals with a wide range of applications of advanced analytical methods, such as mathematical modelling and simulation, statistical analysis and mathematical optimization to support decision-making and improve it and its efficiency (Churchman *et al.*, 1957; Thrusfield & Christley, 2018).

Linking the available theory of complex decision-making with existing data and application to real-world problems can shed light on individual system behaviours and their economic and other implications (Kaufmann & Faure, 1968; Sauter, 2011; Berner & La Lande, 2016). Decision support systems can also be used to integrate formulations that describe farmers' production efficiency, resource reserves and shortage, preferably in real time. While doing so, they provide conclusions about the current and suggestions for alternative production possibilities, conforming to environmental constraints and complying with legislation (Janssen & Van Ittersum, 2007). In general, decision support systems do not provide explicit answers but expand possibilities, reduce the time needed to evaluate and choose, offer guidance to decision makers at the implementation level and improve the quality of solutions (Sauter, 2011).

2.4.1 Sow models

In farming systems, there are many dynamic dependencies and a continuous flow of key decisions to be made. In the process of managing a herd towards farm-specific goals, input factors of production, broadly categorized as land and animal resources, labour, capital, entrepreneurship and knowledge are employed to achieve a specific amount of commodity (Eurostat, 2018).

Mathematical models representing the behaviours of herds have been used for a long time in research (Oltenacu *et al.*, 1980; Allen & Stewart, 1983; Tess *et al.*, 1983). Models are developed for research and teaching purposes but also to assess the consequences of policy changes and technological innovations, and support on-farm decision-making by highlighting the impacts of different choices (Plà *et al.*, 2003). By giving more insight into hypothetical situations, they make the real farm behaviour easier to predict and understand (Janssen & Van Ittersum, 2007).

The goal in mathematical livestock models is to describe and optimize a well-defined problem. In sow farming systems, one specific challenge is that a wide variety of factors are continuously, and in short cycles, interacting hierarchically and dynamically with each other. Moreover, pork production is partitioned into specialized farms, each of which is integrated into the larger framework of the supply chain aiming at best possible overall efficiency (Rodríguez *et al.*, 2014).

The more the models try to resemble the animal, farm or chain level reality, the more complex they become. An increase in computational power has enabled the representation of highly complex systems to solve significant problems. However, the applicability to real on-farm use has not necessarily been improved. Several factors determine model practicality. The most effective models both utilize the power of information technology and represent a compromised simplification of the reality involving the end user (Kamp, 1999; Plà, 2007; Rodríguez *et al.*, 2014).

Methodological approaches of sow herd models have mainly been based on simulation, linear programming and dynamic programming, including Markov decision models (Plà, 2007; Rodríguez-Sánchez *et al.*, 2012). The incorporation of Bayesian methods has also been introduced (Kristensen & Søllested, 2004). In general, the core is in the representation of the productive and reproductive behaviour of the herd over time. Thus, the main elements are reproduction and replacement management. The models take the individual sow lifespan as a reference: a sow follows the path described above in Figure 2 in the Sow production cycle chapter of this thesis and is exposed to unit-specific and farm-specific management.

In particular, sow herd models have been developed to describe how the timing of replacement affects the overall population and farm economy (Dijkhuizen *et al.*, 1986; Huirne *et al.*, 1988; Houben *et al.*, 1990; Huirne *et al.*, 1991; Jalvingh *et al.*, 1992; Huirne *et al.*, 1993; Kristensen & Søllested, 2004). As described in the previous sections, decisions on replacement and policies in sow farming are critical. The goal of a producer is to find a replacement policy that maximizes the expected value of return. The complex and still poorly understood interrelationships among a large number of factors complicate this decision-making. The ongoing changes in the pork production sector, regulations concerning pig welfare and society's growing environmental concerns restrict the margin of benefit for individual farms. Increasing numbers of new variables and constraints further complicate the evaluation of the best possible management alternative. Optimization models considering a wider framework of interacting factors or a pool of farms are likely to play a more important role in modern farm management (Plà, 2007). For such purposes, the models should be improved to better meet the needs of farmers and advisers and to be interpreted in a practical context (Plà, 2007; Rodríguez-Sánchez *et al.*, 2012).

Previous studies have also used several different methods to estimate the effect of diseases. The economic consequences of costly outbreaks of some infectious diseases have been demonstrated in detail (Nieuwenhuis *et al.*, 2012; Schulz & Tonsor, 2015; Halasa *et al.*, 2016; Stygar *et al.*, 2016). However, current models have hardly taken into account the health status or the occurrence of endemic production diseases of sow (Rodriguez *et al.*, 2011). They cause less obvious losses to production and farm profit but occur across all production systems and management styles and cause unnecessary suffering.

Variation among models makes their overall applicability limited. One potential explanation is the origin or quality of data (Plà *et al.*, 2003; Rodríguez *et al.*, 2014). Models used for quantitative descriptions and predictions should be based on empirical data and research as much as possible. Observations can come either from experiments, reliable record-keeping software or well-justified literature but preferably from real farms (Plà, 2007). The research and data concerning diseases, feeding, metabolism, and labour requirements are not vast, but should be incorporated in a user-friendly manner into models for sow herds (Rushton, 2009). In addition, indirect effects of, for example, global markets can be at least as important as the direct effects under steady state conditions and should be accounted for (Rodríguez *et al.*, 2014). Moreover, validation of the models remains a problem (Plà, 2007).

3 OBJECTIVES

The overall aim in this thesis was to investigate sow removal in the rapidly changing Finnish production conditions and to identify factors associated with sub-optimal removal at the sow and at the farm level. The leading hypothesis was that there are patterns of differences in removal between individual sows and farms.

After firstly quantifying current sow productivity and removal in order to provide a standard of reference against which future development may be compared, this thesis had the following more specific objectives (publications are referred to by their Roman numbers I–III):

1. to study the productivity development across parities and over time, and to determine parity-specific removal rates and time-specific removal patterns (I)
2. to study how removal is affected by sow characteristics in different parities and provide risk estimates for further use as input values in economic and other mathematical models (I)
3. to assess the suitability of routinely collected pig registration data to study on-farm removal (II)
4. to characterize farms with contrasting patterns of management routines and housing conditions, and to investigate the relationships between them and on-farm removal (II)
5. to model sow herd dynamics and to study optimal replacement management and the economic aspects of the most relevant production diseases (III).

4 MATERIALS AND METHODS

The thesis is based on three individual studies. This chapter gives an overview of the materials and methods used in them. A more thorough description with detailed statistical depiction can be found in the original publications reproduced in the last chapter of this thesis.

The studies can be divided into three categories. The first two are conveniently split into the animal-level (I) and farm-level approaches (II), describing the population and the husbandry, respectively. They contribute to the profound familiarization of the area and are used to determine the current reality of piglet production in Finnish commercial farms. The third category accounts for both the animal-level and farm-level – the modelling study is based on a typical sow in a representative herd (III). The types of data collected for each category are different and the methods used reflect the differences.

4.1 Sow level approach

Piglet producing farms are using computerized herd health and management monitoring software, in which reproductive, performance and removal data are recorded on a daily basis to enable the user to monitor each individual animal closely and to improve herd management. Altogether 90 farms with an average inventory of 342 (median 124, range 26-2726) breeding sows were selected based on the herd managers' willingness to participate in the study (I). Study herds were required to be users of the WinPig, AgroSoft® herd management monitoring software.

The electronic web backups were firstly managed, processed and converted using WinPig.net, which is the new management system from AgroSoft A/S. Individual herd data files were thereafter imported as csv-files into the open source statistical software RStudio (Team, 2016). Comparable animal level recordings regarding performance and removal were extracted and merged.

All sows in production from 2013 to 2014 in the herds were eligible for inclusion in the study. Altogether, records from 71, 512 parity cycles commencing between 1 July 2013 and 30 June 2014 were selected from the merged sow population database. The cycles were followed over time from the production stage "farrowing" to the a) subsequent farrowing, b) 180 days postpartum or c) removal, whichever occurred first. To differentiate parity cycles 1 through 8, to enable comparison between them and to understand the temporal dynamics of sow removal according to parity number, subsets of data, i.e. cohorts, were formed based on the number of completed farrowings.

Baseline data on the relevant early productive life characteristics and the most recent, i.e. cohort-specific performance data were extracted and categorized. These potential risk factors were linked with time intervals after farrowing and the event of interest – removal from the herd.

The methodological core of the approach was based on classic descriptive epidemiology coupled risk analyses (I). In the available data, removal referred to different types of exit of sows from the herd regardless of the reason and was used as the outcome event of interest.

The descriptive analyses integrated elements of parity cohorts to scrutinize current production capacity of the Finnish sow population with special emphasis on removal. This was done to compare it with recent development, to describe the patterns of removal and identify stages of the parity cycles associated with increased risk of removal from the herd. Time data (in days) after farrowing to removal at different parities and during the parity cycle were analysed.

The impacts of early productive life characteristics were first studied as crude risks of removal. Thereafter, Poisson regression was used. It is typically used for modelling count data (Crawley, 2005). Its extension with a piecewise exponential model represents an alternative approach to modelling survival data (Schukken *et al.*, 2010; Elghafghuf *et al.*, 2014). In the models, the distinction between rate and risk diminished, as a relatively short time interval of 20 days was used as the unit of analysis (Cha *et al.*, 2013). Thus, risk was used throughout the analyses. Impacts of sow characteristics and time period post farrowing on the risk of being removed were evaluated separately for each parity cycle. All potential risk factors were modelled as fixed effects, adjusting for clustering within herd (Bates *et al.*, 2015). The generated models offered a tool for calculating the actual sow removal risks for any given period and combination of characteristics of interest.

4.2 Production systems

All Finnish piglet producing farms were eligible to participate in a survey regarding sow management and housing conditions in 2014 (II). After an extensive publicity campaign and in-person contacts, 43 farms finally agreed upon farm visits. The sample encompassed a diversity of piglet producing farms, including family-managed as well as expanded, larger-scale commercial farms run jointly by several farmers. These farms were scattered across Finland apart from the northernmost areas.

Primary farm level data for the study were gathered during farm visits through face-to-face interviews and an evaluation of the production facilities. A questionnaire to structure the interview and a detailed checklist for observations and measurements in each production unit, breeding, gestation and farrowing, were designed. Data were initially recorded on paper sheets and as Microsoft Word documents, extracted as raw data by means of macros into Excel spreadsheets, merged and further processed and analysed using the open source statistical software RStudio and its packages for multivariate exploratory data analysis (Lê *et al.*, 2008; Kassambara & Mundt, 2017).

Finally, a data set of 114 farm descriptors was obtained after exclusion of variables with missing information, too little or too much variability or without relevant information for the scope of the study. Among these variables the most representative ones, on the basis of their estimated contribution in characterizing the farms, were selected using a previously introduced stepwise selection method (Lê *et al.*, 2008; Lana *et al.*, 2017).

Farm typology construction is a process of classification, description, comparison and interpretation on the basis of selected criteria (Bailey, 1994). In this study (II), the final data set of farm descriptors was used to provide a simplified representation of the data, and explanation of the relationships among them. To structure the diversity across farming systems, the principles of multiple correspondence analysis (MCA) were followed (Lê *et al.*, 2008; Greenacre, 2010; Greenacre, 2017). Thereafter, a hierarchical cluster analysis (HCA) was carried out on the obtained MCA solution (Husson *et al.*, 2010). Finally, the typologies were defined as a specific combination of multiple variables after variable distribution comparisons (Husson *et al.*, 2010).

Registration of livestock is regulated both through application of Finnish and EU legislation (Council Directive 2008/71/EC, 2008). Each animal owner is obligated to report the monthly animal inventories and their changes three times a year to the National Swine Registry, administered by the national authority, the Finnish Food Safety Authority. Pig registration data for the study farms were obtained from this centralized database (II).

To benchmark the current national removal levels, culling and on-farm mortality (spontaneous death and euthanasia) percentages for 2014 were computed. The total number of animals sent for slaughter or which died on-farm was divided by the average of the reported monthly sow inventories. The overall removal percentage was defined as a summation of the obtained percentages. To link different levels of removal with farm descriptors the continuous figures were dichotomized using three threshold values: 30% (C_30), median (C_med) and 50% (C_50) for culling and 5% (M_5), median (M_med) and 15% (M_15) for mortality. All these binary variables took the value of 1 if they exceeded the threshold and 0 otherwise.

In order to recognize the potential associations between sow removal and farm descriptors, the constructed MCA was supplemented with the dichotomized removal figures (Greenacre, 2017). The obtained farm typologies were also compared by their removal patterns.

4.3 Economic model and optimization

Inclusion of large amounts of data from different sources improves models so they better represent real on-farm production circumstances (Plà, 2007; Rushton, 2009). Therefore, the data for this study (III) came from several different sources. The original model was formulated using a dataset obtained from the Finnish Animal Breeding Association (Faba), consisting of animal level data on productivity and genetics from 31,949 litters born in 2002 (Niemi *et al.*, 2010). The model was calibrated using a subset of data collected for study I with 18,753 sows in production in 2014 to account for litter size development and adjust removal rates. The parameter values for the diseases, e.g. prevalence, and effects on performance and survival, were retrieved from a former pig research station database with detailed recordings on performance, health, morbidity and treatments. Biological parameters including gestation length, weaning to oestrus interval, conception rate and weaning age were based on existing information collected from farms and relevant literature. The expenses, e.g. those related to feeds, insemination, sow replacement and labour, were based on national statistics and information acquired from commercial farms. The direct costs of treatments were estimated as an average cost per task. Veterinary care according to the national scheme for herd health management, labour to conduct the diagnosis, administration and cost of treatment were considered.

An existing stochastic dynamic optimization sow herd model, as described by Niemi (2010), was updated and modified to include two of the most common clinical entities that have a reasonable basis for influencing removal decision: postpartum dysgalactia syndrome (PDS/PPDS) and locomotory diseases. They occur frequently in commercial piglet producing herds and cause productivity losses, elevated mortality, increased labour requirements, treatment costs and premature sow removal. PDS/PPDS also may have long-term negative effects on fertility (Peltoniemi *et al.*, 2016). From an economic perspective, these production diseases lower the profit margins, and also impair animal welfare and cause unnecessary suffering (Dijkhuizen *et al.*, 1989; Anil *et al.*, 2009; Maes *et al.*, 2010; Heinonen *et al.*, 2013; Pluym *et al.*, 2013; Cador *et al.*, 2014; Pendl *et al.*, 2017; Pluym *et al.*, 2017).

In the model, the objective function maximizes the sow space unit returns over a given decision horizon by optimizing the voluntary replacement decision. It impacts both the current and future costs and returns, and thus it is important to account for both. Decisions are optimized on the condition that sufficient production capacity is allocated to each production stage.

