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STAYABILITY IN YORKSHIRE SOWS.

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FACTORS AFFECTING MEASURES OF LONGEVITY AND STAYABILITY IN YORKSHIRE SOWS.

By

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ABSTRACT

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Adult sow lifetime is recognized as both an economic and welfare concern. However, there are not consistent definitions of sow longevity. The purpose of this study was to assess the relationship of developmental performance factors with longevity and to determine the genetic variation within six different descriptions of longevity. Longevity definitions included stayability (probability of producing 40 pigs or reaching four parities), lifespan (number of parities accumulated before culling), lifetime prolificacy (number of pigs born alive during a female's lifetime), herdlife (time from first farrowing to culling), and productive life (pigs produced per day of life).

The edited data consisted of 14,262 records from Yorkshire females with at least one farrowing record, from both nucleus and multiplication herds across 21 farms. Within a subset of the data, information was available on the female's litter birth record and corresponding growth and composition data. Furthermore, complete pedigrees were available on 7,487 females. The data were subdivided into two data sets; Data A: female's farrowing records, and Data B: Data A and the information from a female's litter birth record and her growth and backfat data. Due to a reduced number of records with complete pedigree information, two separate analyses were completed.

Initially, a Cox proportional hazards model was used to determine the relationship of developmental factors and first farrowing record with longevity. Those factors that were significantly ($P < 0.0001$) associated with longevity, regardless of definition, were age at first farrowing, litter size at first farrowing and last farrowing, number of stillborn in her first litter, adjusted 21 day litter weight of first litter, herd type (nucleus or multiplier), and standardized variables for backfat and growth. Within a contemporary group, fatter, slower growing gilts had a decreased risk of being culled. Additionally, sows that had more pigs born alive, fewer stillborn, and heavier litters at weaning in their first litter had a decreased risk of being culled. Furthermore, sows from nucleus herds experienced a greater risk of being culled.

Heritability was estimated for four different descriptions of longevity (lifespan, lifetime prolificacy, herdlife, and pigs produced per day of life) with survival analysis by using a proportional hazards model with an underlying Weibull distribution. A threshold model was used to estimate heritability for two descriptions of stayability on a subset of the original data (n=5,889) that did not include censored observations. Fixed effects within the two model types were similar to those reported previously. Random effects were sire and the interaction of herd by year. Fixed effects were consistent in their significance, regardless of statistical model or definition. Heritability estimates ranged from 0.039 to 0.050 and from 0.076 to 0.231 for true and functional definitions of survival analyses, respectively and from 0.117 to 0.200 for threshold analyses.

Results indicated that there are early indicators that can be monitored to provide insight to the future productivity or length of productive life of Yorkshire females. Additionally, sufficient genetic variation exists, regardless of definition, to improve sow longevity. Pork producers can implement management protocols which can extend the productive life of breeding females resulting in improved profitability and animal welfare.

This dissertation is dedicated to my parents for their continued support and to my family, Katie, Carter, and Nolan who all have made great sacrifices to make this possible.

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This project would not have been possible without access to production data from Waldo Farms, DeWitt, NE, Premier Swine Systems, Michigantown, IN, Whiteshire/Hamroc, Albion, IN, and the Zierke Co., Morris, MN. The National Swine Registry granted access to Yorkshire pedigree information and The American Yorkshire Club and The National Pork Board provided partial funding for this project.

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LPL = herd life defined as the number of days between date of first farrowing and culling

MAXPAR = the highest parity completed prior to removal

PLIFE = pigs born alive/day/herd life

PRNBA40 = discrete variable indicating a female produced 40 live pigs prior to removal

PR4PAR = discrete variable indicating a female completed 4 parities prior to removal

SNBA = lifetime pigs born alive

AGEFF = days of age at first farrowing

BF = standardized deviation for back fat within a contemporary group

DAY = standardized deviation for days to 113.6 kg within a contemporary group

D21W = adjusted 21 day litter weight of female's first litter

HT = herd type

OFFTEST = number of days between off test and first farrowing

PGR = birth litter gilt ratio

PHY = herd by birth year

PLBW = birth litter birth weight

PNBA = birth litter number born alive

LNBA = last litter farrowed number born alive

NBA = first litter number born alive

NSTL = first litter number of stillborns

SHY = herd by first farrowing year

WNAGE = days of lactation allowed for first litter

Introduction

Longevity of adult females is a trait with a significant impact on swine farm profitability. An improvement in longevity can result in decreased replacement costs and a higher proportion of mature sows in a herd that have reached their maximum productivity. The swine industry has a hierarchical structure, with many pork producers purchasing out-of-herd replacement gilts. This investment constitutes a major budget decision and ideally, replacement gilts should be maintained until this investment is recuperated. In practice, 40 to 50% of the sows are removed before they complete three to four parities (D'Allaire et al., 1987; Boyle et al., 1998), an age when most replacements barely recover their initial cost (Stalder et al., 2002). Similarly, reports from commercial swine records have shown that sow-culling rates within commercial herds are around 50% and the reported average parity of cull sows in the U.S. is 3.8 (PigCHAMP, 2000-2005). This is alarming since decreased sow longevity is a welfare concern as well as a profitability dilemma. In a simulation of farrow to finish swine farms, improved sow lifetime by one parity increased profit potential by $34 to $150 per sow lifetime, depending on the assumptions made regarding pigs per litter sold, market price and replacement gilt costs (Stalder et al., 2000). Incentives to increase sow longevity include larger litters with heavier pigs in older parities, fewer unproductive days, acquired immunity to herd diseases, higher sow salvage value, and lower replacements costs (D'Allaire et al., 1987; Lucia et al., 2000).

Increased sow mortality, combined with reproductive problems such as failing to cycle in a timely manner, not conceiving, not farrowing, poor performance or physical problems are the major reasons for the increase in replacement rates in commercial sow units (Dial and Koketsu, 1996; Friendship et al., 1996). These high replacement rates result in the need for larger gilt pools and therefore the purchase or production of more breeding gilts. In addition, breeding herd inventories usually have high proportions of low-parity females. Thus, the majority of the female removals occur at low parities and are mostly attributed to reproductive failure (D'Allaire et al., 1987; Dijkhuizen et al., 1989; Patterson et al., 1996).

Improving economic efficiency and animal well being are good reasons to examine what factors might contribute to opportunities to improve longevity. In addition, sows that survive fewer parities are more likely to produce fewer pigs, compared to a sow that remains in the breeding herd for a longer period of time. Fewer parities result in reduced opportunity for sows to be sufficiently productive to achieve a return on their gilt investment cost (Stalder, 2004).

Longevity can be defined in a number of ways and measured using different systems of analysis. Aside from the challenges of defining and quantifying longevity, there are additional influencing factors to account for when measuring longevity or herd life. The relative performance of a sow compared to that of her herd mates can have an impact on culling decisions. Number born, number born alive, number weaned, and wean to estrus intervals relative to herd averages can all play a role in the longevity of a sow. Selection for type traits has an impact on longevity due to their indirect effects. Traits such as underline quality, feet and legs, and lean growth can have an effect on a producer's decision to cull an animal. There is some indication (Pond and Mersmann, 2001) that natural longevity of pigs is 12-15 years when performance is not a factor in removal from the breeding herd. Poor longevity, regardless of the causes, does result in increased breeding herd female replacement rates.

Regardless of the traits being measured or the definition being used, the need to utilize records from sows that have not completed their lifetime performance at the time of data acquisition poses a challenge concerning traditional statistical approaches. There are certain aspects of survival analysis data, such as censoring and non-normality that generate great difficulty when trying to analyze the data using traditional statistical methods. The non-normality aspect of the data violates the normality assumption of most commonly used statistical models. To date, methods used to conduct survival analysis have included linear models, proportional hazards models, and random regression models. In the case of linear model analysis, most studies have applied multiple-trait Restricted Maximum Likelihood (REML) to a sire or animal model to estimate genetic parameters. Cox's semiparametric model is widely used in the analysis of survival data to explain the effect of explanatory variables on hazard rates or relative risk of a sow being culled from the breeding herd in this case. This has been extended to include random effects, as in regular mixed linear models (Ducrocq and Solkner,1998a). Survival data can be fitted with either a Cox proportional hazards model, which allows an unspecified form for the underlying survivor function, or a parametric model in which the distribution of the random disturbance can be taken from a class of distributions that includes the Weibull distribution.

There is clearly an economic incentive to quantify factors that delay a sow's culling. There is suitable statistical methodology that will support this type of research. However, there are not consistent definitions of longevity used across the literature. The purpose of this research was to simultaneously evaluate the relationship of developmental factors and parity one performance with six different definitions of longevity. A unique data set was assembled to complete this project. The data set is an accumulation of both nucleus and multiplication records of Yorkshire sows from four swine seedstock systems (Waldo Farms, DeWitt, NE; Premier Swine Systems, Michigantown, IN; Whiteshire/Hamroc, Albion, IN; and The Zierke Co., Morris, MN). The objectives of this study were as follows:

1. To assess six different measures of longevity and determine what relationship developmental performance characteristics may have with these differing definitions.

2. To estimate the genetic variation for the six different measures of longevity and determine if non-genetic factors influence the heritability estimate.

CHAPTER I

LITERATURE REVIEW

Definitions of Longevity

Before sow longevity can be improved or the reasons that sows vary in their longevity can be examined, the trait itself needs to be defined (Stalder, 2004). Depending on the type of study being conducted, many different terms have been used to describe a female's survival including: herd life, survivability, lifespan, length of productive life, stayability, and lifetime performance. Longevity of sows, defined as the ability to delay involuntary culling, summarizes the effects of functional traits, and of reproductive performance through the removal of sows with inferior fertility or a low capacity to produce pigs (Ducrocq and Sölkner, 1998a). Sow longevity is an example of survival or time-to-event data (Allison, 1997), with time typically being the number of days that a sow remains in the herd and the event being the removal from the herd (e.g., culling or death).

Dekkers and Jairath (1994) outlined three main categories to characterize definitions of longevity. The first category involves traits related to length of total or productive life. This includes measures such as days from birth to culling, days from entering the breeding herd to culling or days from parturition at parity one to removal from the herd. The second category is the ability to reach a predetermined endpoint, for example a specific age or lactation. This is a measure of the sow's stayability. The final category used to define longevity is survival within each consecutive lactation or parity.

There are a variety of ways in which length of productive life has been measured in domestic livestock. In dairy cattle studies, length of productive life has been defined as the number of days from first calving to last test day or last known lactation. Due to the lack of exact culling dates, these endpoints were considered a close approximation (Dekkers et al., 1994; Jairath and Dekkers, 1994; Vukasinovic et al., 1997; Vollema and Groen, 1998). Alternate measures of productive life have been the number of calvings or completed lactations, and days or months in milk over a lifetime (Jairath and Dekkers, 1994; Vollema and Groen, 1998). A similar approach to measuring length of productive life is the evaluation of length of total life. Total productive life is a measure of the number of days or months from birth to date of culling (Vollema and Groen, 1998).

Stayability, the second category outlined by Dekkers and Jairath (1994), is a measure of an animal's ability to remain in the herd to a set endpoint. Among studies on dairy populations, endpoints used in the analysis of stayability are survival to 36, 48, 54, 72, and 84 months (Short and Lawlor, 1992; Vollema and Groen, 1998). Survival through the first lactation can also act as an indicator of stayability. If a cow calved for a second time within 2 years of her first calving date, she was considered to have survived her first lactation (Boettcher et al. 1999).

The final classification by Dekkers and Jairath (1994), survival within consecutive lactations, is not as common in longevity studies. Survival can either be measured on the basis of survival to the next lactation (Jairath et al., 1998), or the time spanned by the data can be divided into successive intervals (Veerkamp et al., 2001). With the second case, survival is coded as a series of binary data. If an animal survives to the next interval, it can be coded as 1, while a failure is coded as 0.

From the initial work conducted in dairy cattle, swine longevity research has evolved. D'Allaire et al. (1992) suggests that when evaluating sow longevity, swine operations could assess removal rate, culling rate, replacement rate, percent gilts in the herd, mean parity of females in inventory, and mean parity at removal. Pork producers have tended to focus on culling and replacement rates as a measure of how herds compare regarding the retention of females within their operations (Deen et al., 2002). The challenge of working with field data, are inconsistent and incomplete recording schemes over time (eg. birth date of purchased gilts) and the variation of management and culling policy across operations. Also, Deen (2003) argued that parity, age at removal, and removal rate are not appropriate measures of longevity because older, less productive sows can be retained just to improve parity or age structure of the herd. Holder et al. (1995), Culbertson and Mabry (1995), and Knauer (2006) took an alternative approach to assessing longevity by assessing the number of pigs weaned per day of life.

More recently, productive life span is a trait which has received increasing attention in animal breeding. Ducrocq (1997) proposed a general strategy for the analysis of a productive life span based on survival analysis as an adequate method for the genetic evaluation of the length of productive life measurements. A number of studies have defined longevity by assessing the length of productive life, lifetime prolificacy, or stayability of a sow. Yazdi et al. (2000b), Serenius and Stalder (2004), and Tarrés et al. (2006) have defined length of productive life as the number of days from the date of first farrowing to the date of culling or censoring. Guo et al. (2001) defined the beginning of a sow's productive life in the nucleus herd as the age in days at first conception, while Rodriguez-Zas et al., (2003) defined herd life as the total number of days from first service (regardless of success) until removal from the herd. Additionally, productive days were defined as the total number of days the sow gestated and lactated until removal from the herd. Lifetime prolificacy was defined by Guo et al. (2001) and Serenius and Stalder (2004) as the number of piglets (born alive) produced during the productive lifespan of the sow and Tholen et al. (1996a) defined stayability as the ability of a sow to produce an additional litter, after producing the previous litter.

Lucia et al. (2000) took an alternative approach to defining longevity. Instead of looking at the lifetime productivity or prolificacy of a female, this study determined the percentage of a sow's lifetime that she was non-productive. The number of days spent in the herd was estimated by the difference between the date of removal and the date of entry, excluding the entry-to-first service interval. For each female, the number of days spent in gestation and lactation during herd life was summed. As a nonproductive day is any day spent by a female in the breeding herd in periods other than lactation or gestation, the proportion of lifetime nonproductive days was calculated by subtracting lactation days and gestation days from total herd days and dividing that quantity by herd days. That value was then multiplied by 100% to express the value for lifetime nonproductive days as a percentage.

Length of productive life provides a complete measure of survival. Using this definition of survival, a value for a female's life is not determined until a sow has been removed from the herd. It is necessary to either wait until a sow has been culled or use a method of analysis that accounts for incomplete or censored records. If culling dates are not recorded, an estimation such as the last farrow date or last service date must be used. Stayability is a measure of herd life that removes the problem of accounting for incomplete records. However, it does not offer insight into survival before or after a predetermined endpoint. Subsequently, the appropriate measure of longevity, for a given study, is dependent on the data available and the objectives of the study.

Survival Analysis

Survival time can be broadly defined as the time to the occurrence of a given event. Statistical techniques used in survival analysis are aimed at modeling and analysis of response times. The goal of survival analysis is to analyze positive measures describing in some sense the width of the interval between an origin point and an endpoint. Often, the endpoint corresponds to death or culling and the length from the origin to the end is measured in number of days or probability of reaching a predetermined point in production (Ducrocq, 1997). Famula (1981) was the first author who proposed survival analysis as a statistical method to analyze length of productive life in dairy cattle. Smith (1983) and Smith and Quaas (1984) used survival analysis techniques to estimate breeding values of sires based on the length of productive life of their daughters. The techniques were further developed and adjusted for large scale applications by Ducrocq (1994) and Ducrocq and Sölkner (1998b).

Genetic evaluation for the length of productive life in livestock species requires specific statistical methods due to: 1) some animals are still alive at the time of evaluation and their complete length of productive life is not known, which implies that records of such individuals must be treated as censored; 2) effects influencing length of productive life do not act linearly and vary with time; and 3) the distribution of length of productive life is often unknown and extremely skewed (Vukasinovic, 1997).

A specific feature of survival analysis is that it can accommodate censoring and uses information available on animals that are still alive. That is, the survival time may either be known to be greater than a certain amount (right censored), less than a certain amount (left censored), or be within a certain range (double censored) (Kachman, 1999). The most frequent type of censoring is right censoring. There are two special cases of right censoring. Type I censoring occurs when the experiment is stopped after a fixed time and Type II censoring occurs when the experiment is stopped after a pre-determined number of failures. Usual causes of right censoring are the absence of failure before the end of the study. An observation is considered censored when a female is still alive at the end of data collection, when she disappears from the herd due to sale to another herd not under a testing program, or when the whole herd is withdrawn from the testing program (Vukasinovic, 1997).

