

THESIS

**GENETIC PARAMETERS AND TRENDS
FOR REPRODUCTIVE AND PRODUCTIVE TRAITS
OF A COMMERCIAL LANDRACE SWINE
POPULATION IN THAILAND**

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GRADUATE SCHOOL, KASETSART UNIVERSITY

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THESIS

GENETIC PARAMETERS AND TRENDS FOR REPRODUCTIVE AND PRODUCTIVE TRAITS OF A COMMERCIAL LANDRACE SWINE POPULATION IN THAILAND

NALINEE IMBOONTA

**A Thesis Submitted in Partial Fulfillment of
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Nalinee Imboonta 2006: Genetic Parameters and Trends for Reproductive and Productive Traits of a Commercial Landrace Swine Population in Thailand. Doctor of Philosophy (Animal Science), Major Field: Animal Science, Department of Animal Science. Thesis Advisor: Associate Professor Sornthep Tumwasorn, Ph.D. 95 pages.

Data of Landrace sows from one herd in Thailand were used to estimate genetic parameters for production and reproduction traits in first and later (2nd to 9th) parities. The investigated reproduction traits were total number of piglets born per litter (TB), number of stillborn piglets (SB), and number of piglets born alive but dead within 24 hours (BAD). Data were also used to estimate genetic parameters and trends. The investigated reproduction traits were age at first conception (AFC), TB, and weaning to first service interval (WSI), over the first four parities. The reproduction data pertained to 12,603 litters born between 1993 and 2005. The production measures were average daily gain (ADG) and backfat thickness (BF). These were recorded from 4,163 boars and 15,171 gilts. Analyses were carried out with a multivariate animal model using average information restricted maximum likelihood procedures.

Heritability estimates of reproduction traits for first parity were 0.21 ± 0.03 for AFC, 0.03 ± 0.02 for TB, 0.04 ± 0.02 for SB, and 0.06 ± 0.02 for BAD. For later parities, they were 0.02 ± 0.02 to 0.11 ± 0.04 for TB, 0.03 ± 0.04 for SB, and 0.02 ± 0.01 for BAD and for WSI over the first three parities it ranged from 0.16 ± 0.03 to 0.18 ± 0.04 . The average heritability estimates for production traits were 0.35 ± 0.02 for ADG and 0.53 ± 0.02 for BF. Genetic correlations between ADG and TB in later parities tended to be favorable, however, they were insignificant when TB in each of parity one to parity four were estimated. Backfat thickness was unfavorably genetically correlated with SB in later parities and the genetic correlations between TB and BAD tended to be unfavorable in all parities. Age at first conception was genetically correlated favorably with TB and WSI in first parity. A moderate unfavorable genetic correlation was estimated between BF and WSI after first litter. Genetic trends were 4.71 ± 1.27 g, -0.23 ± 0.03 mm and 0.23 ± 0.07 days per year for ADG, BF and AFC, respectively. There was no genetic progress for the other traits. It was concluded that selection for low BF will increase SB in later parities and selection for high TB will increase BAD. The result obtained also indicated that selection for low AFC will increase TB and decrease WSI and selection toward reduced BF may have an unfavorable impact on WSI after first litter. Besides, it should be possible to select for ADG and BF without adversely affecting AFC, TB or BAD. The results further revealed that the ongoing selection being used improved growth rate and reduced backfat thickness. However, there was no genetic improvement for TB.

Student's signature

Thesis Advisor's signature

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LIST OF ABBREVIATIONS

ADG	=	Average daily gain
AFC	=	Age at first conception
AI	=	Artificial insemination
BA	=	Number of piglets born alive
BAD	=	Number of piglets born alive but dead within 24 hours of birth
BAD1	=	Number of piglets born alive but dead within 24 hours of birth in first parity
BAD2+	=	Number of piglets born alive but dead within 24 hours of birth in later (2 nd to 9 th) parity
BF	=	Adjusted Backfat thickness
BLUP	=	Best linear unbiased prediction
BV	=	Breeding value
EVAP	=	Evaporative cooling
h^2	=	Heritability
REML	=	Restricted maximum likelihood
AI-REML	=	Average information restricted maximum likelihood
DF-REML	=	Derivative free restricted maximum likelihood
SB	=	Number of stillborn piglets
SB1	=	Number of stillborn piglets in first parity
SB2+	=	Number of stillborn piglets in later (2 nd to 9 th) parity
TB	=	Total number of piglets born per litter
TB1	=	Total number of piglets born per litter in first parity
TB2	=	Total number of piglets born per litter in second parity
TB2+	=	Total number of piglets born per litter in later (2 nd to 9 th) parity
TB3	=	Total number of piglets born per litter in third parity
TB4	=	Total number of piglets born per litter in fourth parity
WSI	=	Transformed weaning to first service interval
WSI1	=	Transformed weaning to first service interval after first litter
WSI2	=	Transformed weaning to first service interval after second litter
WSI3	=	Transformed weaning to first service interval after third litter

GENETIC PARAMETERS AND TRENDS FOR REPRODUCTIVE AND PRODUCTIVE TRAITS OF A COMMERCIAL LANDRACE SWINE POPULATION IN THAILAND

INTRODUCTION

In current commercial pig breeding programs, great emphasis is placed on improving reproduction traits in dam lines (Hansenberg *et al.*, 2001), because productive traits, which have been selection objectives for many years, may be approaching an optimal point (Webb, 1998). Reproductive performance is the major component of sow productivity, and is recognized as a key factor affecting the efficiency and economy of the pig industry and is a leading concern of both commercial producers and breeders (Kim, 2001). The breeding goal is generally to increase the number of piglets weaned per sow per year. Several reports have shown the effectiveness of selection on litter size (Lamberson *et al.*, 1991; Johnson *et al.*, 1999; Noguera *et al.*, 2002; Holl and Robison, 2003).

Since, lean growth rate and litter traits are economically important traits of swine production and thus, both should be emphasized in a swine selection program. For the genetic improvement of increased average daily gain and reduced backfat thickness in pigs, selection has proven to be a successful method in breeding programs (Berruecos *et al.*, 1970; Cleveland *et al.*, 1982; Kennedy *et al.*, 1986). Industry selection practices in recent years have improved lean meat percentage of carcass and growth. However, decreased reproductive performance as a correlated response of selection for productive traits has been studied (Berruecos *et al.*, 1970; Zhang *et al.*, 2000; Holm *et al.*, 2004a). Estimated genetic correlations between productive and reproductive traits are low and inconsistent, sometimes positive or negative (Cleveland *et al.*, 1988; Kuhlert and Jungst, 1993; Rydhmer *et al.*, 1995; Adamec and Johnson, 1997; Ten Napel and Johnson, 1997).

In general, litter size has been the only reproductive trait of the sow included in the breeding goal. Apart from increasing litter size directly, a number of piglets produced per sow per year can be improved by reducing age at puberty and reducing weaning to first service interval. However, neither the nucleus nor the multiplying herds have records of the time of first estrus. Even so, age at first service is a practical way of analyzing field data when the age at puberty is not recorded (Tummaruk *et al.*, 2001).

As traits like litter size are changed by selection, possible correlated responses with other traits need to be considered. In the study of Rydhmer *et al.* (1995), additive genetic variance for litter size is sufficiently large to indicate that selection for improved litter size using an animal model that makes use of all genetic relationships in the data would be successful. Although heritability of reproductive performance is low, using of relatives' records in selection can theoretically result in sizeable gains. Additionally, accurate estimates of genetic parameters will increase the accuracy of estimated breeding value, genetic response of selection and optimizing breeding schemes. More knowledge about relations between reproduction and production traits in sows is needed when designing breeding programs for the future.

Genetic correlations among reproductive traits have been estimated in many studies. Holm *et al.* (2005) found a positive genetic correlation between age at first service and the interval from weaning to first service. Negative correlations between weaning to conception interval and subsequent litter size have been found in large data sets by Dewey *et al.* (1994). Furthermore, the genetic correlation between age at first insemination and litter size was found to be unfavorable by Rydhmer *et al.* (1995) and Hanenberg *et al.* (2001). Hence, it is essential to add age at first service/conception and weaning to first service interval in the estimation of sow efficiency. Reliable genetic parameters for these reproductive traits are needed to see which have potential for genetic improvement, and thus may be included into a breeding program.

A selection index was used to simultaneously improve the lean percentage, average daily gain and total number of piglets born per litter in the herd under study. However, no genetic correlations between these traits have previously been estimated. Single-trait best linear unbiased prediction (BLUP) values have been used in the selection index. Since backfat thickness was the measured trait (unlike the estimated lean percentage), backfat thickness was analyzed instead of lean percentage in this study.

Estimating genetic and environmental trends in a population allows the assessment of the effectiveness of the selection procedure and gives the opportunity for monitoring management conditions. It also supplies the animal breeder with essential information to develop more successful programs in the future. Few studies have provided estimates for genetic correlations involving productive and reproductive traits.

In Thailand, genetic progress for litter size in swine production has not been reported. The swine genetic material used in Thailand mostly originated from temperate areas, such as West Europe and North America, where the climate is quite different from that in Thailand. Thailand has greater average temperatures and humidity and an almost constant day length. Except for housing design, most management procedures are almost the same as in the countries from which the swine breeds originated.

Genetic parameters may vary between populations and environments. It is therefore necessary to estimate genetic parameters specifically for tropical areas. It is essential, as well, to know genetic progress for reproductive traits in swine production. To date, few genetic studies based on data from sows in tropical areas are available. This research will be a preliminary study of genetic progress for reproductive traits in Thailand.

OBJECTIVES

Sows efficiency was retrospectively investigated in a nucleus farm where multiple traits selection for lean percentage, average daily gain and total number of piglets born was performed. In this thesis, average daily gain and backfat thickness were used as productive traits as well as total number of piglets born, still born piglet, piglet born alive but dead within 24 hours after birth, age at first conception, and weaning to service interval were used as reproductive traits of sows.

The purpose of this thesis were to investigate and describe causes of variation in the reproductive performance of sows, to estimate genetic parameters and genetic progress for different productive and reproductive traits of sows raised under tropical condition.

The specific aims were to:

- 1) Analyze the influences of age at first conception, parity, farrowing month and weaning to service interval that effect on reproductive traits
- 2) Estimate heritabilities of productive and reproductive traits
- 3) Estimate genetic correlations between reproductive traits
- 4) Estimate genetic correlations between productive and reproductive traits
- 5) Estimate genetic trends for productive and reproductive traits
- 6) Propose traits for using in selection in order to improve reproductive performance

LITTERATURE REVIEW

1. Productive and reproductive performance

The performance from different experiments both from government farms and private farms has been summarized by Chantsavang (1985). He calculated them as unweighted means, as shown in Table 1. The values are considered as the standard performance values in Thailand. The author concluded that the performance of pig from private farms is higher than from government farms, even though there are many researchers and a lot of new techniques on government farms. This is mainly because in government farms there is less motivation on the part of workers to work longer hours and to solve problems immediately. Often animals in government farms starve or do not receive the correct diet. In general, the average daily gain (ADG) of Large White is better than those of Landrace and Duroc. Backfat thickness (BF) of Duroc is higher than that of Landrace and Large White.

Table 1 Production performance of exotic breeds in Thailand

Farm	Large White	Landrace	Duroc	Average
Average daily gain (g/day)				
Government	601.8 (318) ¹	514.8 (332)	520.0 (206)	545.6
Private	721.5 (1325)	657.8 (990)	668.5 (529)	682.6
Average	661.6	586.3	594.2	
Backfat thickness (mm)				
Government	22.0 (318)	20.7 (332)	24.4 (206)	22.3
Private	19.9 (1325)	20.1 (990)	22.3 (529)	20.8
Average	20.9	20.4	23.3	

¹ The figures in parenthesis indicate the number of observations

Source: Chantsavang (1985)

Almost all of performance studies that were reported in Thailand were done in the government testing station. The performance from different testing stations has been summarized in Table 2. The tested animals were both imported animals and animals that were born in Thailand. The average of ADG and BF of Landrace pigs tested during 1992 to 1996 are 719 g/day and 18.9 mm respectively.

Table 2 Average daily gain and backfat thickness of Landrace pigs under Thai environments

Station	n	ADG (g/day)	BF (mm)	Reference
Tubkwang	341	767	17	Intra (1992)
Tubkwang	391	752	17	Intra <i>et al.</i> (1994)
Tubkwang	732	659	21	Tubcharoen <i>et al.</i> (1994)
Kampeangsaen	176	803	-	Sookmanee <i>et al.</i> (1995)
Ta phra	23	745	13	Intarak <i>et al</i> (1996)

Chantsavang (1987) reported about the difference of the litter sizes of three purebreds from government farms and private farms (Table 3). The performance of sows in private farms is higher than in government farms (9.9 % and 18.3 % more for litter size at birth and at weaning, respectively). The mortality rate in government farms is 46.8% higher than in government farms. The reasons are as already mentioned above. On average, the Large White sows give larger litter sizes (both at birth and at weaning) than Landrace sows and Duroc sows (2.8 % and 12.1 % more for litter size at birth and 6.9 % and 16.4 % more for litter size at weaning, respectively).

Table 3 Litter size and mortality rate of piglets from birth to weaning of three purebreds

Farm	Large White	Landrace	Duroc	Average
Litter size at birth (pigs)				
Government	9.2 (984) ¹	8.5 (938)	8.2 (70)	8.6
Private	9.9 (437)	10.2 (105)	8.6 (273)	9.6
Average	9.6	9.3	8.4	
Litter size at weaning (pigs)				
Government	6.9 (984)	6.7 (938)	6.0 (70)	6.5
Private	8.8 (437)	8.0 (105)	7.1 (273)	8.0
Average	7.9	7.3	6.6	
Mortality rate from birth to weaning (%)				
Government	25.0 (984)	21.2 (938)	26.9 (70)	24.3
Private	11.2 (437)	21.5 (105)	17.0 (273)	16.6
Average	17.8	21.3	21.8	

¹ The figures in parenthesis indicate the number of observations

Source: Chantsavang (1987)

Tuntivisoottikul (1995) conducted a survey and collected data on reproductive performance from six medium sized farms in Thailand. From this survey, she reported that total number of piglets born of Landrace sows produced in Thailand is 10.16 piglets per litter.

In general, it is not easy to obtain data from private commercial farms in Thailand, because the farmers keep their data top secret. This is mainly to avoid problems with income tax and to avoid conflicts through comparison with other commercial farms.

2. Swine Genetic Evaluations in Thailand

The swine researches evaluated by Reodecha (2000) showed that researches in Thailand that related in swine genetic were started in 1986. Until 2000, they have only 24 publications, not thesis or dissertation. They were evaluation of purebred performance, crossbred performance and genetics and breeding in pig production. Reodecha (2000) concluded that one of the weaknesses of pig genetic improvement was that the industry lacked the standard method of measurements which resulted in incomparable research results. Best linear unbiased prediction and models of livestock genetic evaluation have been used by the Swine Group of Charoen Pokphand Co., LTD. since 1992 (personal communication with Dr. Satjar Ravungsook, company's breeder).

Indratula and Sondhipiroj (1996) studied genetic trend of reproductive performance of Large White, Landrace and Duroc sows in Chiangmai livestock research and breeding center from 1974 to 1996. Heritabilities and repeatabilities of litter size at birth, litter weight at 0-8 weeks, survival rate, body weight and daily gain were reported.

Imboonta (1997) evaluated genetic parameters and trends from performance test and reproductive records collected from 1992 to 1996 of Landrace, Yorkshire and Duroc gilts from 4 commercial farms. Genetic parameters of age at first mating and backfat thickness were analyzed simultaneously with multivariate animal model by derivative free-restricted maximum likelihood (DF-REML). The genetic trends of age at first mating and backfat thickness were reported. Furthermore, this study reported that there is negative genetic correlation between age at first mating and backfat thickness.

3. Relationship between Productive and Reproductive Traits

Genetic correlations between productive and reproductive traits seem to be inconsistent sometime favorable and sometime unfavorable. Many studies suggest zero covariance between productive and reproductive traits in swine (Rydhmer *et al.*, 1995; Ducos and Bidanel, 1996; Kerr and Cameron, 1996; Crump *et al.*, 1997), beside, weak genetic correlations between several reproductive and productive traits has also been estimated (Rydhmer, 2000; Peskovicova *et al.*, 2002). However, other recent results show moderate and high genetic correlation between reproductive and productive traits (Hermesch *et al.*, 2000; Holm *et al.*, 2004a).

Unfavorable genetic correlations between litter size and growth were estimated by Hermesch *et al.* (2000). Their results were based on growth performance of boars from 3 to 22 wk of age. Hermesch *et al.* (2000) argued that some of their genetic correlations might be the result of a direct influence of litter size on growth, since growth was measured on offspring from sows. When Holm *et al.* (2004a) used age at 100 kg of live weight as a measure of growth, recorded on-farm on the same animals that provided records for litter size. They found that age at 100 kg of live weight was highly unfavorably correlated with litter size. Even if a random litter effect was included in the model for growth to counteract litter effect.

Kuhlers and Jungst (1993) reported a small, but not significant, increase in litter size at birth when selecting Landrace pigs for a high 200-days weight. That was agreed well with the results of Cleveland *et al.* (1988) that selection for average daily gain and decrease backfat thickness had little effect on litter size and litter weight. While Noguera *et al.* (2002) reported that selection for growth and back fat should result in no or very little correlated response in litter size. Fredeen and Mikami (1986) reported that litter size did not respond to selection index for reducing backfat thickness and increasing growth rate. Similarly, there were no phenotypic correlations between performance-test index and litter size and no genetic and residual correlation between growth rate and litter size (Rydhmer *et al.* 1995).

Correlated response to selection against backfat thickness estimated by Berruecos *et al.* (1970) indicated a decline in litter size. When Holl and Robinson (2003) selected for increased number born alive a significant positive response in estimated breeding values for adjusted backfat was found. By contrast, Rydhmer *et al.* (1995) found a favorable genetic correlation between backfat thickness at performance test of sows and litter size at birth.

Genetic correlations of interval from weaning to service or conception with productive traits have been reported. Adamec and Johnson (1997) found a positive genetic correlation between weaning to conception interval and average daily gain but a negative genetic correlation between weaning to conception interval and backfat thickness. Tholen *et al.* (1996b) also found a negative genetic correlation between weaning to conception interval and backfat thickness, whereas the genetic correlation between weaning to conception interval and average daily gain did not differ significantly from zero. Nevertheless, seven generations of selection for a short interval between weaning and estrus did not change the body condition score of gilts (Ten Napel *et al.*, 1998).