A sow is represented as a production unit in the model. A schematic representation in Figure 2 shows a sow passing through different discrete stages during her life in a cyclic manner until she is replaced by a new parity one sow that restarts the same process. In the dynamic system, each stage is hierarchically associated with three states that describe observable characteristics of a sow and impact the decision: parity number, performance as piglet yield and occurrence of disease. The next state of a sow is not known with certainty. It is affected by the current state, the probability of being diseased and the probability of survival to the next stage. The dynamic system solves these multistage problems sequentially by making decisions at each stage and simulating returns. By including a disease state in the model, the negative effects associated with impaired health, such as lowered production, are addressed. The maximized expected returns on investment given a specific production technology are computed.

4.3.1 Scenarios

After running the baseline scenario (1.), what-if scenarios for demonstration purposes were conducted to assess the magnitude of the effects of diseases, removal and treatment costs. Simulation was run for scenarios 1 through 9. Thereafter, a sensitivity analysis in response to a farm's average replacement rate was conducted. Each of the nine scenarios was simulated with an increased removal rate to resemble a herd where sow longevity is generally poorer than in the standard simulation focusing on a typical herd.

1. Baseline scenario reflecting herds from which the data were derived.

The incidence of PDS/PPDS is

2. reduced by 50% from the baseline scenario.
3. set at 0 (reduced by 100% from the baseline scenario).

The incidence of locomotory disorders is

4. reduced by 50% from the baseline scenario.
5. set at 0 (reduced by 100% from the baseline scenario).

The incidence of PDS/PPDS and locomotory disorders

6. are set at 0.

The probability of removing the sow is

7. decreased by 0.1 (10%) from the baseline scenario.
8. is increased by 0.1 (10%) from the baseline scenario.

Treatment costs of sows suffering from either disease

9. is doubled from the baseline scenario.

5 RESULTS

Studies I and II provide descriptions for the population dynamics and current sow farming systems. Study III describes the relationship between sow removal, health status, productivity level and the economic importance thereof. Only the main findings of the studies are presented below. A more detailed review of the results can be found from the original publications coupled with supplementary material (I) reproduced at the end of this thesis.

5.1 Population characteristics

5.1.1 Sow productivity

The production characteristics of the current population as piglets born in total and the number of stillborn are presented in Table 2 (I). The cohort-specific farrowing is the most recent one, i.e. for cohort 8 the most recent farrowing was the eighth, occurring in the enrolment period from July 1, 2013 to June 30, 2014, whereas the first farrowing of cohort 8 members occurred seven cycles earlier.

Table 2. Descriptive productivity statistics (mean, (SD)) by cohort (vertical) and parity cycle (horizontal). Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) over the enrolment period of 1st July, 2013 through 30th June, 2014. Preceding baseline performance data across all parity cycles before the enrolment period were collected from existing records and linked with cohort specific ones. The most recent farrowing of each cohort is bold (adapted from Bergman et al., Preventive Veterinary Medicine, 159, 30-39, 2018).

	Cohort							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
n[1]	17379	13605	11547	9783	7637	5700	3795	2066
1st litter piglets born	**13.7 (3.5)**	13.5 (3.4)	13.6 (3.2)	13.5 (3.2)	13.4 (3.2)	13.2 (3.1)	13.1 (3.0)	12.9 (2.9)
1stlitter stillborn	**0.88 (1.4)**	0.83 (1.3)	0.85 (1.3)	0.84 (1.3)	0.82 (1.3)	0.76 (1.2)	0.73 (1.1)	0.70 (1.1)
2nd litter piglets born		**14.2 (3.6)**	14.1 (3.5)	14.3 (3.4)	14.3 (3.4)	14.2 (3.4)	14.0 (3.3)	13.7 (3.2)
2nd litter stillborn		**0.88 (1.4)**	0.81 (1.2)	0.79 (1.2)	0.76 (1.2)	0.73 (1.1)	0.71 (1.1)	0.64 (1.0)
3rd litter piglets born			**15.1 (3.6)**	15.2 (3.4)	15.4 (3.4)	15.3 (3.4)	15.1 (3.3)	14.9 (3.2)
3rd litter stillborn			**1.14 (1.6)**	1.03 (1.4)	1.02 (1.4)	0.98 (1.3)	0.93 (1.3)	0.87 (1.2)
4th litter piglets born				**15.4 (3.7)**	15.5 (3.5)	15.6 (3.4)	15.5 (3.4)	15.3 (3.3)
4th litter stillborn				**1.41 (1.8)**	1.28 (1.6)	1.23 (1.5)	1.15 (1.4)	1.05 (1.3)
5th litter piglets born					**15.2 (3.6)**	15.4 (3.5)	15.4 (3.4)	15.3 (3.3)
5th litter stillborn					**1.51 (1.8)**	1.37 (1.6)	1.34 (1.6)	1.23 (1.5)
6th litter piglets born						**15.0 (3.7)**	15.0 (3.5)	15.1 (3.3)
6th litter stillborn						**1.74 (2.0)**	1.50 (1.7)	1.35 (1.6)
7th litter piglets born							**14.5 (3.7)**	14.7 (3.5)
7th litter stillborn							**1.72 (1.9)**	1.41 (1.6)
8th litter piglets born								**14.0 (3.8)**
8th litter stillborn								**1.67 (1.9)**
[1]Number of sows in total								

5.1.2 Litter size development

An outline of productivity development over recent years and across the productive life of a sow is demonstrated in Figure 3. The parity cycle specific average litter sizes are illustrated as different point shapes above one another, representing the change over time, whereas the similar point shapes from left to right demonstrate the biological productivity development as a sow ages from the first to the eighth farrowing.

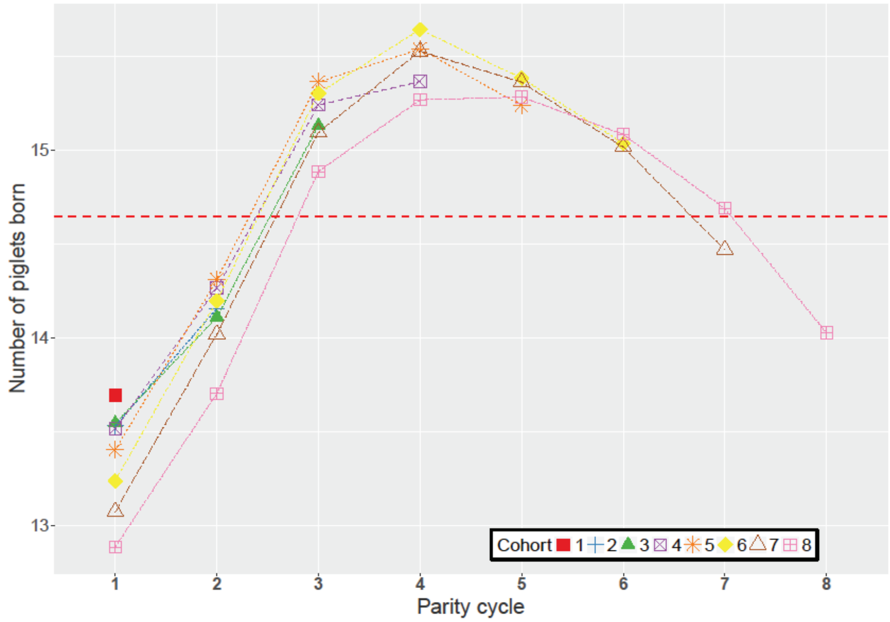

Figure 3 The numbers of piglets born in total in each parity cycle from the first to the eighth (x-axis) and for each cohort (the different point shapes and coloured lines as described in the legend box). Cohort is defined as a group of Finnish sows starting the same parity cycle (1 through 8) over the enrolment period of 1st July, 2013 through 30th June, 2014. The litter sizes of the sows belonging to the same cohort contributed to the group means. The entire performance histories until the cohort specific farrowing were considered. The horizontal broken line represents the overall average litter size.

5.1.3 Removal risk

5.1.3.1 Parity cycle removal risk

The proportion of sows failing to produce another litter and the cumulative stayability are illustrated as a flowchart (Fig. 4). In total, approximately 60% of the sows survived beyond their third farrowing. The best sows in the sample stayed in production for more than eight parity cycles, and the oldest had farrowed 21 times.

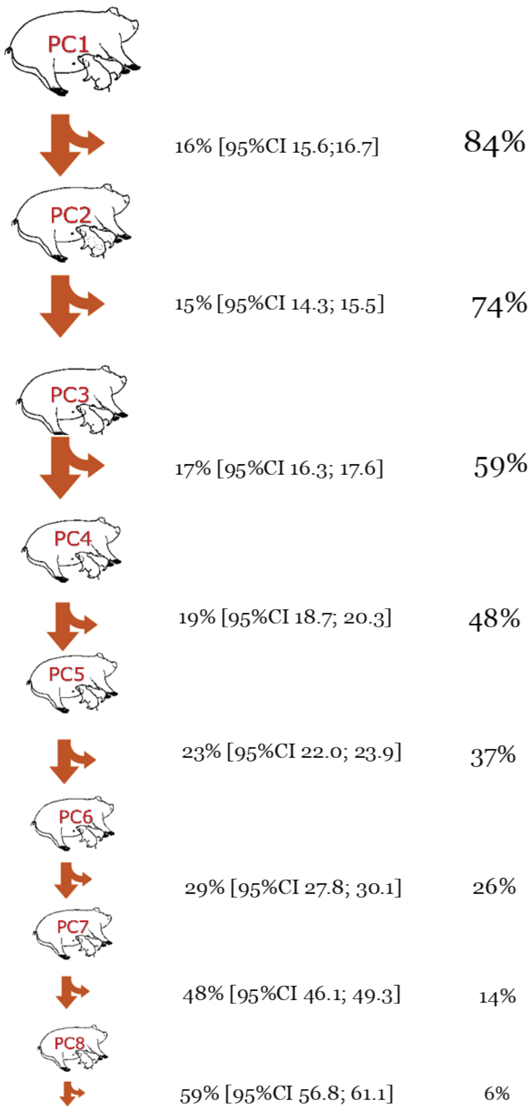

Figure 4 The proportion of sows (percentages (95%confidence intervals)) failing to produce another litter (removal) and the cumulative stayability (on the right) in a sample of Finnish sows starting the same parity cycle (PC) 1 through 8 over the study enrolment period of 1st July, 2013 through 30th June, 2014. Parity specific removal risks were defined as the number of removed sows divided by the number of sows starting that cycle x 100. Stayability was defined as the proportion of previously survived sows multiplied by the probability of survival at that parity.

5.1.3.2 *Removal patterns*

From 71,512 initiated cycles from the first to the eighth, a total of 15,128 culminated in removal. Figure 5 provides temporal information as to when during the cycle removal occurred and demonstrates differences across parities. The profiles represent the percentage distributions of all removals as days from the last farrowing to removal. Time periods post farrowing were also included as risk factors in the models. Detailed parity-specific risk estimates are provided in the supplementary material of publication I, reproduced at the end of this thesis. According to Finnish legislation, sows should nurse for at least 28 days, before which weaning should not occur (Animal Welfare Act 247/1996: Government Decree 15.12.2012/629, 2012).

A negative linear relationship between parity count and the mean days from farrowing to removal was recorded: the mean (median) times from parturition to exit was 65 (41) days, but varied across parities from 74 (62) in the first to 42 and 47 (34, 34) in the eighth and seventh parities, respectively.

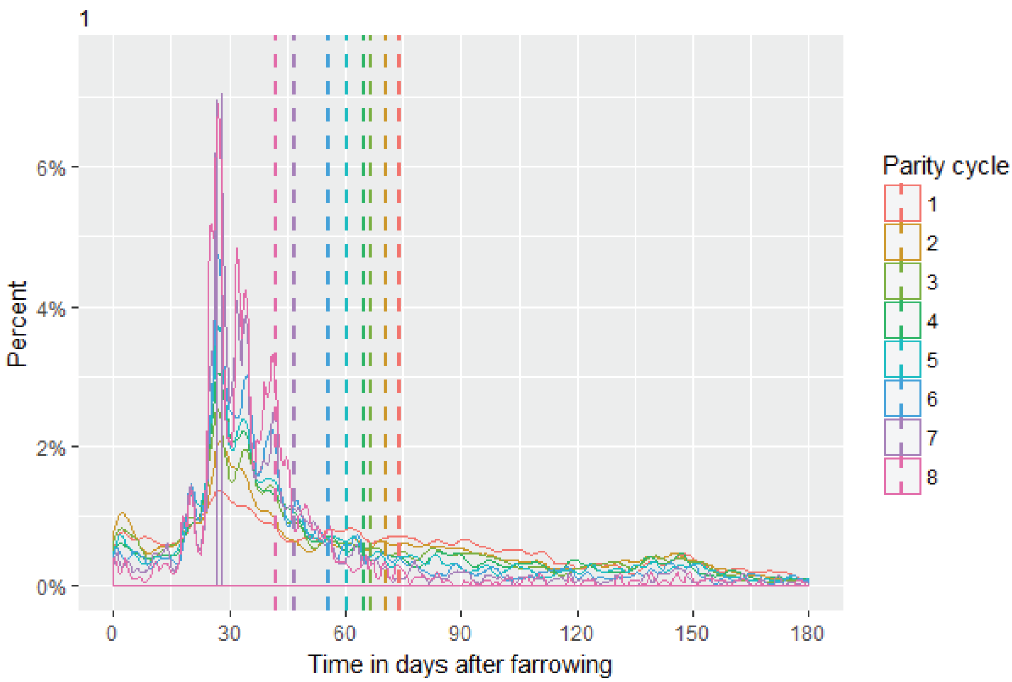

Figure 5 Percentage removal distributions calculated as (removals occurring in a time step/all removals) × 100 separately for each commenced parity cycle 1 through 8 over the study enrolment period of 1st July, 2013 through 30th June, 2014. The broken vertical lines represent the parity-specific mean times from the last farrowing to exit.

5.1.3.2 Risk factors

Parity specific crude removal risks for sows having had a small first litter (<11 piglets) were greater than for sows having farrowed a medium sized (12-15) or large (>15) first litter in parities 1 through 5. However, the difference was significant only in the low parities ($p<0.05$). The impact of a small second litter was more evident than that of a small first litter – sows having farrowed a second litter with fewer than 11 piglets were most likely removed compared to other sows ($p<0.05$). The phenomenon persisted until the seventh parity.

In concordance, the model estimates indicated a protective effect of a medium or large first and second litter compared with the baseline (small litter size). The largest effect was demonstrated for parity two sows that had produced a large litter: a sow with a second litter of 17 piglets or more was less likely to be removed than a sow farrowing 10 piglets or fewer (RR=0.58, 95% CI: 0.5-0.68). All detailed parity-specific estimates are provided in the supplementary material of publication I, reproduced at the end of this thesis.

Furthermore, the model estimates demonstrated that the size of the most recent litter, i.e. the cohort-specific one, had a strong effect on the risk of removal within each parity. The largest litters decreased the risk the most. The greatest effect appeared among the fifth parity sows – a sow with a large fifth litter of more than 16 piglets had only approximately one-third of the removal risk (RR=0.37, 95% CI: 0.31-0.43) of a sow farrowing fewer than 12 piglets.