Survival analysis can also accommodate left truncated records, for which the origin point lays outside the data collection period. An example of a left truncated record is when a female is in production prior to the beginning of the study. Such an individual is considered to be at risk only from the beginning of data collection onward (Vukasinovic, 1997).

Multiple authors (Lee 1992; Vukasinovic 1997; Ducrocq 1987, 1994, 1997; Solkner and Ducrocq 1999; and Kachman 1999) provide a detailed background on the methodology of survival analysis. The distribution of survival times is usually described or characterized by three functions: (1) the survivorship function, (2) the probability density function, and (3) the hazard function. These three functions are mathematically equivalent. If one of them is given, the other two can be derived. For example, let T denote the survival time. The distribution of T can be characterized by the following three functions.

1. *Survivorship Function* (or *cumulative survival rate*). This function, denoted by S(t) is defined as the probability that an individual survives longer than t:

$$S(t) = P(T>t)$$

From the definition of the cumulative distribution function $F(t)$ of T,

$$S(t) = 1 - P \text{ (an individual fails before time t)}$$

$$= 1 - F(t)$$

The graph of S(t) is called the survival curve.

2. *Probability Density Function* (or *Density Function*). The survival time T, a continuous random variable, has a probability density function defined as the limit of the probability that an individual fails in the short interval t to $t + \Delta t$ per unit width Δt, or simply the probability of failure in a small interval per unit time. It can be expressed as

$$f(t) = \lim_{\Delta t \to 0} \frac{P\{an\ individual\ dying\ between\ (t, t+\Delta t)\}}{\Delta t}$$

The density function is also known as the unconditional failure rate.

3. *Hazard Function (instantaneous failure rate or conditional failure rate).* Models for survival analysis can be built from a hazard function. The hazard function $h(t)$ of survival time T gives the conditional failure rate. This is defined as the probability of failure during a very small time interval, assuming that the individual has survived to the beginning of the interval, t to $t + \Delta t$ per unit time, given that the individual has survived to time t:

$$h(t) = \lim_{\Delta t \to 0} \frac{P\{an\ individual\ of\ age\ t\ fails\ in\ the\ time\ (t, t+\Delta t)}{\Delta t}$$

The hazard function can also be defined in terms of the cumulative distribution function $F(t)$ and the probability density function $f(t)$:

$$h(t) = f(t)/\{1 - F(t)\}$$

From its definition, the hazard function must be nonnegative. Additionally, it must be positive at time t unless there is no risk of failure at time t. The hazard rate is an unobserved variable yet it controls both the occurrence and the timing of failure or in this case culling or removal from the herd. It is the fundamental dependent variable in survival analysis. The shape of the hazard function will influence the survivorship function.

Economic impact on improving longevity

As with many aspects of animal breeding, genetic change and selection are often driven by ways to improve economic efficiency within a production system. Sow longevity or the need to identify factors impacting sow longevity is no different. Sow longevity or the length of time that a sow remains in the herd has a major effect on profitability (Pl´a et al., 2003). Replacement decision making is a continual and complex process based on biological and economic considerations (Rajala-Schultz and Grohn, 2001). This continual decision making process is a dynamic one that adapts to changes in replacement rates, salvage value, replacement costs, and revenues per piglet produced (Rodriguez-Zas et al., 2006). Regardless of economic conditions, sows that remain in the breeding herd longer have an increased opportunity to recuperate their initial cost and could result in producing larger and heavier litters, have fewer nonproductive days, improve acquired immunity to diseases, have greater salvage value, and lower replacements costs (D'Allaire and Drolet, 1999; Lucia et al., 2000; Stalder et al., 2002).

Stalder et al. (2004) effectively summarized literature that addressed the issue of economic impact on improving sow longevity. Stevermer (1991) demonstrated that productivity and breakeven price increased through parity seven when a sow's maximum parity was allowed to increase, in a model that assumed 15% replacement rate per parity. Sehested (1996) found that improving longevity by one parity had the same impact as improving lean meat content by 0.5%. He reported that longevity tended to decrease with increasing parity of culling and likely to have little economic impact once average parity at culling was above five. Conversely, a study conducted by Parsons et al. (1990) suggested that productivity of a stable pig herd, and hence its economic status, was insensitive to parity distribution and its underlying culling strategies when first parity females represented either 26% or 30% of the female breeding herd.

Faust et al. (1992, 1993a, 1993b) implemented simulation models to examine the effect of culling rate, replacement gilt costs and other factors on the profitability of commercial pig operations. These models demonstrated that systems with the lowest commercial replacement rates were most profitable and when high replacement rates occurred, replacement gilts were worth no more than 175% of market value. Conversely, when replacement rates were low, replacement gilts were worth as much as 450% of market value. Results showed that greater benefit occurred when maximum parity increased from one to five than from five to ten.

Patterson (1997) reported economic benefits of increasing lifetime production on a piglet basis. Piglet breeding costs are reduced by US$1.61 per piglet when sows with high lifetime production values, a trait closely related to longevity, were compared to sows with low lifetime production values. Similarly, Lucia et al. (2000) indicated that lifetime reproductive performance was better in herds having a higher proportion of high parity females. Dhuyvetter (2000) suggested that the optimal economic time to cull a sow is after her 8th or 9th parity, even though the additional economic benefits of keeping a sow past the sixth parity became marginally less.

Stalder et al. (2004) summarized the "ideal" parity distribution percentage recommendations previously published by Straw (1984), Parson et al. (1990), Muirhead and Alexander (1997), and Morrison et al. (2002). Within an operation, 17 to 30% of the sows should be parity zero females, while 15 to 23% should be parity one sows, 14 to 19% should be parity two sows, 13 to 16% should be parity three sows, 10 to 15% should be parity 4 sows, 5 to 14% should be parity five sows, and the remainder should be comprised of parity six and higher females.

Net present value is defined as the difference between the present value of income and costs including depreciation. Stalder et al., (2000) conducted a net present value analysis, on the basis of 1996 to 2000 average production levels and costs, to determine the number of parities a sow must remain in the breeding herd of a breed-to-wean operation before the initial investment in her is profitable. A replacement gilt must remain in the breeding herd for 3 parities before reaching a positive net present value. Increased length of productive life, and favorable segregated early weaning piglet price produced a higher net present value.

Rodruguez-Zas et al., (2003) utilized a dynamic programming model to find the optimal parity and net present value in breed-to-wean swine herds. The model included income and costs per parity weighted by the discount rate and sow removal rate. Three scenarios that reflect a wide range of cases were considered: low removal rates per parity with no salvage value, high removal rates per parity with no salvage value, and high removal rates per parity with a percentage of the sows having a salvage value. The final scenario represented the optimal average replacement parity and profitability for many U.S. breed-to-wean operations. Sow replacement cost and salvage value had the greatest impact on optimal parity followed by revenues per piglet weaned. Optimal parity varied from 1 to 2 parities in situations with low sow costs, high salvage values, and high revenues per piglet, to 6 to 10 parities for the converse economic situation.

Many computer tools and decision support programs have been developed to examine the impact of sow longevity or an associated trait like culling rate (Stalder et al., 2004). Some of these tools examined the number of parities required before a sow reaches a positive net present value (Stalder et al., 2000; Stalder et al., 2002), while others determine economically optimal culling strategies (Dijkhuizen et al., 1986; Huirne et al., 1988). Still other models estimated the economic value of sow longevity (De Vries, 1989). Additional software tools have been developed to assist producers with sow replacement decisions based on ecomonics and profitability (Jalvingh et al., 1992; Jorgensen et al., 1996; Morrison et al., 2002).

Lacy et al., (2005) created the Swine Replacement Evaluator to economically evaluate an operation's replacement breeding herd female decisions. The spreadsheet is designed for a producer to enter production and financial data specific to their operation. Resulting net present value and internal rate of return (the discount rate that will cause an investment to have a net present value equal to zero) are calculated based on the data specific for individual producers' operation. The gilt replacement worksheets can assist swine producers in determining if purchasing replacement gilts at some price is a profitable decision. Additionally, a producer can use these spreadsheets to determine if breeding females remain in the herd for a sufficient number of parities to recover the initial investment cost of replacement gilts.

Sow longevity has been proven to have an economic impact on swine production. It is important to remember that the exact economic impact of keeping a sow productive, if just for one more parity, is greatly dependent on current market values and the parity distribution within a given producer's operation. In times when market and salvage prices are high, there is a tendency to be stricter with culling criteria. However, when market and salvage prices are low, the economic indicators suggest that producers should keep sows longer (Brandt et al., 1999).

Reasons for removal

The reasons sows are removed from the breeding herd of commercial pig operations are numerous and have been documented in the scientific literature for some time (Stalder et al., 2004). Stalder et al. (2004) provided an informative summary regarding the percentage of sows culled and reasons culled by study. The reasons for culling are categorized by reproductive failure, poor performance, old age, feet, leg, and locomotion disorders, death, farrowing problems, injury, health, disease, and milking problems. It is clear that reproductive failure is the single biggest reason for a sow's removal from the breeding herd accounting for approximately 30% of removals. Reproductive failure can encompass a variety of problems, including failure to cycle, inability to conceive, etc.

If reasons for removal are categorized by parity, a slightly different trend can be seen (Stalder et al., 2004). Reproductive failure and feet and leg problems are the predominant reasons young sows (sows having three parities or less) are culled. Once sows reach a more mature age (above 3 parities), culling for reproductive failure becomes less of an issue and problems like poor performance, age, and even death can be responsible for just as many or more sow removals (Boyle et al., 1998; Lucia et al., 1996). Stalder et al. (2004) concluded that producers are more apt to cull mature sows based on individual performance, whereas the challenge with young sows is maintaining reproductive function.

Mortality can make up a significant portion of the total sows removed from the breeding herd on an annual basis (Stalder et al., 2004). Additionally, annual sow mortality rates have been increasing in recent years (Irwin et al., 2000; Duran, 2001). Stalder et al. (2004) provided a summary of studies that reported mortality rates in breeding sows by causes of death. The most common causes for sow death included torsion and other abdominal organ injuries, heart failure, and cystitis (D'Allaire and Drolet, 1999). Mortalities due to heart failure, torsion, cystitis, and uterine prolapse tended to be problematic in older sows, while arthritis, endometritis, pneumonia, locomotion problems, and ulcers appeared to be primary causes for death among gilts and young sows (Chagnon et al., 1991; Maderbacher et al., 1993). Schultz et al. (2001) reported that 38-40% of sow deaths occurred 100 to 125 days post breeding, a time at which a substantial economic investment had already been made. Other factors such as management, inexperienced labor, housing, rough handling, altering feed quantity or regimen, environmental temperature, and subjection to stressful events can affect mortality rates in swine operations (Stalder et al., 2004). Lucia et al. (2000) analyzed lifetime reproductive performance records from 7,973 females, over a five year period, having distinct reasons for removal. The reasons for removal were categorized across parity categories into reproduction, litter performance, locomotion, and disease problems. The most common removal reason was culling attributed to reproductive disorders (33.6%), followed by culling for sub-optimal litter performance (20.6%).

Rodriguez-Zas et al., (2003) and Engblom et al., (2007) reported similar values for percentage of sows culled for the previously defined reasons for removal. Rodriguez-Zas et al., (2003) reported locomotion problems and old age accounted, on average, for 5.4 and 7.9% per parity or 11.9 and 17.4% per year, respectively. Engblom et al., (2007) summarized the most common removal reasons were reproductive disorders (26.9%), old age (18.7%) and udder problems (18.6%) followed by low productivity (9.5%), lameness and/or foot lesions (8.6%) and traumatic injuries (7.1%). The average parity number at removal for all sows in that study was 4.4. In lower parities, most sows were removed due to reproductive disorders, while udder problems were the most frequent reasons for removal of medium parity sows.

Takai and Koketsu (2007) identified at-risk females having characteristics of at least one of the four subgroups: females with re-services, lactation length < 14 days, weaning-to-first-mating interval ≥8 days, and abortion records. From 117 farms, 102,494 parity records were categorized into at-risk females and non-at-risk females. At-risk females had at least 11.1% lower farrowing rates than non-at-risk females among all parities and seasons of matings ($P < 0.05$). As parity increased, farrowing rate decreased by 11.2% and 5.3% for at-risk and non-at-risk females, respectively. Parity 1 females and those mated during summer had the highest proportion of becoming at-risk females. Furthermore, gilts and sows with abortion records had at least 39.3% lower farrowing rates. There was no difference in the number of pigs born alive between at-risk females and non-at-risk females proving that if at-risk females are closely managed they can be productive. Producers could improve herd productivity by monitoring and taking added management steps to reduce the percentage of at-risk females.

To improve longevity through a reduction in mortality within the breeding herd, it is necessary to determine the specific cause of death by performing necropsy on sows that have died (D'Allaire et al., 1992). The period immediately following parturition is the period when sows are at the greatest risk of death and young sows experience the highest rate of unplanned removal (Deen and Xue, 1999; Engblom et al., 2007). This period of the sow's life cycle should be of particular interest to employees and management within the farrowing segment of the operation (Stalder et al., 2004). To make improvements on sow mortality and culling rates, managers should document the cause for removal for the sows sent to slaughter and also those euthanized and found dead.

Heinonen et al. (1998) collected reproductive organs on 1,708 Finnish female pigs to determine the cause of fertility disturbances in sows and gilts by examining the reproductive organs. A large percentage (52.3%) of the organs had no abnormalities, while 25.1% had inactive ovaries and 6.2% of the reproductive organs possessed cystic ovaries. This is in agreement with Knauer et al. (2006), who reported that of the sows culled for reproductive failure, 86.2% were classified as having normal ovaries. From these results, one could hypothesize that factors other than the health and fitness of a female's reproductive tract is causing reproductive failure among a large percentage of the sows removed for reproductive reasons.

Factors Affecting Longevity

There are a multitude of factors within swine production systems that can either directly or indirectly impact a sow's productive life. These factors include: feeding programs, body composition at selection and body condition throughout a sow's productive life, gilt pool management, age at puberty and first farrowing, lactation length, fertility, season, housing, herd size, sow behavior, feet and leg soundness, employee management, and disease. This section of the literature review will highlight some of the studies summarized by Stalder et al. (2004), along with more recent publications.

Nutrition, defined either as the quantity of feed at a particular stage of life or composition of energy, protein, fiber, vitamins or minerals within the diet, does play a critical role in a female's life cycle. Nutritional management can impact productivity and indirectly affect longevity of a female. Rozeboom (1999) provided a review of various feeding regimens and their impact on sow longevity. The review showed that gilt development nutritional trials have had a mixture of positive and negative impacts on sow longevity. Conversely, Kirkwood (1990) and Edge et al. (2003) independently concluded that there are minimal long-term nutritional treatment effects on lifetime sow performance. Kirkwood (1990) justified that any relationship between body composition at mating and longevity is a reflection of selection for improved females that are conducive to modern conventional management. This improved management minimizes weight and condition loss during lactation resulting in no association between live weight or backfat depth at first breeding.

Long et al. (1998) reported that sows fed a high energy, high protein diet throughout their growing phase had significantly poorer stayability through four parities than gilts fed a high energy, low protein diet. Other studies concluded that limiting energy intake during the growing phase had favorable effects on locomotion, mammary gland growth, and in one study, resulted in a higher proportion of sows producing four litters (te Brake, 1986; den Hartog and Noordewier, 1984; Han et al., 2000; Stalder et al., 1998). Tarres et al. (2003) reported that Duroc females with increased average daily gain from the end of the growth test until mating had a greater culling rate.

Tokach et al. (2000) outlined practical recommendations for gilt development feeding programs. These recommendations included increasing calcium and available phosphorus levels after the gilts have been selected for breeding at approximately 68 to 82 kg. Additionally, it was recommended that gilts be limit fed from 82 kg until 190 days of age or have ad-libitum feed intake of a diet with moderate protein level from 68 to 113.5 kg body weight. Others have also reported on calcium and phosphorus levels in the diet continue to have an impact on reproductive failure and ultimately sow longevity (Arthur et al., 1983; Kornegay et al., 1984; Koketsu et al., 1996). Boyd et al. (2002) also provided numerous nutritional and management recommendations to maximize lifetime sow productivity. Recommendations were provided based on sow body condition scores, predicted energy and lysine needs for lactating first litter sows, and intake targets based on litter size and stage of lactation.