Between-study and between-data set variation in sign and magnitude of the genetic correlations between productive and reproductive traits may result from the fact that the parameter estimates are experiment specific and from differences in selection strategies, populations and environments within the studies (Kerr and Cameron, 1996). Moreover, trait definitions may vary between studies (Rydhmer *et al.*, 1992).

4. Genetic Parameters for Productive Traits

Growth and carcass characters are traits of great importance to the swine industry. This confirmed by the large number of studies that have estimated the parameters of these traits for use in genetic improvement programs. Average daily gain is one of the best known traits in this group. Ferraz and Johnson (1993) used the

REML animal model to estimate the heritabilities for ADG and presented values ranking from 0.23 to 0.34. Li and Kennedy (1994) reported estimates of heritability for days to 113.5 kg ranking from 0.35 to 0.44 based on Yorkshire, Duroc, Hampshire and Landrace.

Backfat thickness is another trait that received much study. Ferraz and Johnson (1993), using four animal models for herds of Landrace and Large White pigs, reported estimates of heritability that range from 0.39 to 0.50 for ultrasonic measure of BF. Chen *et al.* (2002) used Yorkshire, Duroc, Hampshire and Landrace from the National Swine Registry of U.S. and reported heritability estimates of 0.48 to 0.49 for ultrasonic measure of BF.

5. Genetic Parameters for Reproductive Traits

Genetic parameters of reproductive traits have been estimated by a number of researchers. In the earlier studies, genetic parameters for reproductive traits were obtained from daughter-dam regression or half-sib correlations based on the traditional analysis of variance (Urban *et al.*, 1966; Revelle and Robison, 1973). Thereafter the BLUP method with restricted maximum likelihood (REML) to estimate genetic parameters for reproductive traits has become the standard method. This method that incorporates all the genetic relationships among individual available produces smaller sampling variance, and biases due to selection could be reduced.

Reproductive traits of sows can be affected by many factors, such as breed, parity, age at first conception, mating frequency, season, previous lactation length, and weaning to conception interval (Clark and Leman, 1986a, 1986b; Yen *et al.*, 1987). However, computing power and programs have advanced and allow the use of animal models that include a variety of fixed and random effects simultaneously. A number of traits contribute to overall reproductive performance. These include age at puberty, conception rate, litter size at birth and at weaning, weaning to conception interval and so on (Haley *et al.*, 1988).

5.1 Heritabilities for litter traits

Two of the traits most often used as indicators of female reproductive in swine are total number of piglets born per litter and number of piglets born alive. A number of studies have estimated the heritability for total number of piglets born per litter by means of regression of offspring on dam and analysis of variance. Values have ranged from 0.04 to 0.76 (Urban *et al.*, 1966; Young *et al.*, 1978; Bereskin, 1984; Irgang and Robison, 1984). Roehe and Kennedy (1995) estimated heritability for total number of piglets born per litter by the REML procedure and reported values of heritability of different parities ranged from 0.10 to 0.17. The results from several studies were summarized by Rothschild (1996). He reported the average heritability for total number of piglets born per litter to be 0.10 with values ranging from 0 to 0.76.

Estimates of heritability for piglets born alive by paternal half-sib relationships ranged from -0.05 to 0.66 (Young *et al.*, 1977; Young *et al.*, 1978; Pumfrey *et al.*, 1980; Irvin and Swiger, 1984; Ferguson *et al.*, 1985) while the estimates by means of regression of offspring on dam range from 0.05-0.13 (Revelle and Robison, 1973; Bereskin, 1984). Ferraz and Johnson (1993) estimated heritability for this trait by using a REML animal model found values ranged from 0.01 to 0.14. Roehe and Kennedy (1995) using the same methodology produced heritability estimates ranging from 0.09 to 0.14 for number of piglets born alive. Rothschild (1996) reviewed several studies and summarized the heritability for number of piglets born alive ranged from 0 to 0.66 with the mean estimate 0.07.

5.2 Heritabilities for mortality traits

The three common causes of pre-weaning death in piglets are stillbirth, starvation and crushing by the sow (English and Smith, 1975). The exact causes of stillborn piglets are multiple and complex, however, increased duration of farrowing is often associated with a higher stillborn rates (Holm *et al.*, 2004b), and the risk of dying during the farrowing process increases for the piglets born late in the farrowing

(Fraser *et al.*, 1995). Leenhouders *et al.* (1999) showed a positive relationship between the number of stillborn piglets and the number of live-born piglets that died before weaning indicating that in litters with a high incidence of stillbirths there is an overall lower viability also of live-born piglets.

A number of analyses have considered piglet survival to weaning to be a trait of the dam (Knol, 2001; Grandinson *et al.*, 2002). Earlier genetic studies of mortality from birth to weaning have shown low heritabilities (averaging 0.05) from six studies summarized by Lamberson (1990) and from 14 studies summarized by Rothschild and Bidanel (1998). Estimates heritabilities for prenatal survival have been relatively higher, an average of 0.15 (Rothschild and Bidanel, 1998).

Knol (2001) reported that heritability for % litter mortality until day 21 was low (0.07), but significantly different from zero. While estimated heritability of % survival by Zhang *et al.* (2000) was 0.19 and Ferguson *et al.* (1985) reported that heritability of pre-weaning survival were 0.14 and 0.18 for Yorkshires and Durocs, respectively. The heritabilities estimated by Grandinson *et al.* (2002) were at 0.03 for total mortality from birth until 3 weeks of age, 0.04 for stillbirth and 0.01 for crushing. Lund *et al.* (2002) estimated the direct heritability for postnatal mortality at 0.04 and the maternal heritability at 0.08 in Landrace pigs. Very low correlations have been found between the prenatal and postnatal mortality traits (Lund *et al.*, 2002), which indicates that their genetic backgrounds differ greatly.

5.3 Heritabilities for calculated intervals

One of the factors that has an effect on litter traits are intervals such as age at first conception and previous interval between weaning and service (Clark and Leman, 1986a, 1986b). In general, the interval between weaning and service consists of weaning to estrus and estrus to service intervals. Parameter estimates for weaning to estrus interval are expected to be similar to those for weaning to service interval

because only a small amount of variation is added to weaning to estrus interval due to mating policy (Adamec and Johnson, 1997).

Estimates for age at first estrus found in the literature varied from 0.2 to 0.3 (Lamberson *et al.*, 1991; Rydhmer *et al.*, 1994). In addition, estimates of heritability for age at first service or insemination were around 0.3 in the studies of Hanenberg *et al.* (2001) and Holm *et al.* (2005).

The estimated heritability for weaning to estrus interval was low (0.03) for a commercial swine population in Thailand (Suwanasopee, 2006). Estimate of heritability for weaning to service interval was 0.14 in Adamec and Johnson (1997). Ten Napel *et al.* (1995a) found comparably larger estimates, between 0.36 and 0.44, of heritability for weaning to estrus interval. Since the distribution of calculated intervals was left skewed, several researchers have tried to modify this characteristic. Ten Napel *et al.* (1998) derived three new traits, which were normal, prolonged and incidence of a prolonged interval, from weaning to estrus. The estimates of heritability for normal, prolonged interval and incidence of prolonged intervals were 0.18, 0.17 and 0.27 respectively.

5.4 Genetic correlations between reproductive traits

Irgang *et al.* (1994) reported low genetic correlations for litter size between first and second parities in the range of 0.32 to 0.48, but higher correlations between first and third, and second and third parities, in the range of 0.77 to 1.00, respectively. These estimates for litter size between first and second parity are lower than those reported by Johansson and Kennedy (1985) and in contrast with estimates reported by Haley *et al.* (1988). The genetic correlation between numbers of piglets born alive in first parity and that in second parity was estimate to be 0.7 (Rydhmer *et al.*, 1995). Roehe and Kennedy (1995) reported that genetic correlations for litter traits between adjacent parities were substantially less than one, and that heritability increase with parity in Landrace sows. Alfonso *et al.* (1997) estimated genetic

correlations between parities with bivariate analyses and found them close to one and similar for number of piglets born alive and number of piglets born in total in the first five parities.

There are few estimates for genetic correlations between litter size and other reproductive traits such as age at first service and weaning to service interval. Genetic correlation between age at first service and number of live-born piglet was positive in Norwegian Landrace sows (Holm *et al.*, 2005). The result indicated that selection for increased number of born alive piglet would slightly increase age at first service. In a contrary, the genetic correlation between age at first insemination and total number of piglets born in the study of Dutch Landrace sows is near zero (Hanenberg *et al.*, 2001).

Genetic correlation between age at first mating and interval from weaning to next mating is moderate and positive (Hanenberg *et al.*, 2001). In addition, selection for younger pig at puberty has had a favorable effect on the interval from weaning of the first litter to service (Holder *et al.*, 1995; Sterning *et al.*, 1998). These results were in agreement with the study of Holm *et al.* (2005). They reported that selection for decreased age at first service will have a favorable effect on weaning to first service intervals. Conversely, selection for decreased weaning to first service intervals will reduce the probability of a return, and also selection for decreased age at first service seems to have an unfavorable effect on return rate both on gilts and sows (Holm *et al.*, 2005).

In a study by Sterning *et al.* (1998), gilts with a high age at puberty had higher litter weight gain and also higher weight loss during lactation than gilts with a low age at puberty. They argued that this phenomenon could have an influence on the relationship between age at puberty and weaning to service interval. Besides, a large weight loss during lactation could delay the return to estrus after weaning (Sterning *et al.*, 1990).

Genetic correlations of weaning to service interval with number of piglets born in total, number of piglets born alive and number of piglets weaned were found to be 0.13, 0.08 and 0.13 respectively (Adamec and Johnson, 1997). Similar relationships between weaning to estrus interval and litter size were previously reported in studies by Ten Napel *et al.* (1995a).

Ten Napel and Johnson (1997) reported that correlated responses for litter size to a selection for a short weaning to estrus interval are small and depend highly on the environment in which the population is selected. Genetic correlations between weaning to conception interval and litter traits were zero or slightly negative in Adamec and Johnson (1997).

Negative relationships between weaning to estrus interval and subsequent litter size have been found by Kemp and Soede (1996). However, in the study of Holm *et al.* (2005) the genetic correlation between interval from weaning to first service after first litter and number of live-born piglets in second litter was close to zero. The estimated genetic correlation between total number of piglets born in first parity and interval from weaning to first service after first parity was near zero (Hananberg *et al.*, 2001). In the study of Tholen *et al.* (1996b) the genetic correlation between weaning to conception interval after first parity and number of piglets born alive in first and third parity was favorable, whereas the genetic correlation to number of piglets born alive in second parity was unfavorable.

Genetic correlations between number of piglets born in total and number of piglets born alive were high (Johansson and Kennedy, 1985; Roehe and Kennedy, 1995), so genetic improvement of number of piglets born in total would also increase number of piglets born alive. However, selection for number of piglets born in total always has the risk of increasing numbers born dead (Johnson *et al.*, 1999). Lund *et al.* (2002) also found positive genetic corrections between total born and piglet survival.

Litter size is unfavorably correlated to piglet survival and vitality, and selection for litter size has a negative impact on pre-weaning mortality and birth weight (Roehe, 1999; Knol, 2001; Lund *et al.*, 2002). Increased litter size generally results in lower birth weights, with a decreased probability of survival (Roehe and Kalm, 2000). Low birth weight is also genetically correlated with greater piglet mortality caused by crushing (Grandinson *et al.*, 2002). On the other hand, Grandinson *et al.* (2002) reported a positive genetic correlation between birth weight and stillbirth, indicating that piglets with genetic capacity for a high birth weight have more stillborn piglets when they become mothers.

Litter size at weaning has been of greater commercial importance than litter size at birth (Haley *et al.*, 1988). However, selection for number of piglet wean is very difficult to record under conditions of cross fostering (Roehe and Kennedy, 1995).

MATERIALS AND METHODS

Animals

All animals included in the two trials in the thesis were purebred Landrace pigs from one nucleus herd located in eastern Thailand. Productive records were available for gilts and boars performance tested between 1993 and 2005. Reproductive records were also available for sows farrowing between 1993 and 2005. Replacement gilts and boars were usually recruited from within the herd, however, some animals (19% of sires and 4% of sows) were imported from abroad (Australia, Northern Ireland, Norway, Sweden and the United States of America). Fresh semen was also imported from abroad, approximately every three years.

General Management

1. Housing

The sows were kept in individual stalls ($0.6 \times 2.1 \text{ m}^2$) during mating and gestation and in individual farrowing pens ($1.85 \times 2.2 \text{ m}^2$), with a stall ($0.60 \times 2.20 \text{ m}^2$) inside the farrowing pen, during lactation. The boars were kept in individual pens ($2.2 \times 2.4 \text{ m}^2$). Since the farm was established in 1972, the sows had been housed in open buildings equipped with cooling systems such as water dripping, sprinkling and fans. After 1996, sows and boars were housed in evaporative cooling (EVAP) system buildings.

Evaporative cooling reduces the air temperature by humidification. Water is sprayed on a cooling pad in one end of the closed building. Hot outdoor air passes through the pads, using the exhaust fan at the other end of the building, and the air temperature is reduced when the water evaporates. This process reduces the temperature with a complementary increase of the relative humidity and water vapor content in the air (Simmons and Lott, 1996). The temperature inside an EVAP system

building can be reduced approximately 5 to 10°C below the outside temperature (Saengsukeeluck, 2001). Thus, the variation of temperature inside an EVAP system building depends on temperature outside the building. The side wall along the length of an EVAP building is made, in part, of translucent plastic sheets; therefore, an EVAP building has ambient photoperiod.

2. Feeding

All boars, gilts and sows received feed of the same composition at all stages of the reproductive cycle. The feed contained approximately 17% crude protein and 13 MJ of digestible energy per kilogram as-fed basis. The boars were fed 2.5 kg/day. Gilts were fed 2.5 kg/day from the performance test until the first successful mating. Gilts and sows were fed 1.8 kg/day from mating to 12 weeks of gestation, and, thereafter, 3 kg/day until 7 days before expected farrowing, when the feed amount was reduced to 2 kg/day. Lactating sows were fed 2.5, 4.5, and 6 kg/day during week 1, 2, and 3 of lactation, respectively. After weaning, the sows were moved to the mating-gestation area, where they were fed 2 kg/day until mating. All animals had free access to water via nipple drinkers.

3. Mating

After the performance test at 22 weeks of age, replacement gilts were penned in groups of three to five animals and they were observed for estrus in these pens. Before the expected second observed estrus, gilts were moved into the mating area for boar contact, where they were kept in individual stalls. Approximately three months after the performance test, gilts without any signs of estrus were culled. Gilts were mated on the second observed estrus, or later, at a minimum age of 32 weeks and at a minimum body weight of 130 kg. However, owing to a new management strategy, gilts were mated at a higher body weight (minimum 140 kg) from 2002 and onwards. Estrous detection was performed twice a day, in the morning and evening. If the onset of standing heat was detected in the evening, gilts were inseminated in that

evening and sows were inseminated in the next morning. The sows were inseminated artificially three times per estrus, every 12 hours. All sows produced purebred piglets. Artificial insemination (AI) doses were produced within the herd and all breeding was performed with AI. Hormonal induction of estrus and farrowing were not performed.

4. Farrowing

Sows were moved to the farrowing house one week before the expected farrowing date and were supervised day and night around farrowing. New born piglets were monitored and handled once a day between 10:00 and 12:00 a.m. Numbers of piglets born alive (BA), stillborn piglets (SB), and piglets born alive but dead within 24 hours of birth (BAD; e.g. weak, crushed or malformed) were recorded at this handling. No cross-fostering was performed before the piglets were handled on the first day. Some cross-fostering was performed after the first day, but it was not recorded. Low weight male piglets and male piglets with abnormal characteristics (e.g., hernia, cryptorchidism, abnormal feet and legs) or from parents with undesirable breeding values were castrated in the farrowing house. The lactation period was approximately 18 days.

5. Weaning

At weaning, which was performed on Monday and Thursday each week, piglets were moved to a nursery house, whereas the sows were moved to the mating area and stalled adjacent to boar(s). Sows that did not show estrus within seven days after weaning were intensively stimulated to come into estrus. Stimulation included relocation to another individual stall, or relocation, combined with grouping three to four sows together, and introducing them into the boar pen for 10 minutes, twice a day.

6. On Farm Testing

All gilts and intact young boars were performance tested from 9 to 22 wk of age. During the performance test, these animals were fed ad libitum and penned in groups of 18 to 20 animals of the same sex. Animals were weighted and measured for backfat thickness at the end of the test period at approximately 22 week of age. Backfat thickness was measured ultrasonically at the 10th rib and 6.5 cm from the midline and adjusted to 100 kg body weight by equation [1] modified from National Swine Improvement Federation guidelines (NSIF, 2005). Growth was expressed as average daily gain (ADG) from 9 to 22 weeks of age.

$$BF = \text{ActualBF} + \left[\frac{(100 - \text{ActualWeight}) \times \text{ActualBF}}{\text{ActualWeight} - 25} \right] \quad [1]$$

where BF is the adjusted backfat thickness.

7. Selection

The gilts were selected on the basis of their production (backfat thickness and ADG) and the sows were culled based on their reproductive performance (total number of piglets born, including mummified piglets). After 1996, selection was based on an index score, comprising the estimated breeding values for lean percentage (estimated from backfat thickness and loin eye area), ADG and total number of piglets born, equation [2]. This selection index was used for selection of both males and females. The breeding goal was changed in 1999. From then on, a minimum criterion of 12 mm BF was used for pigs (boars and gilts) selected for replacement.

$$\text{Index} = 100 + 3.298(\text{BVleanpercentage}) + 1.813(\text{BVADG}) + 4.889(\text{BVTB}) \quad [2]$$

where BV is the breeding value.

Since backfat thickness was the measured trait (unlike the estimated lean percentage), backfat thickness was analyzed instead of lean percentage in this study. After the performance test, 10 % of the selected young boars and 50 % of the selected gilts were used for replacement in this nucleus farm and the rest were sold as breeding animals to other farms.

Trial 1

1. Data Description

Reproductive records were available covering the total number of piglets born in first and later parities (TB1 and TB2+), the number of stillborn piglets in first and later parities (SB1 and SB2+), and the number of piglets born alive but dead within 24 hours of birth in first and later parities (BAD1 and BAD2+), to sows farrowing between 1993 and 2005. Performance test data were also available covering ADG and BF for gilts and boars tested between 1993 and 2005.