The numbers of stillborn piglets in the low parities were also linked to the removal risk in several subsequent parities. Two or more dead piglets increased the removal risk compared with sows that produced solely viable piglets until the sixth parity.

5.2 Production systems

5.2.1 Multiple correspondence analysis (MCA)

Figure 6 presents the multiple correspondence (MCA) solution for the most informative variable categories to characterize the farms. The two-dimensional display uncovers variable

Figure 6 Multiple correspondence analysis (MCA) graph of the farm descriptors supplemented with different levels of removal. It shows the relations between management practices and housing conditions (gradient-coloured) and the dichotomized (0/1) removal levels (in black) of culling <30% (C_30), <median (C_med) and <50% (C_50) and mortality <5% (M_5), <median (M_med) and <15% (M_15) in 43 farms in Finland, 2014. The two perpendicular coordinate axes are referred to as Dim1 (x) and Dim2 (y). To interpret the graph, the violet coloured categories are considered to make the strongest contributions, whereas the orange ones the least, and the points close together in the same quadrants along a similar direction from the centroid are indicative of possible associations. The acronyms of the farm variable categories are specified in Table 1 in article II, reproduced at the end of this thesis (adapted from Bergman et al, *Porcine Health Management*, 5:12, 2019).


Variable categories – MCA
Dim 1 (20.5%)
Dim 2 (10.9%)
contrib

relationships. In the graph, subjects with many frequent variable categories are located near the origin of the dimensions, whereas the further a category lies from the origin, the greater the deviation is from the expected, or from the sample average pattern.

The first dimension accounted for 20.5% of the variance and was best described by the number of sows per caretaker and herd size. Characteristic variables of the dimension were also the ones capturing information about the flooring, the use of bedding material and room size in the breeding unit. Moreover, the type of flooring, the use of bedding and nesting materials in the farrowing unit and the use of bedding material in the gestation unit and space allowance were also characteristic of the dimension.

The second dimension accounted for 10.9% of the variance and was best described by variables that were mainly related to gestation: use of bedding and rooting materials, manure management, group size and flooring. This dimension was also partly described by the use of farrowing induction.

The dichotomized removal figures: 30% (C_30: C_30_0/C_30_1), median (C_med) and 50% (C_50) for culling and 5% (M_5), median (M_med) and 15% (M_15) for mortality were added to the MCA graph to provide visualization of their distribution along the dimensions. They can be interpreted by their co-location with the farm descriptors. The variables representing culling below the median or 30% are in the lower right quadrant, whereas the ones above 30%, the median and 50% are all located in the upper left quadrant. The coordinates of the variables representing the increasing levels of mortality shift gradually from the positive to the negative side of the first dimension.

5.2.2 Removal figures

In 2014, the average overall sow removal percentage in the study sample was 47.7% (95% CI: 43.3-52.2), of which 38% (95% CI: 34.1-42.0) were sent to slaughter and 9.7% (95% CI: 7.9-11.5) died on-farm. Figure 7 illustrates the overall percentages as well as the comparisons for the farm clusters.

5.2.3 Farm clustering and their typology characteristics

MCA was used as a pre-processing step for classification purposes (Husson *et al.*, 2010) (II). The solution was introduced to hierarchical cluster analysis (HCA). Based on the level of similarity within and between members, the analysis revealed 3 farm clusters. The farm typology characterisation was based on these clusters and tested by comparing variable distributions (hypergeometric test) to identify over-represented or under-represented sub-categories in the sample (Husson *et al.*, 2010).

CLUSTER 1 with the highest levels of removal

Herds in cluster 1 were most frequently large, having more than 635 sows ($p<0.01$) with more sows per caretaker ($p<0.01$). Large room sizes were mostly favoured both in the breeding ($p<0.05$) and gestation units ($p<0.05$), where also higher stocking density was

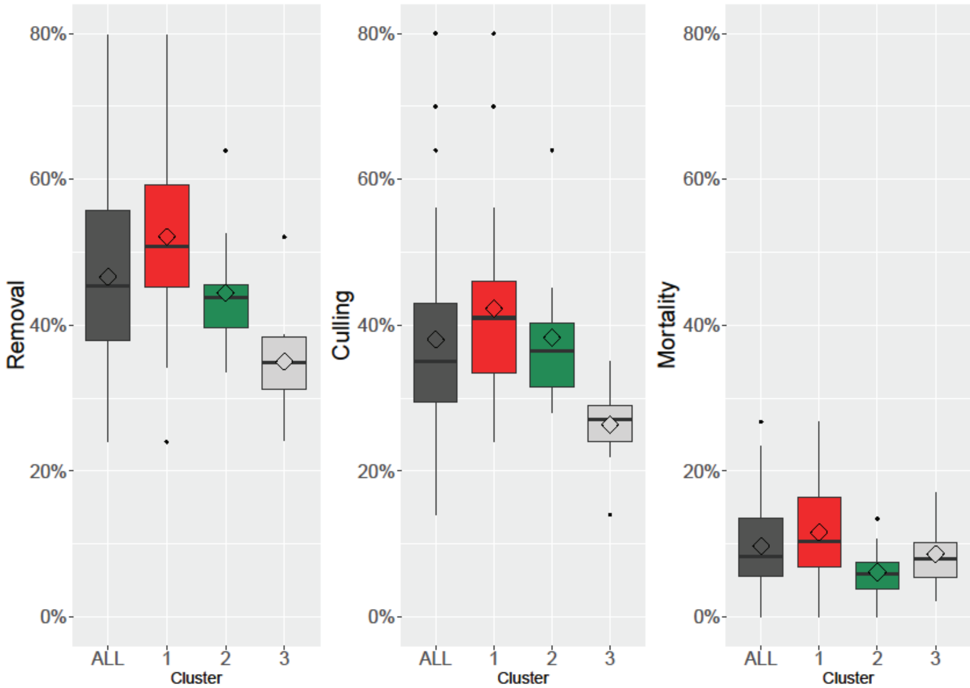

Figure 7 Boxplots showing median (central thick lines), 25 and 75% quartile ranges around the median (box width) and mean (diamond) of the three separate removal figures (removal, culling and mortality) for the entire sample (dark grey) and each farm typology (1 in red, 2 in green and 3 in light grey). (adapted from Bergman et al., *Porcine Health Management*, 5:12, 2019)

most common ($p<0.01$). The sows in these farms were also most likely to have smaller farrowing pens ($p<0.01$).

The use of a combined breeding and gestation units was hardly ever observed in cluster 1 farms ($p<0.01$). Invariably, locked stalls were used in the breeding unit ($p<0.01$).

The floor was never completely solid in either the breeding unit ($p<0.01$) or the farrowing pens ($p<0.05$). More than 20% slatted floors in the gestation unit were commonly observed ($p<0.01$), and manure was mostly managed as slurry ($p<0.01$) in these farms. An inadequate amount of bedding material predominated in the breeding ($p<0.01$) and gestation units ($p<0.01$) as well as farrowing pens ($p<0.05$) compared with the other two clusters. In addition, dirtier pens were more likely to be observed in the cluster 1 breeding ($p<0.05$) and gestation units ($p<0.01$).

In cluster 1 the average culling percentage was 42.3% (95% CI: 36.7–47.8) and mortality 11.6% (95% CI: 8.9–14.3). Considering the various dichotomized threshold levels, it was observed that farms from this cluster most frequently had culling levels above 30% ($p<0.05$) and the overall sample median ($p<0.05$) as well as mortality levels above all the investigated levels ($p<0.05$) compared with clusters 2 and 3. In particular, the overall frequency of on-farm mortality above 15% across the whole sample was 18.6%. Altogether 87.5% of the farms exceeding this level of 15% belonged to cluster 1 and 37.5% of the farms in cluster 1.

CLUSTER 2 with the lowest levels of mortality

Cluster 2 farms did not differ significantly from the others in terms of size, but an intermediate number of sows per caretaker, i.e. 58-147, was most common ($p<0.05$). Larger breeding and intermediate gestation unit room sizes and larger gestation sow group sizes (>10 sows) were common, but the differences were not significant. A very common feature of this cluster was to have more space in the gestation unit for the sows ($p<0.01$), and more than half of these farms also had larger farrowing pens compared with the farms of the other clusters ($p<0.05$).

As in the cluster 1 farms, locked stalls were mostly used in the breeding unit also in cluster 2 farms.

A solid floor in the gestation unit characterized cluster 2 farms ($p<0.01$) and manure was most often managed dry ($p<0.01$). Furthermore, these farms were the most frequent users of a lot of bedding material in the breeding ($p<0.05$) and gestation units ($p<0.01$), where the most frequent use of a lot of rooting material was also recorded ($p<0.01$). Gestation pens were hardly ever evaluated as being dirty ($p<0.05$).

With the mortality percentage of 6.1 (95% CI: 3.3-8.9) this cluster differed significantly from cluster 1 ($p<0.05$). Considering the dichotomized thresholds across the clusters, cluster 2 farms were most likely to have their mortality levels both under the entire sample median, and also under 5% ($p<0.05$). In total, 16.3% of all the farms succeeded in keeping their on-farm mortality below the 5% level. Altogether 57.1% of these farms belonged to cluster 2 and 40.0% of the farms in cluster 2 remained below the 5% mortality level.

CLUSTER 3 with the lowest levels of culling

Most of the farms in cluster 3 were smaller housing fewer than 103 sows ($p<0.01$) and had on average fewer sows per caretaker (< 58 sows) ($p<0.01$). It was most usual to keep the gestating sows in rooms smaller than 50 animals ($p<0.01$) as well as in groups smaller than 11 sows ($p<0.05$).

The use of combined breeding and gestation units was common ($p<0.01$). Trough feeding was most common ($p<0.05$). The four distinct gestation unit types (group housing with electronic transponders, pens without stalls with trough feeding, pens with stalls or locked stalls) were mainly uniformly distributed across the sample farms, apart from pens without stalls, which were mostly common in cluster 3 farms ($p<0.05$).

Induced parturition was hardly ever used on these farms ($p<0.05$) and the use of oxytocin during farrowing was least frequently reported.

Farm personnel seemed most active in providing at least some bedding ($p<0.05$), a lot of rooting ($p<0.01$) and a lot of nesting materials in the farrowing pens ($p<0.01$).

With an average culling of 26.3% (95% CI: 21.5-31.2) the cluster differed statistically significantly from clusters 1 ($p<0.01$) and 2 ($p<0.01$). In concordance, these farms differed from the other farms in having dichotomized culling levels most often under 30% and the overall sample median ($p<0.05$). Only one farm had its culling percentage exceeding the overall sample median. The overall frequency of culling below the level of 30% was 32.6%. Altogether 50% of farms below 30% culling level belonged to cluster 3. Of cluster 3 farms, 66.7% were associated with culling levels below 30%.

With an average mortality percentage of 8.7% (95% CI: 4.9-12.4) this cluster did not differ significantly from the other two. However, more than half of the farms in this cluster had their on-farm mortality levels under the overall sample median and only one exceeded the 15% level.

5.3 Economic model

5.3.1 Lifetime performance

The overall lifetime productivity as a result of each of the different simulation scenarios assessing the magnitude of the effects of diseases, removal and treatment costs is presented in Table 3. In the baseline scenario, on average, a sow produced 3.48 litters. Across the what-if scenarios, the mean parity fluctuated between 2.3 and 4.56 and the numbers of lifetime weaned and sold piglets were 45.7 and 44.2 at their highest, respectively.

Table 3. Lifetime piglet yield (number of weaned and sold piglets) and expected number of litters produced per sow, according to the dynamic programming model for the standard simulation baseline scenario and eight what-if scenarios. Each of the nine scenarios was repeated with an increased removal rate to resemble a herd with a poorer longevity compared to the standard (sensitivity analysis). The maximum productivity values are (scenario 7) bold and in blue whereas the lowest values (scenario 8) are bold and in red (adapted from Niemi et al., Frontiers in Veterinary Medicine, 2017).

Scenarios		Standard simulation			Sensitivity analysis		
		Piglets sold	Piglets weaned	Number of litters	Piglets sold	Piglets weaned	Number of litters
1)	Baseline	34.0	35.1	3.48	29.1	30.1	2.90
2)	PDS/PPDS −50%	35.4	36.6	3.62	30.2	31.2	3.00
3)	PDS/PPDS −100%	36.8	38.1	3.76	31.4	32.4	3.10
4)	Locomotory disorders −50%	34.6	35.8	3.54	29.6	30.6	3.00
5)	Locomotory disorders −100%	35.2	36.4	3.61	30.1	31.1	3.00
6)	PDS/PPDS, locomotory disorders −100%	38.1	39.3	3.88	32.5	33.5	3.30
7)	Probability of removal – 10%	**44.2**	**45.7**	**4.56**	**37.3**	**38.6**	**3.80**
8)	Probability of removal + 10%	**26.8**	**27.7**	**2.72**	**23.3**	**24.1**	**2.30**
9)	Treatment costs doubled	34.1	35.2	3.49	29.1	30.1	2.90

5.3.2 Production capacity requirements

The results concerning the optimal decision based on litter size varied among the what-if scenarios, as illustrated in Figure 8 for a subset of them. According to the baseline, a sow needed to produce a litter of at least six piglets in the seventh and of 12 in the eighth parity cycle to remain in the herd, whereas with a lower probability of removal larger litter sizes were required. In contrast, with a higher probability of removal, i.e. poorer herd longevity, sows with lower productivity levels had to be kept in the herd.

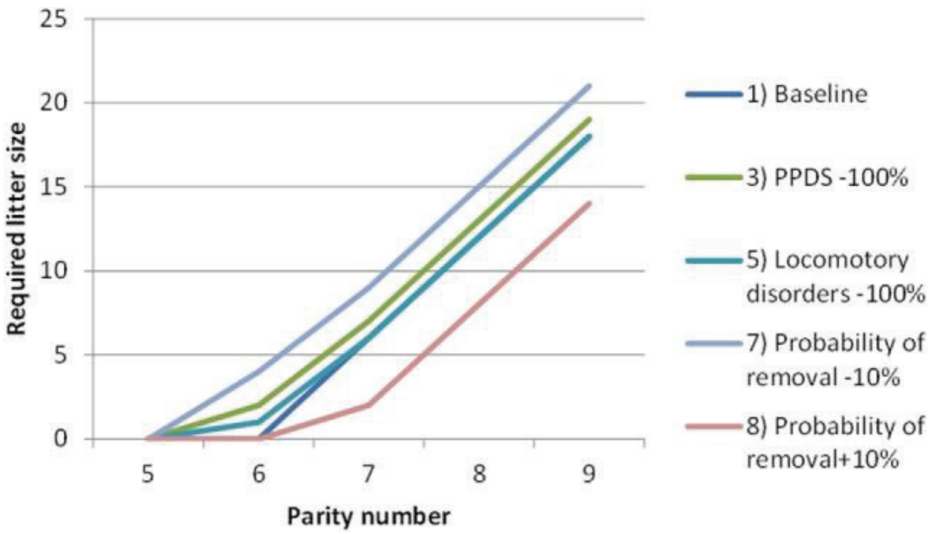

Figure 8 The minimum litter size (by parity number) that a sow must exceed in order to remain in the herd, according to five standard what-if scenarios simulated using the dynamic programming model. PDS/PPDS, postpartum dysgalactia syndrome. (from Niemi et al., *Frontiers in Veterinary Medicine,* 2017)

5.3.3 Economic consequences

Figure 9 (left) shows the expected return on fixed costs per sow space unit, i.e. the expected value of current and replacement sows over the entire decision horizon of a farm. The return was €3,962 for a sow space unit in the baseline scenario. It was €279 and €110 higher after elimination of PDS/PPDS and locomotory diseases, respectively. It was also demonstrated that the 10% change in the removal rate caused the most significant changes among the scenarios which were analysed. The changes in treatment prices also affected the expected returns. Sensitivity analysis accounting for a generally poorer longevity revealed that the results were sensitive for removal rate: the returns were lower and the corresponding disease effects were more evident (Figure 9, right).