Patience (2003) reported that gilt body composition, the relative proportion of fat and muscle in relation to body weight, can be altered to meet some target. He continued that the body composition targets to optimize production and longevity have not been established. These optimum composition levels would be dependent on the genetic background of the sow herd and type of housing. Stalder et al. (2004) stated that some minimum level of backfat is needed for replacement gilts so that they maximize lifetime number of piglets born alive. Challinor et al. (1996) reported that gilts that had 18 to 22 mm of backfat at a average weight of 150 kg averaged 7.2 more piglets over five parities than did gilts with 14 to16 mm backfat. Brisbane and Chenais (1996) reported that increased backfat levels of gilts adjusted to 100 kg influenced survival rates of Canadian Landrace females. Survival through the fourth parity was 10% higher in gilts from the highest backfat category (>18 mm) when compared to gilts from the leanest backfat category (<10 mm). Tummaruk et al. (2001) reported that gilts with higher adjusted backfat had more live born piglets in their second parity when compared to gilts with low backfat. Lopez-Serrano et al. (2000) and Tholen et al. (1996b) concluded that there is an antagonistic relationship between backfat and stayability. Geiger et al. (1999) reported that gilts with 18 mm or less backfat at selection experienced higher mortality rates compared to those with more than 18 mm of backfat. Tarres et al. (2006) created different hypothetical situations in order to determine the optimal animal body type at first farrowing to maximize longevity. They reported that optimal backfat thickness should be more than 16 mm at the end of the growth test and maintain this level until the first parturition without exceeding 19 mm.

In related research, Stalder et al. (2005) reported similar results on the effects of growth and compositional traits on reproductive performance in U.S. Landrace sows. Females from the lowest backfat group (≤ 9.0 mm) had fewer lifetime number of piglets born alive and females from the fattest group (≥ 25.0 mm) produced more pigs born alive during their lifetime than sows from intermediate backfat classes. Additionally, the fattest group averaged a greater maximum number of parities when compared to the other five backfat groups.

On the contrary, Young et al. (1991), Kerr and Cameron (1995), Rozeboom et al. (1996), and Yazdi et al. (2000b) reported different relationships among backfat and longevity or lifetime productivity than the previously mentioned studies. These reports concluded that backfat thickness of gilts did not account for a substantial amount of variation in the number of pigs born alive in parity one, two, or three or overall, and did not adversely affect reproduction performance or longevity.

Many authors have reported that once a female enters the breeding herd and becomes a productive sow, composition or body condition can play a critical role in maximizing longevity. Depending on stage of production (early gestation, late gestation, or lactation), there are optimum levels of body reserves (both energy and protein) required to avoid decreased milk production, rebreeding problems, and other reproductive malfunctions. MacLean (1968) first described the "thin sow" problem as starting with unusually high weight loss in lactation, followed by failure to gain enough weight prior to farrowing the next litter. This becomes a cumulative process with the sow continuing to lose weight in successive lactations and leads to reproductive failure, emaciation, and possibly death. To assess body condition within a production operation Charette et al. (1996) proposed a combination of linear scores and semi-quantitative scores. This scoring system took into consideration both changes in backfat and body weight. Whittmore et al. (1980) found that sows with 6.3 mm of "mid-back" fat depth or less at weaning was indicative of an eventual thin sow that would experience reproductive failure, and result in an early removal from the breeding herd. Reese et al. (1982) and

Tantasuparuk et al. (2001) found that thin sows at weaning experienced prolonged intervals from weaning to estrus. Esbenshade et al. (1986) concluded that fat and weight loss was inevitable during lactation, but greater losses were experienced in early parities and by higher producing sows. Ritter et al. (1999) concluded that sows that were a body condition score less than four (1-5 scale) had a higher incidence of shoulder lesions. Stalder et al. (2004) summarized the benefits of improved body condition at weaning. The list of benefits included improved animal welfare, decreased sow mortality, improved replacement rates, lower wean to estrus intervals, and better reproductive performance in the next litter. Additionally, sows with improved body condition would have greater economic value at culling. Knauer et al. (2006) characterized the physical condition of cull sows from U.S. Midwestern sow harvest plants and concluded that variation in body condition was associated with multiple abnormal conditions of sows. Serenius et al. (2006b) summarized results from the National Pork Producers Council Maternal Line National Genetic Evaluation and identified that within genetic lines, sows with lower feed intake and greater backfat loss during lactation had a shorter productive lifetime. It was recommended that sow feed intake and backfat loss during lactation in nucleus and multiplication breeding herds should be considered.

Growth or average daily gain measured during the grow-finish period has been associated with longevity. Tholen et al. (1996b), Lopez-Seranno et al. (2000), and Tummaruk et al. (2001a) have all reported antagonistic relationships between growth and lifetime productivity and/or longevity. However, Yazdi et al. (2000a) Young et al. (1991), and Newton and Mahan (1993) found no relationship between pre-adult growth and the ability of a sow to produce pigs over their productive lifespan or their lifetime prolificacy. Similar to backfat, varying results were found by these studies pertaining to growth. Stalder et al. (2005) concluded that days to 113 kg provided a significant source of variation for lifetime number weaned, lifetime weight of weaned piglets and first farrowing age on Landrace females. Females were grouped into six categories based on the standard deviation of each adjusted growth and compositional trait. Females from the two highest days to 113 kg groups (≥196 days to 113.4kg) had a greater age at first farrowing when compared to gilts in the faster growing groups. Females in the highest (> 210 days) days to 113 kg group had more lifetime number of piglets weaned and higher lifetime weight of piglets weaned.

Stalder et al. (2004) justified that these inconclusive results could be due to differences in timing of measurement, methodology, or the measurement of the trait itself. They continue to hypothesize that for compositional traits (e.g. growth, backfat, and loin muscle size) measured at or near selection, it appeared that several of these traits may have some minimum and/or maximum value that is necessary to maximize lifetime productivity.

Several authors have reported gilts that reach puberty at an earlier age, have improved reproductive performance or longevity (Staler et al., 2004). Chapman et al. (1978) and Holder et al. (1995) reported similar results that reduced age at puberty resulted in favorable productivity increases in females. Culbertson and Mabry (1995) reported that sows had reached higher parities at removal when they were first mated at a younger age. LeCozler et al. (1998) concluded that reduced age at first farrowing resulted in more piglets produced over a sow's lifetime and an increase in parity at removal. Koketsu et al. (1999) conducted an observational cohort study of data from 33 farms and results indicated that increasing the age at first mating was associated with low farrowing rates of maiden females and older age at first conception was associated with lower parity at removal, shorter reproductive herd life, and fewer lifetime pigs born alive. Additionally, gilts that recycled before first farrowing produced fewer pigs throughout their lifetime and had a lower parity at removal. Not all studies have reported favorable association between reduced age at first farrowing and longevity. Brooks and Smith (1980) and MacLean et al. (2001) reported no significant difference in productivity given varying ages of onset at puberty, either induced or naturally occurring.

Within modern pork production, there has been a trend to wean pigs at a younger age. It has been thought that shorter lactation length allows pork producers to maximize throughput through the farrowing facilities, improving economic efficiency within the operation, and improve piglet health, due to depleted maternal antibody levels after 21 days of lactation (Stalder et al., 2004). Stalder et al. (2004) summarized a number of studies and the results indicated that shortened lactation length clearly has a negative impact on sow longevity. Shortened lactation length results in re-breeding challenges resulting in sow removal due to reproductive failure, the primary reason for sow removal. Many of the challenges of early weaning are associated with factors that ultimately impact sow longevity.

Seasonal variation has been proven to impact reproductive performance within various types of swine operations. The degree of variation is dependent on the individual operation. More modern facilities attempt to control temperature extremes and duration of light to alleviate some reproductive performance issues brought on by seasonal changes (Love et al., 1993). Thacker (2002) described typical attributes of seasonal infertility as 1) delayed onset of puberty, 2) prolonged wean to estrus intervals, 3) reduced farrowing rate, and 4) increased abortions. Prunier et al. (1997) reported that high ambient temperature resulted in reduced appetite, milk production, and an increase in body reserve mobilization. Koketsu and Dial (1997), Black et al. (1993), Xue et al. (1994), Koketsu et al. (1995b), Koketsu (2000) and Tummaruk et al. (2000) all concluded that sows which farrowed in the summer had lighter litter weights, longer wean to first service intervals, and an increased mortality risk when compared to other times of year. As a result, sow culling has been reported to be higher during the summer months (Irwin and Deen, 2000).

Herd size has been found to have a direct association with high breeding female mortality risks in the U.S. As herd size increases by 500 females, mortality risk increased by 0.44% (Koketsu, 2000). Babot et al., (2003) found that herd size has a significant effect on reproductive performance. The best performance was obtained with herds with 401 to 600 sows compared to herd sizes of < 200 or > 800 sows. The effect of herd size could be directly related to type of management. Even though large farms can hire specialized workers, these workers are responsible for a greater number of sows per person and have less time to pay attention to sows showing clinical symptoms. Another concern related to herd size is the difficulty in eliminating or controlling a disease, particularly if purchased replacement gilts from another source are frequently introduced.

Type of housing seems to have some interaction with the seasonality of reproductive fitness. Love et al. (1995) and Hurtgen and Leman (1980) reported that sows in gestation crates experience little or no depression in farrowing rate during the summer months when compared to sows gestated in groups. On the contrary, Peltoniemi et al. (1999) reported a seasonal affect on reproductive measures on sows housed either in groups or individually in stalls.

Along with type of housing, type of flooring has been reported to impact sow longevity. Smith and Robertson (1971) and D'Allaire et al. (1989) reported an increase in culling among sows housed on totally or partially slatted floors. Additionally, Ehlorsson et al. (2002) reported that sows on partially slatted flooring had a higher incidence of hoof cracking and heel injuries compared to sows on solid flooring. Feet and leg soundness, locomotion problems and claw disorders can be major contributors to sow culling (Stalder et al., 2004). Various systems for scoring feet and leg soundness have been developed (Van Steenbergen, 1989; Andersen and Hansen, 1996; Grindflek and Sehested, 1996; Lundeheim, 1996; Velander, 1996). Multiple studies have reported that feet and leg conformation scores are moderately heritable with estimates ranging from 0.01 to 0.47 (Bereskin, 1979; Lundeheim, 1996; Rothschild and Christian, 1988; Huang et al., 1995; De Koning, 1996; Serenius et al., 2001; Jorgensen, 1996). Lopez-Serrano et al. (2000) reported favorable genetic correlation between stayability and leg score in both Landrace and Large White sows. Brandt et al. (1999) and Jorgensen (2000) determined the feet and leg quality had a significant influence on the productive life of sows. Grindflek and Sehested (1996) and Jorgensen (1996) reported that sows with some flex to their front pasterns have a positive influence on longevity, while sows that are straight off their front end and rigid on their pastern have more locomotion problems resulting in a shorter herd life. On the contrary, Karina et al. (2006) assigned conformation scores for the forelimbs and hind limbs on 961 gilts to determine the association between limb conformation scores in gilts and the retention through the second parity. Survival times for females on the basis of conformation scores for the forelimbs and hind limbs differed significantly for total sow removals and removals as a result of lameness. Risk of removal, specifically as a result of lameness, increased as conformation score for the hind limbs became poorer. Tarres et al. (2006) reported that exterior traits (number of teats, and feet and leg scores, on a scale from 1 to 7) had a moderate effect on the risk of culling compared with other factors. Sows with an undesirable leg score of 2 had a 1.4 times greater risk of being culled than sows with an intermediate and more desirable score of 4. Knauer et al. (2006) collected hoof quality data on 3,156 sows at two Midwestern sow processing plants and reported the most common foot lesions observed were on the rear (67.5%) and front (32.8%) pads of heavier conditioned, higher parity sows. Additionally, cracked toes were found on the front and rear feet of approximately 20% of sows, which were usually poorer conditioned, lower parity sows.

Genetic control of sow longevity

Longevity, along with many other economically important traits in livestock production, is influenced by genetics and/or breed composition. Some of the genetic effects can impact longevity through their correlation with other important traits. Serenius et al. (2004) estimated the genetic associations of prolificacy with performance, carcass, meat quality, and leg conformation traits on the Finnish Landrace and Large White populations. In general, prolificacy traits tended to be favorably correlated with performance traits and unfavorably correlated with carcass traits. No clear association was found for prolificacy traits with meat quality or leg scores. It was suggested that possible improvement in the accuracy of estimated breeding values may be achieved by accounting for genetic associations between prolificacy, carcass, and performance traits. Imboonta et al. (2007) reported heritabilities for reproduction traits for first parity females of 0.03 for total number of piglets born, 0.04 for number of stillborn piglets, 0.06 for number of piglets born alive but dead within 24 hours, versus later parities of 0.07, 0.03, and 0.02, respectively. Heritability estimates for average daily gain and backfat were 0.38 and 0.61, respectively. Interestingly, there were favorable genetic correlations found between average daily gain and total born and unfavorable genetic correlations between backfat and total born. Additionally, backfat was genetically unfavorably correlated with number of stillborn piglets in later parities. As a result, selection for high growth rate could increase total born, and selection for low backfat will decrease total born and increase number of stillborn. Arango et al. (2005) studied the genetic relationship between grouped reasons for sow removal in consecutive parities. Estimates of heritability were 0.18 for reproductive reasons, 0.13 for non-reproductive reasons, and 0.15 for other reasons. Results suggest that additive genetic variance exists for parity at removal and different reasons of removal.

Stalder et al. (2004) summarized a number of studies reporting genetic factors affecting longevity. Ivkove et al. (1986) reported that crossbred sows averaged 5.3 litters while purebred sows averaged 4.4 litters at culling. They also noted that 55.2% of culling in purebred sows occurred in the first three parities. During the first three parities, only 40.4% of the overall culling occurred in the crossbred sows. Jorgensen (2000) reported that mean age and number of litters at removal were lower in purebred Yorkshire sows when compared to crossbred sows. Specifically, purebred sows had higher culling for locomotion problems and reproductive failure. Sehested and Schjerve (1996) reported similar results in which parity at culling averaged 3.01 for purebred sows and 3.61 for crossbred sows. Hall et al. (2002) conducted a study involving Meishan and Duroc crossbred sows and reported that breed composition of crossbred females can influence longevity. Rodriguez-Zas et al. (2003) noted differences that approached a full parity difference between some genetic lines. They also reported significant differences in instantaneous sow removal rates among the genetic lines investigated. Ehlers et al. (2005) estimated variance components and heritabilities for sow productivity traits on purebred versus crossbred sows. Results suggested that pooling of purebred and crossbred data may be considered, which may potentially increase the accuracy of breeding value estimates.

Johnson (2000) initially reported results from the National Pork Board Maternal Line Project which demonstrated that traits contributing to longevity and attrition were heritable. The same report noted line differences for percentage of sows producing four litters, live pigs per sow life, and average sow life. Goodwin (2004) extended the analysis of the same maternal line study and found similar differences through the sixth parity. Serenius et al. (2006b) continued work with the National Pork Board Maternal Line Project data by applying non-parametric proportional hazards models to compare longevity of sows from the 6 commercial genetic lines and developmental factors that may impact longevity. Results indicated that one line of sows had a lower risk of being culled than sows from the other lines.

Most quantitative traits in animal genetics are approximated using normal distributions, and classical procedures can be used for the estimation of genetic parameters such as heritability (Yazdi et al., 2002). For the Gaussian linear mixed model, the best predictor of individual breeding values is linear, where the heritability of the trait is given by the ratio of the additive genetic variance to the total phenotypic variance (Korsgaard et al., 2000). On the contrary, the theory of the statistical analysis of survival data is based on the use of special modeling distributions (e.g. exponential, Weibull, lognormal, gamma). The parametric distributions used for longevity traits often come from the family of generalizations of exponential distributions. Survival models that include random effects, which are required in genetic evaluation, are referred to as frailty models. The frailty term is defined as an unobserved random quantity which affects multiplicatively the hazard of individuals or groups of individuals (Ducrocq, 1997). When a term is defined separately for each individual, the frailty component extracts part of the unobserved variation between individuals and therefore allows for a correction of the possible discrepancy between the true variance of the observations and the one specified by the model. Such an extra variation is referred to as "overdispersion" (Louis, 1991; Tempelman and Gianola, 1994). Survival analysis is considered theoretically superior in longevity analysis (Serenius, 2004; Serenius and Stalder, 2006). This approach accounts for censored observations, non-normal distributions, and models time-dependent effects. However currently, only single-trait analysis is possible when using the Survival Kit (Serenius and Stalder, 2004). On the contrary, linear model analysis is capable of implementing multiple-trait models. Serenius and Stalder (2006) summarized the current literature regarding the genetics of sow longevity and discussed the available breeding value estimation methods for sow longevity traits. Additionally, heritability estimates from numerous studies are summarized by the definition of longevity used and the genetic relationship of prolificacy traits, leg conformation, and developmental traits on longevity. There is a need for continued research to determine the best methodology for estimating breeding values for sow longevity. Also, additional focus needs to be directed towards determining the magnitude of non-additive genetic variation that affects fitness traits such as sow longevity (Falconer and Mackay, 1996). As a result, Serenius et al. (2006a) estimated variance components, including dominance genetic variation, for overall leg action, length of productive life and sow stayability until third and fifth parity in Finnish pig populations. These investigators recommended that the effect of dominance should be accounted for in the breeding value estimation of sow longevity, especially when data from crossbred animals are included in the analysis.