2. Traits Analyzed

The litter size or total number of piglets born (TB) in first and later parities was defined as the total number of piglets born including BA, SB, and BAD. Mummified piglets were excluded from TB, since their numbers were difficult to record precisely. Only litters with at least one TB were included in analysis. Parities greater than nine were excluded.

A stillborn piglet was defined as a piglet found dead behind the sow at, or immediately after farrowing. Born alive but dead within 24 hours of birth was defined as a piglet died from weakness, being crushed or malformed within 24 hours of birth. The mortality traits in this study were SB and BAD.

Growth rate was expressed as ADG from 9 to 22 weeks of age. Backfat thickness was defined as adjusted backfat thickness (BF) and standardized to 100 kg body weight by equation [1] modified from National Swine Improvement Federation guidelines (NSIF, 2005). Average daily gain records that were less than 480 g or greater than 1,100 g were set as missing value. Adjusted backfat thickness records that were less than 7 mm and greater than 25 mm were set as missing value.

Average daily gain and BF were recorded on-farm on the same animals that provided records for reproductive traits. All sows with records from second parity also had records from first parity.

The minimum number of observations per year-month level was 14 for first parity and 36 for later parities. After editing, the final data contained 19,334 production records from 4,163 young boars and 15,171 gilts, and reproduction records of 3,074 sows, with 12,603 litters.

3. Statistical Analyses

Descriptive statistics were obtained using MEANS and FREQ procedures in the SAS program (SAS, 2004). Multiple comparisons among TB, SB or BAD from different parities were obtained by using LSMEANS statement in the GLM procedure. The statistical models in the GLM procedure included the effect of parity. And also, multiple comparisons among TB, SB or BAD from different farrowing month were obtained by using LSMEANS statement in the GLM procedure. The statistical models in the GLM procedure included the effect of farrowing month.

Initially, several fixed effects and covariates were examined for their significance ($P < 0.05$) in univariate models using ordinary least squares. From these general linear models, only the significant influenced fixed effects were included in the final models. Fixed effects affecting the studied traits were presented in Table 4. A random litter effect was included in preliminary analyses but since it had no significant effect it was not included in the final models.

Models for TB, SB and BAD included non genetic effects of contemporary group (farrowing year - month), age at conception for first parity or parity for later parities. For ADG and BF, a combination of birth year and month, sire line, and sex were included in the model. Sire line is line of the fathers of gilts and of young boars that were purebred Landrace sires separated by a mating scheme of this nucleus herd.

Table 4 Fixed effects included in the statistical models

Fixed effects	Traits ¹				
	ADG	BF	TB	SB	BAD
Year×month at birth	✓	✓	–	–	–
Sire line ²	✓	✓	–	–	–
Sex	✓	✓	–	–	–
Year×month at farrowing	–	–	✓	✓	✓
Age at conception (for 1 st parity)	–	–	✓	✓	✓
Parity (for later parities)	–	–	✓	✓	✓

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth

² line of fathers of gilts and young boars belonging to three different Landrace lines using in the nucleus herd

For the genetic analyses, ages at conception of first parity were grouped into three classes (less than 32, 32 to 40 and more than 40 weeks). Parities were grouped into seven classes (1, 2, 3, 4, 5, 6 and 7 to 9). Two-month farrowing periods (January/February, March/April, May/June, July/August, September/October and November/December) were constructed and used for reproductive traits analyses and two-month birth periods were used for productive traits analyses. Having a reasonable size of contemporary group was important for reliable genetic evaluations. Furthermore, a contemporary group should have no more than a three- to four-week span in ages to help reduce environmental differences (NSIF, 2005). Since there were small numbers of animal per one-month group, the authors chose to construct two-month group for these analyses.

Multivariate analyses were performed for all traits for (1) first parity and (2) second to ninth parity (repeatability model). Because of computational limitations, it was not possible to fit all the traits into the same analysis. Furthermore, SB and BAD are autocorrelated, because stillborn piglets can not die after birth. Therefore, parameters were estimated with four-trait analyses (ADG, BF, TB and SB; ADG, BF, TB and BAD) of data from first parity or later parities.

The statistical model, in matrix notation, was:

$$\mathbf{y} = \mathbf{X}\mathbf{b} + \mathbf{Z}\mathbf{a} + \mathbf{W}\mathbf{p} + \mathbf{e}, \quad [3]$$

where

- \mathbf{y} = the vector of observations of the studied traits (four traits simultaneously),
- $\mathbf{X}, \mathbf{Z}, \mathbf{W}$ = the known incidence matrices for fixed and random effects,
- \mathbf{b} = the vector of fixed effects,
- \mathbf{a} = the vector of additive genetic effects,
- \mathbf{p} = the vector of permanent environment effects,
- \mathbf{e} = the vector of residuals.

The matrix \mathbf{W} and the vector \mathbf{p} were only included in the repeatability model. The (co)variance matrices of random effect factors in \mathbf{a} , \mathbf{p} , and \mathbf{e} were assumed to be:

$$\text{var} \begin{bmatrix} \mathbf{a} \\ \mathbf{p} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{G} \otimes \mathbf{A} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{P} \otimes \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{R} \otimes \mathbf{I} \end{bmatrix}, \quad [4]$$

where

- \mathbf{A} = the additive genetic relationship matrix between animals,
- \mathbf{I} = the identity matrix,
- $\mathbf{G}, \mathbf{P}, \mathbf{R}$ = the (co)variance matrices for the vectors \mathbf{a} , \mathbf{p} , and \mathbf{e} , respectively.

The (co)variance components were estimated with REML method (Johnson and Thompson, 1995), using the DMU package (Madsen and Jensen, 2000). Presented heritabilities and correlations were averages of estimates of the multivariate analyses, including either SB or BAD. Standard errors of the estimates were derived from the average information matrix. Correlations differed more than $1.96 \times SE$ were considered significantly different from zero (Holm *et al.*, 2004a; Serenius *et al.*, 2004b).

Trial 2

1. Data Description

Reproductive records were available covering age at first conception (AFC), total number of piglets born (TB) in the first, second, third, and fourth parities (TB1, TB2, TB3 and TB4), and weaning to first service interval after the first, second, and third litter, to sows farrowing between 1993 and 2005. Average daily gain and adjusted backfat thickness records were also available for gilts and boars tested between 1993 and 2005.

2. Traits Analyzed

Age at first conception was defined as the number of days from birth to first successful mating within 400 days of age. Day zero is the day when the gilt was born. A mating was considered successful when it resulted in a farrowing 105 to 124 days later.

The total number of piglets born in the first, second, third and fourth parities was defined as the total number of piglets born including born alive and born dead. Mummified piglets were excluded from TB, since their numbers were difficult to record precisely. Only litters with at least one TB were included in analysis.

Weaning to first service interval was defined as the number of days from weaning to first service (1 to 50 days). The day of weaning was defined as day zero. One percent of the interval record was greater than 50 days and thus set as a missing value. Before analysis, a logarithmic transformation was performed for intervals of six days or more, according to Ten Napel *et al.* (1995a), and as used by Hanenberg *et al.* (2001) and Holm *et al.* (2004a). Transformed weaning to first service interval (WSI) was equal to observed interval if the observed interval was lower than six days. If observed interval was equal to or greater than six days, then

$$WSI = \frac{\ln(\text{ObservedInterval})}{\ln(6) - \ln(5)} - \left[\frac{\ln(6)}{\ln(6) - \ln(5)} - 6 \right] \quad [5]$$

where WSI = transformed weaning to first service interval.

Let, WSI1 = transformed weaning to first service interval after first litter
 WSI2 = transformed weaning to first service interval after second litter
 WSI3 = transformed weaning to first service interval after third litter

Growth rate was expressed as ADG from 9 to 22 weeks of age. Backfat thickness was defined as adjusted backfat thickness and standardized to 100 kg body weight by equation [1] modified from National Swine Improvement Federation guidelines (NSIF, 2005).

Average daily gain and BF were recorded on-farm on the same animals that provided records for reproductive traits. All sows with records from second parity also had records from first parity.

After editing, the final data contained 19,334 production records from 4,163 young boars and 15,171 gilts, and reproduction records of 3,074 sows, with 9,194 litters.

3. Statistical Analyses

Descriptive statistics were obtained using MEANS and FREQ procedures in the SAS program (SAS, 2004). Multiple comparisons among TB or WSI from different parities were obtained by using LSMEANS statement in the GLM procedure. The statistical models in the GLM procedure included the effect of parity.

Initially, several fixed effects and covariates were examined for their significance ($P < 0.05$) in univariate models using ordinary least squares. From these

general linear models, only the significant influenced fixed effects were included in the final models. Fixed effects affecting the studied traits were presented in Table 5. A random litter effect was included in preliminary analyses but since it had no significant effect it was not included in the final models.

Table 5 Fixed effects included in the statistical models

Fixed effects	Traits ¹				
	ADG	BF	AFC	TB	WSI
Year×month at birth	✓	✓	✓	–	–
Sire line ²	✓	✓	–	–	–
Sex	✓	✓	–	–	–
Genetic group	✓	✓	✓	✓	✓
Year×month at farrowing	–	–	–	✓	✓
Age at farrowing	–	–	–	✓	✓
Lactation Length					
Linear	–	–	–	–	✓
Quadratic	–	–	–	–	✓

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, TB = total number of piglets born, WSI = transformed weaning to first service interval

² line of fathers of gilts and young boars belonging to three different Landrace lines using in the nucleus herd

In order to assign animals into a group that had similar environmental conditions (i.e. contemporary group), two-month farrowing periods (January/February, March/April, May/June, July/August, September/October and November/December) were constructed and used for reproductive traits analyses and two-month birth periods were used for productive traits analyses. Having a reasonable size of contemporary group was important for reliable genetic evaluations. Furthermore, a

contemporary group should have no more than a three- to four-week span in ages to help reduce environmental differences (NSIF, 2005). Since there were small numbers of animal per one-month group, the authors chose to construct two-month group for these analyses.

Because there were irregularly imported boars and gilts, thus, parents of the base animals were assigned to one genetic group (568 animals) and parents of imported animals (912 animals) were assigned to seven genetic groups. The later genetic groups were defined by a combination of country, where those animals were born, and year, when those animals were imported (Australia 1999, 40 animals; Northern Ireland 1987 - 1992, 21 animals; Northern Ireland 1993 - 1996, 57 animals; Norway 1991, 28 animals; Norway 1994 - 2002, 292 animals; Sweden 1990 - 1994, 13 animals; USA 1993 – 2000, 561 animals).

These genetic groups were used to account for the differences among genetic sources of those imported animals, according to the principles outlined in Westell *et al.* (1988). Identified animals were related back to genetic groups of the ancestors with the submatrix of the additive genetic relationship matrix corresponding to relationships between identified animals and the ancestors (Westell *et al.*, 1988).

The statistical model, in matrix notation, was

$$y = Xb + ZQg + Za + e \quad [6]$$

where

- y** = the vector of observations of the traits studied
(four or five traits simultaneously),
- X, Z** = the known incidence matrices for fixed and random effects,
- Q** = the submatrix of the additive genetic relationship matrix relating identified animals to genetic groups,

- b** = the vector of fixed effects,
g = the vector of effects of groups to which ancestors have been assigned,
a = the vector of additive genetic effects,
e = the vector of residuals.

The (co)variance matrices of random effect factors in **a** and **e** were assumed to be

$$\text{var} \begin{bmatrix} \mathbf{a} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{G} \otimes \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{R} \otimes \mathbf{I} \end{bmatrix} \quad [7]$$

where

- A** = the additive genetic relationship matrix between animals,
I = the identity matrix,
G, R = the (co)variance matrices for the vectors **a** and **e**, respectively.

For first parity, a five traits analysis (ADG, BF, AFC, TB1 and WSI1) was performed and the effect of age at farrowing was dropped out of the model of TB1 and WSI1. Records from parities 2, 3 and 4 were analyzed separately, in four traits analyses (ADG, BF, WSI1 and TB2; ADG, BF, WSI2 and TB3 and ADG, BF, WSI3 and TB4).

The (co)variance components were estimated with the average information restricted maximum likelihood (AI-REML) method (Johnson and Thompson, 1995), using the DMU package (Madsen and Jensen, 2000). Breeding values were estimated with BLUP method, using the DMU package. When the same trait was included in *i* (*i* = 2, 4) analyses, presented parameters are the averages of estimates of the *i* multivariate analyses. Standard errors of the estimates were derived from the average information matrix. Correlations differed more than $1.96 \times \text{SE}$ were considered significantly different from zero (Holm *et al.*, 2004a; Serenius *et al.*, 2004b).

Phenotypic trends were partitioned into genetic and environmental components by mixed-model methodology. Environmental trends for TB and WSI were measured from the average year-month of farrowing solutions and for ADG, BF and AFC were measured from the average year-month of birth solutions. In order to investigate the improvement of husbandry, environmental trends were estimated in the present study. Genetic trends were estimated by regression of the average estimated breeding value on the year of birth of animals with records, and weighted by number of observations.

RESULTS

Trial 1

1. Descriptive Statistic

Descriptive statistics of the traits analyzed in this study are given in Table 6. In 84% of litters, no piglets were stillborn (SB = 0) and in 72% of litters, no live born piglets died (BAD = 0). The distribution of reproductive records over parities is shown in Table 7.

Table 6 Number of records, mean, standard deviation (SD), minimum (Min), and maximum (Max) of reproductive and productive traits

Traits ¹	No. of records	Mean	SD	Min	Max
<i>Production</i>					
ADG, g/day	19,334	780	100	480	1099
BF, mm	15,755	13.9	3.6	6.7	25
<i>Litter size</i>					
TB, pigs/litter	12,599	10.03	2.64	1	20
SB, pigs/litter	12,603	0.21	0.59	0	13
BAD, pigs/litter	12,603	0.42	0.79	0	9

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth.

Table 7 Number of reproductive¹ records in each parity

Parity	TB	SB	BAD
1	3,074	3,077	3,077
2	2,358	2,359	2,350
3	1,976	1,976	1,976
4	1,638	1,638	1,638
5	1,328	1,328	1,328
6	1,016	1,016	1,016
7 – 9	1,029	1,029	1,029

¹ TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth.

2. Fixed Effects

Only 9% of gilts conceived at an age less than 32 wk, 78% conceived at 32 to 40 wk, and 13% conceived at greater than 40 wk. Gilts in the first, second, and third age group had 9.85 ± 0.17 , 10.04 ± 0.06 , and 9.6 ± 0.14 piglets/litter, respectively. The second age group gilts had more TB ($P < 0.05$) than the older age group. Age at conception had no effect on SB or BAD of primiparous sows.

The effect of parity number on TB, SB, and BAD is shown in Figure 1. The TB decreased in the second parity and thereafter increased with the number of parities, reaching a plateau in parities 4 and 5. Stillborn piglets were low in parities 2 and 3, but high both in parity 1 and after parity 4. The number of BAD in parities 2 and 3 was significantly lower than BAD in other parities. The effect of parity on SB and BAD was also significant ($P < 0.05$) when TB was included in the model.

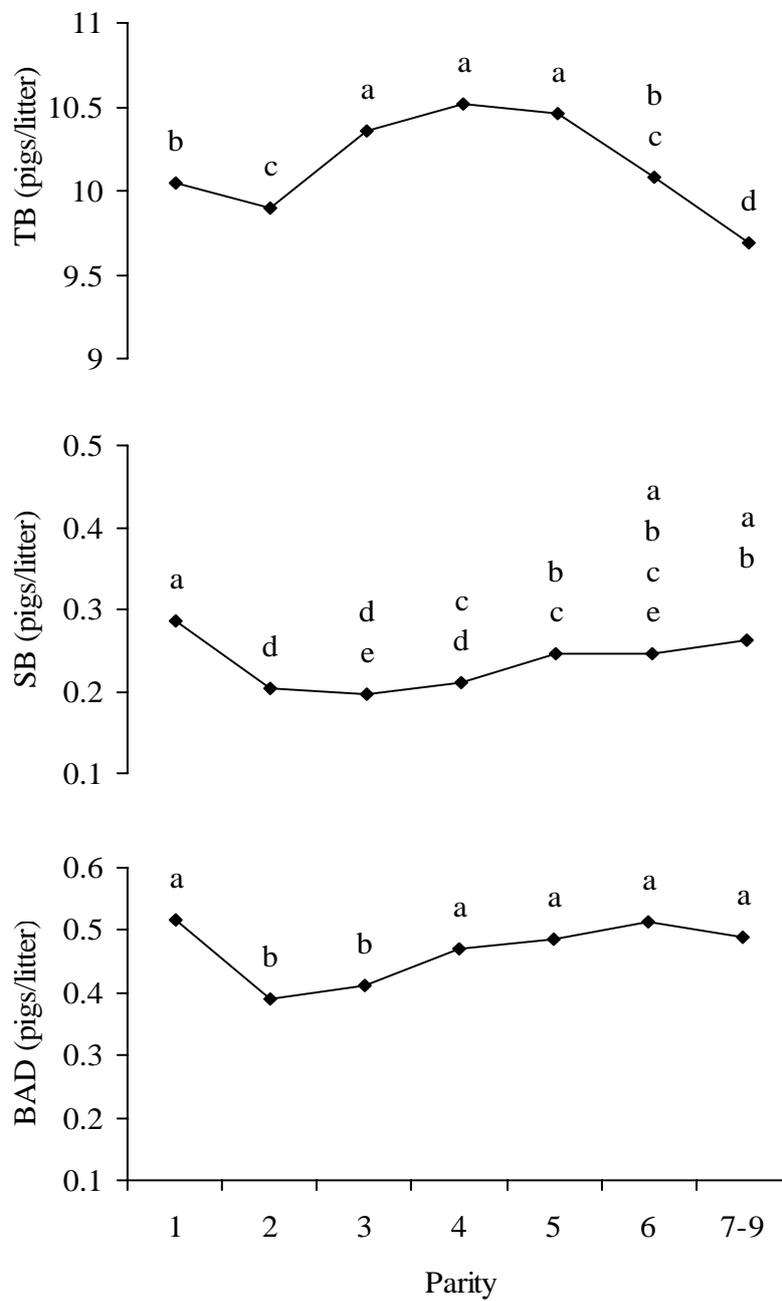


Figure 1 Effect of number of parities on variations in total number of piglets born (TB), stillborn piglets (SB), and born alive but dead within 24 hours (BAD).

Note ^{a-e} Least-square means without a letter in common are significantly different ($P < 0.05$).