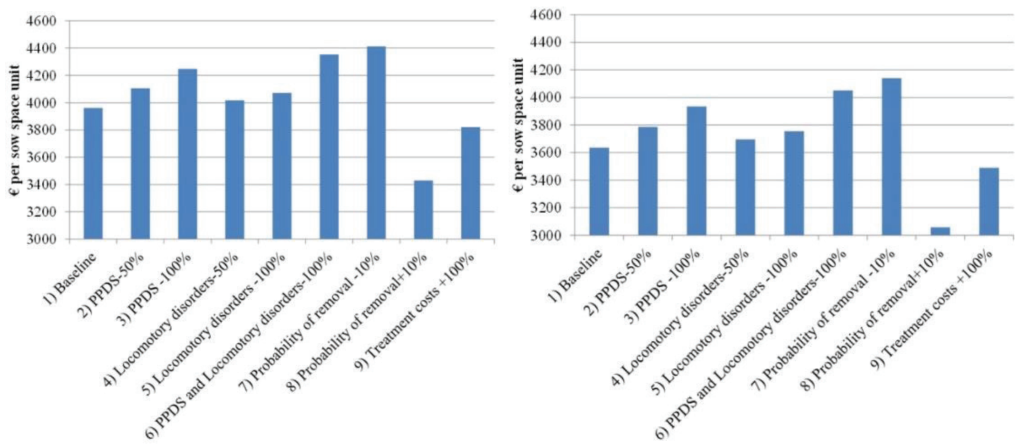

Figure 9 Return on fixed costs as euros per sow space unit simulated by the dynamic programming model. The results based on the standard simulation baseline scenario and eight what-if scenarios are presented on the left. In the sensitivity analysis, each of the nine scenarios was repeated with an increased removal rate to resemble a herd with a poorer longevity, replacement decision were solved and corresponding returns computed, on the right. PDS/PPDS, postpartum dysgalactia syndrome. (from Niemi et al., *Frontiers in Veterinary Medicine, 2017*).

Per affected sow, the losses caused by diseases were €300-470 and €290-330 for PDS/PPDS and locomotory disorders, respectively. The corresponding losses in total for an average sized herd of 469 sows in the 2014 data set approximated to €11,000€ annually. Expanding the perspective to national level yielded a rough estimate of annual losses of 2 to 4 million euros because of PDS/PPDS and locomotory disorders in Finland.

6 DISCUSSION

Herd sizes have been increasing, income margins narrowing and production environments changing rapidly. Current pig breeding places increasing demands on farmers' overall management skills. Sow removal is a complex phenomenon influenced by several factors. Finding the right balance between keeping a herd young enough with a good health status while maintaining a desired number of productive sows is a continuous everyday challenge. Excessive removal is costly and can partly explain the profound difference between a farm's failure and success. There is an urgent need for accurate information for management support.

We anticipated to generate fresh figures on sow removal under current Finnish production conditions. Additionally, we aimed to provide more insight into the discussion on replacement, the existing possibilities and potential factors involved in the selection of animals to the long-surviving ones. We also questioned the prominent role of quantitative measures in piglet production and investigated the dissimilarities across farming systems. Moreover, we assessed the economic value of improved animal health and removal.

6.1 Quantifying removal figures to provide a reference

Herd turnover and mortality in particular are two of the animal-based measures reflecting wellbeing, morbidity and mortality on-farm (Ortiz-Pelaez *et al.*, 2008; Welfare Quality®, 2009; Alvasen *et al.*, 2014a; Thomsen & Houe, 2018; Oie, 2019). However, to our knowledge, no national benchmark figures for sow removal exist. We established a baseline for culling and mortality in an evidence-based, well-studied fashion (II). Our figures were retrieved from regular, mandatory recordings. For the animal inventories a more precise approach considering the monthly animal inventories to average herd sizes was used to improve the quality of the estimates (Fetrow et al., 2006).

Secondary animal registration data proved useful for research purposes to quantify removal levels at the herd and national levels. These data may also be suitable for multidimensional animal welfare monitoring (Ortiz-Pelaez *et al.*, 2008; Thomsen & Houe, 2018). However, in this project we were able to retrieve estimates for removal only for 12 months. Any trends appearing would require continuous monitoring to detect unusual patterns, to identify problem herds and to improve the survey of the national course in culling and on-farm mortality (Alvasen *et al.*, 2014b).

The average culling and mortality over the 12-month monitoring period accorded with published internationally reported averages (Engblom *et al.*, 2007; Koketsu, 2007a; Sasaki & Koketsu, 2008a; Jensen *et al.*, 2012; Masaka et al., 2014; Tani *et al.*, 2018). In line with previous reports, large differences were observed in our study population also, implying that it is conceivable to strive for and reach certain specified targets. As an example, some farms did succeed in keeping their removal levels below 5% (II). In addition, the currently sought target levels for replacement are likely to be reconsidered in the near future due to various production constraints, environmental issues and animal welfare objectives (Honeyman, 1996; EFSA, 2007; Gerber *et al.*, 2013; FAO, 2016; European Comission, 2018).

The inability to compare culling and mortality studies due to inconsistent use of terminology and methods complicates the interpretation of any removal results. The means for calculating and reporting removal rates at parity, herd and national levels differ (Fetrow et al., 2006; Jensen *et al.*, 2012; Knage-Rasmussen *et al.*, 2015; Wang *et al.*, 2019). A long term, nation-wide benchmarking of removal on mutually agreed terms would be practical to demonstrate and monitor replacement management. It might also be suitable for multidimensional and among-countries comparative animal-welfare evaluation.

6.2 Prolificacy and its development

Multidisciplinary research over recent decades has accelerated the breeding of highly prolific sows (Southwood & Kennedy, 1991; Estany & Sorensen, 1995; Merks *et al.*, 2000; Marantidis *et al.*, 2013). Various novel management practices have further enabled the increased efficiency of reproduction in breeding herds (Koketsu *et al.*, 2006; Koketsu, 2007b; Heim *et al.*, 2012; Baxter *et al.*, 2013; Koketsu *et al.*, 2017). Our results show that this also holds true for the Finnish sow population (I).

We quantified the average current sow production levels to help in considering further targets and to provide a reference against which future development could be compared. On average, at an individual animal level, the productivity was already relatively high with an average litter size of 14.65 (± 0.5) in the entire study population. Over a time period that corresponds with seven parity cycles of a sow, an increase from parity one prolificacy level of 12.9 to almost 14 piglets was observed. A recent study by Hasan et al. (2019) with a limited number of Finnish farms and litters of average mature sows indicated that litter sizes are continuously increasing. They reported mean numbers of piglets born in total ranging from 14.6 to 17.1. In turn, Serenius et al. (2003) presented results from Finnish sows born between 1985 and 1999. In comparison with this past litter information showing prolificacy of 10.4 and 10.8 piglets for first parity Landrace and Finnish Large White females, respectively, there has been an increase in first litter size of approximately three piglets (Serenius et al. 2003).

However, we found the largest, biology-based differences in production capacity across parities (I). Piglet yield exceeded 15 already in the third farrowing, but to realize the full performance potential in terms of litter size, a sow would need to reach her fourth parity. Even thereafter, the litter size only gradually started to decline. However, our data indicated that the genetic potential in the most recent cohorts could not be fully exploited. The observed increase in early litter sizes was not associated with a consistent increase in subsequent parities according to the biological productivity.

Low, i.e. first and second parity, litter sizes have been shown to be associated with subsequent parity and lifetime performance, potentially improved reproductive fitness as well as stayability (Sasaki *et al.*, 2011; Iida & Koketsu, 2015; Iida *et al.*, 2015; Andersson *et al.*, 2016; Gruhot, 2017b). In line, our results indicated that larger litters tended to reduce the risk of removal compared to the smallest ones (I). However, high level of involuntary culling due to other common reasons, e.g. reproduction and locomotory disorders, complicate the implementation of any predetermined selection on performance level (Engblom, 2008). Our modelling study also pointed out that litter size could be emphasized more if the overall removal rate was reduced and sow health improved, because at a lower overall removal rate, the sow needed to produce larger litters to stay in the herd (III). Thus, limited opportunities to make decision to cull young sows based on inadequate performance and differences in voluntary replacement criteria, farm-specific perceptions and production goals may partly explain the hardly noticeable improvements in litter size in later parity cycles. Furthermore, it is also known that sow productivity, especially litter size, can vary substantially and can be markedly influenced by management, feeding regimen, housing factors and potentially season (Lawlor & Lynch, 2007; Iida *et al.*, 2015).

Increased litter sizes have been preferred and considered as an important and positive overall change (Koketsu, 2007a; Iida & Koketsu, 2015; Iida *et al.*, 2015; Koketsu *et al.*, 2017). However, along with the genetic improvement in trait performance, various correlated responses have been emerging (Roehe, 1999; Merks, 2000; Roehe & Kalm, 2000; Lund *et al.*, 2002; Milligan *et al.*, 2002; Canario *et al.*, 2006; Hellbrügge *et al.*, 2008; Rutherford *et al.*, 2013). There is a wealth of evidence that increased fertility is a greater burden for the sow both during pregnancy and thereafter while nursing, and it is coupled with offspring related problems (Roehe, 1999; Lund *et al.*, 2002; Quiniou *et al.*, 2002; Rekiel *et al.*, 2014). Andersen *et al.* (2011) suggested based on their behavioural study that considering sibling competition, piglet survival and development, 10–11 piglets likely reflect the upper limit that the domestic sow is capable of properly caring for. Therefore, lactation management including nursing and fostering techniques to improve piglet survival is an everyday challenge in high performance herds (Baxter *et al.*, 2013; Ferrari *et al.*, 2014; Alexopoulos *et al.*, 2018). In particular, basic husbandry routines, monitoring and housing aspects in early lactation must be carefully addressed (Koketsu *et al.*, 2006; Alonso-Spilsbury *et al.*, 2007). Nonetheless, along with this equalisation of the litter sizes, stress is induced both by separation and introduction to sows and piglets and the population is exposed to an increased amount of pathogen transfer (Robert & Martineau, 2001; Baxter *et al.*, 2013; Rutherford *et al.*, 2013).

Understanding parity differences in performance of sows and consequences of high prolificacy is important when making replacement decisions, controlling herd age structure and especially when tailoring nursing-related management protocols to ensure sufficient overall production to meet the farm-specific targets.

6.2 Early sow removal

Indisputably, targeted selection strategies have succeeded in making sows more prolific. At the same time, we demonstrated culling of these improved sows on commercial farms from 15 to 17% in low parities: one in six young sows had been considered unfit for further production, meaning that less than 60% of the initiating gilt inventory made it through the third parity cycle to farrow a fourth litter (I). The proportion of removed first parity sows was even higher in the research farm dataset used in study III, where after the first farrowing 25% of sows were removed from the herd. The highest overall percentage of treated sows and removal rate after treatment was also found at the first parity.

A comparison between studies is hardly possible. Mostly, the parity-specific removal is described as a proportion of all culls regardless of the size of the original animal inventory (Engblom *et al.*, 2007; Segura-Correa *et al.*, 2011; Masaka et al., 2014; Wang *et al.*, 2019). This is probably due to the difficulty of retrieving information on the specific numbers of productive animals and herd-specific parity distribution. We reported the parity specific wastage, the number of sows removed during a particular cycle commenced during a short period of time (one year) divided by the number of sows at the start of that cycle, to better highlight current problem areas as also suggested by Koketsu (2007a) and Houška (2009). The observed levels in our study accorded with Andersson *et al.* (2016) who reported the removal in a comparable manner in another Fenno-Scandinavian sow population. Greater first parity removal percentages (exceeding 20%) were also reported earlier (Dagorn & Aumaitre, 1979; Dijkhuizen *et al.*, 1989; Koketsu, 2007a). In contrast, a skilfully detailed study on Spanish sows reported slightly lower early removal rates. However, the data set was constructed differently and stratification on pregnancy status was used (Tani *et al.*, 2018).

The high sow turnover in low parities results, paradoxically, in an even younger population (Houška, 2009). Gilts and younger sows are shown to have poorer performance, lower reproductive fitness and they often accumulate high number of non-productive days. High proportion of low parity sows suffer from and are culled due to various reproductive reasons (Lucia Jr *et al.*, 2000; Tummaruk *et al.*, 2000; Engblom *et al.*, 2008b; Hoving, 2012; Ferrari *et al.*, 2014; Craig *et al.*, 2017). In our study, more days from farrowing to removal and smaller litter sizes were observed to be associated with low parity sows (I). Research has also indicated that first parity piglets are not only lighter at birth but worsened preweaning growth rates have also been demonstrated (Miller *et al.*, 2008). Greater disease susceptibility, medication rates, mortality and poorer future performance have also been documented (Mabry, 2016; Craig *et al.*, 2017). Studies have not been able to prove fostering of first parity progeny on to multiparous sows or provision of supplemental milk to improve growth and survival, i.e. these piglets continue to lag behind (Miller *et al.*, 2012).

From one economic point of view, replacements due to first and second parity removals have been considered unprofitable investments because the positive net value is not obtained (Stalder *et al.*, 2003; Sasaki *et al.*, 2012). A recent American study estimated that better longevity and retaining sows into their later parities (5 through 9) increased the financial returns from piglet producing herds (Gruhot *et al.*, 2017a). We also concluded based on our economic simulation that a healthy sow should stay in the herd until her sixth to tenth parity (III). However, a very low sow turnover may compromise the achievement of genetic objectives, which, on the other hand, is not in contrast with concrete physiological limitations of the sow if selection efforts were to focus on genetically induced large litter sizes alone.