Reported estimates of the heritability for stayability, analyzed using linear models ranged from 0.02 to 0.11 (Tholen et al., 1996a, 1996b; Lopez-Serrano et al., 2000; Serenius and Stalder, 2004), while the survival analyses estimates for length of productive life have ranged from 0.11 to 0.31 (Yazdi et al., 2000a, 2000b; Serenius and Stalder, 2004). Serenius (2004), who justified the difference in the estimates, indicates that environmental effects are modeled more accurately in survival analysis than in linear model analysis, due to the ability to model the farm-year effect as a time dependent variable and the inclusion of censored records. The Cox and Weibull frailty models have been used for analyzing survival data. In these models, it is assumed that log frailty is the sum of log gamma and/or normally distributed random variables. When including an error term in log frailty, heritability can be defined on the log frailty scale, as well as on the linear scale (Korsgaard et al., 2000). Ducrocq (1987) derived the heritability on the logarithmic scale (h^2_{log}) for Weibull sire model as follows:

$$h^2_{log} = 4\,\sigma^2_s/(\sigma^2_s + \pi^2/6)$$

where $\pi^2/6$ in this equation is the variance of an extreme value distribution and σ^2_s is the sire variance.

Stalder et al. (2004) and Serenius and Stalder (2006) summarized the following studies with reported heritabilities. Crump (2001) reported heritability estimates ranging from 0.11 to 0.21, depending on whether survival analysis, linear model, or generalized linear model methods were used. Additionally, he reported unfavorable genetic correlations between average daily gain and survival and backfat and survival. Lopez-Serrano et al. (2000) found heritability estimates for stayability ranged from 0.07 to 0.11 in Landrace sows. Tholen et al. (1996b) reported that heritability for stayability from parity one to two, one to three, and one to four was 0.05, 0.06 and 0.09, respectively. Additionally, stayability was unfavorably correlated with average daily gain and backfat and favorably correlated with weaning to conception interval. Fortin and Cue (2002) reported heritabilities for length of productive life in Yorkshire and Landrace populations of 0.16 and 0.13, respectively. Yazdi et al. (2000a) reported heritability estimates for longevity ranging from 0.11 to 0.27 on the original scale. The estimates were similar within each group of models, averaging 0.13 for the time-independent and 0.25 for the time-dependent herd by year effect in the model. Correlations between the sires' breeding value estimates ranged from 0.96 to 0.98 among the differing models. Gou et al. (2001) reported that heritability for lifetime prolificacy was 0.25 for length of productive life. Serenius and Stalder (2004) estimated heritabilities using both a survival analysis procedure and linear models. The heritability estimates for length of productive life were lower for the linear model (0.05 to 0.10) than for survival analysis (0.16 to 0.19). The authors mentioned that in their survival analysis the residual variance was not estimated but rather assumed that the residual effects followed the extreme value distribution and they cautioned that the different heritability estimates were not comparable. Yazdi et al. (2000b) reported heritabilities in the original scale for longevity ranged from 0.21 to 0.31 on a study of survival of Swedish Landrace and Yorkshire sows.

Heritability estimates for longevity indicate that selection for improved longevity is possible, but improvement would be likely to be slow (Stalder et al., 2004). Additionally, both favorable and unfavorable genetic correlations of production traits and exterior traits have been reported to influence the productive life of sows (Napel and Johnson, 1997; Tholen et al., 1996a, 1996b; Serenius et al., 2004; Serenius et al., 2006a; Tarres et al., 2006; Imboonta et al., 2007). Consideration needs to be given to how longevity will be defined (e.g. stayability, length of productive life, or lifetime prolificacy) and the effect that performance characteristics may have on each definition. It appears that how longevity is defined within a population can impact resulting heritabilities.

True vs. Functional Herd life

Ducrocq et al. (1988a) made an important distinction between true and functional measures of herd life. These distinctions were applied to the concept of stayability. This ability is referred to as true stayability when the reason for leaving the herd is not taken into account. The removal of an animal from the herd can be either voluntary or involuntary. Voluntary culling is based on management decisions made by the producer. Involuntary culling is the removal of an animal due to factors beyond the control of the producer such as failure to breed or locomotion disorders. The capacity of an animal to avoid involuntary culling is termed functional stayability. In measuring functional stayability, true stayability is adjusted for factors such as backfat, growth, or number of piglets born. For example, Serenius and Stalder (2004) conducted two separate longevity analyses. For the first model, the only effects included in the model were farm-year held as a fixed time-dependent variable and a random genetic sire effect to approximate true length of productive life. For the second model, the fixed effects of leg score, number of weaned piglets in first litter and a regression of age at first farrowing also were included in the model to approximate functional length of productive life. Heritabilities from the two models were slightly higher for functional length of productive life, indicating that the fixed effects included in the model can influence heritability estimates.

Summary

It has been established that decreased sow longevity can lead to economic inefficiency and animal well being concerns. Improved sow longevity could have an impact on profitability by reducing annual replacement gilt costs and the added management required of purchased gilts. Sow longevity is clearly a complex trait with many developmental factors that can influence a female's length of productive life. Additionally, the positive estimates of heritability indicate that there is genetic variation among the animals that can be utilized for improving longevity. However, given the low heritability of survival traits, it may be necessary to utilize correlated traits measured early in life to substantially augment improvement in longevity. Furthermore, multiple definitions have been utilized to define a female's productive life. Length of productive life is the most common but has not been concluded that it is the most effective definition. The following research addresses some of the current issues facing survival analysis in swine.

CHAPTER II

CHARACTERIZATION OF SOW LONGEVITY AND THE DEVELOPMENTAL FACTORS THAT INFLUENCE IT

Abstract

The length of adult sow life is now recognized as both an economical and welfare concern. However, there are no consistent definitions to measure sow longevity. This study assessed six different descriptions of longevity and determined the relationship of developmental performance factors with them. Longevity definitions included stayability (probability of producing 40 pigs or probability of reaching four parities), lifespan (number of parities a female has accumulated before culling), lifetime prolificacy (number of pigs born alive during a female's productive lifetime), herdlife (time from first farrowing to culling) and productive life (pigs produced per day of life). Data consisted of 14,262 records of Yorkshire females from both nucleus and multiplication herds across 21 farms from four seedstock systems. Within a subset of the data, information was available on the female's litter birth record and her growth and composition data. Therefore, the data were subdivided into two data sets, consisting of; A: Data from a female's farrowing records, and B: Data A and information from a female's litter birth record and a female's growth and backfat data. A Cox proportional hazards model was used to determine the relationship of developmental factors and first farrowing record with longevity. Those factors that were significantly ($P < 0.0001$) associated with longevity, regardless of definition, were age at first farrowing, litter size at first farrowing and last farrowing, number of stillborn in first litter, adjusted 21 day litter weight of first litter, herdtype, backfat, and growth. Within a contemporary group,

fatter, slower growing gilts had a decreased risk of being culled. Additionally, sows that had more pigs born alive, fewer stillborn, and heavier litters at weaning in their first litter had a decreased risk of being culled. Furthermore, sows from nucleus herds experienced a greater risk of being culled. Many factors impacted longevity, regardless of definition. Pork producers can implement management protocols which can extend the productive life of breeding females resulting in improved profitability and animal welfare.

Introduction

For the past two decades, pig genetic improvement has focused on production (growth, carcass, and meat quality) and reproduction characteristics (litter size) (Tarres, 2005). Selection for increased lean growth along with the acceleration of the reproductive rhythm of sows have resulted in culling rates within commercial herds in excess of 50% (Rodriguez-Zas et al., 2003; Tarres, 2005). Sows are replaced, on average, by the third or fourth parity (D'Allaire et al., 1987; Boyle et al., 1998) through involuntary and voluntary culling practices. Longevity of sows summarizes the effects of functional traits on the ability to delay involuntary culling (Ducrocq and Solkner, 1998a). Longevity of adult females is a trait with a significant impact on swine farm profitability. An improvement in longevity can result in decreased replacement costs and a higher proportion of mature sows in a herd that have reached their maximum productivity. The length of the adult productive life of a sow is recognized as both an economical and a welfare concern.

Stalder et al., (2004) reported that there are a multitude of factors within swine production systems that can either directly or indirectly impact a sow's productive life. Developmental factors such as growth rate, body composition at selection, age at puberty and first farrowing, and feet and leg soundness have been proven to influence longevity. Additionally, parity one lactation length and wean to estrus interval are early indicators of a female's fertility and potential length of productive life. The most consistent source of variation across studies is the herd by year interaction. Sow housing and behavior, herd size, seasonal fertility, disease, gilt pool management, and human interaction have been associated with explaining the variation in longevity. As a result, it is important to assess each production unit independently when quantifying sow longevity. Management practices of producers, farm employees and also breeding programs should focus on improving sow longevity.

There has not been a clear consensus in the scientific literature regarding the definition of longevity. Yazdi et al. (2000b), Serenius and Stalder (2004) and Tarres et al. (2003, 2006) defined longevity as length of productive life (number of days from first farrowing to removal from the herd). Sow longevity has been defined by Serenius and Stalder (2004) as lifetime prolificacy (the total number of pigs produced in a sow's lifetime) and length of productive life (the number of days from the date of first farrowing to the date of culling or censoring). Holder (1995) and Knauer et al., (2006) combined a measure of productivity into a continuous measure of time as pigs born alive per day of herd life.

The objective of this study was to assess six different measures of longevity and determine what relationship developmental performance characteristics may have with these differing definitions.

Materials and Methods

Data

A unique data set has been assembled to complete this project. The data was an accumulation of both nucleus and multiplication records of Yorkshire females from four swine seedstock systems (Waldo Farms, DeWitt, NE; Premier Swine Systems, Michigantown, IN; Whiteshire/Hamroc, Albion, IN; and the Zierke Co., Morris, MN). Herd production data from computer software (HERDSMAN™) was extracted from each of these farms and merged into a common data set for analysis purposes. All crossbred and non-Yorkshire sows were removed. Individual pig performance and farrowing records from 21 different farms, which were associated within these four seedstock systems were merged into one data set for analysis.

From these 21 farms, records on Yorkshire females born from 1988 through 2002, with at least one farrowing record, were available. Information from the female's birth litter along with her performance for age at 113 kg and backfat thickness adjusted to 113 kg as suggested by National Swine improvement Federation (1996) were merged with subsequent sow performance records. Individual parity records were then summed across parities to accumulate total sow performance and determine the last record in the database for an individual female. Additionally, a code indicating if an animal had been culled or was still in production was available and was used to indicate censoring. The culling reason was not available. Variables with extreme values, more than four standard deviations away from the mean, were deleted. Additionally, if two variables were highly correlated (eg. number born and number born alive), the variable that had a higher frequency of recording was retained for analysis. Due to incomplete data recording across farms and even within a farm over time, not all sows had complete records for birth litter traits, growth rate and backfat thickness. To make optimal use of the data, the data set was split into two. After editing the largest data set (Data A), 14,262 records from Yorkshire sows with at least one farrowing were considered for survival analysis, including 10,651 (74.68%) and 3,611 (25.32%) uncensored and censored records, respectively. Information included a sow's first parity information along with her lifetime productivity data. The individual record for each female included herd type (either multiplier (1) or nucleus (2)) (HT), sow herd (the herd that the female was a productive sow), date of first farrowing, date of culling, age at first farrowing (AGEFF), number born alive in the first litter (NBA), number of stillborn in the first litter (NSTL), length of lactation in the first parity (WNAGE), adjusted 21 day litter weight from the first litter (D21W), and litter size (born alive) at the last farrowing (LNBA).

The second data set (Data B) contained 4,272 records from Yorkshire sows with at least one farrowing record, with 3,395 (79.47%) and 877 (20.53%) uncensored and censored records, respectively. Data B contained all variables previously listed in Data A, along with information related to the sow's birth litter record and adjusted days to 113 kg and adjusted backfat thickness at 113 kg. Standardized variables were created for growth and backfat thickness. Within a pig herd, contemporary group was defined by birth month and year. Means and standard deviations were calculated within each of these subclasses and then a female's individual backfat measurement and growth record were deviated from the contemporary group mean and then divided by the standard deviation for that particular contemporary group. This approach allowed for comparisons across contemporary groups accounting for differences in methodology of data collection and environment.

The individual record for each female included all covariates present in Data A, along with pig herd (the herd that the female was born in), date of birth, birth litter number born alive (PNBA), birth litter birth weight (PLBW), percentage of gilt pigs in birth litter (PGR), standardized deviation for backfat thickness (BF), and standardized deviation for adjusted days to 113 kg (DAY).

Six different definitions of longevity were developed. Length of productive life was determined as the number of days from the date of first farrowing to the date of culling or censoring (LPL). Similarly, the lifespan of a sow was determined as the maximum parity she completed prior to removal (MAXPAR). Lifetime prolificacy was determined as the number of piglets (born alive) produced during the LPL of the sow (SNBA). Stayablility, has been defined as a binary trait measuring whether a sow has survived in a herd until some defined fixed parity or time (Serenius and Stalder, 2004). From this definition, two different discrete measures were determined using production based thresholds. They were the ability of a sow to achieve 4 parities prior to removal (PR4PAR) and the ability of a sow to produce 40 pigs prior to removal (PRNBA40). A measure of length of life and a measure of productivity were combined to determine the final response variable by each female's SNBA divided by the difference between cull date and birth date (PLIFE).

Statistical Analysis

A Cox proportional hazards model was used to determine the relationship of developmental factors with longevity (Cox, 1972). All analyses were conducted using the PHREG procedure within SAS 9.1 (SAS Inst. INC., Cary, NC). Initially, all possible fixed effects were tested for their level of significance in a univariate model with each of the six response variables. Predictors with Chi-square test significance levels at P-value of <0.25 were included in the final model. A primary assumption of the Cox proportional hazard model is proportionality, that is that the estimated hazards over time will be constant for two females with particular values for the covariates. Proportionality was tested by including time-dependent covariates in the model. Time-dependent covariates are interactions of the predictors with time. It was concluded through likelihood ratio tests, that the initial model violated the proportionality assumption. As a result, models were stratified by the interaction of sow herd by farrow year for Data A and by the interaction of pig herd by birth year for Data B to satisfy the proportionality assumption. The final stratified regression model for Data A included the fixed effects of AGEFF, NBA, NSTL, LNBA, D21W, WNAGE, and HT and for Data B the models included all of the covariates listed for Data A with the addition BF, DAY, PNBA, PLBW, and PGR. All covariates were included in each model for each response variable. Additionally, all possible first level interactions of covariates, that were not highly correlated ($r \geq 0.60$), were tested and were found to be not significant.

Results and Discussion

Descriptive statistics for the data are presented in Table II.2. The average LPL for Yorkshire females was 488.8 days, with a mean parity at removal or censoring of 3.5. Throughout their productive lifecycle, females produced on average 34.9 pigs with an average age of first farrowing of 366.2 days. Additionally, 62% and 59% of sows were removed or considered censored before producing 40 live piglets or completing 4 parities, respectively. The descriptive statistics of the data are consistent with other survival analysis studies (Yazdi, 2000b; Stalder et al., 2004; Serenius and Stalder, 2004).