In Thailand, there are three seasons: hot season (March to June), rainy season (July to October) and winter (November to February). Figure 2 shows farrowing month (season) effect on TB, SB, and BAD. Farrowing month significantly influenced TB in first parity and SB in all parities. Primiparous sows farrowing between July and October had the lowest TB. Primiparous and multiparous sows farrowing in September/October had the lowest SB. The difference in SB between farrowing month was confounded with variations in TB. After an appropriate adjustment had been made for TB, however, it was found that farrowing month did not have a significant effect on SB. In addition, farrowing month had no effect on BAD.

The effect of birth month on ADG and BF is shown in Figure 3. Pigs that were born in September/October had the greatest ADG whereas those were born in May/June had the lowest ADG. Pigs born in November/December had the lowest BF. Sire line influenced both ADG and BF. Young boars had higher ADG and lower BF than gilts.

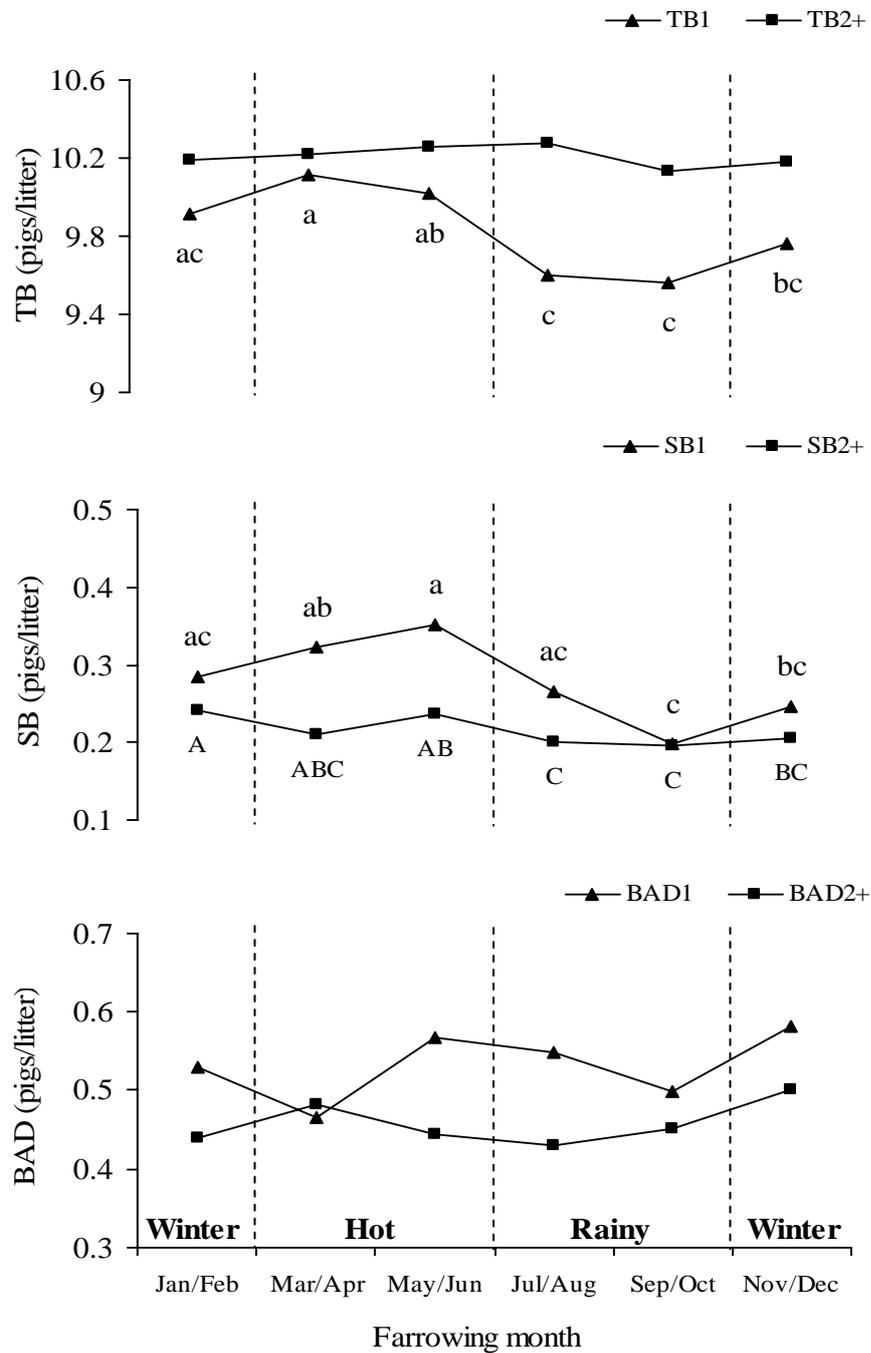


Figure 2 Farrowing month effect on total number of piglets born (TB), stillborn piglets (SB), and born alive but dead within 24 hours (BAD) in first parity (1) and later parity (2+) sows.

Note Least-square means (within line) without any letter in common are significantly different ($P < 0.05$).

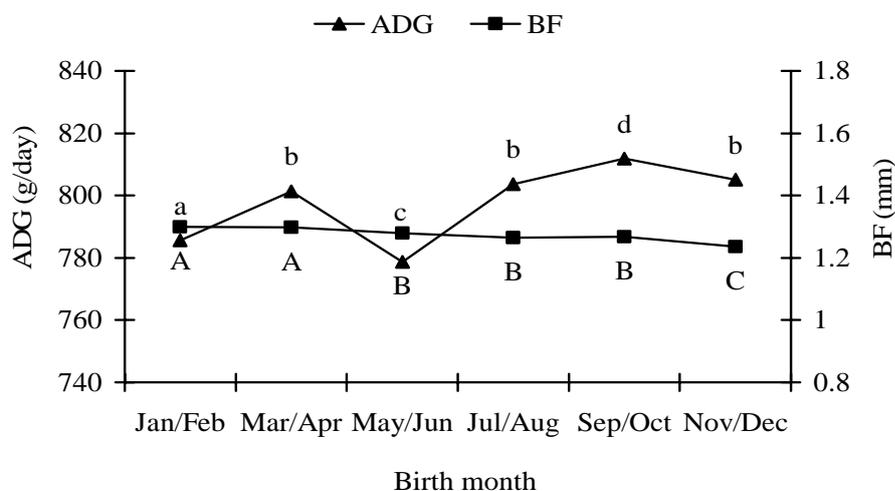


Figure 3 Effect of birth month on average daily gain (ADG) and adjusted backfat thickness (BF).

Note Least-square means (same line) without any letter in common are significantly different ($P < 0.05$).

3. Genetic Parameters

Heritabilities and the proportion of permanent environmental variances to total variances of reproductive and productive traits are presented in Table 8. Heritability for TB1 was relatively low. Heritabilities for BAD and SB were somewhat greater in the first than in later parities. There was no permanent environmental variance for SB in later parities.

Estimated genetic and phenotypic correlations between reproductive and productive traits are presented in Tables 9 and 10. The magnitude of genetic correlations varied from low to moderate (0.02 to 0.40) and had high standard errors (0.04 to 0.39). Both favorable and unfavorable associations between reproductive and productive traits were found. Phenotypic correlations between reproductive and productive traits were low in first parity but greater in later parities.

Table 8 Heritabilities (h^2) and permanent environmental variances in proportion to total variances (c^2) of reproductive and productive traits

Traits ¹	$h^2 \pm SE$	$c^2 \pm SE$
<i>Productive</i>		
ADG	0.38 ± 0.02	–
BF	0.61 ± 0.02	–
<i>Reproductive</i>		
TB1	0.03 ± 0.02	–
SB1	0.04 ± 0.02	–
BAD1	0.06 ± 0.02	–
TB2+	0.07 ± 0.01	0.07 ± 0.01
SB2+	0.03 ± 0.04	0.00 ± 0.01
BAD2+	0.02 ± 0.01	0.02 ± 0.01

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth. First parity traits are indicated with a 1 and later parity traits with 2+ (repeatability model).

Table 9 Genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive traits and reproductive traits of first parity sows

Traits ¹	ADG	BF	TB	SB	BAD
ADG		-0.02 ± 0.04	0.18 ± 0.22	0.16 ± 0.19	0.22 ± 0.16
BF	-0.04		0.34 ± 0.22	-0.04 ± 0.18	-0.03 ± 0.15
TB	0.04	0.01		0.23 ± 0.39	0.34 ± 0.34
SB	-0.01	-0.01	0.03		–
BAD	0.04	-0.01	0.19	–	

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth.

Table 10 Genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive traits and reproductive traits of later parities sows

Traits ¹	ADG	BF	TB	SB	BAD
ADG		-0.03 ± 0.04	0.22 ± 0.09	0.03 ± 0.11	-0.23 ± 0.13
BF	-0.04		0.14 ± 0.08	-0.22 ± 0.11	0.11 ± 0.11
TB	0.15	-0.44		-0.08 ± 0.19	0.40 ± 0.19
SB	0.78	-0.08	0.04		–
BAD	0.10	-0.11	0.21	–	

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth.

The estimated genetic correlations between ADG and TB were favorable in both first and later parities (Tables 9 and 10). The genetic correlation between ADG and SB in first parity was unfavorable. The genetic correlation between ADG and BAD was unfavorable in first parity and favorable in later parities. Genetic correlations of BF with TB and SB were unfavorable in all parities. The genetic correlation of TB with SB was moderate and unfavorable in first parity, and low but favorable in later parities. Genetic correlations estimated between TB and BAD were unfavorable in all parities.

Table 11 shows genetic and phenotypic correlations between reproductive traits measured in different parities. Genetic correlations were high, but phenotypic correlations were low.

Table 11 Genetic and phenotypic correlations between reproductive traits of first and later parities sows

Traits ¹	Genetic correlation	Phenotypic correlation
TB1 and TB2+	0.85 ± 0.13	0.13
SB1 and SB2+	0.79 ± 0.16	-0.01
BAD1 and BAD2+	0.71 ± 0.24	0.06

¹ TB = total number of piglets born, SB = number of stillborn piglets, BAD = number of piglets born alive but dead within 24 hours of birth. First parity traits are indicated with a 1 and later parity traits with a 2+ (repeatability model).

Trial 2

1. Descriptive Statistics

Descriptive statistics of the analyzed traits are given in Table 12. Total number of piglets born decreased in the second parity and thereafter increased with each parity number. Weaning to service interval was longest for first parity sows and declined as the parity number increased.

Frequency distributions of observed (not transformed) WSI for first to third parity sows and the means of the following TB each day after weaning are shown in Figure 4. A large proportion of the sows were in estrus within a week. Eighty percent, 91% and 93% of first-, second- and third-parity sows were bred within seven days post weaning, respectively. Means of the subsequent TB were plotted from day 1 to days 30 owing to the few records of sows that were mated later than 30 days post weaning.

Numbers of sows in estrus of first parity were highest on day 5 after weaning whereas those of second and third parity were highest on day 4 after weaning. The pattern of TB in the subsequent litter related to WSI was similar for all parities. Mean of TB was highest at days 4 and declined as WSI increased until approximately one week after farrowing and thereafter the mean of TB fluctuated.

The average age at first conception was 251.19 days (Table 12). Frequency distribution of AFC is shown in Figure 5. Fifty and 90 % of gilts were first mated within 245 days and 286 days of age, respectively.

Table 12 Number of records, means, standard deviations, minimum (Min), and maximum (Max) of productive and reproductive traits

Traits ¹	No. of records	Mean (SD) ²	Min	Max
<i>Productive</i>				
ADG, g/day	19,334	780 (100)	480	1,099
BF, mm	15,755	13.86 (3.56)	6.99	25.00
<i>Reproductive</i>				
AFC, days	3,695	251.19 (26.77)	171	395
TB1, pigs/litter	3,074	9.95 (2.66) ^a	1	18
TB2, pigs/litter	2,441	9.76 (2.64) ^b	1	18
TB3, pigs/litter	2,024	10.22 (2.64) ^c	1	19
TB4, pigs/litter	1,655	10.32 (2.57) ^c	1	19
WSI1, days	2,891	8.03 (7.98) ^x	1	49
WSI2, days	2,461	5.72 (4.25) ^y	1	50
WSI3, days	2,040	5.47 (4.12) ^y	1	49

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, TB1, TB2, TB3 and TB4 = total number of piglets born in parities 1, 2, 3 and 4, WSI1, WSI2 and WSI3 = weaning to first service interval (not transformed) after 1st, 2nd and 3rd litters

² Mean values within TB-trait or WSI-trait without any letter in common are significantly different ($P < 0.05$)

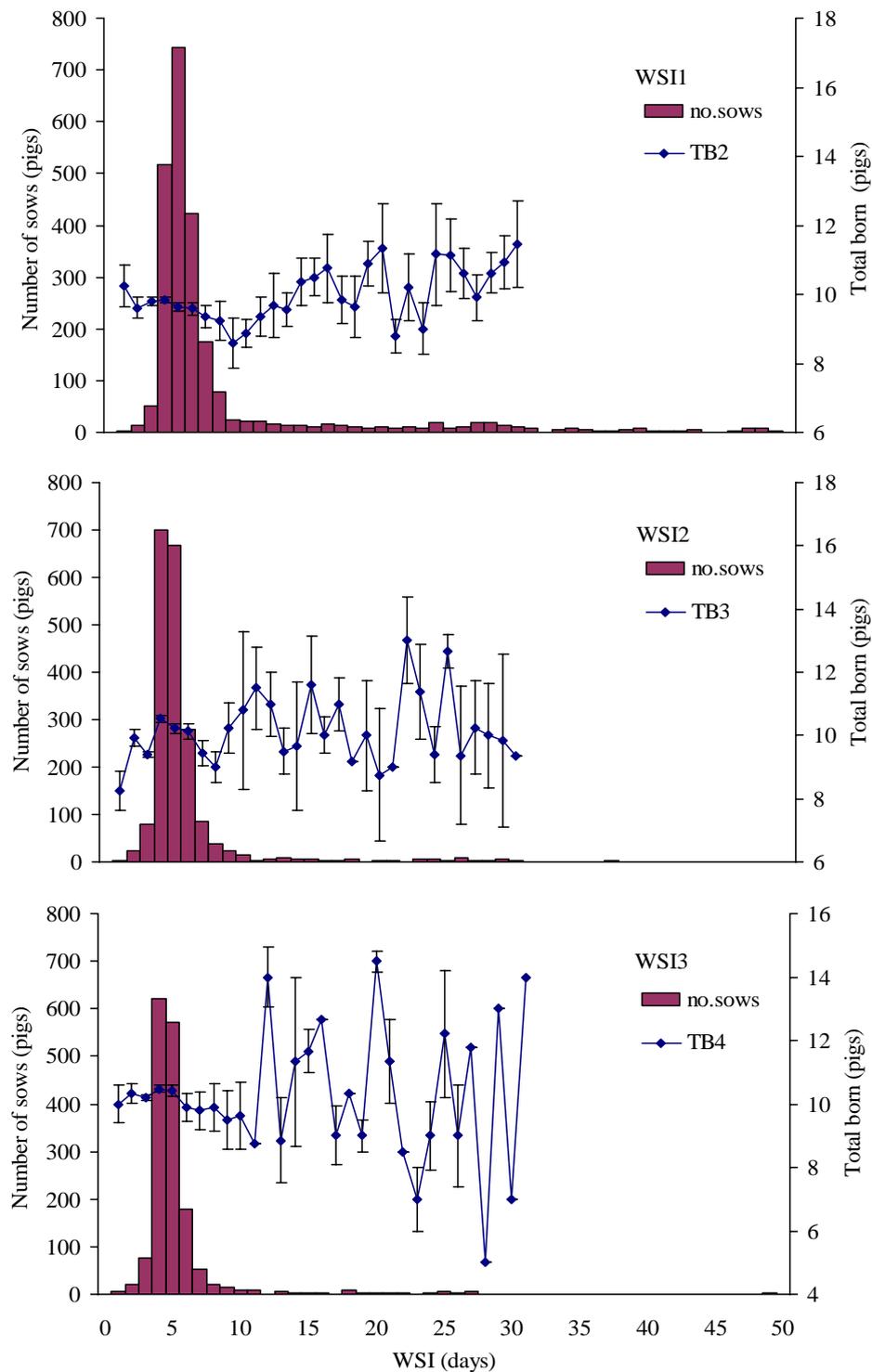


Figure 4 Frequency distributions of weaning to first service interval (WSI, not transformed) for the first to third parity sows and the mean of TB in the following litter, over each day after weaning.

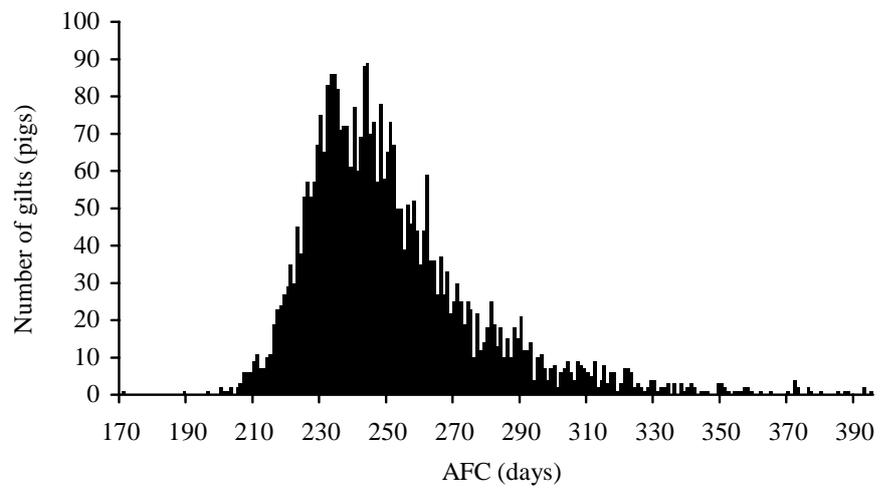


Figure 5 Frequency distribution of age at the first conception (AFC).

2. Genetic Parameters

Heritabilities of productive and reproductive traits are presented in Table 13. Heritabilities for productive traits were high, whereas heritabilities for TB were low and heritabilities for AFC and WSI were moderate. Heritabilities for TB increased at the fourth parity.