Our simulation scenarios with real life parameter values demonstrated relatively poor lifetime performance as piglets weaned and number of litters produced per sow (III). On the basis of the best scenario, an average sow, on an average farm, with 4.56 produced litters had just reached the full performance capacity before she was culled. It is evident that only decreasing the proportion of first parity litters with progeny that exhibit weakened performance and retaining mature sows and a static herd size result in performance enhancements (Stalder *et al.*, 2003; Mabry, 2016; Koketsu *et al.*, 2017). In addition, farrowing intervals have been shown to be shorter between later parity cycles than those between earlier ones and farrowing rates of older sows higher indicating additional advantages related to mature sows and efficiency of piglet production (Koketsu *et al.*, 1999; Serenius *et al.*, 2003). Furthermore, if sows are not productive for a long time or won't even reach their full performance potential, they have more of an environmental impact in terms of use of resources such as land and energy and emission of pollutants such as ammonia and methane (De Vries & De Boer, 2010). The role of overall sustainability is likely to be emphasized in the future instead of focusing on purely quantitative performance measures (FAO, 2018). Improved use of animal resources, overall herd management routines, optimal feeding regimen, better health and animal welfare must be considered in expanding the scale of production to avoid serious environmental impacts (Steinfeld *et al.*, 2006; Gerber *et al.*, 2013; Ogino *et al.*, 2013; Alary *et al.*, 2016; Wang *et al.*, 2016; Butterworth & Farm Animal Welfare, 2017; Mottet *et al.*, 2017).

Raising a durable, robust, well-selected female and supporting her through first lactation are key elements in decreasing sub-optimal removal. There are several aspects that have been referred to in the literature to promote sow longevity such as an early focus on locomotor conformation and health, genetic potential, optimal nutrition, reproductive management as well as appropriate environmental conditions including housing and floor design, to prepare gilts for long and successful productive futures in the breeding herd (Le Cozler *et al.*, 1998; Tantasuparuk, 2001; Serenius & Stalder, 2004; Stalder *et al.*, 2004; Serenius & Stalder, 2006; Lawlor & Lynch, 2007; Engblom *et al.*, 2009; Koketsu *et al.*, 2017).

6.4 Farming styles

As reviewed thoroughly by Stalder *et al.* (2004) there are several determinants to sow longevity. The farm can significantly modify the sow-level outcomes independently of the sow's characteristics. Understanding that the farm is a complex system with strengths and limitations, goals and perceptions, is essential for improving not only the farm economy but also the conditions for the animals (Den Hartog *et al.*, 1993; Gonyou, 2002; Stalder *et al.*, 2004; Engblom, 2008).

As opposed to the traditional hypothesis testing, we used an exploratory approach in the form of MCA to clarify the complexity of associations between the farm as a whole and sow removal (II). It proved applicable in representing underlying structures in large sets of data of a diversity and mostly quantitative nature as suggested by Greenacre (1984). The complexity of associations between the farm descriptors was demonstrated in a visually interpretable and communicative manner, which is of relevance in conveying information (Greenacre, 2010; Greenacre, 2017; Eurostat 2018).

Through real field data, we could also profile piglet-producing farms with contrasting patterns of management practices and housing and link them to sow removal (Husson *et al.*, 2010). Three farm typologies were identified. Typology 1 farms were characterized by features more indicative of semi-intensive or intensive farming compared with the other farms. They had larger herd size (>635) and more sows (>148) per caretaker. Both the culling and mortality levels were higher in this group. Typology 2 farms were estimated to have the best animal welfare considering a combination of environmental factors such as enrichment and space allowance and the lowest overall level of sow mortality as an animal-based indicator. Typology 3 farms implemented supplementary welfare-friendly initiatives, were smaller in herd size (<103), group and room sizes and had fewer sows per caretaker (<58), suggesting a rather non-intensive style of production. These farms had the lowest culling levels.

Capturing the heterogeneity of farms through typology construction is a useful step in analysing farm performance, resources and limitations. Typologies can be further used for many purposes, such as selecting representative farms as cases for studies, targeting interventions and for the extension of technologies or to support the identification of farm development and evolution patterns.

On a specific farm, various development suggestions towards more sustainable, animal-friendly and consumer accepting pork production might only be given appropriate weights when considered in relation to a larger number of farm descriptors. The lack of capital may have resulted in sub-optimal housing conditions or impaired management practices. The cost efficiency of each investment must be thoroughly examined as only the most essential ones can be prioritized. We identified potential interactions between single aspects of farm management and housing conditions, which together may determine whether or not specific recommendations are optimal in the wider context of the entire farm.

6.5 Optimal replacement

In relation to previous studies, we provided a new way of examining the effect of animal health on production and replacement management to guide strategic decision-making and motivate and direct preventive work (III). By modelling the effect of production diseases, with special emphasis on sow removal, the monetary burden represented by diseases and sub-optimal removal rates was demonstrated.

The results suggested that the occurrence of postpartum dysgalactia syndrome and locomotory disorders produce small costs at the individual sow level. However, the difference between the best and worst scenarios with regard to health and removal were notable. In addition, as the piglet production units are becoming larger, the average farm-level losses can rise to substantial levels as well as the differences between the best and worst performers.

We showed that sow health, longevity, productivity and economic results are linked to each other. First of all, we showed that the return on investment was highest if a farmer managed to avoid excessive removal (III). This also improved the opportunities for selection on performance because the optimal decision based on the production capacity of a sow was dependent on the overall removal rate for the herd and its health status. Voluntary replacement was suggested only for the oldest sows, especially when farrowing small litters. It was optimal to keep healthy sows with an average or high productivity in the herd as long as possible, i.e. until their ninth or tenth parity. In addition, a noteworthy fact was that herds with a poorer original longevity, i.e. higher turnover rate, appeared to suffer more from diseases than the typical herds with a lower turnover.

Production diseases such as the ones investigated in this study are a challenging area for prevention and, naturally, preventive measures also incur costs. Using decision support models, producers can weigh the fundamental consideration of whether investments in improved animal health are worth the costs. The costs of a disease in general must be estimated and it should be assessed whether it would be worth trying to do something about it. From the viewpoint of economic theory, it is probably rational to reduce the occurrence of production diseases, but complete prevention is hardly realistic. Our preliminary demonstrations may motivate farmers to become aware of the importance of lowering disease incidences and overall replacement rate in order to improve animal health and the profitability of the farm.

6.6 Limitations

Some advantages and disadvantages arose as a result of how the materials and methodologies were chosen, which need to be considered when interpreting the results and planning future research.

There is an ongoing need for properly collected, managed and within studies comparable good quality data (Rushton, 2009). It is also important for researchers to closely consider the farm reality (Plà, 2007). However, farm level data straight from the producers are difficult to obtain due to the compulsory criterion: the willingness to participate and share. In this project, the recruitment proved even more difficult and time consuming than anticipated. The pork industry in Finland has been in the middle of much heated discussion in recent years. In general, producers were interested in the content of the research, but people were very worried and suspicious of the confidentiality aspects and the potential increase in personal workload, and consequently elected not to participate.

Although this project accounted for a marked proportion of all the breeding sows in Finland and a diversity of farms, the volunteer participants likely represent the better end of the Finnish commercial farms. We could only quantify the differences between the volunteer farms and the remaining population with regard to herd size. It may well be argued that due to our convenience sampling the results cannot be generalized. However, there must always be a balance between the constraints of obtaining data, related costs and what can be learned from them. In addition, as with observational studies in general, causal relationships should not be inferred from the results.

Another source of bias is related to secondary, electronic data. As opposed to controlled experiments, they are independent of the researcher. They are originally recorded for purposes other than scientific ones and without any previous guidance to make the recordings reliable or detailed. In particular, in removal studies, it would be necessary to separate events (spontaneous death and euthanasia) that are beyond the control of the producer from those that are within it. Furthermore, for example genotypes and reproductive data were not consistently recorded and yet could not be included in the analyses. Nevertheless, in this manner of data collection, numerous observations originating from a diversity of farms across the whole country can be made available. Electronic farm-level data should be respected as a good resource by farmers, advisers and researchers. Secondary data gathered via other routes, such as national registries, are also valuable as long as their weaknesses are identified and taken into account, and preferably validated.

The farm-level data were collected in a cross-sectional study by interviews, potentially leading towards answers describing measures believed to be applied by the workers or to be socially more acceptable, rather than revealing the measures actually applied (Nederhof, 1985). Person-to-person data collection may also encompass the risk of misinterpretation. Observations in the housing facilities allowed partial compensation for this potential response bias.

Even with limitations, our study can be considered valid for introducing an empirical base that could be used to motivate debate on future piglet production system development. It also delivered useful evidence relevant for stakeholders to engage in and further promote research into identification, monitoring and management of sow removal and health, aspects that are difficult to investigate by controlled experiments. We wish to have emphasized awareness of multidisciplinary approaches in integrating accurate epidemiological livestock data into larger frameworks and identifying current bottlenecks in available data and modelling methodology.

7 CONCLUSIONS

The leading hypothesis in this thesis was supported: there are wide range of differences in removal patterns between sows and overall production circumstances. Therefore, no single replacement rate or standard recommendations on optimal removal exist. When determining sow removal policy, strengths and limitations within each individual farm and its animal population must be considered.

More specifically it is concluded that,

- In the Finnish sow population, the average litter sizes already routinely exceeded those suggested to be in line with the natural nursing ability of individual sows. Larger litters may lead to significant management challenges and interventions to raise the extra piglets. Risks to the health and welfare of both piglets and sows are also imposed.

- There was a relatively high wastage of sows in low parities and the removal decisions were delayed compared with the later parities. Early removal of sows prevented them from reaching their full biological performance potential.

- Sow performance affected removal. Especially small litter sizes and the number of stillborn resulted in higher risk of removal.

- Legislated animal registration data may be used to quantify sow removal at the farm level in Finland. On average, culling, and especially mortality, were at a relatively high level. The wide variation between farms indicates that there is room for improvement. However, for comparison and monitoring purposes, a more detailed contextualization within and among countries is needed.

- The complex structure of farms was highlighted and three typologies with contrasting patterns of housing and management were identified. Furthermore, farm typologies were associated with removal. Typology 1 included farms with features indicative of semi-intensive or intensive farming and the highest level of culling and mortality. Typology 2 farms were estimated to have the best animal welfare among the sample farms based on a combination of environmental indicators and the lowest level of on-farm sow mortality. Typology 3 followed a strategy of rather non-intensified system and showed the lowest level of culling.

- Sow replacement, health and economic returns are linked to each other. Optimizing removal markedly increases sow longevity, lifetime piglet yields and monetary net returns. It was also shown that production diseases cause constant economic losses. Herds with a higher sow replacement rate appeared to suffer even more from diseases than herds with a lower one.

8 RECOMMENDATIONS

Based on this study, we would motivate good record-keeping practices with special emphasis on removal at the farm level. This would expand data usefulness for producers and researchers as described below.

- Sow retention and longevity should be continuously measured, and the measurements compared with standards and targets to monitor development at the farm. Producers need to be aware of the herd's culling and mortality rates and keep proper records for each sow to be able to optimise removal according to the farm specific preferences. Awareness may intrinsically help to avoid excessive removal.

- It is of great importance to be able to distinguish between the three types of destinations (slaughter, spontaneous death and euthanasia) in herd management systems (destination-specific removal). Destination-specific recording scheme improves especially the identification of on-farm mortality patterns. In order to reduce the prevalence of sow mortality, special attention needs to be drawn to specific risk factors and their combinations at the herd and the sow level. Postmortem examinations can be used to increase knowledge of what actually causes spontaneous death and euthanasia and to guide necessary control measures in order to decrease mortality and avoid unnecessary delay in euthanasia of unhealthy sows.

- To further improve understanding of the farm-specific removal patterns it is recommended to record primary removal reasons from a list of unambiguous reasons for all cull sows (reason-specific removal). Reason-specific records are helpful in tailoring preventive actions to improve farm functionality, economy and sow health.

- Determining the proportion of animals that do not make it through the low parities (parity-specific removal) is a useful measure for characterising sow retention problems. In determining parity-specific culling criteria, the biological productivity development, reproductive traits and herd parity distribution should be considered.

9 FUTURE IMPLICATIONS

Further international research is needed to assess the availability, suitability and comparability of mandatory, routinely recorded animal data for multidimensional animal welfare monitoring purposes.

Welfare implications between spontaneous death and euthanasia may differ. It would be essential to record these two separately for each removed sow to evaluate differences in the relative proportions and risk factors of the two types of death over a number of years. In addition, to better understand why sows die on farm, postmortem examinations would be informative. We have already started a project to explore this area. However, to carry out a harmonized, larger scale postmortem study internationally would be invaluable.

Large differences between farms in removal rates were observed. In addition to housing and management, we assume that the complexity is highly influenced by farmers' attitudes and decision-making. Further multidisciplinary research including social sciences is needed to gain more insight into the influence of farmer's personality types and perceptions on sow removal, culling guidelines and actual practices.

It may be speculated that the potential lack of time per animal may lead to unnecessary culling decisions and even increased on-farm mortality at all production stages. The association between workload and working time allocated per animal, sow health and removal should be further studied.

Despite extensive research on locomotory disorders, they remain a major concern in the pig industry. They are also reported to be one of the main removal reasons and cause of on-farm deaths and euthanasia. The findings of our study can serve as a useful reference for future studies investigating housing and management features - separately and synergistically - to ensure locomotory soundness and prevent unplanned removal.

Furthermore, aggression is a recognized disadvantage of group housing of gestating sows, but the potential direct (aggressive behaviour) and indirect (e.g. through lameness, traumatic injuries or lower feed intake) links to an elevated risk of being removed is not well-studied.

At the sow level, several studies have estimated the risk of removal based on quantitative electronic records. However, limited research has focused on investigating the interrelationship between clinical variables of sows and removal. We have already carried out data collection using systematic clinical examination of individual sows to study the variation of common clinical variables and associate them with the risk of removal.

Lastly, due to my deep personal interest and environmental concern, another suggestion would be to conduct a life cycle analysis to evaluate the complete impact of sow removal on the environment.

REFERENCES

Abiven, N., Seegers, H., Beaudeau, F., Laval, A. & Fourichon, C. 1998. Risk factors for high sow mortality in French swine herds. *Preventive Veterinary Medicine,* 33**,** 109-119.

Alary, V., Corbeels, M., Affholder, F., Alvarez, S., Soria, A., Valadares Xavier, J. H., Da Silva, F. a. M. & Scopel, E. 2016. Economic assessment of conservation agriculture options in mixed crop-livestock systems in Brazil using farm modelling. *Agricultural Systems,* 144**,** 33-45.

Alexopoulos, J. G., Lines, D. S., Hallett, S. & Plush, K. J. 2018. A Review of Success Factors for Piglet Fostering in Lactation. *Animals : an open access journal from MDPI,* 8**,** 38.

Allen, M. A. & Stewart, T. S. 1983. A simulation model for a swine breeding unit producing feeder pigs. *Agricultural Systems,* 10**,** 193-211.