Results from the proportional hazards models and the discrete logistic models are presented in Tables II.3 through II.8 for Data A and Tables II.9 through II.14 for Data B. The Chi-Square value and a probability of significance value is provided to assess the significance of each variable included in the models. To compare the influence of each covariate on the respective response variable, one should consider the sign (+,-) of the parameter estimate for each covariate. The sign of the parameter estimate indicates either an increasing (+) or a decreasing (-) hazard given a one unit increase in the covariate with the assumption that all other covariates are held constant. Additionally, the hazard ratio is provided for each covariate. Hazard ratios greater than 1 indicate an increase in risk of removal while a hazard ratio less than 1 indicates a decrease in risk of removal. For example in Data A within the LPL definition of longevity, AGEFF had a positive parameter estimate and a hazard ratio of 1.002. This indicates that as AGEFF increased by 1 day and all other covariates were held constant, the risk of a sow being culled increased by 0.2%. Initially, this may not seem important, but if the average AGEFF was increased by 10 days this would increase the risk of removal by 1.0%.

Data A

The effect of age at first farrowing on the risk of being culled in the present study was highly significant ($P<0.0001$), regardless of the definition. Additionally, the hazard ratios were very similar across definition ranging from 1.002 to 1.004. The positive sign of the parameter estimate indicates that the greater the age at first farrowing, the greater the risk of a sow being culled. These findings were consistent with several authors who have reported gilts that reach puberty at an earlier age, or were first mated at a younger age, have improved reproductive performance or longevity (Culbertson and Mabry, 1995; Tholen et al., 1996a and 1996b; LeCozler et al., 1998; Koketus et al., 1999; Yazdi et al., 2000b; Stalder et al., 2004; Serenius and Stalder, 2007). An increased AGEFF may be an indicator of the delayed onset of puberty or could be attributed to maiden gilts that did not conceive on the first service. Delayed AGEFF could be considered an early indicator of reproductive fitness or lack thereof. Sterning et al. (1998) reported a tendency for sows that were older at puberty to show delayed return to estrus after weaning. However, Serenius and Stalder (2007) did caution against breeding immature gilts. They summarized previous reports which indicated that litter size at first farrowing tended to increase with the increase in age at first farrowing or at first mating (Schukken et al., 1994; Tummaruk et al., 2001a). They suggested that an optimal age at first conception may be close to 200 to 210 days.

The current results indicate that the performance of a female during her first litter does provide insight for the rest of her productive life. The prolificacy traits evaluated in the current study were total number of piglets born alive and number of stillborn piglets. Additionally, adjusted 21 day litter weight was included in the model. Sows that had more pigs born alive, fewer stillborn fetuses, and weaned heavier litters, tended to have a decreased risk of being culled across all definitions. Sows that had one more pig born alive in their first litter had a decreased relative culling rate that ranged from 1.4% for LPL to 10% for PLIFE. The three definitions that included a productivity component (PLIFE, SNBA, PRNBA40) reported higher hazard ratios than those definitions that were more time dependent (LPL, MAXPAR, PR4PAR). The number of stillborn piglets was highly significant ($P<0.0001$) across all definitions. As the number of stillborn piglets increased by one piglet, the relative culling rate increased from 4.6% to 6.2% depending on definition. This indicator of neonatal piglet mortality rate had a strong negative association with longevity.

Sows that weaned heavier litters, in their first parity, experienced a decreased risk of being culled. A one kilogram increase in adjusted 21 day litter weight tended to decrease the risk of removal by 0.4% on average across the six definitions. The number of pigs born in a female's last litter was also strongly significant ($P<0.001$) across all definitions. Similarly to NBA, if a sow had one more pig in her last litter her relative culling risk was reduced by as little as 1% for MAXPAR and as much as 7% for PRNBA40. Once again, LNBA reported higher risk ratios for definitions that include a productivity component when compared to definitions that were time dependent only. These results are in agreement with Yazdi et al. (2000b) who reported a decreased risk ratio with increasing litter size for both first and last litter size across all models when longevity was defined as length of productive life. Additionally, Serenius and Stalder (2007) concluded that a small number of pigs born at first farrowing had a detrimental impact on length of productive life. These results were not in agreement with Serenius et al. (2006b) who concluded, on a different field data set comparing six different genetic lines, that there was no clear association between litter size and length of productive life when culling due to poor reproductive performance was not practiced. According to the present study, small litter sizes in the first and last parity resulted in earlier removal from the herd. Cause of culling was not available for this study, thus it was impossible to directly distinguish between voluntary and involuntary culling of these sows.

Length of lactation in the first litter (WNAGE) was not significant for SNBA, PLIFE, PRNBA40, and PR4PAR, but was significant ($P<0.05$) for LPL and MAXPAR. It should be noted that with the exception of PRNBA40, the sign of the parameter estimates were positive across all definitions. These results are not in agreement with a number of studies summarized by Stalder et al. (2004), which indicated that shortened lactation length had a negative impact on sow longevity. It was concluded that weaning at early ages could adversely impact sow longevity through increased culling due to reproductive failure. Studies that found a clear negative association of lactation length with longevity reported on lactation lengths of 16 days or less (Koketsu, 1995a; Xue et al., 1997). The mean lactation length for this study was 20.1 days. This longer lactation length could explain the non significance of WNAGE. Females that are allowed to lactate longer in their first parity experience shorter wean to estrus intervals and higher conception rates.

With the exception of LPL, HT affected all other definitions. Sows from nucleus herds had an increased relative risk of being culled by 42% for SNBA and 68% for PLIFE and MAXPAR. Additionally, sows from nucleus herds were 3 times more likely to be removed prior to producing 40 pigs or completing 4 parities. Without reasons for culling, the effects of herd type were implicitly the result of the differences in herd management and variation in culling criteria between multiplier herds and nucleus herds.

Data B

The standardized variables for backfat and days to 113 kg significantly influenced all definitions of longevity. The estimated hazard coefficients for BF were negative indicating that fatter gilts within a contemporary group tended to have a decreased risk of being culled. Additionally, the estimated hazard coefficients for DAY were negative indicating that slower growing gilts within a contemporary group tended to have a decreased risk of being culled. The hazard ratios for both covariates revealed that with a one unit change the risk of being culled decreased anywhere from 6.7% to 15.8%, depending on the definition.

The results in the present study are in agreement with a number of studies that concluded that gilts which had higher backfat were more productive or experienced a longer productive life. Stalder et al. (2004) concluded that there may be a minimum level of backfat needed for replacement gilts for them to maximize lifetime number of piglets born alive. Challinor et al. (1996), Brisbane and Chenais (1996), and Geiger et al. (1999) all indicated that gilts that had greater than 18 mm of backfat were more productive, experienced less mortality and had a decreased risk of being culled. Similarly, Terres et al. (2003) reported that optimum backfat thickness was 16 mm at 96.2 kg in Duroc females. Stalder et al. (2005) reported that females from the fattest group ($\geq$ 25.0mm) produced more pigs born alive during their lifetime than sows from intermediate backfat classes. These studies collectively support the results from the current study that increased backfat levels in replacement gilts favor a longer, more productive herd life. Not all literature reports are in complete agreement with the current findings. Young et al. (1991), Rozeboom et al. (1996), Kerr and Cameron (1995), and Yazdi et al. (2000b) reported that backfat thickness of gilts did not account for a substantial amount of variation in the number of pigs born alive and did not adversely affect reproduction performance or longevity. Serenius and Stalder (2007) reported that backfat thickness had a very small effect on risk of removal in a Finnish crossbred population, though females that had more backfat thickness tended to have a lower risk of being culled.

The results in the present study are in agreement with others that reported an antagonistic relationship between growth rate and measures of longevity, either direct or indirect (Tholen et al., 1996b; Lopez-Seranno et al., 2000; Tummaruk et al., 2001a). However, this antagonistic relationship seems to be population dependent. Yazdi et al. (2000b), Serenius and Stalder (2004), and Serenius and Stalder (2007) found no significant effect of daily gain on longevity.

Current results indicate that covariates for traits measured within a female's birth litter (PNBA PLBW, PGR) did not significantly impact longevity, regardless of definition. Serenius and Stalder (2007) also concluded that the litter size in which the sow was born into did not significantly impact her length of productive life.

With the exception of WNAGE, covariates for first litter performance traits (NBA, NSTL, D21W) included in the analysis for both Data A and Data B were highly significant with similar parameter estimates and hazard ratios. Sows that had more piglets born alive, fewer stillborn piglets, and weaned heavier litters in their first parity had a decreased risk of removal. Additionally, an increase in the number of pigs born alive in a female's last litter decreased her risk of removal. Furthermore, herd type was highly significant for all definitions with the exception of PLIFE. Regarding the other five definitions, sows from nucleus herds had an increased relative risk of being culled by an average of 43%.

The current results indicate that regardless of definition, developmental and performance of first parity females does provide insight into the longevity of the

Yorkshire females in this population. Within a contemporary group of potential replacement females, gilts that grew slower and had more backfat had a decreased risk of being culled. Additionally, parity 1 sows that farrowed at a younger age, were more prolific, had fewer stillborn fetuses, and weaned heavier litters tended to have a decreased risk of being removed. These results indicate that there are early indicators that can be monitored to provide insight to the future productivity or length of productive life of Yorkshire females. The six different definitions yielded similar results indicating that the "best" definition for assessing longevity could be considered producer dependent.

Table II.1. Definitions of variable acronyms used in model development

Variable	Acronym
Number of days between date of first farrowing and removal, d	LPL
Number of parities a sow had completed	MAXPAR
Pigs born alive per day of sow herd life	PLIFE
Binary indicator variable if a sow had produced 40 pigs (0,1)	PRNBA40
Binary indicator variable if a sow had completed 4 parities (0,1)	PR4PAR
Total number born alive over lifetime	SNBA
Herd type, 1 multiplier, 2, nucleus	HT
Age at first farrowing, d	AGEFF
[a]Standardized deviation for adjusted backfat, mm	BF
[a]Standardized deviation for adjusted days to 113 kg	DAY
Adjusted 21 day litter weight in parity 1 litter, kg	D21W
Birth litter gilt ratio	PGR
Birth litter, litter birth weight, kg	PLBW
Birth litter number born alive	PNBA
Last litter number born alive	LNBA
First litter number born alive	NBA
First litter number stillborn	NSTL
First litter lactation length, d	WNAGE

[a]Adjusted female record was deviated from the birth month and year mean for gilts tested within herd and divided by the standard deviation.

Table II.2. Number of observations, means, standard deviations, minimums, maximum values of the traits studied in U.S. purebred Yorkshire sows.

Trait[a]	No.	Mean	SD	MIN	MAX
LPL,d	14,262	488.8	411.4	10	3,548
MAXPAR	14,262	3.5	2.4	1	14
SNBA	14,262	34.9	27.4	0	182
PLIFE	14,262	0.036	0.016	0	0.277
PRNBA40[b]					
0	8,857				
1	5,405				
PR4PAR[b]					
0	8,409				
1	5,853				
AGEFF,d	14,262	366.2	46.2	251	600
NBA	14,262	9.4	3.0	0	20
NSTL	14,262	0.7	1.2	0	14
LNBA	14,262	9.5	3.3	0	20
D21W, kg	14,262	51.1	14.3	4.54	115.9
WNAGE, d	14,262	20.1	5.0	0	40
BF	5,861	-0.21	0.912	-3.16	3.85
DAY	5,962	-0.33	0.855	-3.21	3.58
PGR	7,906	0.54	0.15	0.07	0.92
PNBA	8,465	10.8	2.8	1	20
PLBW, kg	6,879	16.12	4.42	1.36	34.1

[a]See Table II.1 for acronym definitions.

Table II.3. Estimated hazard ratios for Data A for LPL[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0019	<0.0001	1.002	1.001	1.002
NBA	-0.0139	0.0005	0.986	0.978	0.994
NSTL	0.0445	<0.0001	1.046	1.027	1.065
LNBA	-0.0161	<0.0001	0.984	0.978	0.990
D21W	-0.0037	<0.0001	0.996	0.995	0.997
WNAGE	0.0081	0.0115	1.008	1.002	1.014
HT	0.0879	0.1846	1.091	0.959	1.241

[a]Number of observations = 12,851.
[b]See Table II.1 for acronym definitions.

Table II.4. Estimated hazard ratios for Data A for SNBA[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0017	<0.0001	1.002	1.001	1.002
NBA	-0.0643	<0.0001	0.938	0.930	0.945
NSTL	0.0501	<0.0001	1.051	1.032	1.071
LNBA	-0.0599	<0.0001	0.942	0.936	0.948
D21W	-0.0030	<0.0001	0.997	0.996	0.998
WNAGE	0.0047	0.1378	1.005	0.998	1.011
HT	0.3513	<0.0001	1.421	1.254	1.610

[a]Number of observations = 12,851.
[b]See Table II.1 for acronym definitions.

Table II.5. Estimated hazard ratios for Data A for PLIFE[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0042	<0.0001	1.004	1.004	1.005
NBA	-0.1054	<0.0001	0.900	0.893	0.907
NSTL	0.0437	<0.0001	1.045	1.026	1.064
LNBA	-0.1016	<0.0001	0.903	0.898	0.909
D21W	-0.0016	<0.0001	0.998	0.998	0.999
WNAGE	0.0033	0.3106	1.003	0.997	1.010
HT	0.5196	<0.0001	1.681	1.488	1.900

[a]Number of observations = 12,851.

[b]See Table II.1 for acronym definitions.

Table II.6. Estimated hazard ratios for Data A for MAXPAR[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0021	<0.0001	1.002	1.002	1.003
NBA	-0.0209	<0.0001	0.979	0.970	0.988
NSTL	0.0557	<0.0001	1.057	1.035	1.081
LNBA	-0.0102	0.0066	0.990	0.982	0.997
D21W	-0.0039	<0.0001	0.996	0.995	0.997
WNAGE	0.0075	0.0447	1.008	1.000	1.015
HT	0.5206	<0.0001	1.683	1.459	1.941

[a]Number of observations = 12,851.
[b]See Table II.1 for acronym definitions.

Table II.7. Estimated hazard ratios for Data A for PRNBA40[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0027	<0.0001	1.002	1.001	1.003
NBA	-0.0590	<0.0001	0.943	0.930	0.956
NSTL	0.0587	0.0004	1.061	1.027	1.096
LNBA	-0.0724	<0.0001	0.930	0.919	0.941
D21W	-0.0048	<0.0001	0.994	0.994	0.997
WNAGE	-0.0021	0.7024	0.998	0.987	1.009
HT	1.3336	<0.0001	3.799	3.079	4.687

[a]Number of observations = 12,851.
[b]See Table II.1 for acronym definitions.

Table II.8. Estimated hazard ratios for Data A for PR4PAR[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
AGEFF	0.0024	<0.0001	1.002	1.002	1.003
NBA	-0.0323	<0.0001	0.968	0.995	0.981
NSTL	0.0597	0.0002	1.062	1.028	1.096
LNBA	-0.0338	<0.0001	0.967	0.956	0.978
D21W	-0.0050	<0.0001	0.995	0.993	0.996
WNAGE	0.0016	0.7680	1.002	0.991	1.012
HT	1.3154	<0.0001	3.726	3.019	4.600

[a]Number of observations = 12,851.
[b]See Table II.1 for acronym definitions.

Table II.9. Estimated hazard ratios for Data B for LPL[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.1001	<0.0001	0.905	0.868	0.943
DAY	-0.1093	<0.0001	0.896	0.857	0.938
PNBA	0.0136	0.2194	1.014	0.992	1.036
PLBW	-0.0033	0.3508	0.997	0.990	1.004
PGR	0.2104	0.0760	1.234	0.978	1.557
AGEFF	0.0031	<0.0001	1.003	1.002	1.004
NBA	-0.0048	0.4640	0.995	0.983	1.008
NSTL	0.0681	<0.0001	1.071	1.038	1.105
LNBA	-0.0184	0.0004	0.981	0.972	0.992
D21W	-0.0047	<0.0001	0.995	0.994	0.997
WNAGE	-0.0088	0.1649	0.991	0.979	1.004
HT	0.4859	<0.0001	1.626	1.470	1.798

[a]Number of observations = 4,272.

[b]See Table II.1 for acronym definitions.

Table II.10. Estimated hazard ratios for Data B for SNBA[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.1082	<0.0001	0.897	0.861	0.935
DAY	-0.0933	<0.0001	0.911	0.871	0.952
PNBA	0.0066	0.5503	1.007	0.985	1.029
PLBW	-0.0029	0.4053	0.997	0.990	1.004
PGR	0.1475	0.2101	1.159	0.920	1.460
AGEFF	0.0025	<0.0001	1.003	1.002	1.003
NBA	-0.0548	<0.0001	0.947	0.935	0.959
NSTL	0.0738	<0.0001	1.077	1.004	1.111
LNBA	-0.0583	<0.0001	0.941	0.934	0.953
D21W	-0.0044	<0.0001	0.996	0.994	0.997
WNAGE	-0.0104	0.0991	0.990	0.977	1.002
HT	0.2948	<0.0001	1.343	1.217	1.482

[a]Number of observations = 4,272.
[b]See Table II.1 for acronym definitions.