Table 13 Heritabilities of productive and reproductive traits

Trait ¹	five traits analysis	four traits analysis ²
<i>Productive</i>		
ADG	0.31 ± 0.02	0.31 ± 0.02 ³
BF	0.45 ± 0.02	0.45 ± 0.02 ³
<i>Reproductive</i>		
AFC	0.21 ± 0.03	–
TB1	0.03 ± 0.02	–
TB2	–	0.02 ± 0.02
TB3	–	0.04 ± 0.03
TB4	–	0.11 ± 0.04
WSI1	0.17 ± 0.03	0.16 ± 0.03
WSI2	–	0.16 ± 0.04
WSI3	–	0.18 ± 0.04

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, TB1, TB2, TB3 and TB4 = total number of piglets born in parities 1, 2, 3 and 4, WSI1, WSI2 and WSI3 = transformed weaning to first service interval after 1st, 2nd and 3rd litters

² One analysis for each of parity, including ADG, BF, WSI and the following TB

³ Averaged from means and SEs of three analyses

Genetic correlations between parities were estimated in multiple trait analyses including ADG, BF and TB over four parities or WSI over three parities. The correlations between TB in the different parities were low, ranging from 0.26 to 0.50. The corresponding correlations for WSI were higher, ranging from 0.65 to 0.81.

Estimated genetic and phenotypic correlations between productive and reproductive traits of first parity sows are presented in Table 14. The magnitude of genetic correlations varied from low to moderate (0.02 to 0.48) and had high standard errors (0.04 to 0.27). Both favorable and unfavorable associations between reproductive and productive traits were found. Phenotypic correlations between productive and reproductive traits were low. The estimated genetic correlation between BF and WSI1 was moderate but unfavorable. The genetic correlations of AFC with TB1 and WSI1 were moderate and favorable.

Table 14 Genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive and reproductive traits of first parity sows (five traits analyses)

Traits ¹	ADG	BF	AFC	TB1	WSI1
ADG		-0.05 ± 0.04	0.04 ± 0.08	-0.04 ± 0.18	-0.08 ± 0.09
BF	-0.04		-0.02 ± 0.08	-0.02 ± 0.18	-0.27 ± 0.09
AFC	-0.04	-0.02		-0.48 ± 0.25	0.35 ± 0.13
TB1	0.04	-0.01	-0.05		0.07 ± 0.27
WSI1	-0.04	-0.06	0.07	0.05	

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, TB1 = total number of piglets born in 1st parity, WSI1 = transformed weaning to first service interval after first litter

Estimated genetic and phenotypic correlations between productive and reproductive traits of later parities are presented in Table 15. The estimated genetic correlations between ADG and TB were moderate (0.19 to 0.30) with different sign and they were not significantly different from zero. All of genetic correlations between ADG and WSI were negative (-0.01 to -0.08). The estimated genetic correlations between BF and WSI were negative and moderate (-0.11 to -0.27). The genetic correlation between WSI and subsequence TB was negative in first parity but positive in second and third parities. The only significant genetic correlation was found between BF and WSI1. All phenotypic correlations were low.

3. Environmental Trend

Environmental trends are shown in Figure 6. There were no animals in some contemporary groups for 1993 and for 2005 resulting in no solution on the environmental effects for the first and the last year. Furthermore, number of records for BF and AFC were small in 2004 so trends of all traits were eliminated from the figure. Thus environmental trends were plotted from 1994 to 2003 and the presented results are deviated from the solutions for 1994. Estimated environmental trends for BF, TB1, WSI1 and WSI2 were significantly different from zero ($P < 0.05$) (Table 16). The environmental trend for ADG decreased from 1996 to 1998, during which the trend in AFC was increasing.

Table 15 Genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive and reproductive traits of later parities sows (four traits analyses)

Trait ¹	ADG	BF	WSI1	WSI2	WSI3	TB2	TB3	TB4
ADG		- 0.05 ± 0.04	- 0.08 ± 0.09	- 0.03 ± 0.10	- 0.01 ± 0.10	0.30 ± 0.25	- 0.19 ± 0.19	0.20 ± 0.13
BF	- 0.04		- 0.27 ± 0.09	- 0.11 ± 0.10	- 0.12 ± 0.10	0.03 ± 0.22	- 0.16 ± 0.18	0.14 ± 0.13
WSI1	- 0.04	- 0.06		–	–	- 0.07 ± 0.34	–	–
WSI2	0.01	- 0.03	–		–	–	0.01 ± 0.30	–
WSI3	- 0.03	- 0.02	–	–		–	–	0.05 ± 0.23
TB2	0.04	0.03	0.05	–	–		–	–
TB3	0.00	0.03	–	- 0.02	–	–		–
TB4	0.05	0.03	–	–	0.03	–	–	

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, WSI1, WSI2 and WSI3 = transformed weaning to first service interval after 1st, 2nd and 3rd litters TB2, TB3 and TB4 = total number of piglets born in parities 2, 3 and 4

Table 16 Annual environmental and genetics trends for productive and reproductive traits (1993–2003)

Trait ¹	Environmental trend	Sig.	Genetic trend	Sig.
<i>Productive</i>				
ADG, g/day	-1.21 ± 2.05	ns	4.71 ± 1.27	0.01
BF, mm	-0.24 ± 0.07	0.05	-0.23 ± 0.03	0.01
<i>Reproductive</i>				
AFC, days	0.58 ± 1.20	ns	0.23 ± 0.07	0.01
TB1, pigs/litter	0.10 ± 0.03	0.05	-0.01 ± 0.00 ²	0.01
TB2, pigs/litter	0.04 ± 0.04	ns	0.02 ± 0.01	ns
TB3, pigs/litter	0.04 ± 0.05	ns	-0.02 ± 0.00 ²	ns
TB4, pigs/litter	-0.02 ± 0.07	ns	0.02 ± 0.02	0.01
WSI1, days	-0.08 ± 0.03	0.05	0.01 ± 0.01	ns
WSI2, days	-0.09 ± 0.04	0.05	0.00 ² ± 0.01	ns
WSI3, days	-0.05 ± 0.03	ns	-0.00 ² ± 0.01	ns

¹ ADG = average daily gain, BF = adjusted backfat thickness, AFC = age at first conception, TB1, TB2, TB3 and TB4 = total number of piglets born in parities 1, 2, 3 and 4, WSI1, WSI2 and WSI3 = transformed weaning to service interval after 1st, 2nd and 3rd litters

² Values below 0.005

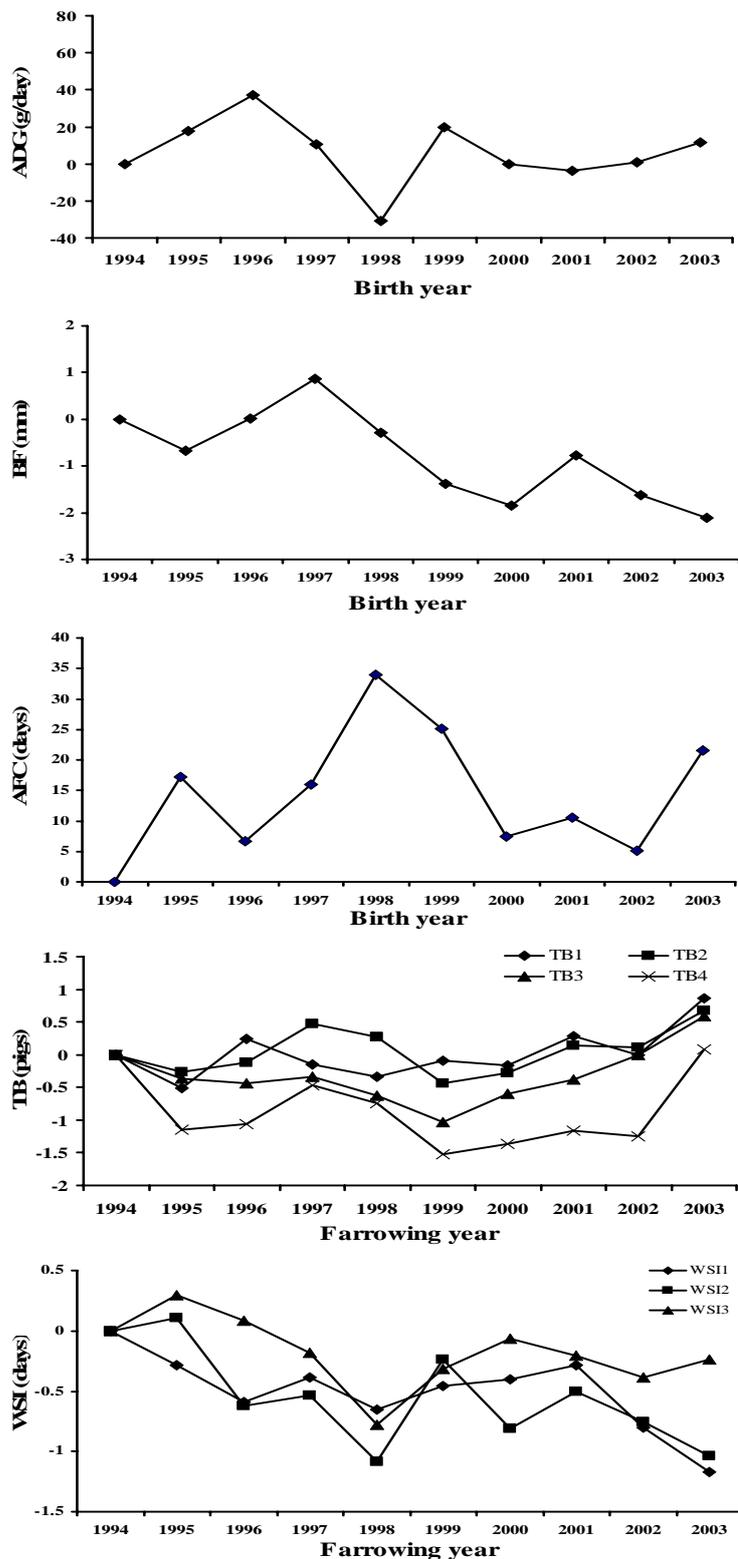


Figure 6 Environmental trends for average daily gain (ADG), adjusted backfat thickness (BF), age at first conception (AFC), total number of piglets born in first to fourth parity (TB1-4) and transformed weaning to first service interval after first to third litter (WSI1-3) from 1994 to 2003.

4. Genetic Trends

The genetic trends for ADG, BF, AFC, TB and WSI are presented in Figure 7. There were small numbers of animals in 2004 and 2005, so trends of all traits were eliminated from the figure. The presented results are deviated from the solutions for 1993. The estimated genetic trends were relatively small and sometimes unfavorable (Table 16). Estimated genetic trends for selection traits (ADG, BF and TB4) were significantly favorable, whereas the trend for AFC was significantly unfavorable.

During the last four years, the estimated genetic trends for TB1 and TB3 were negative and parallel, while the trends for TB2 and TB4 were positive and parallel. Even though the genetic correlations among the TB of different parities were positive, their genetic trends were not alike. All estimated genetic trends for WSI were small and none was significantly different from zero (Table 16).

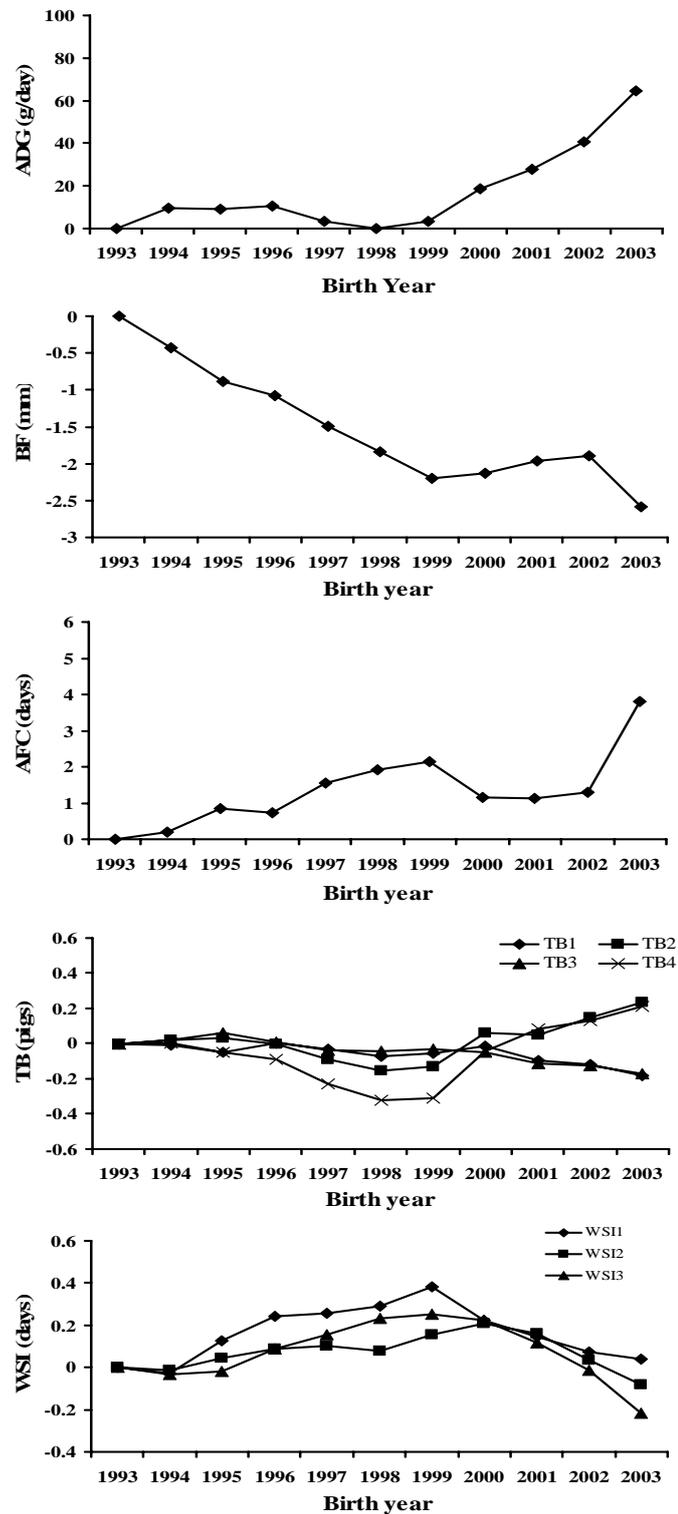


Figure 7 Genetic trends for average daily gain (ADG), adjusted backfat thickness (BF), age at first conception (AFC), total number of piglets born in first to fourth parity (TB1-4) and transformed weaning to first service interval after first to third litter (WSI1-3) from 1993 to 2003.

DISCUSSION

Trial 1

1. Fixed Effects

Litter size increased as the age at first conception increased from the first age group (<32 weeks) to the second age group (32 to 40 weeks). This confirms previous studies (Clark *et al.*, 1988; Dewey *et al.*, 1995). Gilts in the third age group produced smaller litters than gilts in younger age groups. In this study, one, five, and 33% of gilts in the first, second and third age groups, respectively, had to be mated twice to conceive (data not shown). Schukken *et al.* (1994) showed in a retrospective study that sows conceiving at an advanced age are culled for reproductive failure more often than sows conceiving when younger. It might be hypothesized that gilts with low fertility became pregnant at a later age (>40 weeks), and subsequently had smaller litters.

Litter size increased with parity number, reaching a plateau at parities 4 to 5, and then declining. This finding was in accordance with earlier studies (Roehe and Kennedy, 1995; Tantasuparuk *et al.*, 2000). Our finding that second parity sows had small litter size disagrees, however, with studies by Dewey *et al.* (1995) and Roehe and Kennedy (1995). According to a review of Ten Napel *et al.* (1995b), selection for production and reproduction traits may limit feed intake capacity, reduce body reserves at first farrowing and increase milk production. Furthermore, primiparous sows have attained only 40 to 50% of their final mature size at the time of first conception (Whittemore, 1996). Hence they must simultaneously produce milk for the first litter and continue to grow. These effects may increase the probability of significant depletion of body weight during first lactation and result in reduction in the number of piglets in the second litter.

There was no farrowing month (seasonal) effect on TB in the older sows, but the farrowing month effect on gilt litters in this study was strong. Tummaruk *et al.* (2004) also showed that season has a more pronounced effect on gilts than it does on older sows in Thailand. It appears, then, that sows adapt to climatic changes with increasing age. This study showed a reduction in the litter size of first parity sows farrowing during the rainy season (Figure 2). These sows had been mated during the hot season. This finding confirms the results of other studies, which indicate that sows bred during the hot season produce smaller litters (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004). It has been reported that high ambient temperature alters reproduction by acting directly on ovarian function or via the hypothalamic pituitary axis by affecting estrus, ovulation, gametes and embryo survival (Wettemann and Bazer, 1985; Armstrong *et al.*, 1986). The small litters born in the rainy season in this study might be explained by a poor fertilization rate, reduced levels of embryonic survival, or both. There was no seasonal variation in SB. This finding is in accordance with a previous study conducted in Thailand (Tantasuparuk *et al.*, 2000).

2. Genetic Parameters

Estimate of heritability for ADG is consistent with an estimate of 0.32 for days to 100 kg reported by Ducos *et al.* (1993). Li and Kennedy (1994) reported estimates of heritability for days to 113.5 kg ranking from 0.35 to 0.44 based on Yorkshire, Duroc, Hampshire and Landrace. Estimate of heritability for BF was in the range of estimates from previous studies. Ferraz and Johnson (1993), using four animal models for herds of Landrace and Large White pigs, reported estimates of heritability that range from 0.39 to 0.50 for ultrasonic measure of BF. Chen *et al.* (2002) used Yorkshire, Duroc, Hampshire and Landrace from the National Swine Registry of U.S. and reported heritability estimates of 0.48 to 0.49 for ultrasonic measure of BF.

The estimates of heritability for TB in the current study are lower than the average value of 0.11 presented in the literature review undertaken by Rothschild and Bidanel (1998). Heritability for TB was estimated at 0.10 in Gu *et al.* (1989). Roehe

and Kennedy (1995) estimated heritabilities for TB from 0.09 to 0.16 in Landrace and Yorkshire sows. Estimates of permanent environmental effects for TB vary in the literature from 0.00 to 0.12 (Lamberson *et al.*, 1991; Hanenberg *et al.*, 2001), and the estimate from this study falls in between these values. Heritability estimates for mortality traits in the current study are low, but significantly greater than zero, except for SB in later parities. Knol (2001) estimated slightly higher heritabilities for SB (0.05) and litter mortality (0.08), calculated as the percentage of live piglets dying from birth to weaning.