Alonso-Spilsbury, M., Ramirez-Necoechea, R., González-Lozano, M., Mota-Rojas, D. & Trujillo-Ortega, M. E. 2007. Piglet survival in early lactation: a review. *Journal of Animal and Veterinary Advances,* 6**,** 76-86.

Alvasen, K., Jansson Mork, M., Dohoo, I. R., Sandgren, C. H., Thomsen, P. T. & Emanuelson, U. 2014a. Risk factors associated with on-farm mortality in Swedish dairy cows. *Preventive Veterinary Medicine,* 117**,** 110-20.

Alvasen, K., Roth, A., Jansson Mork, M., Hallen Sandgren, C., Thomsen, P. T. & Emanuelson, U. 2014b. Farm characteristics related to on-farm cow mortality in dairy herds: a questionnaire study. *Animal,* 8**,** 1735-42.

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). *Behavioral Ecology and Sociobiology,* 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 Veterinaria Scandinavica,* 58**,** 1-9.

Anil, L., Anil, S. S., Deen, J., Baidoo, S. K. & Wheaton, J. E. 2005a. Evaluation of well-being, productivity, and longevity of pregnant sows housed in groups in pens with an electronic sow feeder or separately in gestation stalls. *American Journal of Veterinary Research,* 66**,** 1630-8.

Anil, S. S., Anil, L. & Deen, J. 2005b. Evaluation of patterns of removal and associations among culling because of lameness and sow productivity traits in swine breeding herds. *Journal of the American Veterinary Medical Association,* 226**,** 956-961.

Anil, S. S., Anil, L. & Deen, J. 2008. Analysis of periparturient risk factors affecting sow longevity in breeding herds. *Canadian Journal Of Animal Science,* 88**,** 381-389.

Anil, S. S., Anil, L. & Deen, J. 2009. Effect of lameness on sow longevity. *Journal of the American Veterinary Medical Association,* 235**,** 734-738.

Animal Welfare Act 247/1996: Government Decree 15.12.2012/629, 2012. Asetus sikojen suojelusta 15.12.2012/629. 2012. *In: Valtioneuvosto* (ed.) *629/2012.*

Arango, J. 2005. Study of codes of disposal at different parities of Large White sows using a linear censored model. *Journal of Animal Science,* 83**,** 2052-7.

Bailey, K. D. 1994. *Typologies and taxonomies: an introduction to classification techniques. No. 102*, Sage.

Balogh, P., Kapelański, W., Jankowiak, H., Nagy, L., Kovacs, S., Huzsvai, L., Popp, J., Posta, J. & Soltesz, A. 2015. The productive lifetime of sows on two farms from the aspect of reasons for culling. *Annals of animal science,* 15**,** 747-758.

Barnett, J. L., Hemsworth, P. H., Cronin, G. M., Jongman, E. C. & Hutson, G. D. 2001. A review of the welfare issues for sows and piglets in relation to housing. *Australian Journal of Agricultural Research,* 52**,** 1-28.

Bates, D., Mächler, M., Bolker, B. & Walker, S. 2015. Fitting Linear Mixed-Effects Models Using {lme4}. Journal of Statistical Software.

Baxter, E. M., Rutherford, K. M. D., D'eath, R. B., Arnott, G., Turner, S. P., Sandøe, P., Moustsen, V. A., Thorup, F., Edwards, S. A. & Lawrence, A. B. 2013. The welfare implications of large litter size in the domestic pig II: management factors. *Animal Welfare,* 22**,** 219-238.

Berner, E. S. & La Lande, T. J. 2016. Overview of Clinical Decision Support Systems. *In:* Berner, E. S. (ed.) *Clinical Decision Support Systems: Theory and Practice.* Cham: Springer International Publishing.

Boogaard, B. K., Boekhorst, L. J. S., Oosting, S. J. & Sørensen, J. T. 2011. Socio-cultural sustainability of pig production: Citizen perceptions in the Netherlands and Denmark. *Livestock Science,* 140**,** 189-200.

Boyle, L., Leonard, F. C., Lynch, B. & Brophy, P. 1998. Sow culling patterns and sow welfare. *Irish Veterinary Journal***,** 51(7), 354-357.

Boynton, P. M. & Greenhalgh, T. 2004. Selecting, designing, and developing your questionnaire. *BMJ,* 328**,** 1312-1315.

Brandt, H. 1999. Factors affecting survival rate of crossbred sows in weaner production. *Livestock Production Science,* 57**,** 127-135.

Butterworth, A. & Farm Animal Welfare, C. 2017. *Sustainable agriculture and farm animal welfare,* London, DEFRA Farm Animal Welfare Committee.

Cador, C., Pol, F., Hamoniaux, M., Dorenlor, V., Eveno, E., Guyomarc'h, C. & Rose, N. 2014. Risk factors associated with leg disorders of gestating sows in different group-housing systems: A cross-sectional study in 108 farrow-to-finish farms in France. *Preventive Veterinary Medicine,* 116**,** 102-110.

Canario, L., Roy, N., Gruand, J. & Bidanel, J. P. 2006. Genetic variation of farrowing kinetics traits and their relationships with litter size and perinatal mortality in French Large White sows. *Journal of Animal Science,* 84**,** 1053-1058.

Cha, E., Hertl, J. A., Schukken, Y. H., Tauer, L. W., Welcome, F. L. & Gröhn, Y. T. 2013. The effect of repeated episodes of bacteria-specific clinical mastitis on mortality and culling in Holstein dairy cows. *Journal of Dairy Science,* 96**,** 4993-5007.

Chagnon, M., D'allaire, S. & Drolet, R. 1991. A prospective study of sow mortality in breeding herds. *Canadian Journal of Veterinary Research,* 55**,** 180-184.

Christensen, G., Vraa-Andersen, L. & Mousing, J. 1995. Causes of mortality among sows in Danish pig herds. *The Veterinary record,* 137**,** 395-399.

Churchman, C. W. 1957. Introduction to operations research, New York (NY), Wiley.

Council Directive. 2008. Council Directive 2008/71/EC of 15 July 2008 on the identification and registration of pigs. *In:* Union, T. C. O. T. E. (Ed.)*L 213/31.*

European Comission. 2017a. *The CAP in your Country.* Available: https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/by_country/documents/cap-in-your-country-fi_en.pdf [Accessed July 15 2019].

European Comission. 2017b. *Modernising and simplifying the CAP: Economic challenges facing EU agriculture.* Available: https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/key_policies/documents/eco_background_final_en.pdf [Accessed July 15 2019].

European Comission. 2018. *Future of the common acricultural policy.* Available: https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/future-cap_en [Accessed June 11]

Craig, J. R., Collins, C. L., Bunter, K. L., Cottrell, J. J., Dunshea, F. R. & Pluske, J. R. 2017. Poorer lifetime growth performance of gilt progeny compared with sow progeny is largely due to weight differences at birth and reduced growth in the preweaning period, and is not improved by progeny segregation after weaning1. *Journal of Animal Science,* 95**,** 4904-4916.

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

D'allaire, S., Drolet, R. & Chagnon, M. 1991. The causes of sow mortality: A retrospective study. *The Canadian Veterinary Journal,* 32**,** 241.

D'allaire, S., Stein, T. E. & Leman, A. D. 1987. Culling patterns in selected Minnesota swine breeding herds. *Canadian Journal of Veterinary Research,* 51**,** 506-512.

Dagorn, J. & Aumaitre, A. 1979. Sow culling: Reasons for and effect on productivity. *Livestock Production Science,* 6**,** 167-177.

Dalin, A. M., Gidlund, K. & Eliasson-Selling, L. 1997. Post-mortem examination of genital organs from sows with reproductive disturbances in a sow-pool. *Acta Veterinaria Scandinavica,* 38**,** 253-262.

De Jong, E., Appeltant, R., Cools, A., Beek, J., Boyen, F., Chiers, K. & Maes, D. 2014. Slaughterhouse examination of culled sows in commercial pig herds. *Livestock Science,* 167**,** 362-369.

De Vries, M. & De Boer, I. J. M. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science,* 128**,** 1-11.

Deen, J. & Xue, J. 1999. Sow mortality in the US: An industry-wide perspective *Proceedings of the Allen D. Leman Swine Conference,* 26**,** 91-94.

Den Hartog, L. A., Backus, G. B. C. & Vermeer, H. M. 1993. Evaluation of housing systems for sows *Journal of Animal Science,* 71**,** 1339-1344.

Dijkhuizen, A. A., Krabbenborg, R. M. M. & Huirne, R. B. M. 1989. Sow replacement: A comparison of farmers' actual decisions and model recommendations. *Livestock Production Science,* 23**,** 207-218.

Dijkhuizen, A. A., Morris, R. S. & Morrow, M. 1986. Economic optimization of culling strategies in swine breeding herds, using the "PorkCHOP computer program". *Preventive Veterinary Medicine,* 4**,** 341-353.

Dohoo, I., Martin, S. & Stryhn, H. 2009a. *Veterinary epidemiologic research.* 2nd Edition ed. Prince Edward Island, Canada: Charlottetown, 2009: VER Inc.

Dohoo, I. R., Martin, W. & Stryhn, H. 2009b. Questionnaire design. In: Dohoo, I.R., Martin, W. & Stryhn, H. (ed.) *Veterinary epidemiologic research.* Prince Edward Island, Canada: Charlottetown, 2009: VER inc.

EFSA 2007. Animal health and welfare aspects of different housing and husbandry systems for adult breeding boars, pregnant, farrowing sows and unweaned piglets - Scientific Opinion of the Panel on Animal Health and Welfare. *European Food Safety Authority, EFSA Journal,* 572**,** 1-13.

EFSA 2014. Scientific Opinion concerning a Multifactorial approach on the use of animal and non-animal-based measures to assess the welfare of pigs. *EFSA Panel on Animal Health and Welfare, European Food Safety Authority, EFSA Journal,* 12(5):3702**,** 101.

Ek-Mex, J. E., Segura-Correa, J. C., Alzina-Lopez, A. & Batista-Garcia, L. 2015. Lifetime and per year productivity of sows in four pig farms in the tropics of Mexico. *Tropical Animal Health and Production,* 47**,** 503-9.

Elghafghuf, A., Stryhn, H. & Waldner, C. 2014. A cross-classified and multiple membership Cox model applied to calf mortality data. *Preventive Veterinary Medicine,* 115**,** 29-38.

Engblom, L. 2008. *Culling and Mortality among Swedish Crossbred Sows.* Theses and Dissertations. Swedish University of Agricultural Sciences.

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. *Journal of Animal Breeding and Genetics***,** 138-144.

Engblom, L., Eliasson-Selling, L., Lundeheim, N., Belak, K., Andersson, K. & Dalin, A. M. 2008a. Post mortem findings in sows and gilts euthanised or found dead in a large Swedish herd. *Acta Veterinaria Scandinavica,* 50**,** 25.

Engblom, L., Lundeheim, N., Dalin, A.-M. & Andersson, K. 2007. Sow removal in Swedish commercial herds. *Livestock Science,* 106**,** 76-86.

Engblom, L., Lundeheim, N., Schneider Mdel, P., Dalin, A. M. & Andersson, K. 2009. Genetics of crossbred sow longevity. *Animal,* 3**,** 783-90.

Engblom, L., Lundeheim, N., Strandberg, E., Schneider, M. D. P., Dalin, A. M. & Andersson, K. 2008b. Factors affecting length of productive life in Swedish commercial sows. *Journal of Animal Science,* 86**,** 432-441.

Estany, J. & Sorensen, D. 1995. Estimation of genetic parameters for litter size in Danish Landrace and Yorkshire pigs. *Animal Science,* 60**,** 315-324.

Eurostat 2018. *Agriculture, forestry and fishery statistics* (2018 ed.). Available: https://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-FK-18-001. [Accessed July 15 2019].

FAO. 2019. *FAO Food Price Index*. Available: http://www.fao.org/worldfoodsituation/foodpricesindex/en/ [Accessed July 12 2019].

FAO. 2016. *Sustainable Development Goals* . Available: http://www.fao.org/sustainable-development-goals/en/ [Accessed January 2 2019].

FAO. 2018. *The future of food and agriculture – Alternative pathways to 2050. Summary version.*, Rome. 60 pp. Licence: CC BY-NC-SA 3.0 IGO.

Feldpausch, J. A., Jourquin, J., Bergstrom, J. R., Bargen, J. L., Bokenkroger, C. D., Davis, D. L., Gonzalez, J. M., Nelssen, J. L., Puls, C. L. & Trout, W. E. 2019. Birth weight threshold for identifying piglets at risk for preweaning mortality. *Translational Animal Science,* 3(2)**,** 663-640

Ferrari, C. V., Sbardella, P. E., Bernardi, M. L., Coutinho, M. L., Vaz, I. S., Wentz, I. & Bortolozzo, F. P. 2014. Effect of birth weight and colostrum intake on mortality and performance of piglets after cross-fostering in sows of different parities. *Preventive Veterinary Medicine,* 114**,** 259-266.

Fetrow, J., Nordlund, K. V. & Norman, H. D. 2006a. Invited Review: Culling: Nomenclature, Definitions, and Recommendations. *Journal of Dairy Science,* 89**,** 1896-1905.

Fitzgerald, R. F. 2009. *An evaluation of practices to improve sow productive lifetime and producer profitability. Iowa State University.* Graduate Theses and Dissertations. *Paper 10575. 138 pp.* Available: https://lib.dr.iastate.edu/etd/10575. Iowa State University.

Fraser, D., Weary, D. M., Pajor, E. A. & Milligan, B. N. 1997. A scientific conception of animal welfare that reflects ethical concerns. *Animal Welfare,* 6**,** 187-205.

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*, Food and Agriculture Organization of the United Nations (FAO).

Gibon, A., Sibbald, A. R., Flamant, J. C., Lhoste, P., Revilla, R., Rubino, R. & Sørensen, J. T. 1999. Livestock farming systems research in Europe and its potential contribution for managing towards sustainability in livestock farming. *Livestock Production Science,* 61**,** 121-137.

Gjein, H. & Larssen, R. B. 1995. The effect of claw lesions and claw infections on lameness in loose housing of pregnant sows. *Acta Veterinaria Scandinavica,* 36**,** 451-459.

Gonyou, H. W. Group housing: alternative systems, alternative management. *Proceedings Allen D. Leman Swine Conference*, 2002. 198–201.

Greenacre, M. 2010. *Biplots in Practice*. *In:* BBVA, F. (ed.).

Greenacre, M. 2017. *Correspondence Analysis in Practice*. New York: Chapman and Hall/CRC.

Greenacre, M. J. 1984. *Theory and applications of correspondence analysis,* London, Academic P.

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. *Journal of Swine Health and Production,* 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. *Livestock Science,* 196**,** 22-27.

Halasa, T., Bøtner, A., Mortensen, S., Christensen, H., Toft, N. & Boklund, A. 2016. Simulating the epidemiological and economic effects of an African swine fever epidemic in industrialized swine populations. *Veterinary Microbiology,* 193**,** 7-16.