Table II.11. Estimated hazard ratios for Data B for PLIFE[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.1052	<0.0001	0.900	0.864	0.938
DAY	-0.0693	0.0021	0.933	0.893	0.975
PNBA	-0.0076	0.4936	0.992	0.971	1.014
PLBW	-0.0004	0.8894	1.000	0.993	1.006
PGR	0.1148	0.3293	1.122	0.891	1.413
AGEFF	0.0046	<0.0001	1.005	1.004	1.005
NBA	-0.1007	<0.0001	0.905	0.893	0.916
NSTL	0.0594	0.0002	1.061	1.029	1.095
LNBA	-0.1004	<0.0001	0.904	0.895	0.914
D21W	-0.0030	<0.0001	0.997	0.995	0.998
WNAGE	-0.0151	0.0175	0.985	0.973	0.997
HT	0.0135	0.7850	1.014	0.919	1.118

[a]Number of observations = 4,272.

[b]See Table II.1 for acronym definitions.

Table II.12. Estimated hazard ratios for Data B for MAXPAR[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.0948	<0.0001	0.909	0.873	0.948
DAY	-0.0825	0.0003	0.921	0.881	0.963
PNBA	0.0084	0.4428	1.008	0.987	1.031
PLBW	-0.0019	0.5744	0.998	0.991	1.005
PGR	0.1137	0.2542	1.143	0.908	1.439
AGEFF	0.0022	<0.0001	1.002	1.001	1.003
NBA	-0.0062	0.3297	0.994	0.981	1.006
NSTL	0.0641	<0.0001	1.066	1.034	1.100
LNBA	-0.0085	0.1066	0.992	0.981	1.002
D21W	-0.0039	<0.0001	0.996	0.995	0.998
WNAGE	-0.0101	0.1104	0.990	0.978	1.002
HT	0.2801	<0.0001	1.323	1.199	1.460

[a]Number of observations = 4,272.
[b]See Table II.1 for acronym definitions.

Table II.13. Estimated hazard ratios for Data B for PRNBA40[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.1608	<0.0001	0.851	0.794	0.913
DAY	-0.1437	0.0003	0.866	0.802	0.935
PNBA	0.0213	0.2530	1.022	0.985	1.059
PLBW	-0.0071	0.2365	0.993	0.982	1.005
PGR	0.3583	0.1036	1.401	0.933	2.108
AGEFF	0.0024	0.0011	1.002	1.001	1.004
NBA	-0.0461	<0.0001	0.955	0.934	0.997
NSTL	0.1036	0.0003	1.107	1.049	1.193
LNBA	-0.0705	<0.0001	0.931	0.914	0.950
D21W	-0.0067	<0.0001	0.993	0.991	0.996
WNAGE	-0.0274	0.0088	0.972	0.953	0.993
HT	0.3964	<0.0001	1.486	1.259	1.755

[a]Number of observations = 4,272.
[b]See Table II.1 for acronym definitions.

Table II.14. Estimated hazard ratios for Data B for PR4PAR[a]

Variable[b]	Parameter Estimate	Prob. > Chi-Square	Hazard Ratio	95% Hazard Ratio Confidence Interval	
BF	-0.1722	<0.0001	0.842	0.786	0.902
DAY	-0.1418	0.0002	0.868	0.804	0.936
PNBA	0.0196	0.3244	1.018	0.982	1.055
PLBW	-0.0063	0.2688	0.994	0.982	1.005
PGR	0.2937	0.1395	1.356	0.898	2.003
AGEFF	0.0024	<0.0001	1.003	1.001	1.004
NBA	-0.0209	0.0647	0.979	0.958	1.001
NSTL	0.0831	0.0023	1.085	1.030	1.146
LNBA	-0.0289	0.0022	0.970	0.954	0.990
D21W	-0.0068	<0.0001	0.993	0.991	0.996
WNAGE	-0.0251	0.0152	0.975	0.956	0.995
HT	0.3037	0.0002	1.355	1.152	1.594

[a]Number of observations = 4,272.
[b]See Table II.1 for acronym definitions.

CHAPTER III

HERITABILITY OF LONGEVITY IN YORKSHIRE FEMALES

Abstract

The purpose of this study was to assess the genetic variation within six different sow longevity descriptions. Heritability was estimated for four different descriptions of longevity using a proportional hazards model with an underlying Weibull distribution. The definitions included herdlife (time from first farrowing to culling), lifespan (number of parities a female has accumulated before culling), lifetime prolificacy (number of piglets born alive during the lifetime of the sow), and a combination of prolificacy and length of productive life (number of pigs produced per day of life). Data consisted of 7,487 records of Yorkshire females with at least one farrowing record, from both nucleus and multiplication herds across 21 farms from four seedstock systems. A threshold model was used to estimate heritability for two descriptions of stayability (probability of producing 40 pigs or probability of reaching 4 parities) on a subset of the original data (n=5,889) that did not include censored observations. Terms for both models included first litter performance effects of: age at first farrowing, number born alive, number of stillborns, adjusted 21 day litter weight, and length of lactation along with the number born alive at last recorded farrowing. Additionally, number born alive, litter birth weight and percentage of gilts born in a female's birth litter and her growth and backfat records were included. These variables were treated as fixed and time-independent. The random effects of sire and the interaction of herd by year were included in all models. Heritability estimates ranged from 0.043 to 0.059 and from 0.120 to 0.231 for true and functional definitions of survival analyses, respectively, and from 0.117 to 0.200 for

threshold analyses. Sufficient genetic variation exists, regardless of definition, to improve sow longevity.

Introduction

In animal breeding, economic incentive drives selection pressure. Producers strive to produce high quality, consumer acceptable products in an efficient, humane manner. As consumers have demanded a leaner pork product that is inexpensive, the swine industry has responded by increasing lean content and maximizing the number of pigs produced per sow per year over the past 20 years. Resulting removal rates in commercial herds are commonly between 40 and 55%, with the majority of sows being removed prior to completing 4 parities (Lucia, 1996; Rodriguez-Zas et al., 2003; Tarres, 2006). Consequently, higher replacement rates due to poor longevity increase the number of replacement gilts needed and breeding herd inventories have a high proportion of low parity females. According to Lucia et al. (2000) and Stalder et al. (2002) at least three litters are required from a sow before her developmental and variable costs are recovered and there is positive cash flow for the producer.

Longevity of sows summarizes the effects of functional traits, defined as the ability to delay involuntary culling (Ducrocq and Solkner, 1998a). One method for analyzing longevity data is survival analysis which allows inclusion of both censored and uncensored records of animals (Cox, 1972). This approach relies on the concept of hazard, instantaneous or age-specific failure rate (Lawless, 1982; Lee, 1992) or, the animal's risk of being culled at time *t*, conditional upon survival to time *t* (Ducrocq, 1987; Ducrocq and Solkner 1998b). Proportional hazard models can be semiparametric or parametric depending on whether on not the baseline hazard distribution is assumed to be arbitrary or parametric (Yazdi et al., 2002). Proportional hazards models have been extended to incorporate time-dependent covariates, random effects, and genetic relationships between animals. Alternatively, generalized linear mixed sire models have been used to analyze measures of stayability in beef cattle and pigs (Kadermideen et al., 2004; Martinez et al., 2005; Guerra et al., 2006). Reproductive performance is a major component of culling decisions, and stayability is an indicator of reproductive performance (Martinez et al., 2005). Threshold models have been developed for binomial data to estimate or predict effects on a continuous underlying "liability" variable, on which linearity is imposed (Kadarmideen et al., 2004).

Sow longevity and/or reproductive traits in general are lowly heritable and some production traits such as backfat thickness and daily gain have been reported to be unfavorably correlated (Lopez-Serrano et al., 2000). Heritability is necessary to calculate expected responses to selection and to predict breeding values. Stalder et al., (2004) and Serenius and Stalder (2006) provided summaries of heritability estimates from the literature. Heritability estimates for stayability ranged from 0.05 to 0.11 (Lopez-Serrano et al., 2000; Tholen et al., 1996a, 1996b) and from 0.11 to 0.31 for survival analysis (Yazdi et al., 2000a, 2000b; Serenius and Stalder, 2004).

There has not been a clear consensus in the scientific literature regarding the definition of longevity. Additionally, it is not clear what influence other indicator traits or productivity measures have on longevity. The objective of this study was to estimate the genetic variation for six measures of longevity and determine if correction for non-genetic factors influenced the magnitude of the heritability estimates.

Materials and Methods

Data

The data was an accumulation of both nucleus and multiplication records of Yorkshire females from four swine seedstock systems (Waldo Farms, DeWitt, NE; Premier Swine Systems, Michigantown, IN; Whiteshire/Hamroc, Albion, IN; and the Zierke Co., Morris, MN).

From these 21 farms, records on Yorkshire sows born from 1988 through 2002, with at least one farrowing record, were available. Information from the female's birth litter, along with her performance for age at 113 kg and backfat thickness adjusted to 113 kg as suggested by National Swine improvement Federation (1996), were merged with subsequent sow performance records. Further details of data editing and variable definition can be found in Hoge (2009a). Due to incomplete data recording across farms and even within a farm over time, not all sows had complete records for birth litter traits, growth rate and backfat thickness. To make optimal use of the data, the data set was divided into two. After editing the largest data set (Data A), 7,487 records of Yorkshire sows with at least 1 farrrowing were considered for survival analysis, including 5,889 (78.65%) and 1,598 (21.35%) uncensored and censored records, respectively. The average censoring rate across all four survival definitions was approximately 21%. The data set comprised a total of 697 sires with an average of 10 daughters each (range 2-175). Information included sows' first parity information along with her lifetime productivity data. The individual record for each female included herd type (either multiplier (1) or nucleus (2)) (HT), sow herd (the herd that the female was a productive sow), date of first farrowing, date of culling, age at first farrowing (AGEFF), number born alive in first litter (NBA), number of stillborn in first litter (NSTL), length of lactation in first parity (WNAGE), adjusted 21 day litter weight of first litter (D21W), and litter size (born alive) at last farrowing (LNBA).

The second data set (Data B) contained 3,886 records of Yorkshire sows with at least 1 farrowing record, with 2,995 (77.07%) and 891 (22.93%) uncensored and censored records, respectively. Additionally, the data set comprised a total of 520 sires with an average of 7 daughters each (range 2-131). Data B contained all variables previously listed in Data A, along with information related to the sow's birth litter record and adjusted days to 113 kg and adjusted backfat thickness at 113 kg. Standardized variables were created for growth and backfat thickness (see Hoge 2009a for details). Within a pig herd, contemporary group was defined by birth month and year.

The individual record for each female included all covariates present in Data A, along with pig herd (the herd that the female was born in), date of birth, birth litter number born alive (PNBA), birth litter birth weight (PLBW), percentage of gilt pigs in birth litter (PGR), standardized deviation for backfat thickness (BF), and standardized deviation for adjusted days to 113 kg (DAY).

A subset of Data A and Data B was used for generalized linear mixed model analyses. These data sets excluded censored observations and sires with less than 2 daughter records. There were 5,889 sow records included in the analyses for Data A with 540 sires represented and 2,995 sow records included in the analyses for Data B with 346 sires represented.

Six different definitions of longevity were developed. Length of productive life was determined as the number of days from the date of first farrowing to the date of culling or censoring (LPL). Similarly, the lifespan of a sow was determined as the maximum parity she completed prior to removal (MAXPAR). Lifetime prolificacy was determined as the number of piglets (born alive) produced during the LPL of the sow (SNBA). Stayablility, has been defined as binary trait measuring whether a sow has survived in a herd until some defined fixed parity or time (Serenius and Stalder, 2004). From this definition, two different discrete measures were determined using production based thresholds. They were the ability of a sow to achieve 4 parities prior to removal (PR4PAR) and the ability of a sow to produce 40 pigs prior to removal (PRNBA40). A measure of length of life and a measure of productivity were combined to determine the final response variable by each female's SNBA divided by the difference between cull date and birth date (PLIFE).

Statistical Analysis -

In the current study, statistical analyses were based on survival analysis to identify and evaluate the impact of factors influencing removal of Yorkshire females for LPL, MAXPAR, PLIFE, and SNBA. The proportional hazard model following a Weibull distribution was applied to the data using the Survival Kit (Ducrocq and Solkner, 2001). A discrete-time model that assumes survival data are measured on a discrete scale with few classes, described by Prentice and Gloeckler (1978), was used in the analysis for MAXPAR. The validity of the Weibull distribution was assessed by plotting the log(-log(S(*t*))) against the log(*t*), where S(*t*) is the Kaplan-Meier survivor function and *t* is time (Figure III.1 through III.4). The plots of this relationship revealed approximately straight lines indicating the Weibull distribution was assumed to fit the data appropriately. Preliminary survival analyses were carried out using a Cox proportional hazards model to examine the confounding and interaction between fixed effects. No significant interactions were found between fixed effects. The hazard function on a sow was modeled according to Ducrocq et al., 1988:

$$h(t, w(t)) = \lambda\rho(\lambda t)^{\rho-1}\exp\{w(t)'\theta\}$$

Where $h(t, w(t))$ is the hazard function of an individual depending on time t (or a function of time), and $\lambda\rho(\lambda t)^{\rho-1}$ is the baseline hazard function which is assumed to follow a Weibull distribution, where λ and ρ are location and shape parameters of the baseline Weibull hazard function. Vector $\theta' = \{b'u'\}$ is a vector of fixed (b) and random (u) covariates with a corresponding incidence matrix $w(t)' = \{x(t)'\ z(t)'\}$. For Data A, time independent fixed effects included in b were AGEFF, NBA, NSTL, LNBA, D21W, WNAGE, and HT and for Data B the models included all of the covariates listed for Data A with the addition BF, DAY, PNBA, PLBW, and PGR. The genetic effect of sire and the time dependent herd-year interaction were treated as random effects and included in u. The sire effect was assumed to have zero mean and var(sire) = $A\sigma^2_s$, where σ^2_s is the sire variance, and A is the additive relationship matrix among the sires. Tempelman (1998) encouraged treating contemporary groups as random to allow useful implementation of generalized linear animal models. However, this is in contrast to what has historically been done by animal breeders due to concerns regarding prediction bias when contemporary groups and genetic values are correlated. Tempelman (1998) justified the treatment of herd-year-season effects as random and included the possibility of modeling autoregressive or other temporal correlation structures over sequential year-seasons to alleviate the extreme category problem, and lessening the impact of model misspecification to make the statistical analysis more robust. Additionally, Yazdi et al.

(2000b) reported that the model that best described the data in their study was when herd-year was treated as random and time dependent. Records of sows were more thoroughly corrected for the effect of herd-year when it was treated as time-dependent versus time independent. Furthermore, Yazdi et al. (2000b) concluded that the decrease in the sire variances observed when herd-year was changed from fixed to random indicated that differences in the longevity of sows related to herd-year had partly genetic origin and modified the variability of longevity due to sire.

Two separate longevity analyses were carried out for each response variable. The first was to approximate true longevity; thus, random time-dependent herd-year and genetic sire effects were the only effects included in the model. To approximate functional longevity, all covariates were included in each model for each response variable. The heritability of longevity was calculated from the sire variance component as a proportion of phenotypic variance of the Weibull distribution. The heritability (h^2) on the logarithmic scale from survival analysis was calculated as shown by Ducrocq and Casella (1996):

$$h^2 = 4\sigma^2_S/(\pi^2/6+\sigma^2_S)$$

Where $\pi^2/6$ is the variance of the extreme value distribution (Lawless, 1982).