Estimates of genetic correlations between the traits examined in the current study ranged from -0.23 to 0.40 and had high standard errors. In general, these estimates did not diverge from zero. The only favorable and significant genetic correlation was between ADG and TB in later parities. The genetic correlation between ADG and TB in first parity was also favorable, in keeping with previous studies (Kerr and Cameron, 1996; Serenius *et al.*, 2004a). Holm *et al.* (2004a), by contrast, found a positive (unfavorable) genetic correlation between age at 100 kg and number of piglets born alive. Tummaruk *et al.* (2001) reported that gilts with greater growth rate had larger litter size than those with lower growth rate. Perhaps gilts with high growth rate consume more feed, are healthier, and have a better nutrient base for subsequent reproductive performance than slow-growing gilts. Because age is the most important factor in gilts attaining puberty (Hughes, 1982), gilts with high ADG tend to be heavier at puberty. King (1989) showed that live weight at 165 days of age, rather than BF, influenced ovulation rate in gilts. Thus, selection for high ADG may increase TB. The current study, however, indicates that such selection would increase piglet mortality in the first parity.

The estimated genetic correlation between BF and SB in later parities was unfavorable. This is in agreement with Knol (2001), who found that genetic correlations between piglet survival and BF were moderately positive and Arango *et al.* (2005), who reported a negative genetic correlation between sows' backfat and number of piglets born dead in their first parity.

The genetic correlations between TB and SB in first parity and between TB and BAD in all parities were unfavorable. This is in line with the finding of Johnson *et al.* (1999) that selection for large litters increases the number of stillborn piglets. Lund *et al.* (2002) also found unfavorable genetic correlations between total born and piglet survival. Increased litter size generally results in lower birth weights, with a decreased probability of survival (Roehre and Kalm, 2000). On the other hand, Grandinson *et al.* (2002) reported a positive genetic correlation between birth weight and stillbirth. Other factors, such as time from beginning to end of parturition, also determine the number of stillborn piglets (Holm *et al.*, 2004b). According to Thornbury *et al.* (1993) delayed gut maturation was found in piglets with low birth weight. Moreover, the development of the central nervous system may be compromised by a critical endocrine component in piglets with low birth weight (Wise *et al.*, 1997). Low birth weight is also genetically correlated with greater piglet mortality caused by crushing (Grandinson *et al.*, 2002). Selection only on total litter size will, therefore, almost certainly increase piglet mortality. The inclusion of selection on BAD or SB, although these traits have low heritabilities, will likely increase the number of piglets produced per litter.

Trial 2

1. Descriptive Statistic

Litter size showed an increase with parity number. This finding is in accordance with earlier studies (Roehe and Kennedy, 1995; Tantasuparuk *et al.*, 2000). Our finding that second parity sows have smaller litters disagrees, however, with studies by Dewey *et al.* (1995) and Roehe and Kennedy (1995). The reasons that might explain this phenomenon had already been discussed in trial 1.

Sterning *et al.* (1990) and Tantasuparak *et al.* (2001) showed that sows with greater weight loss had longer weaning to estrus interval. Subsequent litter sizes decreased when weaning to estrus interval increased up to 10 days (Marois *et al.*, 2000; Tummaruk *et al.*, 2000). In this study, only 55% of first parity sows were in estrus within five days after weaning, as compared to 73% and 78% of second and third parity sows. Moreover, the mode of WSI1 is day 5, versus day 4 for WSI2 and WSI3. This difference may explain parts of the drop in litter size from TB1 to TB2, since an increase in WSI is related to a smaller litter (Figure 4 and Tummaruk *et al.*, 2000).

2. Genetic Parameters

The heritability for AFC is high in comparison with that of other reproduction traits in this study. Estimates for age at first service or insemination found in the literature vary around 0.3 (Hanenberg *et al.*, 2001; Holm *et al.*, 2005), which is higher than the estimate for AFC in this study. The AFC distribution was not normal; there was a marked increase in frequency after 220 days (Figure 5). AFC is supposed to reflect pubertal age, but the gilts that reach puberty early were not detected in this study, since estrous monitoring started at a given age. The heritability of AFC is probably lower than pubertal age heritability would have been, since all genetic variation between gilts was not revealed.

Estimated heritabilities of TB in the first three parities are lower than the value 0.11 taken from the literature review of Rothschild and Bidanel (1998), whereas the estimate of heritability for TB in the fourth parity agrees with the value from this literature. The estimation of genetic parameters for TB in different parities might be biased due to the fact that only TB from one parity was included in each multi-trait analysis, whereas selection was based on TB in several parities. It was, however, not possible to include all parities in the same multi-trait analysis.

Heritability estimates for weaning to estrus interval found in the literature range from 0.14 to 0.36 in the review by Ten Napel *et al.* (1995b), and from 0.01 to 0.10 for weaning to conception interval in the study by Tholen *et al.* (1996a). Heritability estimates from the present study are slightly higher than the estimates of Adamec and Johnson (1997), Hanenberg *et al.* (2001) and Holm *et al.* (2005) who found heritabilities of 0.14, 0.07 to 0.14 and 0.03 to 0.08 respectively for weaning to first insemination/service. The high heritability in this study could be due to high quality estrous monitoring in the nucleus herd. Estrous detection was performed twice a day, in the morning and in the evening, by experienced staff, in the presence of boars. The staff worked from 07:00 to 17:00 in the mating barn.

Nucleus and multiplying herds seldom have records of the time of first estrus. Age at first service is a practical way of analyzing field data when the age at puberty is not recorded and it has been used in several genetic analyses, e. g. Hanenberg *et al.* (2001) and Holm *et al.* (2004b). Results regarding the genetic correlation between growth and pubertal age by Rydhmer *et al.* (1992) and those between growth and age at first farrowing by Rydhmer *et al.* (1995) showed a high favorable genetic correlation (-0.31 and -0.61). A negative genetic correlation between ADG and AFC was also found in this study but it was close to zero. The genetic correlation between BF and AFC was also near zero. This is in agreement with new estimates from Holm *et al.* (2004a). The results implied that selecting for increase ADG or decrease BF would not affect AFC in our population.

This study shows that selection for a younger AFC will increase the total number of piglets born in first parity, whereas Holm *et al.* (2005) found the opposite. According to their study, selection for decreased age at first service will decrease the number of live-born piglets in the first parity. This controversy might be caused by the average age at service, which was lower than in our study (220 versus 251 days). There is a low genetic correlation (-0.08) between age at first insemination (AFI) and TB in the study of Hanenberg *et al.* (2001), where the average AFI is 234 days. From these studies and our study, we can assume that the genetic correlation between AFC and TB depended on the age at service. Gilts that are mated very young may produce small litters due to low maturity at mating, and gilts that are mated very late may produce small litters due to reproduction problems.

The estimated genetic correlations between TB1 and WSI1 and between WSI and the TB in the following litter were close to zero. These results are in agreement with the findings of Holm *et al.* (2005). Also, in the study of Hanenberg *et al.* (2001) the genetic correlation between TB1 and WSI1 is estimated at -0.08. The weak phenotypic correlation between TB1 and WSI1 in the present study might have been caused by cross-fostering of piglets. Another possible explanation might be good management during lactation, so that large weight loss was avoided. This is confirmed by the rather high percentage of sows that were in estrus within seven days after weaning.

A high positive genetic correlation was found between AFC and WSI1 (0.35). That is in agreement with previous studies (Hanenberg *et al.*, 2001; Holm *et al.*, 2005), confirming that selection for low age at first mating will have a favorable effect on the interval from weaning to service. It should be mentioned that the average AFC in this study was 17 days and 32 days higher than that in the data used by Hanenberg *et al.* (2001) and Holm *et al.* (2005) respectively. Based on these three studies, the genetic correlation seems to be higher when average AFC is higher. In a study by Sterning *et al.* (1998), gilts with a high age at puberty had higher litter weight gain and also higher weight loss during lactation than gilts with a low age at puberty. They also

found that gilts that were younger at puberty had shorter weaning to ovulation interval and stronger estrous symptoms after the first parity than gilts older at puberty.

3. Environmental and Genetic Trend

Environmental trends (Figure 6, Table 11) were both negative and positive for studied traits. However, the environmental trends that were significantly different from zero only for BF, TB1, WSI1 and WSI2. The genetic trend for ADG was positive (Figure 7, Table 11). The yearly genetic progress was estimated at 4.71 g/day or 0.60 % of the mean growth.

The decrease in BF was due to improvement in husbandry and also due to genetic change during the time of the study. The slight increase in TB1 during the time of the study was due to improvement in husbandry. There was very little genetic change for TB1 over the same period.

There was no genetic change for ADG before 1999 and the rate of genetic progress seems to accelerate during the last four years. For BF, on the other hand, there was a clear progress before 1999. One reason for BF progress in the early year might be that BF has the highest heritability of the three selection traits, thus, it was easier to achieve progress in BF than in ADG and TB. However, according to our unpublished result when only BF breeding values of animals born after 1999 were analyzed, there was no genetic progress ($P > 0.05$) for BF from then on. A possible explanation is a minimum criterion of 12 mm BF that had been used for replacement gilts since 1999.

The 2-days change in AFC from 1993 to 1999 was significant when only estimated breeding values of gilts born in that period were analyzed. That increase in AFC might be associated with the genetic decrease in BF during that period. Age at first service and conception rate were not studied but the phenotypic mean of age at first service changed from 251.16 days in 1993 to 267.45 days in 1999 and 243.95

days in 2003. The change in the genetic trend of AFC in 2002 (Figure 7) indicates that the genetic parts of AFC (age at first ovulation, ability to show estrus, ability to become pregnant) are difficult to separate from the management parts. From 2002 and onwards, all gilts should reach 140 kg before first service.

The low genetic progress in TB could be the result of the selection that was applied which was ineffective because of low heritabilities, even though the breeding organization put a much higher economic weight on litter size than on other traits in the index as shown in equation [1]. In addition, the imported genetic material came from different sources that had different breeding goals. European pigs were selected for leanness and they produced smaller litters than the pigs imported from the USA (personal communication with Dr. Satjar Ravungsook, company's breeder). We have no explanation for the differences between parities, with negative trends for TB1 and TB3 and positive trends for TB2 and TB4. The genetic correlations with ADG and BF do, however, also differ between TB1 and TB3 on the one hand and TB2 and TB4 on the other.

The change in the genetic trend of AFC during the last years should be followed up carefully during the coming years, especially since there are strong genetic correlations between high AFC and low TB as well as a longer WSI. Both the environmental and the genetic trends of WSI are favorable after year 1999. Since the genetic correlation between WSI and TB is low and insignificant, there seem to be no urgent need to include WSI as a selection trait. Monitoring WSI will still be important for the herd production, since sows tend to give birth to large litters if they are mated on day 4 after weaning.

CONCLUSIONS

Two investigations of this thesis involved two productive traits and different reproductive traits obtained from Landrace sows raised in Thailand. The first study examined genetic variations of and relationships among studied traits. The studied traits were ADG, BF, TB, SB, and BAD. The second study involved estimation of genetic parameters and trends for production and reproduction traits. In addition to the traits in first study, AFC and WSI were examined. The following conclusions were drawn from the present investigations:

1. Gilts conceived at 32 to 40 weeks of age have more TB than gilts that conceived at an older age. Age at conception has no effect on SB or BAD of primiparous sows. Parity number influences TB, SB and BAD. For these sows, reared in the tropics, the second litter is the smallest litter. Farrowing month significantly influences TB1 but older sows seem to be less affected by seasonal effects. Weaning to service interval was longest for 1st parity sows. Sows tend to give birth to large litters if they are mated on day 4 after weaning.

2. Heritabilities of productive traits are moderate to high whereas those of reproductive traits are low, except for AFC and WSI. Heritabilities of TB in the first three parities were near zero whereas that of the fourth parity was moderate. The heterogeneous heritabilities of TB suggest that there are different genetic basis for TB across the reproductive life span of sows.

3. Age at first conception is genetically correlated with TB1 and WSI1. These correlations suggest that selecting for younger AFC could have favorable consequences for TB1 and WSI1 of sows. However, there is no genetic relationship between WSI and subsequent TB. The genetic correlation between TB and SB is moderate and unfavorable in first parity. The genetic correlations between TB and BAD are unfavorable in all parities. Thus, selection for litter size will result in greater mortality after birth.

4. Genetic correlation between ADG and TB₂₊ was favorable when TB₂₊ was analyzed with a repeatability model (Trial 1). Selection for high growth rate would result in more piglets born per litter in later parities. However, genetic correlations between ADG and TB were not significant when TB in each of parity were estimated separately (Trial 2). Genetic correlations between BF and TB were not significant indicating that it should be possible to select against backfat thickness without adversely affecting TB. Selection for low backfat thickness will, however, probably increase the incidence of stillbirth in later parities.

5. Genetic trends estimated from these data suggest that selection practices have been successful for ADG, BF and TB₄. Total number of piglets born per litter for first parity sows shows a significantly negative genetic trend. According to a negative genetic correlation between AFC and TB₁ in this population, it might be possible to improve TB₁ by reducing AFC.

6. Based on these results, it is recommended to include AFC and BAD in the breeding evaluation together with litter size and performance traits to ensure a sustainable genetic progress. Since the genetic correlation between WSI and TB is low and insignificant, there seem to be no urgent need to include WSI as a selection trait. Litter size (TB) from different parities should probably be considered as different traits, because of the dissimilarity of their heritabilities and the present lack of genetic progress in TB₁.

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APPENDIX

Appendix Table 1 Number of records, mean, standard deviation (SD), minimum (Min), and maximum (Max) of productive traits

Traits ¹	No. of records	Mean	S.D.	Min	Max
ADG, g/day	19,334	780	100	480	1099
BF, mm	15,755	13.9	3.6	6.7	25.0
LP, %	16,041	55.6	3.0	46.0	64.8
LG, g/day	15,822	359	39	270	480

Note Lean percentage and LG were the estimated traits that were also available in this data set.

¹ ADG = average daily gain, BF = adjusted backfat thickness, LP = lean percentage, LG = lean gain

Appendix Table 2 Heritabilities (diagonal), genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive traits

Traits ¹	ADG	BF	LP	LG
ADG	0.38	-0.02	-0.08	0.88
BF	-0.03	0.63	-0.81	-0.39
LP	-0.02	-0.64	0.41	0.30
LG	0.88	-0.31	0.29	0.36

Note Lean percentage and LG were the estimated traits that were also available in this data set.

¹ ADG = average daily gain, BF = adjusted backfat thickness, LP = lean percentage, LG = lean gain

Appendix Table 3 Mean heritabilities (diagonal), genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive traits and total number of piglets born per litter in first to fourth parity

Traits ¹	ADG	BF	TB1	TB2	TB3	TB4
ADG	0.31	-0.05	-0.02	0.18	-0.10	0.20
BF	-0.04	0.45	0.00	-0.02	-0.11	0.14
TB1	0.04	-0.01	0.04	0.26		
TB2	0.04	0.02	0.10	0.07	0.50	
TB3	0.01	0.03		0.14	0.07	0.30
TB4	0.04	0.03			0.13	0.10

Note Heritabilities and genetic correlation between ADG and BF in the table were estimated from the estimates resulting from four-traits analyses (ADG, BF, TB1, TB2; ADG, BF, TB2, TB3 and ADG, BF, TB3, TB4).

¹ ADG = average daily gain, BF = adjusted backfat thickness, TB1 to TB4 = total number of piglets born per litter in first to third litter.

Appendix Table 4 Heritabilities (diagonal), genetic (above the diagonal) and phenotypic (below the diagonal) correlations between productive traits and weaning to service interval after first to third litter

Traits ¹	ADG	BF	WSI1	WSI2	WSI3
ADG	0.31	-0.04	-0.07	-0.03	-0.02
BF	-0.04	0.45	-0.27	-0.10	-0.12
WSI1	-0.04	-0.06	0.16	0.64	0.65
WSI2	0.01	-0.03	0.24	0.17	0.81
WSI3	-0.03	-0.02	0.19	0.22	0.20

Note The estimates in table were estimated by using five-traits model (ADG, BF, WSI1, WSI2, WSI3).

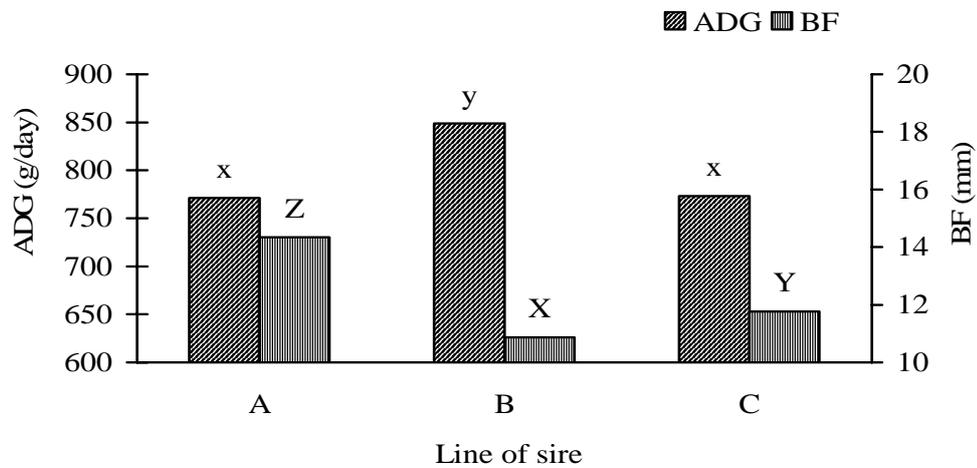
¹ ADG = average daily gain, BF = adjusted backfat thickness, WSI1 to WSI3 = weaning to service interval after first to third litter

Appendix Table 5 Heritabilities (diagonal), genetic (above the diagonal) and phenotypic (below the diagonal) correlations between total numbers of piglets born in each parity

Traits ¹	TB1	TB2	TB3	TB4	TB5	TB6	TB7
TB1	0.07	0.97	0.93	0.86	0.62	0.38	0.41
TB2	0.10	0.13	0.99	0.96	0.66	0.42	0.45
TB3	0.11	0.16	0.19	0.98	0.67	0.43	0.47
TB4	0.13	0.16	0.20	0.21	0.67	0.44	0.47
TB5	0.09	0.14	0.16	0.17	0.31	0.49	0.45
TB6	0.06	0.08	0.10	0.11	0.15	0.29	0.46
TB7	0.05	0.08	0.10	0.10	0.12	0.12	0.23

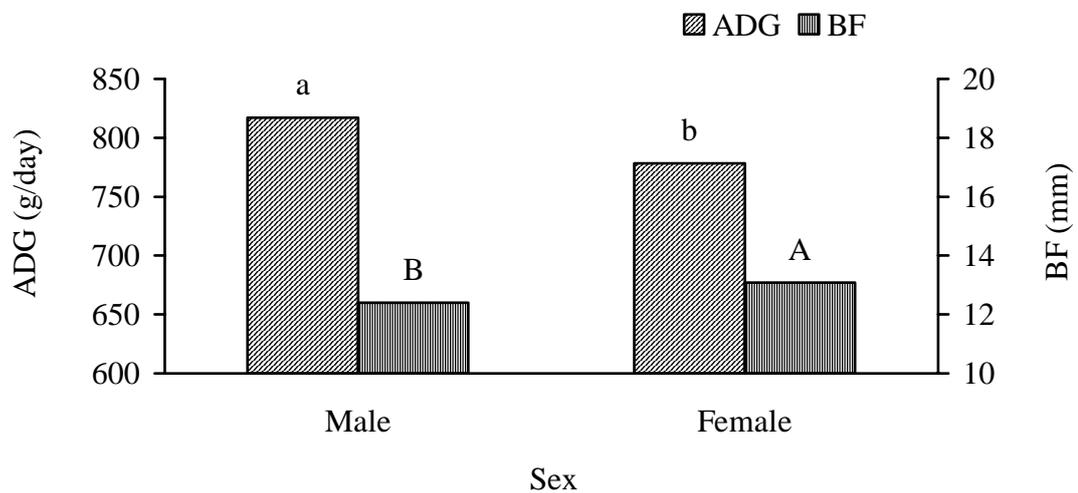
Note The estimates in table were estimated by using seven traits models (TB1, TB2, TB3, TB4, TB5, TB6, TB7).