Hasan, S., Orro, T., Valros, A., Junnikkala, S., Peltoniemi, O. & Oliviero, C. 2019. Factors affecting sow colostrum yield and composition, and their impact on piglet growth and health. *Livestock Science,* 227**,** 60-67.

Heim, G., Mellagi, A. P. G., Bierhals, T., De Souza, L. P., De Fries, H. C. C., Piuco, P., Seidel, E., Bernardi, M. L., Wentz, I. & Bortolozzo, F. P. 2012. Effects of cross-fostering within 24h after birth on pre-weaning behaviour, growth performance and survival rate of biological and adopted piglets. *Livestock Science,* 150**,** 121-127.

Heinonen, M., Oravainen, J., Orro, T., Seppä-Lassila, L., Ala-Kurikka, E., Virolainen, J., Tast, A. & Peltoniemi, O. a. T. 2006. Lameness and fertility of sows and gilts in randomly selected loose-housed herds in Finland. *Veterinary Record,* 159**,** 383-387.

Heinonen, M., Peltoniemi, O. & Valros, A. 2013. Impact of lameness and claw lesions in sows on welfare, health and production. *Livestock Science,* 156**,** 2-9.

Hellbrügge, B., Tölle, K. H., Bennewitz, J., Henze, C., Presuhn, U. & Krieter, J. 2008. Genetic aspects regarding piglet losses and the maternal behaviour of sows. Part 1. Genetic analysis of piglet mortality and fertility traits in pigs. *Animal,* 2**,** 1273-1280.

Hemsworth, P. H., Coleman, G. J. & Barnett, J. L. 1994. Improving the attitude and behaviour of stockpersons towards pigs and the consequences on the behaviour and reproductive performance of commercial pigs. *Applied Animal Behaviour Science,* 39**,** 349-362.

Hoge, M. D. & Bates, R. O. 2011. Developmental factors that influence sow longevity. *Journal of Animal Science,* 89**,** 1238-1245.

Honeyman, M. S. 1996. Sustainability issues of US swine production. *Journal of Animal Science,* 74**,** 1410-1417.

Houben, E. H. P., Thelosen, J. G. M., Huirne, R. B. M. & Dijkhuizen, A. A. 1990. Economic comparison of insemination and culling policies in commercial sow herds, assessed by stochastic simulation. *Netherlands Journal of Agricultural Science,* 38**,** 201-204.

Houška, L. 2009. The relationship between culling rate, herd structure and production efficiency in a pig nucleus herd. *Czech Journal of Animal Science,* 54**,** 365-75.

Hoving, L. L. 2012. *The second parity sow : causes and consequences of variation in reproductive performance*. Graduate Theses and Dissertations. Wageningen University. Available: https://library.wur.nl/WebQuery/wurpubs/423896.

Hoving, L. L., Soede, N. M., Graat, E. a. M., Feitsma, H. & Kemp, B. 2010. Effect of live weight development and reproduction in first parity on reproductive performance of second parity sows. *Animal Reproduction Science,* 122**,** 82-89.

Huirne, R. B. M., Dijkhuizen, A. A. & Renkema, J. A. 1991. Economic optimization of sow replacement decisions on the personal computer by method of stochastic dynamic programming. *Livestock Production Science,* 28**,** 331-347.

Huirne, R. B. M., Dijkhuizen, A. A., Van Beek, P. & Hendriks, T. H. B. 1993. Stochastic dynamic programming to support sow replacement decisions. *European Journal of Operational Research,* 67**,** 161-171.

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. *Journal of Agricultural Economics,* 39**,** 426-438.

Husson, F., Josse, J. & Pagès, J. 2010. Principal component methods-hierarchical clustering-partitional clustering : why would we need to choose for visualizing data? Applied mathematics department, Rennes.

Iida, R. & Koketsu, Y. 2014. Climatic factors associated with peripartum pig deaths during hot and humid or cold seasons. *Preventive Veterinary Medicine,* 115**,** 166-172.

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. *Preventive Veterinary Medicine* 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. *Journal of Animal Science,* 93**,** 2501-2508.

Jalvingh, A. W., Dijkhuizen, A. A., Van Arendonk, J. a. M. & Brascamp, E. W. 1992. An economic comparison of management strategies on reproduction and replacement in sow herds using a dynamic probabilistic model. *Livestock Production Science,* 32**,** 331-350.

Janssen, S. & Van Ittersum, M. K. 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems,* 94**,** 622-636.

Jensen, T. B., Toft, N., Bonde, M. K., Kongsted, A. G., Kristensen, A. R. & Sorensen, J. T. 2012. Herd and sow-related risk factors for mortality in sows in group-housed systems. *Preventive Veterinary Medicine,* 103**,** 31-7.

Kamp, J. 1999. Knowledge based systems: from research to practical application: pitfalls and critical success factors. *Computers and Electronics in Agriculture,* 22**,** 243-250.

Kaneko, M., Iida, R. & Koketsu, Y. 2013. Herd management procedures and factors associated with low farrowing rate of female pigs in Japanese commercial herds. *Preventive Veterinary Medicine,* 109**,** 69-75.

Kassambara, A. & Mundt, F. 2017. *Factoextra: extract and visualize the results of multivariate data analyses*. R package version 1.0. 4. 2017.

Kaufmann, A. & Faure, R. 1968. *Introduction to operations research.* Mathematics in science and engineering.

Kauppinen, T. 2013. *Farm animal welfare and production in relation to farmer attitudes.* Theses and Dissertations. University of Helsinki.

King, V. L., Koketsu, Y., Reeves, D., Xue, J. & Dial, G. D. 1998. Management factors associated with swine breeding-herd productivity in the United States. *Preventive Veterinary Medicine,* 35**,** 255-264.

Kirk, R. K., Svensmark, B., Ellegaard, L. P. & Jensen, H. E. 2005. Locomotive Disorders Associated with Sow Mortality in Danish Pig Herds. *Journal of Veterinary Medicine Series A,* 52**,** 423-428.

Knage-Rasmussen, K. M., Rousing, T., Sørensen, J. T. & Houe, H. 2015. Assessing animal welfare in sow herds using data on meat inspection, medication and mortality. *Animal,* 9**,** 509-515.

Knauer, M., Stalder, K. J., Serenius, T., Baas, T. J., Berger, P. J., Karriker, L., Goodwin, R. N., Johnson, R. K., Mabry, J. W., Miller, R. K., Robison, O. W. & Tokach, M. D. 2010. Factors associated with sow stayability in 6 genotypes. *Journal of Animal Science,* 88**,** 3486-3492.

Knauer, M. T. 2011. Phenotypic and genetic correlations between gilt estrus, puberty, growth, composition, and structural conformation traits with first-litter reproductive measures. *Journal of Animal Science,* 89**,** 935-942.

Koketsu, Y. 2000. Retrospective analysis of trends and production factors associated with sow mortality on swine-breeding farms in USA. *Preventive Veterinary Medicine,* 46**,** 249-256.

Koketsu, Y. 2005. Six component intervals of nonproductive days by breeding-female pigs on commercial farms. *Journal of Animal Science,* 83**,** 1406-1412.

Koketsu, Y. 2007a. Longevity and efficiency associated with age structures of female pigs and herd management in commercial breeding herds. *Journal of Animal Science,* 85**,** 1086-1091.

Koketsu, Y. 2007b. Technical note: High-performing swine herds improved their reproductive performance differently from ordinary herds for five years1. *Journal of Animal Science,* 85**,** 3110-3115.

Koketsu, Y., Dial, G. D., Pettigrew, J. E. & King, V. L. 1997. Influence of feed intake during individual weeks of lactation on reproductive performance of sows on commercial farms. *Livestock Production Science,* 49**,** 217-225.

Koketsu, Y., Takahashi, H. & Akachi, K. 1999. Longevity, lifetime pig production and productivity, and age at first conception in a cohort of gilts observed over six years on commercial farms. *Journal of Veterinary Medical Science,* 61**,** 1001-1005.

Koketsu, Y., Takenobu, S. & Nakamura, R. 2006. Preweaning mortality risks and recorded causes of death associated with production factors in swine breeding herds in Japan. *Journal of Veterinary Medical Science,* 68**,** 821-826.

Koketsu, Y., Tani, S. & Iida, R. 2017. Factors for improving reproductive performance of sows and herd productivity in commercial breeding herds. *Porcine Health Management,* 3**,** 1.

Kortesmaa, T., Jokela, A. & Salo-Kauppinen, R. 2017. *Ruoka-ja luonnonvaratilastojen e-vuosikirja 2017: Tilastoja maataloudesta, metsäsektorilta sekä kala-ja riistataloudesta.* Natural Resources Institute Finland.

Kristensen, A. R. & Søllested, T. A. 2004. A sow replacement model using Bayesian updating in a three-level hierarchic Markov process. *Livestock Production Science,* 87**,** 13-24.

Lana, R. M., Riback, T. I. S., Lima, T. F. M., Da Silva-Nunes, M., Cruz, O. G., Oliveira, F. G. S., Moresco, G. G., Honório, N. A. & Codeço, C. T. 2017. Socioeconomic and demographic characterization of an endemic malaria region in Brazil by multiple correspondence analysis. *Malaria Journal,* 16**,** 397.

Lawlor, P. G. & Lynch, P. B. 2007. A review of factors influencing litter size in Irish sows. *Irish veterinary journal*, 60, 359.

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. *Livestock Production Science,* 53**,** 135-142.

Lê, S., Josse, J. & Husson, F. 2008. FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software,* 25.

Lucia Jr, T., Dial, G. D. & Marsh, W. E. 2000. Lifetime reproductive performance in female pigs having distinct reasons for removal. *Livestock Production Science,* 63**,** 213-222.

Lund, M. S., Puonti, M., Rydhmer, L. & Jensen, J. 2002. Relationship between litter size and perinatal and pre-weaning survival in pigs. *Animal Science,* 74**,** 217-222.

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

Maes, D., Papadopoulos, G., Cools, A. & Janssens, G. P. J. 2010. Postpartum dysgalactia in sows: pathophysiology and risk factors. *Tierärztliche Praxis Ausgabe G: Großtiere/Nutztiere,* 38**,** S15-S20.

Maes, D., Pluym, L. & Peltoniemi, O. 2016. Impact of group housing of pregnant sows on health. *Porcine Health Management,* 2**,** 17.

Marantidis, A., Papadopoulos, A. I., Michailidis, G. & Avdi, M. 2013. Association of BF gene polymorphism with litter size in a commercial pig cross population. *Animal Reproduction Science,* 141**,** 75-79.

Marquer, P., Rabade, R. & R., F. 2014. *Agriculture and fisheries Statistics in focus 15/2014* Available: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/3688.pdf [Accessed 2019, July 12].

Masaka, L., Sungirai, M., Nyamukanza, C. & Bhondai, C. 2014b. Sow removal in a commercial pig herd in Zimbabwe. *Tropical Animal Health and Production,* 46**,** 725-731.

Merks, J. W. M. 2000. One century of genetic changes in pigs and the future needs. *BSAP Occasional Publication,* 27**,** 8-19.

Merks, J. W. M., Ducro-Steverink, D. & Feitsma, H. 2000. Management and genetic factors affecting fertility in sows. *Reproduction in Domestic Animals,* 35**,** 261-266.

Miller, Y., Collins, A. M., Smits, R. J., Emery, D., Begg, D. & Holyoake, P. K. 2008. Improving the performance of the progeny of gilts. *Final report. 2D–1010506. The Pork Cooperative Research Centre. Available at*. Available: http://apri.com.au/2D-101_Final_report_0811.pdf

Miller, Y. J., Collins, A. M., Smits, R. J., Thomson, P. C. & Holyoake, P. K. 2012. Providing supplemental milk to piglets preweaning improves the growth but not survival of gilt progeny compared with sow progeny1. *Journal of Animal Science,* 90**,** 5078-5085.

Milligan, B. N., Fraser, D. & Kramer, D. L. 2002. Within-litter birth weight variation in the domestic pig and its relation to pre-weaning survival, weight gain, and variation in weaning weights. *Livestock Production Science,* 76.

Ministry of Agriculture and Forestry. 2019. *Maa- ja metsätalousministeriö.* Available: https://mmm.fi/ruoka-ja-maatalous [Accessed July 12 2019].

Morris, J. R., Hurnik, J. F., Friendship, R. M. & Evans, N. M. 1998. The effect of the Hurnik-Morris (HM) system on sow reproduction, attrition, and longevity. *Journal of Animal Science,* 76**,** 2759-2762.

Mote, B. E. 2009. Identification of genetic markers for productive life in commercial sows. *Journal of Animal Science,* 87**,** 2187-2195.

Mottet, A., Henderson, B., Opio, C., Falcucci, A., Tempio, G., Silvestri, S., Chesterman, S. & Gerber, P. J. 2017. Climate change mitigation and productivity gains in livestock supply chains: insights from regional case studies. *Regional Environmental Change,* 17**,** 129-141.

Munsterhjelm, C., Heinonen, M. & Valros, A. 2015. Application of the Welfare Quality® animal welfare assessment system in Finnish pig production, part II: associations between animal-based and environmental measures of welfare. *Animal Welfare,* 24**,** 161-172.

Nederhof, A. J. 1985. Methods of coping with social desirability bias: A review. *European journal of social psychology,* 15**,** 263-280.

Niemi, J., Partanen, K., Puolanne, E., Ruusunen, M., Sévon-Aimonen, M.-L., Voutila, L., Siljander-Rasi, H. & Serenius, T. 2010. *Sikarotyhdistelmien erot tuotanto-ja lihan laatuominaisuuksissa ja erojen taloudellinen merkitys.* Natural Resources Institute Finland.

Niemi, J. & Väre, M. 2019. *Suomen maa-ja elintarviketalous 2019*. 36/2019. Available: http://jukuri.luke.fi/handle/10024/544348. [Accessed June 12 2019].

Nieuwenhuis, N., Duinhof, T. F. & Van Nes, A. 2012. Economic analysis of outbreaks of porcine reproductive and respiratory syndrome virus in nine sow herds. *Veterinary Record,* 170**,** 225.

Ogino, A., Osada, T., Takada, R., Takagi, T., Tsujimoto, S., Tonoue, T., Matsui, D., Katsumata, M., Yamashita, T. & Tanaka, Y. 2013. Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids. *Soil Science and Plant Nutrition,* 59**,** 107-118.

OIE. 2019. *World Organisation for Animal Health (OIE).* Terrestrial animal health code (2019) . Available: http://www.oie.int/en/standard-setting/terrestrial-code/access-online [Accessed July 12 2019].

Oltenacu, P. A., Milligan, R. A., Rounsaville, T. R. & Foote, R. H. 1980. Modelling reproduction in a herd of dairy cattle. *Agricultural Systems,* 5**,** 193-205.

Ortiz-Pelaez, A., Pritchard, D. G., Pfeiffer, D. U., Jones, E., Honeyman, P. & Mawdsley, J. J. 2008. Calf mortality as a welfare indicator on British cattle farms. *The Veterinary Journal,* 176**,** 177-181.