Single-trait threshold analyses were conducted to estimate heritability of two measures of stayability (PRNBA40 and PR4PAR) using a generalized linear mixed sire model for binary data with a logit link. All analyses were conducted using the GLIMMIX procedure within SAS (SAS Inst. INC., Cary, NC). Conditional on the fixed and random effects, stayability traits were assumed to follow a binomial distribution. The linear mixed model predictor used was modeled according to Martinez et al. (2005):

$$\eta = Xb + Zs$$

where η is the vector of linear predictors, which is related to predictions on the observational scale through the inverse link function; b is $p \times 1$ vector of fixed effects; s is a $q \times 1$ vector of random effects, and X, Z are known incidence matrices for b and s, respectively, relating the observations in y, the $n \times 1$ vector of observations, or its conditional expectation to fixed and random effects, respectively. Covariates were treated similarly to survival analysis with Data A, fixed effects included were AGEFF, NBA, NSTL, LNBA, D21W, and WNAGE and for Data B the models included all of the covariates listed for Data A with the addition BF, DAY, PNBA, PLBW, and PGR. For both Data A and Data B, the fixed effect HT was removed to satisfy convergence criterion. Time dependent herd-year interaction and sire were treated as random effects. The residual variance on the underlying scale was assumed to be 1 (Kadarmideen et al., 2004; Martinez et al., 2005). The link between observed threshold of producing 40 pigs or completing 4 parities and the underlying liability is a "threshold point". This is defined by the link function which relates $E(y|\beta,\mu,\lambda)$ to the observed mean. Estimates of heritability with threshold models were obtained as described by Kadarmideen et al. (2004) using a logit model:

$$h^2 = \frac{4\sigma_s^2}{(\sigma_s^2 + \sigma_e^2 * \frac{\pi^2}{3})},$$

where $\sigma_e^2 = 1$ and σ_s^2 was the estimate of the sire variance.

To test the significance of the sire variance estimates, a Z statistic was calculated by dividing the estimate of the sire variance by its standard error.

Results and Discussion

Descriptive statistics for the data are presented in Table III.2. The average LPL for Yorkshire females was 505.2 days. This relates closely to the mean parity at removal of 3.6. Females farrowed their first litter at approximately 1 year of age with an average of 9.4 pigs born alive. Throughout their productive lifetime females produced just over 36 pigs born alive with an adjusted litter 21 day weight of 51.7 kg. The mean age at weaning was just under 21 days. The descriptive statistics of the data are consistent with other survival analysis studies (Yazdi, 2000; Stalder et al., 2004; Serenius and Stalder, 2004; Serenius and Stalder 2007; Engblom et al., 2008).

To test the significance of different covariates, a likelihood-ratio test was carried out for models used in survival analysis. The results of the log likelihood tests from survival analysis are presented in tables III.3 for Data A and III.4 for Data B. The P-values and R^2 of Maddala (measure of proportion of variation explained by the model) are based on log likelihood differences when one effect at a time was excluded from the model. For Data A, all covariates included in the model were significant for all response variables with the exception of WNAGE for MAXPAR, SNBA, and PLIFE. For Data B, current results indicate that a female's birth litter covariates included in the analysis (PNBA, PLBW, PGR) were not significant, regardless of definition. The standardized variables for backfat and days to 113 kg were significant ($P<0.001$) across all definitions of longevity. These results are in agreement with Hoge (2009a) where a Cox proportional hazards model was used on a larger data set from the same population for preliminary variable selection. Furthermore, the sign (+ or -) of the hazard coefficients for each covariate were the same for the Cox proportional hazards models used in Hoge

(2009a) and the Weibull frailty models used in this study. Within a contemporary group, fatter, slower growing gilts had a decreased risk of being culled. Additionally, sows that had more pigs born alive, fewer stillborn, and heavier litters at 21 days of lactation for their first litter had a decreased risk of being culled. The primary focus of this study was to assess genetic variation; therefore hazard rates for each covariate were not presented. For further details related to the influence of covariates on various measures of longevity on this population and a comparison with other studies, see Hoge (2009a).

The levels of statistical significance of the covariates tested in the threshold are presented in table III.5. Similar to survival analysis, using either Cox or Weibull proportional hazards models, all first litter performance traits were significant, with the exception of WNAGE for PRNBA40. Covariates related to a female's birth litter performance were not significant for either response variable, while BF and DAY were significant ($P<0.01$) for PR4PAR.

Estimates of sire variance components and heritability are presented in table III.6. Heritability estimates were low for true longevity (range 0.043 to 0.059). When fixed effects were included for functional estimates of longevity, heritability estimates were higher for Data A with a range from 0.120 for MAXPAR to 0.190 for LPL and for Data B with a range 0.132 for MAXPAR to 0.231 for LPL. This increase in heritability estimates indicates that correcting for a female's developmental factors and first litter performance proves beneficial when estimating sire variance. Heritability estimates yielded from threshold analysis, when censored records were excluded, were 0.156 and 0.117 for Data A and 0.176 and 0.200 for Data B for PRNBA40 and PR4PAR, respectively. Caution should be used when making direct comparisons of heritability estimated from the threshold analysis to those obtained from survival analysis, due to differences in censoring rates. Gou et al., (2001) reported heritability estimates for length of productive life using a linear mixed model with censoring was 0.25 for the actual level of censoring (15.5%), and it tended to decrease to 0.18 and 0.16 as simulated censoring increased to 25 and 35%, respectively. When all censored records were excluded, the heritability estimate for length of productive life was 0.45. These results showed that as censoring rates decreased, estimates of heritability were increased, indicating that censoring rates can influence estimates of sire variance in the present data.

Results from this study are in agreement with previous findings where heritability estimates of length of productive life from survival analysis has ranged between 0.10 and 0.31 (Yazdi et al., 2000b; Serenius and Stalder, 2004; Serenius and Stalder, 2007). Additionally, Gou et al., (2001) and Serenius and Stalder (2004) reported that heritability estimates of lifetime prolificacy were slightly lower than those for length of productive life, which agrees with results from the current study. Heritability estimates were slightly higher for LPL (0.190 for Data A and 0.231 for Data B) than for SNBA (0.172 for Data A and 0.181 for Data B) and PLIFE (0.168 for Data A and 0.192 for Data B), both measures of lifetime prolificacy. Serenius and Stalder (2004) also reported that length of productive life and lifetime prolificacy were genetically highly correlated (r_g>0.95) indicating that selection for one will result in genetic gain in the other. Additionally, Tholen et al., (1996) and Lopez-Serrano et al. (2000) used linear models and reported heritability estimates for stayability (the probability of the sow surviving in the herd from parity 1 to parity 4 and from parity 1 to parity 3, respectively) to be 0.08 and 0.10. Fernandez de Sevilla et al., (2008a) reported the variance component for the sire genetic effect was 0.03, using a Cox semiparametric proportional hazards model. Heritability estimates from this study ranged from 0.05 to 0.07, using three different equations for calculating heritability. Fernandez de Sevilla et al., (2008b) used a competing risk approach on the same population of Duroc sows. These investigators reported estimates of heritability for longevity related to low productivity culling and these estimates ranged from 0.008 to 0.024. Heritability estimates for low fertility culling ranged from 0.017 to 0.083. These low heritability estimates could be partially attributed to the high censoring rates within the data (81.09% and 93.19%, respectively). Fernandez de Sevilla et al., (2008) concluded that there were substantial discrepancies in the sources of variation and genetic background of sow longevity depending on the cause of failure.

Martinez et al., (2005) estimated genetic parameters for stayability to specified ages for Hereford cows using a generalized linear mixed model for binary data and a linear mixed model. Investigators reported that estimates of heritability for stayability were higher for threshold model analysis (range of 0.09 to 0.30) as compared to estimates obtained from linear mixed model analysis (range 0.05 to 0.09). Guerra et al., (2006) estimated the heritability of calving rate and calf survival in a multibreed population with linear, threshold, and logistic, generalized mixed sire models. Reported heritabilities for calving rate were 0.063, 0.150, and 0.130 and calf survival were 0.049, 0.160, and 0.190 for linear, threshold, and logistic models, respectively. Heritability estimates for calving rate and calf survival from the linear mixed sire model were similar to threshold and logistic model estimates when transformed to an underlying scale.

The relative culling rate for daughters of sires ranged from 0.77 to 1.32 across definitions of longevity in survival analysis. This corresponds to the lowest and highest risk of culling for daughters of a common sire compared to daughters of an average sire which have a relative risk of culling equal to 1. Daughters from the poorest sires had 1.71 times higher risk of culling compared with daughters of the best sires. The ranges of relative culling rates for daughters were similar to those reported by Yazdi et al., (2000b).

The fact that herd-year environmental effects impact longevity and/or stayability has been readily documented (Yazdi et al., 2000b; Serenius and Stalder, 2004; Serenius and Stalder, 2007; Serenius et al., 2008). Operations have different culling policies and management practices. Additionally, these culling policies and management practices may change from year to year. The current results indicate relative culling rates for herd-year ranged from 0.54 to 1.48 across definitions of longevity. Within the worst herd-year combination, females had 2.74 times higher risk of culling compared to the best herd-year combination, indicating that herd-year had a large influence on the risk of culling, regardless of definition. Serenius et al., (2008) recommended that if breeding value estimation is routinely conducted, solutions for herd-year interaction classes should be available for producers to utilize so as to make more effective management decisions. Investigators do caution that a significant amount of data is required before herd-year-season solutions can be routinely utilized to make decisions.

The current results indicate that regardless of definition, the estimated heritabilities suggest that direct genetic improvement for improved longevity is feasible. Additionally, correcting for developmental factors and performance of first parity lactation does increase estimates of sire variances and results in higher heritability estimates. Furthermore, covariates included in the model had similar influence when using a Cox semi-parametric model, Weibull frailty model, or a threshold model.

Table III.1. Definitions of variable acronyms used in model development

Variable	Acronym
Number of days between date of first farrowing and removal, d	LPL
Number of parities a sow had completed	MAXPAR
Pigs born alive per day of sow herd life	PLIFE
Binary indicator variable if a sow had produced 40 pigs (0,1)	PRNBA40
Binary indicator variable if a sow had completed 4 parities (0,1)	PR4PAR
Total number born alive over lifetime	SNBA
Herd type, 1 multiplier, 2, nucleus	HT
Age at first farrowing, d	AGEFF
[a]Standardized deviation for adjusted backfat, mm	BF
[a]Standardized deviation for adjusted days to 113 kg	DAY
Adjusted 21 day litter weight in parity 1 litter, kg	D21W
Birth litter gilt ratio	PGR
Birth litter, litter birth weight, kg	PLBW
Birth litter number born alive	PNBA
Last litter number born alive	LNBA
First litter number born alive	NBA
First litter number stillborn	NSTL
First litter lactation length, d	WNAGE

[a]Adjusted female record was deviated from the birth month and year mean for gilts tested within herd and divided by the standard deviation.

Table III.2. Number of observations, means, standard deviations, minimums, maximum values of the traits studied in the Yorkshire Population

Trait[a]	No.	Mean	SD	MIN	MAX
LPL,d	7,487	505.2	407.7	10	3487
MAXPAR	7,487	3.6	2.4	1	14
SNBA	7,487	36.1	27.1	0	182
PLIFE	7,487	0.038	0.017	0	0.277
PRNBA40					
0	3,462				
1	2,427				
PR4PAR					
0	3,242				
1	2,647				
AGEFF,d	7,487	364.9	43.7	253	597
NBA	7,487	9.4	3.1	0	19
NSTL	7,487	0.7	1.2	0	13
LNBA	7,487	9.5	3.5	0	20
D21W, kg	7,487	51.6	14.5	4.5	115.9
WNAGE, d	7,487	20.3	4.7	0	40
BF, dev	3,886	-0.26	0.92	-3.19	3.89
DAY, dev	3,886	-0.41	0.82	-3.14	3.58
PGR	4,148	0.53	0.14	0.08	0.92
PNBA	4,148	10.8	2.9	1	20
PLBW, kg	4,148	35.9	9.8	3.0	75

[a]See Table III.1 for acronym definitions.

Table III.3. Likelihood ratio test, including P values and reliabilities (R^2) for Data A when the covariates were tested by excluding one at a time (last) from the full model[a]

Variable[b]	LPL		MAXPAR		SNBA		PLIFE	
	P value	R^2	P value	R^2	P value	R^2	P value	R^2
HT	< 0.001	0.23	< 0.001	0.20	< 0.0001	0.19	< 0.001	0.27
AGEFF	< 0.001	0.23	< 0.001	0.21	< 0.0001	0.18	< 0.001	0.25
NBA	< 0.001	0.23	< 0.001	0.22	< 0.0001	0.17	< 0.001	0.23
NSTL	< 0.001	0.23	< 0.001	0.22	< 0.0001	0.19	< 0.001	0.27
LNBA	< 0.001	0.23	0.001	0.21	0.0021	0.16	< 0.001	0.22
D21W	< 0.001	0.24	< 0.001	0.21	< 0.0001	0.19	< 0.001	0.28
WNAGE	< 0.001	0.24	0.024	0.21	0.0125	0.19	0.213	0.27

[a]Number of observations = 7,487.
[b]See Table III.1 for acronym definitions.

Table III.4. Likelihood ratio test, including P values and reliabilities (R^2) for Data B when the covariates were tested by excluding one at a time (last) from the full model[a]

Variable[b]	LPL		MAXPAR		SNBA		PLIFE	
	P value	R^2	P value	R^2	P value	R^2	P value	R^2
HT	< 0.001	0.17	< 0.001	0.21	< 0.001	0.19	< 0.001	0.27
AGEFF	< 0.001	0.16	< 0.001	0.21	0.002	0.18	< 0.001	0.25
NBA	< 0.001	0.18	< 0.001	0.22	< 0.001	0.17	< 0.001	0.23
NSTL	< 0.001	0.17	< 0.001	0.22	< 0.001	0.19	< 0.001	0.27
LNBA	< 0.001	0.17	< 0.001	0.22	< 0.001	0.16	< 0.001	0.22
D21W	< 0.001	0.17	< 0.001	0.21	< 0.001	0.18	< 0.001	0.27
WNAGE	< 0.001	0.18	0.002	0.22	0.002	0.19	0.363	0.27
PNBA	0.984	0.18	0.410	0.22	0.651	0.19	0.012	0.27
PLBW	0.323	0.18	0.639	0.22	0.244	0.19	0.463	0.27
PGR	0.134	0.17	0.146	0.22	0.312	0.19	0.300	0.27
BF	0.006	0.17	< 0.001	0.22	< 0.001	0.19	0.002	0.27
DAY	< 0.001	0.16	< 0.001	0.22	< 0.001	0.19	< 0.001	0.27

[a]Number of observations = 3,882.
[b]See Table III.1 for acronym definitions.

Table III.5. Level of statistical significance of the covariates included in the analyses of PRNBA40[a] and PR4PAR[a] for Data A and Data B

Variable[a]	PRNBA40		PR4PAR	
	Data A	Data B	Data A	Data B
AGEFF	***	***	***	***
NBA	***	***	***	**
NSTL	**	**	**	**
LNBA	***	***	*	**
D21W	***	***	***	**
WNAGE	NS	NS	*	*
PNBA	—[b]	NS	—	NS
PLBW	—	NS	—	NS
PGR	—	NS	—	NS
BF	—	*	—	**
DAY	—	NS	—	**

[a]See Table III.1 for acronym definitions.
[b]Covariate was not considered in the model.
*P<0.05; **P<0.01; ***P<0.001; NS = not significant.