¹ TB1 to TB7 = total number of piglets born per litter in first to seventh parity



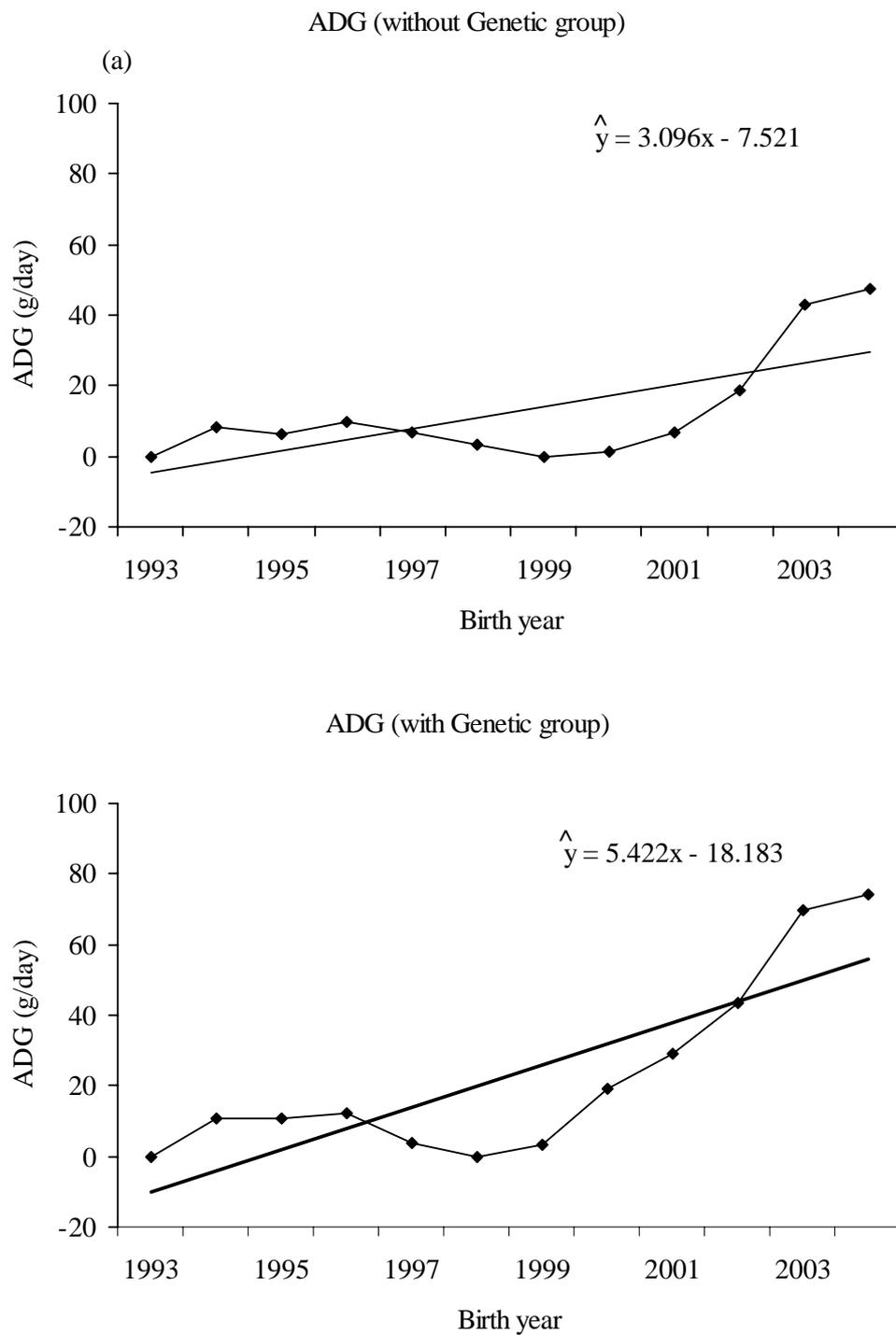
Appendix Figure 1 Effect of sire lines (A, B, C: used in the nucleus herd) on average daily gain (ADG) and adjusted backfat thickness (BF).

Note Least-square means without a letter in common (x,y; X, Y, Z) are significantly different ($P < 0.05$).

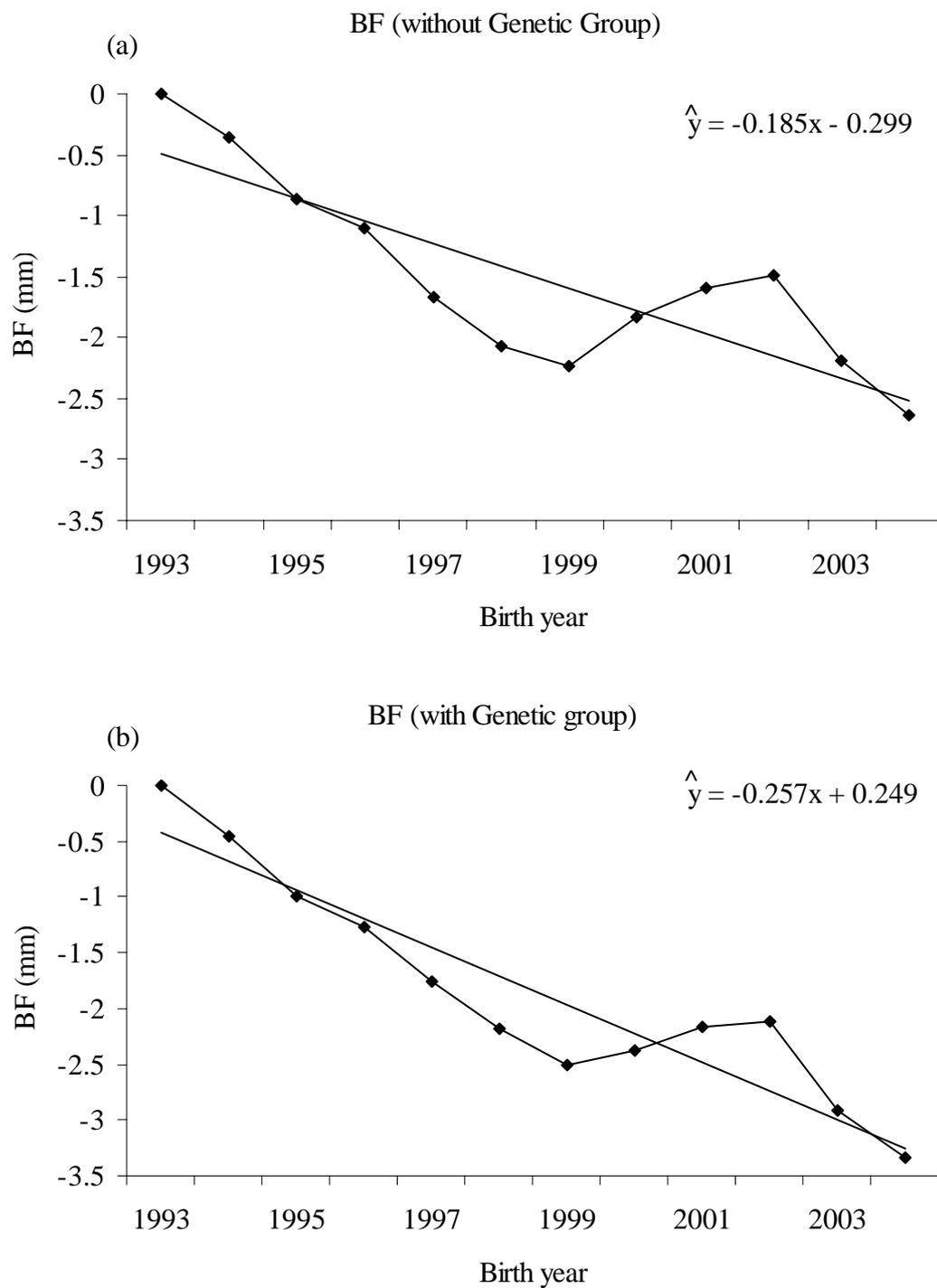


Appendix Figure 2 Effect of genders on average daily gain (ADG) and adjusted backfat thickness (BF).

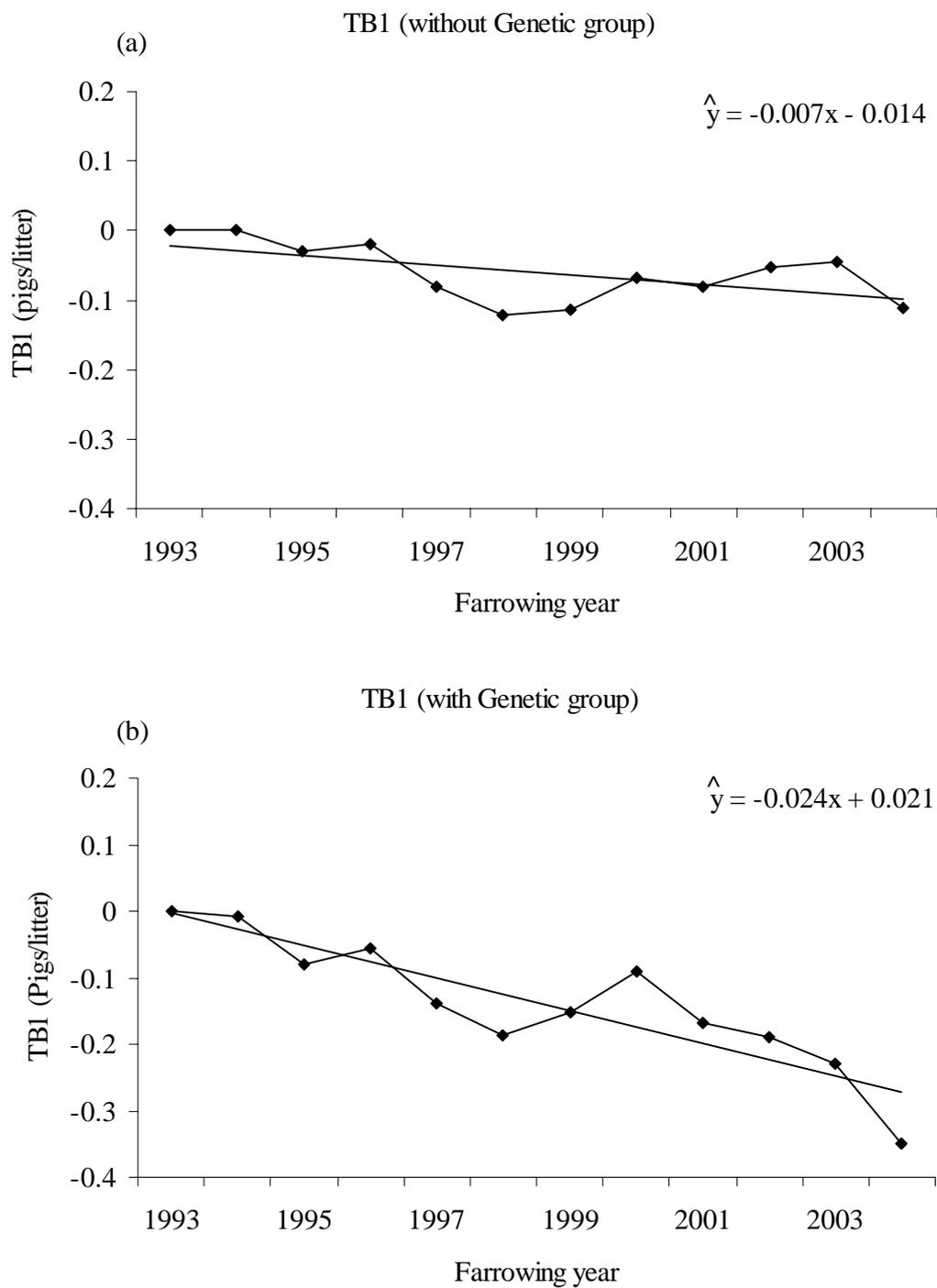
Note Least-square means without a letter (a, b; A, B) in common are significantly different ($P < 0.05$).



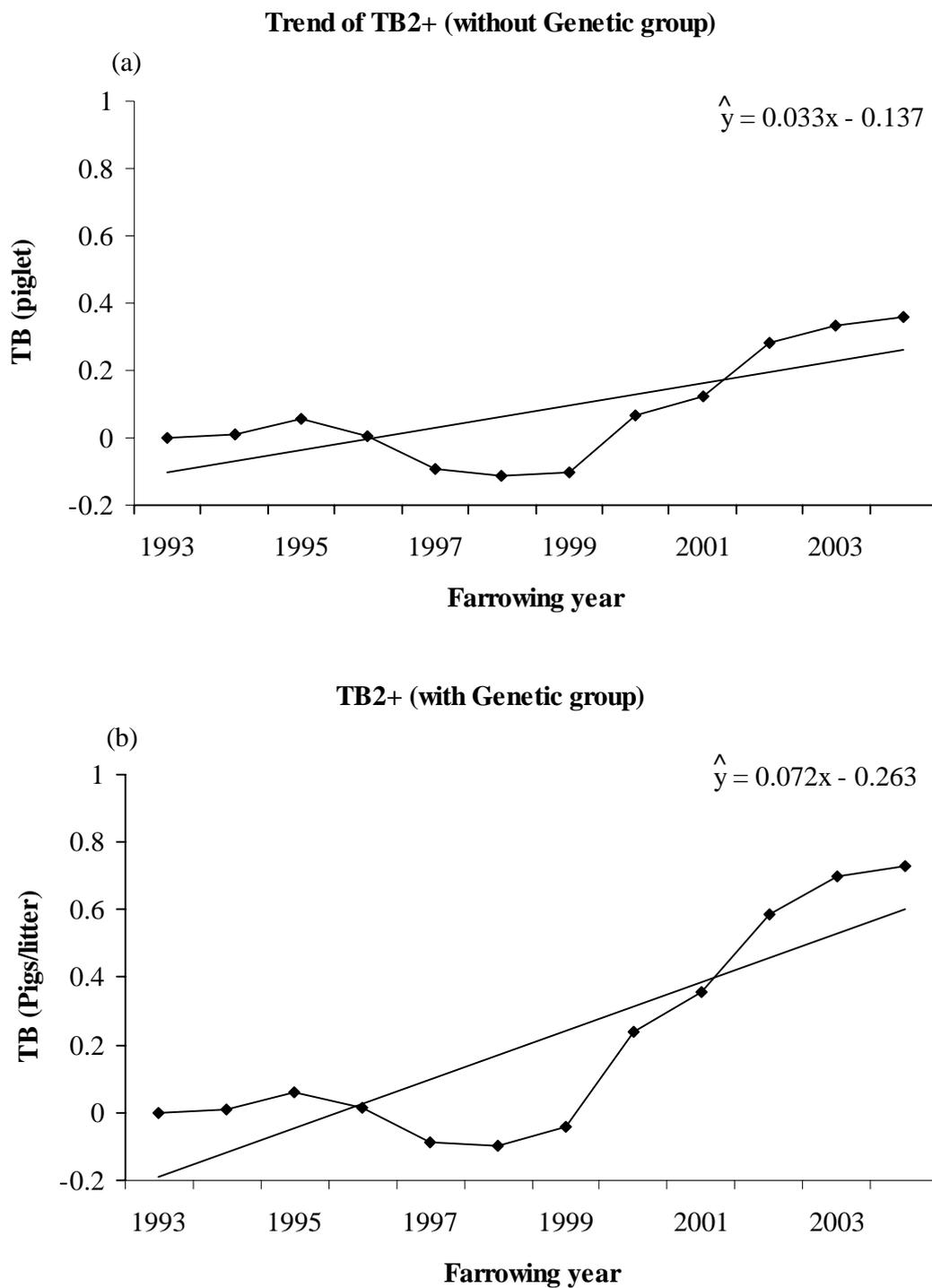
Appendix Figure 3 Genetic trends for average daily gain (ADG) calculated from model without (a) or with (b) genetic groups from 1993 to 2004.