OSF, Official Statistics of Finland. 2019. Agriculture (web publication). Helsinki: Natural Resources Institute Finland. Available: http://stat.luke.fi/en/maatalous [Accessed July 12 2019].

Peltoniemi, O. a. T., Björkman, S. & Oliviero, C. 2016. Parturition effects on reproductive health in the gilt and sow. *Reproduction in Domestic Animals,* 51**,** 36-47.

Pendl, W., Jenny, B., Torgerson, P. R., Spring, P., Kümmerlen, D. & Sidler, X. 2017. Effect of herd health management on the prevalence of postpartum dysgalaktie syndrome (PPDS) and the treatment incidence. *Schweizer Archiv fur Tierheilkunde,* 159**,** 109-116.

Plà, L. M. 2007. Review of mathematical models for sow herd management. *Livestock Science,* 106**,** 107-119.

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

Pluym, L., Van Nuffel, A., Dewulf, J., Cools, A., Vangroenweghe, F., Van Hoorebeke, S. & Maes, D. 2011. Prevalence and risk factors of claw lesions and lameness in pregnant sows in two types of group housing. *Veterinarni Medicina,* 56**,** 101–109.

Pluym, L., Van Nuffel, A. & Maes, D. 2013. Treatment and prevention of lameness with special emphasis on claw disorders in group-housed sows. *Livestock Science,* 156**,** 36-43.

Pluym, L. M., Maes, D., Van Weyenberg, S. & Van Nuffel, A. 2017. Risk factors for development of lameness in gestating sows within the first days after moving to group housing. *The Veterinary Journal,* 220**,** 28-33.

Pukara, A. 2018. *Sianlihantuottajien tulevaisuudennäkymät.* Theses and Dissertations. Seinäjoen ammattikorkeakoulu.

Quiniou, N., Dagorn, J. & Gaudré, D. 2002. Variation of piglets' birth weight and consequences on subsequent performance. *Livestock Production Science,* 78**,** 63-70.

Ratzan, L. 2004. *Understanding Information Systems : What They Do and Why We Need Them,* Chicago, ALA Editions of the American Library Association.

Razdan, P., Tummaruk, P., Kindahl, H., Rodriguez-Martinez, H., Hultén, F. & Einarsson, S. 2004. The impact of induced stress during Days 13 and 14 of pregnancy on the composition of allantoic fluid and conceptus development in sows. *Theriogenology,* 61**,** 757-767.

Rekiel, A., Więcek, J., Batorska, M. & Kulisiewicz, J. 2014. Effect of sow prolificacy and nutrition on preand postnatal growth of progeny – a review. *Annals of Animal Science,* 14**,** 3-15.

Robert, S. & Martineau, G. P. 2001. Effects of repeated cross-fosterings on preweaning behavior and growth performance of piglets and on maternal behavior of sows. *Journal of Animal Science,* 79**,** 88-93.

Rodríguez-Sánchez, S. V., Plà-Aragonés, L. M. & Albornoz, V. M. 2012. Modeling tactical planning decisions through a linear optimization model in sow farms. *Livestock Science,* 143**,** 162-171.

Rodriguez-Zas, S. 2006. Impact of biological and economic variables on optimal parity for replacement in swine breed-to-wean herds. *Journal of Animal Science,* 84**,** 2555-2565.

Rodriguez-Zas, S. L., Southey, B. R., Knox, R. V., Connor, J. F., Lowe, J. F. & Roskamp, B. J. 2003. Bioeconomic evaluation of sow longevity and profitability. *Journal of Animal Science,* 81.

Rodriguez, S. V., Jensen, T. B., Pla, L. M. & Kristensen, A. R. 2011. Optimal replacement policies and economic value of clinical observations in sow herds. *Livestock Science,* 138**,** 207-219.

Rodríguez, S. V., Plà, L. M. & Faulin, J. 2014. New opportunities in operations research to improve pork supply chain efficiency. *Annals of Operations Research,* 219**,** 5-23.

Roehe, R. 1999. Genetic determination of individual birth weight and its association with sow productivity traits using Bayesian analyses. *Journal of Animal Science,* 77**,** 330-343.

Roehe, R. & Kalm, E. 2000. Estimation of genetic and environmental risk factors associated with pre-weaning mortality in piglets using generalized linear mixed models. *Animal Science,* 70**,** 227-240.

Rushton, J. 2009. *The economics of animal health and production*, Cabi.

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. *Animal Welfare,* 22**,** 199-218.

Sanz, M., Perfumo, C. J., Alvarez, R. M., Donovan, T. & Almond, G. W. 2007. Case report: assessment of sow mortality in a large herd. *Journal of Swine Health and Production,* 15**,** 30-36.

Sasaki, Y. & Koketsu, Y. 2008a. Mortality, death interval, survivals, and herd factors for death in gilts and sows in commercial breeding herds. *Journal of Animal Science,* 86**,** 3159-3165.

Sasaki, Y. & Koketsu, Y. 2008b. Sows having high lifetime efficiency and high longevity associated with herd productivity in commercial herds. *Livestock Science,* 118**,** 140-146.

Sasaki, Y. & Koketsu, Y. 2012. A herd management survey on culling guidelines and actual culling practices in three herd groups based on reproductive productivity in Japanese commercial swine herds. *Journal of Animal Science,* 90**,** 1995-2002.

Sasaki, Y., Mctaggart, I. & Koketsu, Y. 2012. Assessment of lifetime economic returns of sows by parity of culled sows in commercial breeding herds. *Journal of Veterinary Epidemiology,* 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. *Livestock Science,* 139**,** 252-257.

Sauter, V. L. 2011. *Decision Support Systems for Business Intelligence,* Hoboken, United States, John Wiley & Sons, Incorporated.

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. *Preventive Veterinary Medicine,* 97**,** 150-156.

Schulz, L. L. & Tonsor, G. T. 2015. Assessment of the economic impacts of porcine epidemic diarrhea virus in the United States. *Journal of Animal Science,* 93**,** 5111-5118.

Segura-Correa, J. C., Ek-Mex, E., Alzina-López, A. & Segura-Correa, V. M. 2011. Frequency of removal reasons of sows in Southeastern Mexico. *Tropical Animal Health and Production,* 43**,** 1583-1588.

Serenius, T., Sevón-Aimonen, M. L. & Mäntysaari, E. A. 2003. Effect of service sire and validity of repeatability model in litter size and farrowing interval of Finnish Landrace and Large White populations. *Livestock Production Science,* 81**,** 213-222.

Serenius, T. & Stalder, K. J. 2004. Genetics of length of productive life and lifetime prolificacy in the finnish landrace and large white pig populations. *Journal of Animal Science,* 82**,** 3111-3117.

Serenius, T. & Stalder, K. J. 2006. Selection for sow longevity. *Journal of Animal Science,* 84**,** E166-E171.

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.

Serenius, T., Stalder, K. J. & Puonti, M. 2006. Impact of dominance effects on sow longevity. *Journal of Animal Breeding & Genetics,* 123**,** 355-361.

Sørensen, J. T. & Fraser, D. 2010. On-farm welfare assessment for regulatory purposes: Issues and possible solutions. *Livestock Science,* 131**,** 1-7.

Southwood, O. I. & Kennedy, B. W. 1991. Genetic and environmental trends for litter size in swine. *Journal of Animal Science,* 69**,** 3177-3182.

Spoolder, H., Bracke, M., Mueller-Graf, C. & Edwards, S. 2011. Preparatory work for the future development of animal based measures for assessing the welfare of pigs - Report 1: Preparatory work for the future development of animal based measures for assessing the welfare of sow, boar and piglet including aspects related to pig castration. *EFSA Supporting Publications,* 8**,** 178E.

Spoolder, H. a. M., Geudeke, M. J., Van Der Peet-Schwering, C. M. C. & Soede, N. M. 2009. Group housing of sows in early pregnancy: A review of success and risk factors. *Livestock Science,* 125**,** 1-14.

Stalder, K. J., Knauer, M., Baas, T. J., Rothschild, M. F. & Mabry, J. W. 2004. Sow longevity. *Pig News and Information,* 25**,** 53-74.

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. *Journal of Swine Health and Production,* 11**,** 69-74.

Stein, T. E., Dijkhuizen, A., D'allaire, S. & Morris, R. S. 1990. Sow culling and mortality in commercial swine breeding herds. *Preventive Veterinary Medicine,* 9**,** 85-94.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. & De Haan, C. 2006. Livestock's long shadow: environmental issues and options. *Food and Agriculture Organization of the United Nations, Rome*.

Stevenson, A. 2010. 'cull'. *In: Stevenson A. (ed.) Oxford Dictionary of English*. Oxford University Press. Available: https://www.oxfordreference.com/view/10.1093/acref/9780199571123.001.0001/m_en_gb0196570 [Accessed September 26 2019]

Stygar, A. H., Niemi, J. K., Oliviero, C., Laurila, T. & Heinonen, M. 2016. Economic value of mitigating Actinobacillus pleuropneumoniae infections in pig fattening herds. *Agricultural Systems,* 144**,** 113-121.

Tani, S., Piñeiro, C. & Koketsu, Y. 2016. Recurrence patterns and factors associated with regular, irregular, and late return to service of female pigs and their lifetime performance on southern European farms. *Journal of Animal Science,* 94**,** 1924-1932.

Tani, S., Piñeiro, C. & Koketsu, Y. 2018. Culling in served females and farrowed sows at consecutive parities in Spanish pig herds. *Porcine Health Management,*4**,** 3.

Tantasuparuk, W. 2001. Weaning-to-service interval in primiparous sows and its relationship with longevity and piglet production. *Livestock Production Science,* 69**,** 155-162.

Tantasuparuk, W., Dalin, A. M., Lundeheim, N., Kunavongkrit, A. & Einarsson, S. 2001. Body weight loss during lactation and its influence on weaning-to-service interval and ovulation rate in Landrace and Yorkshire sows in the tropical environment of Thailand. *Animal Reproduction Science,* 65**,** 273-281.

Tarrés, J., Tibau, J., Piedrafita, J., Fàbrega, E. & Reixach, J. 2006. Factors affecting longevity in maternal Duroc swine lines. *Livestock Science,* 100**,** 121-131.

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

Tess, M. W., Bennett, G. L. & Dickerson, G. E. 1983. Simulation of genetic changes in life cycle efficiency of pork production. I. A bioeconomic model. *Journal of Animal Science,* 56**,** 336-353.

Thomsen, P. T. & Houe, H. 2018. Cow mortality as an indicator of animal welfare in dairy herds. *Research in Veterinary Science,* 119**,** 239-243.

Thrusfield, M. & Christley, R. 2018. *Veterinary epidemiology*, John Wiley & Sons.

Thrusfield, M., Christley, R., Brown, H., Diggle, P. J., French, N., Howe, K., Kelly, L., O'connor, A., Sargeant, J. & Wood, H. 2018. Data collection and management. *In: Thrustfield M.&Christey, R. (ed.) Veterinary Epidemiology,* John Wiley & Sons.

Trienekens, J. & Wognum, N. 2009. Introduction to the European pork chain. European pork chains–Diversity and quality challenges in consumer-oriented production and distribution. *Wageningen: The Netherlands: Wageningen Academic Publishers***,** 19-36.

Tummaruk, P., Lundeheim, N., Einarsson, S. & Dalin, A. M. 2000.Reproductive performance of purebred Swedish Landrace and Swedish Yorkshire sows: I. Seasonal variation and parity influence. *Acta Agriculturae Scandinavica, Section A-Animal Science,* 50**,** 205-216.

Tummaruk, P., Lundeheim, N., Einarsson, S. & Dalin, A. M. 2001. Effect of birth litter size, birth parity number, growth rate, backfat thickness and age at first mating of gilts on their reproductive performance as sows. *Animal Reproduction Science,* 66**,** 225-237.

Tuyttens, F. a. M. 2005. The importance of straw for pig and cattle welfare: A review. *Applied Animal Behaviour Science,* 92**,** 261-282.

Vallet, J. L., Calderón-Díaz, J. A., Stalder, K. J., Phillips, C., Cushman, R. A., Miles, J. R., Rempel, L. A., Rohrer, G. A., Lents, C. A., Freking, B. A. & Nonneman, D. J. 2016. Litter-of-origin trait effects on gilt development. *Journal of Animal Science,* 94**,** 96-105.

Wang, C., Wu, Y., Shu, D., Wei, H., Zhou, Y. & Peng, J. 2019. An Analysis of Culling Patterns during the Breeding Cycle and Lifetime Production from the Aspect of Culling Reasons for Gilts and Sows in Southwest China. *Animals,* 9**,** 160.

Wang, X., Wu, X., Yan, P., Gao, W., Chen, Y. & Sui, P. 2016. Integrated analysis on economic and environmental consequences of livestock husbandry on different scale in China. *Journal of Cleaner Production,* 119**,** 1-12.

Welfare Quality ® 2009. Welfare Quality ®, 2009. Welfare Quality ® assessment protocol for pigs (sows and piglets, growing and finishing pigs). Lelystad, Netherlands.

WinPig.net Agrosoft, WinPig.net. Available: http://agrosoft.eu/uk/products/winpig-net-2/

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. *Livestock Science,* 115**,** 195-205.

Wolfert, S., Ge, L., Verdouw, C. & Bogaardt, M.-J. 2017. Big Data in Smart Farming – A review. *Agricultural Systems,* 153**,** 69-80.

Yang, H., Eastham, P. R., Phillips, P. & Whittemore, C. T. 1989. Reproductive performance, body weight and body condition of breeding sows with differing body fatness at parturition, differing nutrition during lactation, and differing litter size. *Animal Science,* 48**,** 181-201.

Yatabe, Y., Iida, R., Piñeiro, C. & Koketsu, Y. 2019. Recurrence patterns and lifetime performance of parity 1 sows in breeding herds with different weaning-to-first-mating intervals. *Porcine Health Management,* 5**,** 15.

Yazdi, M. H., Lundeheim, N., Rydhmer, L., Ringmar-Cederberg, E. & Johansson, K. 2000. Survival of Swedish Landrace and Yorkshire sows in relation to osteochondrosis: a genetic study. *Animal Science,* 71**,** 1-9.

Yun, J., Swan, K.-M., Vienola, K., Farmer, C., Oliviero, C., Peltoniemi, O. & Valros, A. 2013. Nest-building in sows: effects of farrowing housing on hormonal modulation of maternal characteristics. *Applied Animal Behaviour Science,* 148**,** 77-84.

Zhao, Y., Liu, X., Mo, D., Chen, Q. & Chen, Y. 2015. Analysis of reasons for sow culling and seasonal effects on reproductive disorders in Southern China. *Animal Reproduction Science,*159**,** 191-197.

Zurbrigg, K. & Blackwell, T. 2006. Injuries, lameness, and cleanliness of sows in four group-housing gestation facilities in Ontario. *Journal of Swine Health and Production,* 14**,** 202-206.