Table III.6. Additive sire variance (σ_s^2) and heritability (h^2) estimates obtained from survival analysis and threshold analysis

	Data A			Data B		
	σ_s^2 [b]	*SE*	h^2	σ_s^2 [b]	*SE*	h^2
Survival Analysis						
LPL [a]						
True	0.020*	0.011	0.048	0.025*	0.011	0.059
Functional	0.082***	0.013	0.190	0.101***	0.014	0.231
MAXPAR[a]						
True	0.020*	0.011	0.048	0.021*	0.012	0.050
Functional	0.051***	0.012	0.120	0.056***	0.012	0.132
SNBA[a]						
True	0.018*	0.011	0.043	0.020*	0.012	0.048
Functional	0.074***	0.013	0.172	0.078***	0.012	0.181
PLIFE[a]						
True	0.021*	0.012	0.050	0.022*	0.011	0.053
Functional	0.072***	0.013	0.168	0.083***	0.014	0.192
Threshold Analysis						
PRNBA40[a]	0.147**	0.046	0.156	0.106*	0.062	0.117
PR4PAR[a]	0.152**	0.045	0.176	0.197**	0.071	0.200

[a]See Table III.1 for acronym definitions.
[b]$Pr(Z \leq -z)$*P<0.05; **P<0.01; ***P<0.001

Figure III.1. Graphical test for validity of Weibull distribution for LPL

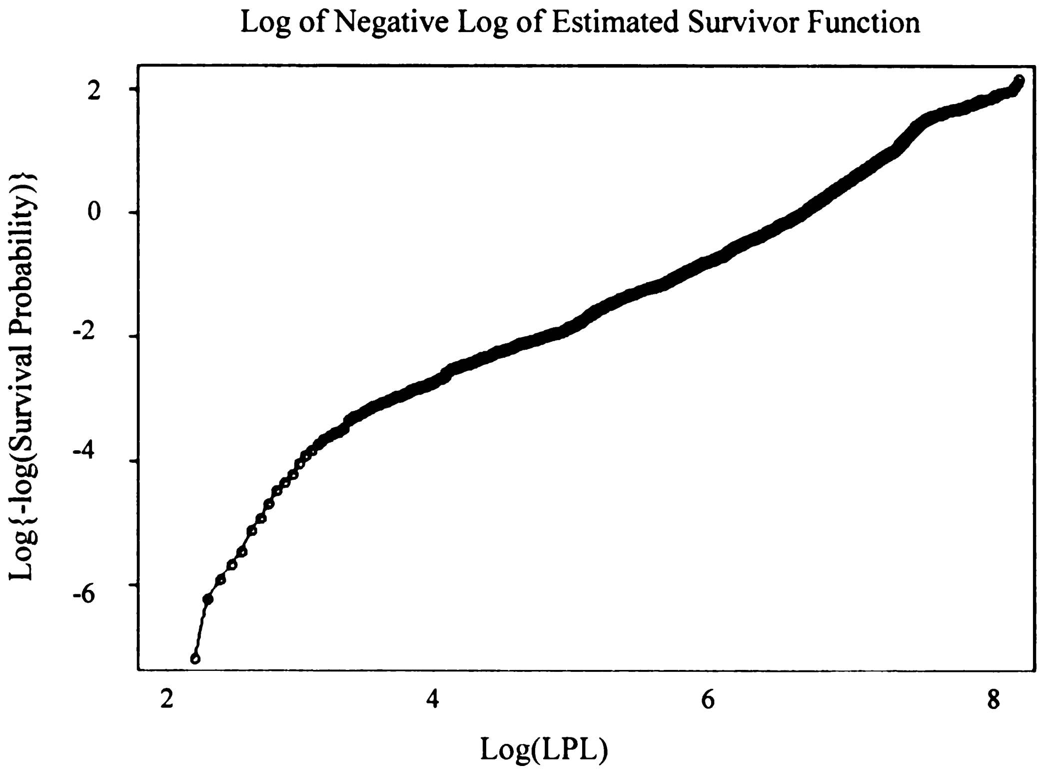


Figure III.2. Graphical test for validity of Weibull distribution for MAXPAR

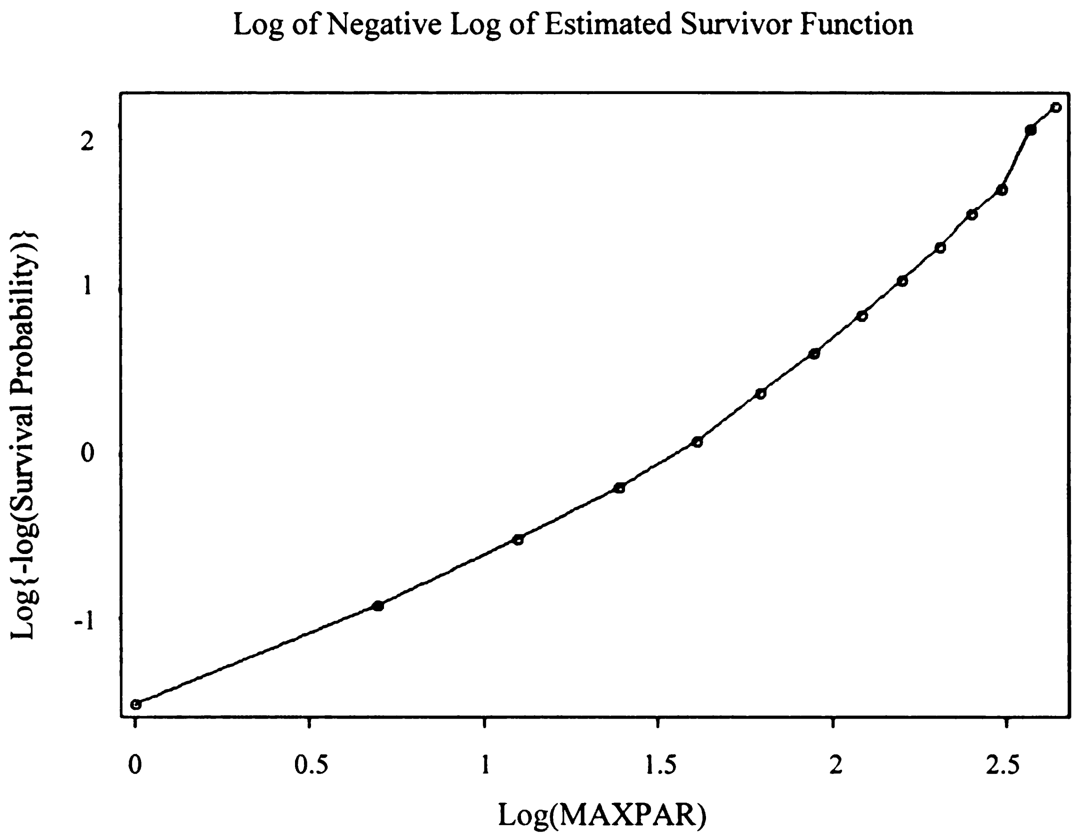


Figure III.3. Graphical test for validity of Weibull distribution for SNBA

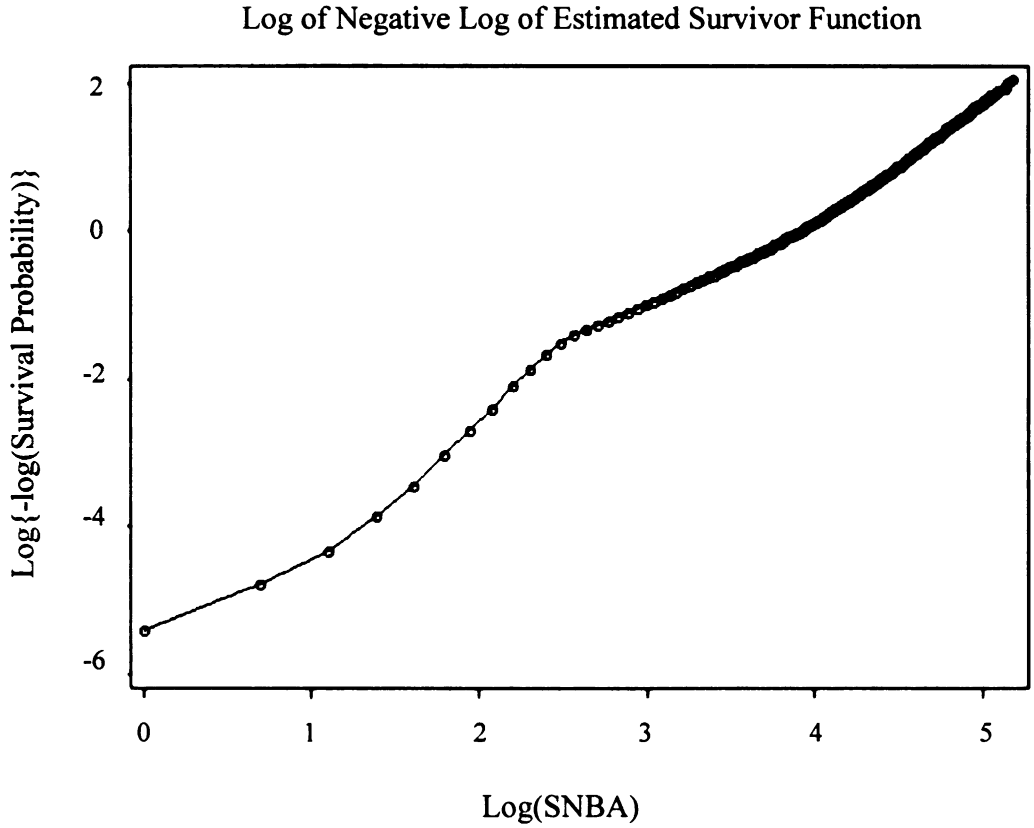
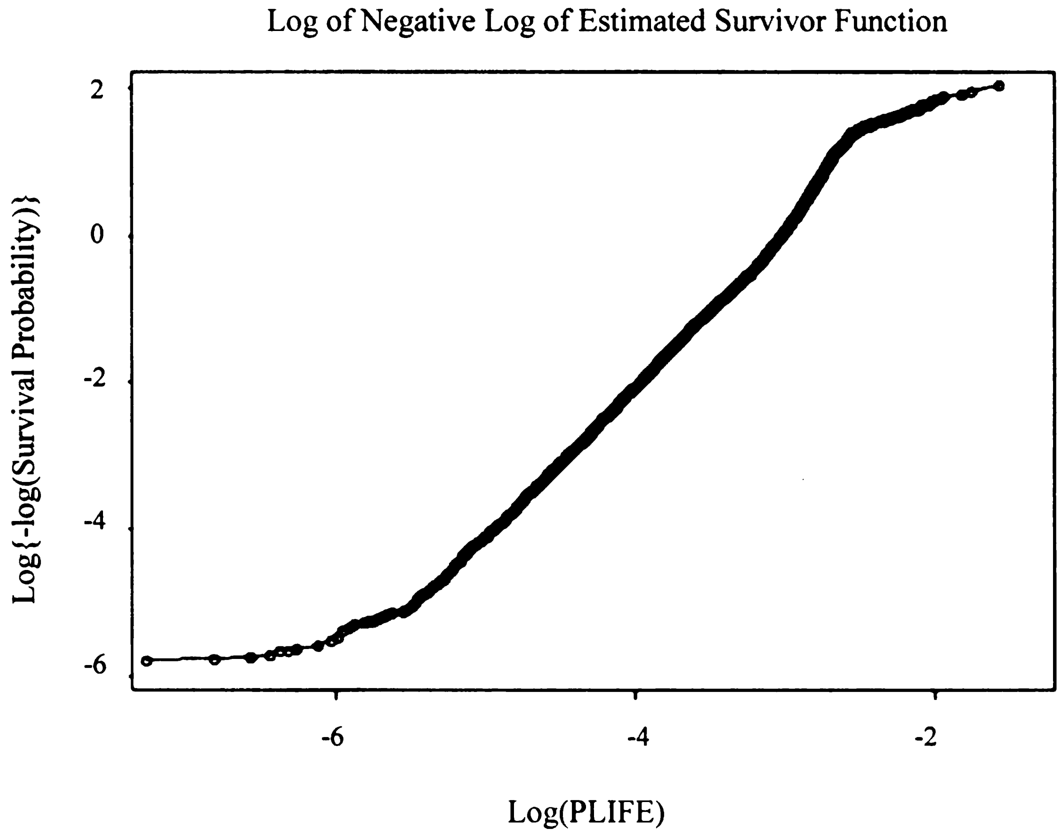


Figure III.4. Graphical test for validity of Weibull distribution for PLIFE



SUMMARY AND CONCLUSIONS

The length of adult sow productive life is now recognized as both an economic and welfare concern. However, there are not consistent definitions to measure sow longevity. The initial objective of this study evaluated six different descriptions of longevity and determined the relationship of developmental performance factors with them. The second objective was to assess the genetic variation within the six different descriptions of longevity. Longevity definitions included stayability (probability of producing 40 pigs or probability of reaching four parities), lifespan (number of parities a female has accumulated before culling), lifetime prolificacy (number of pigs born alive during a female's productive lifetime), herdlife (time from first farrowing to culling) and pigs produced per day of life.

To meet these two objectives, a unique data set was assembled. The data was an accumulation of both nucleus and multiplication records of Yorkshire females from four swine seedstock systems (Waldo Famrs, DeWitt, NE; Premier Swine Systems, Michingantown, IN; Whiteshire/Hamroc, Albion, IN; and the Zierke Co., Morris, MN). Individual pig performance and farrowing records from 21 different farms, which were associated within these four seedstock systems were merged into one data set for analysis. Due to incomplete data recording across farms and even within a farm over time, not all sows had complete records for birth litter traits, growth rate and backfat thickness. To make optimal use of the data, the data set was divided into two.

To meet the first objective, a Cox proportional hazards model was used to determine the relationship of developmental factors with longevity. There were 14,262 (Data A) records of Yorkshire sows that included a sow's first parity information along with her lifetime productivity data. The second data set (Data B) contained 4,272 records that included information from Data A, along with information related to the sow's birth litter record and adjusted days to 113 kg and adjusted backfat thickness at 113 kg. The average length of productive life for Yorkshire females was 488.82 days, with a mean parity at removal or censoring of 3.49. Females produced on average 34.93 pigs with an average age of first farrowing of 366.2 days. The effect of age at first farrowing on the risk of being culled was highly significant (P<0.0001). The older a female was at first farrowing the greater the risk of being culled. Additionally, the results indicated that the performance of a female during her first litter does provide insight for the rest of her productive life. Sows that had more pigs born alive, fewer stillborn fetuses, and had heavier 21 day litter weights, tended to have a decreased risk of being culled. The length of lactation in the first litter was significant (P<0.05) for length of productive life and lifespan. With the exception of length of productive life, herd type affected the other five definitions. Sows from nucleus herds had an increased relative risk of being culled that ranged from 42% to 68%, depending on the definition. The standardized variables for backfat and days to 113 kg significantly influenced all definitions of longevity. Within a contemporary group, fatter, slower growing gilts tended to have a decreased risk of being culled. Current results indicate that covariates for traits measured within a female's birth litter did not significantly impact longevity.

The second objective was to estimate the genetic variation for six measures of longevity and determine if non-genetic factors influenced the magnitude of the estimates of the genetic variances and the resulting heritability estimates. A reduced number of sows had complete pedigree information available. As a result, Data A consisted of

7,487 records that were daughters of 697 sires and Data B consisted of 3,886 records that were daughters of 520 sires. Censoring rates were 21.35% and 22.93% for Data A and Data B, respectively. Survival analysis was used to identify and evaluate the impact of factors influencing the removal of females and to estimate the sire variances for length of productive life, lifespan, and lifetime prolificacy. Heritability estimates derived from survival analysis ranged from 0.039 to 0.231. Estimates of heritability were similar across all four definitions, but were the lowest when only the random effects of sire and herd-year were included (0.039 to 0.050). When developmental factors and first litter performance traits were included in the model, heritability estimates increased across all four definitions (0.076 to 0.231).

The current results indicated that regardless of definition, developmental factors and performance of first parity females does provide insight into the longevity of the Yorkshire females in this population. Additionally, the heritability estimates suggest that direct genetic improvement for improved longevity is feasible. Furthermore, correcting for developmental factors and performance of first parity females did increase estimates of sire variances, resulting in higher heritability estimates. The six different definitions yielded similar results indicating that the "best" definition for assessing longevity could be considered producer dependent. These results will provide guidelines on assessing sow longevity within swine operations. Producers, wanting to improve sow longevity, can select a set of variables and a definition of longevity that is most suitable for their operation.

This study was not without limitations. The first limitation was related to inaccurate and inconsistent recording of reasons for removal. This variable was intended to be utilized in the analyses, but it was concluded that the lack of completeness eliminated the possibility of inclusion into the models. Another variable that was intended to be evaluated was number of services prior to first conception. Due to the incompleteness of breeding records, this variable was eliminated from the study. The final limitation of the data was related to herd type. Approximately 65% of the data came from nucleus herds versus 35% from multiplier herds. Caution should be used in interpreting the results due to the fact that females within a nucleus herd experience more voluntary culling in order to maximize genetic progress. Older sows have a longer generation interval and this can potentially slow genetic change.

It has been proven that improving sow longevity holds economic incentives. Future research efforts should include a type or structure score at selection into the breeding herd. Selection for correctly structured females could potentially impact the length of productive life of females. Additionally, feed consumption and body fat should be monitored throughout a female's first lactation. Sows that have a greater appetite are more likely to maintain an acceptable body composition at weaning and ultimately decrease the number of non-productive days a female experiences between parity one and parity two. Finally, efforts should be focused on identifying genetic markers that influence length of productive life. If genes are identified that impact measures of longevity, the selection for these favorable traits can be implemented in both sexes and earlier in life. Although the amount of available literature has increased substantially, there still is a substantial amount of research to assist the swine industry to improve longevity within the U.S. sow herd.

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