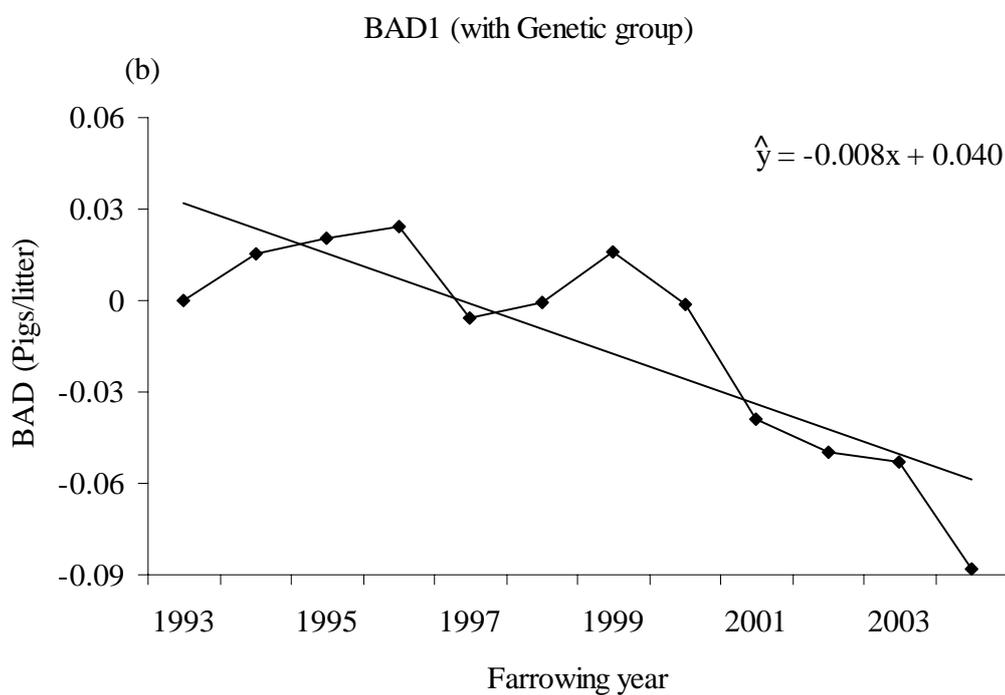
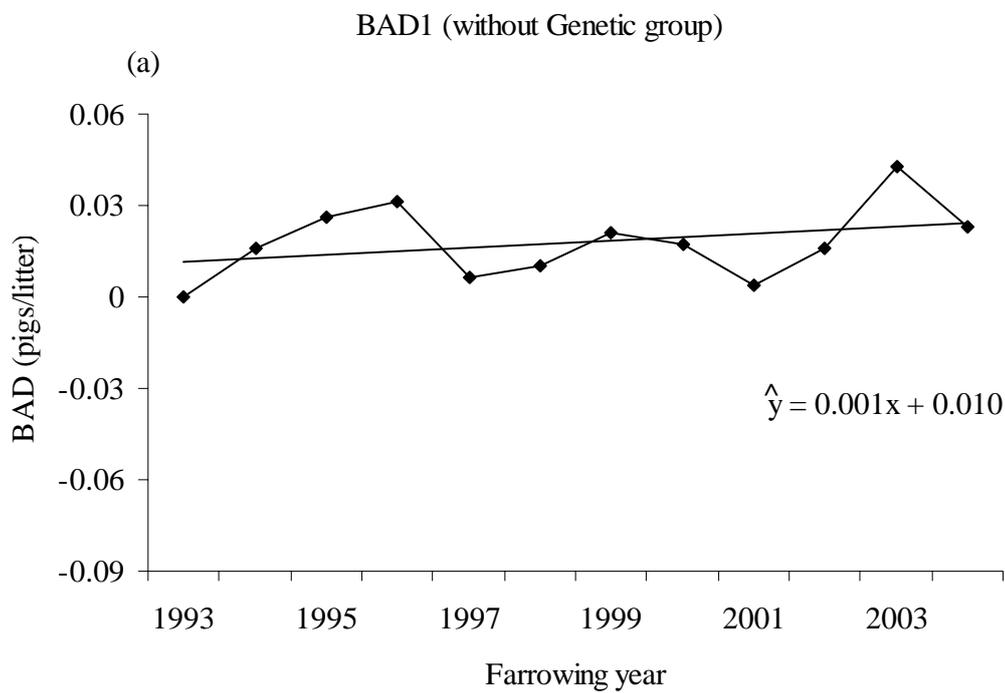
Appendix Figure 4 Genetic trends for adjusted backfat thickness (BF) calculated from model without (a) or with (b) genetic groups from 1993 to 2004.



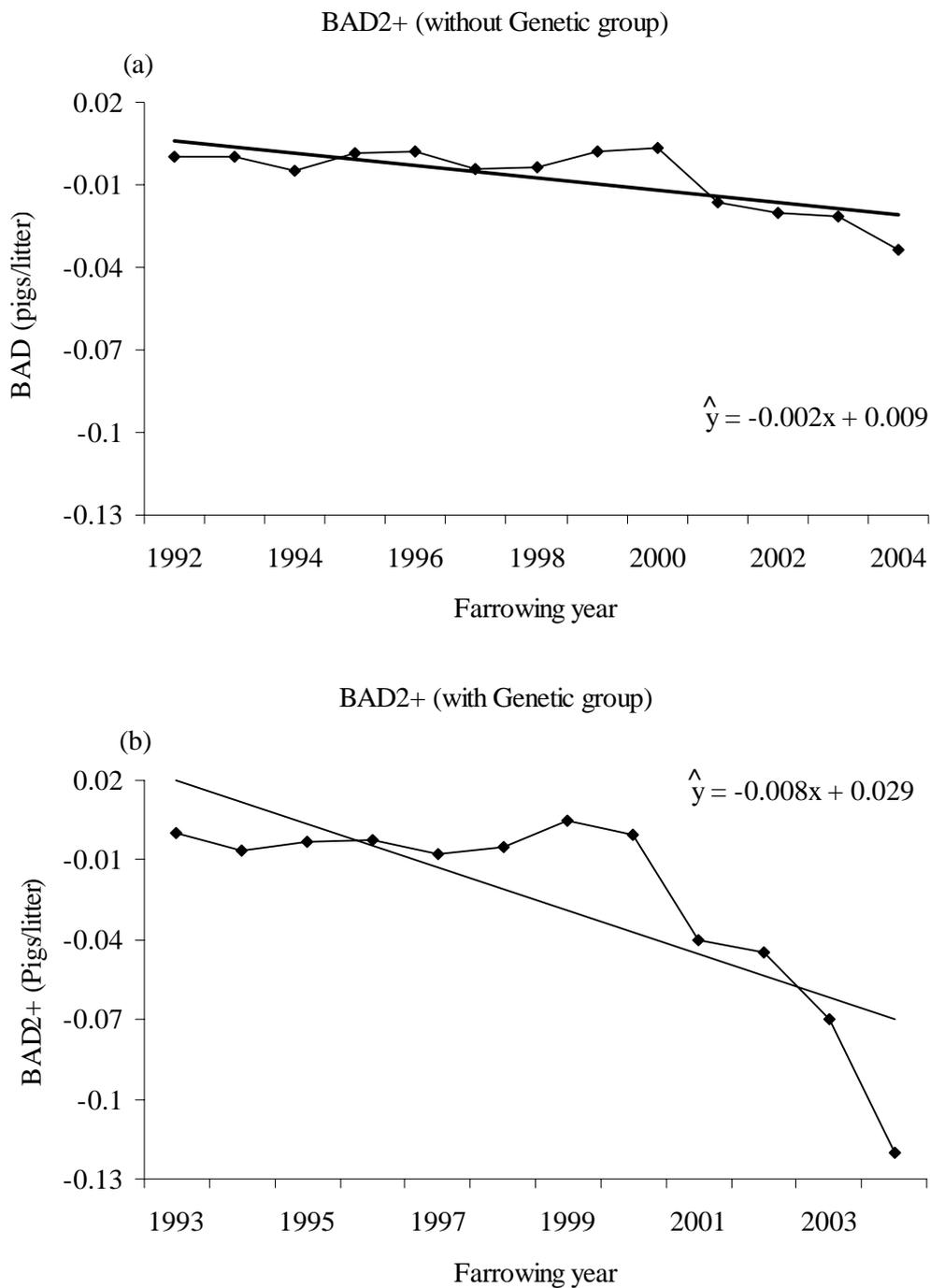
Appendix Figure 5 Genetic trends for total number of piglets born per litter in first parity sows (TB1) calculated from model without (a) or with (b) genetic groups from 1993 to 2004.



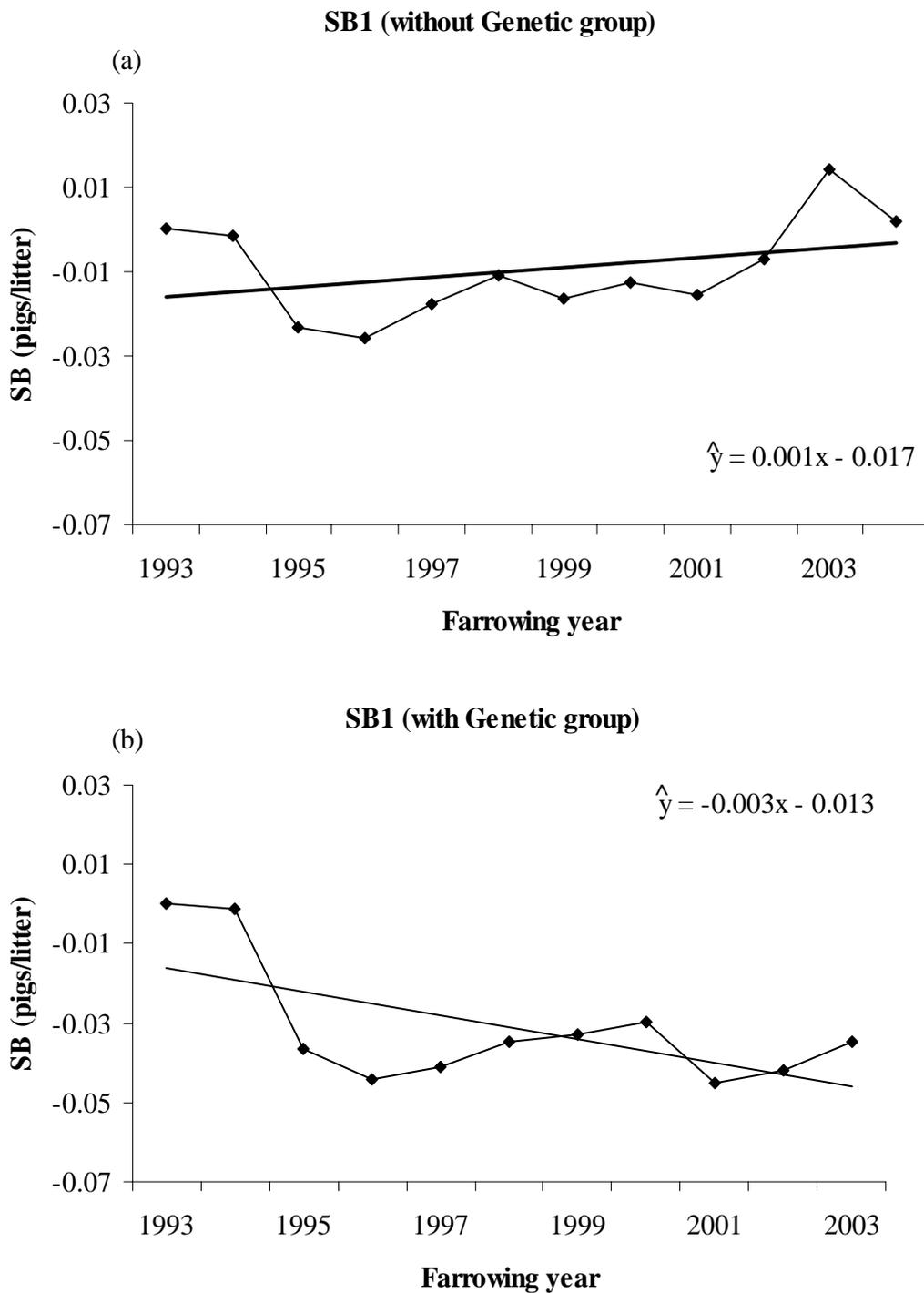
Appendix Figure 6 Genetic trends for total number of piglets born per litter in later parity sows (TB2+) calculated from repeatability model without (a) or with (b) genetic groups from 1993 to 2004.



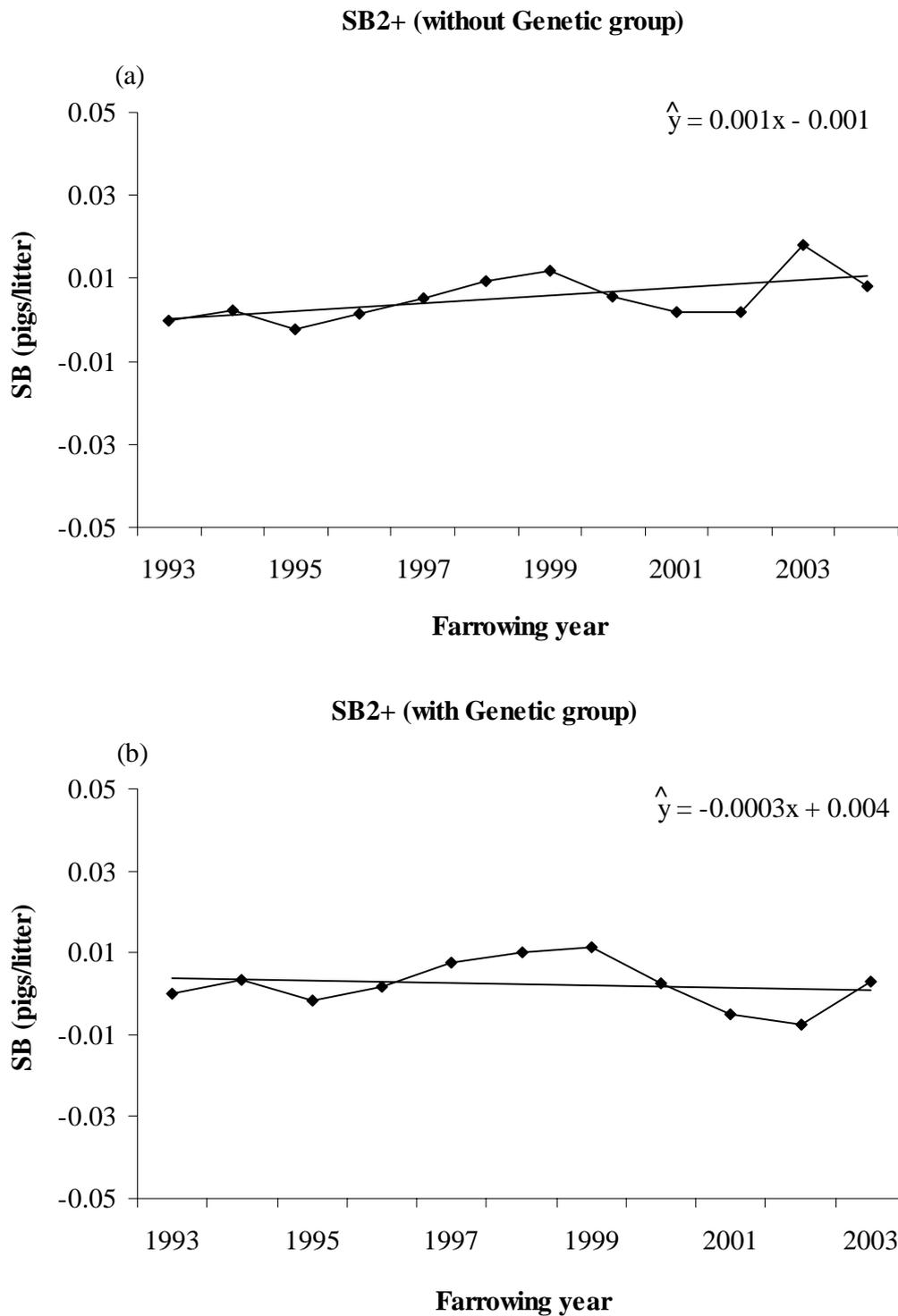
Appendix Figure 7 Genetic trends for number of piglets born alive but dead within 24 hours after birth in first parity sows (BAD1) calculated from model without (a) or with (b) genetic groups from 1993 to 2004.



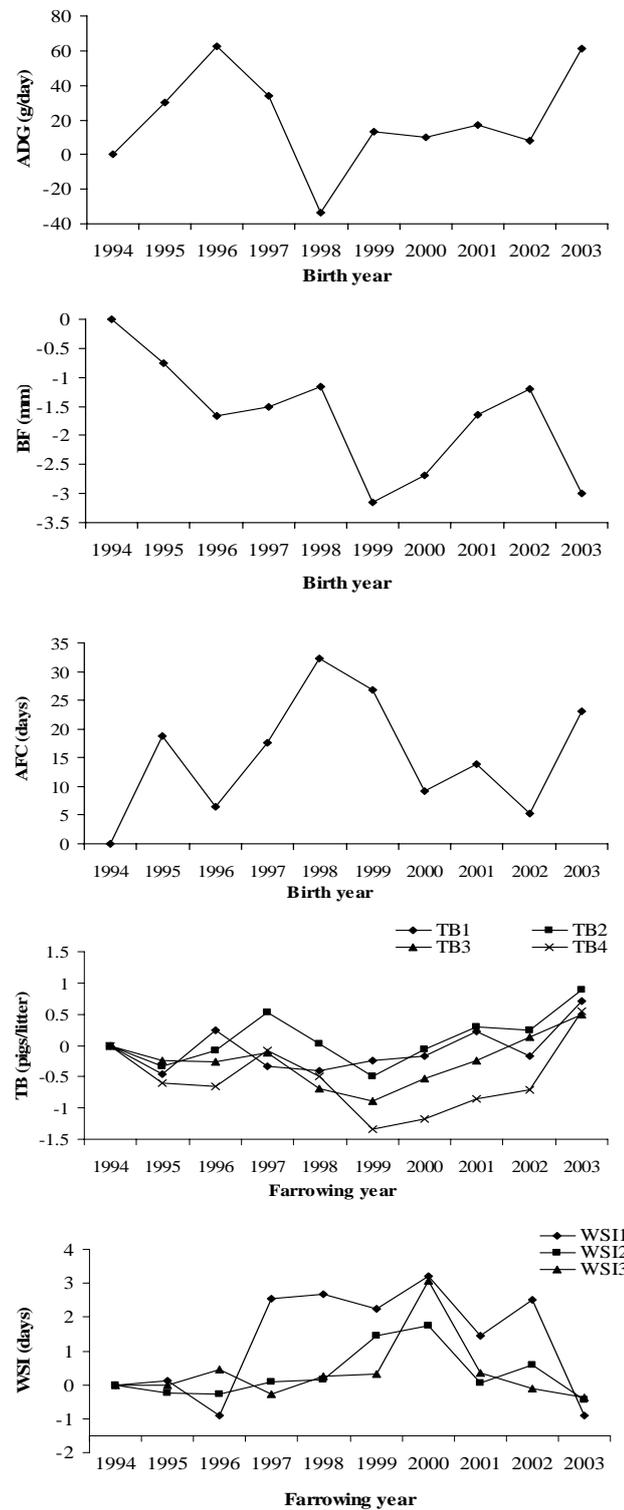
Appendix Figure 8 Genetic trends for number of piglets born alive but dead within 24 hours after birth in later parity sows (BAD2+) calculated from repeatability model without (a) or with (b) genetic groups from 1993 to 2004.



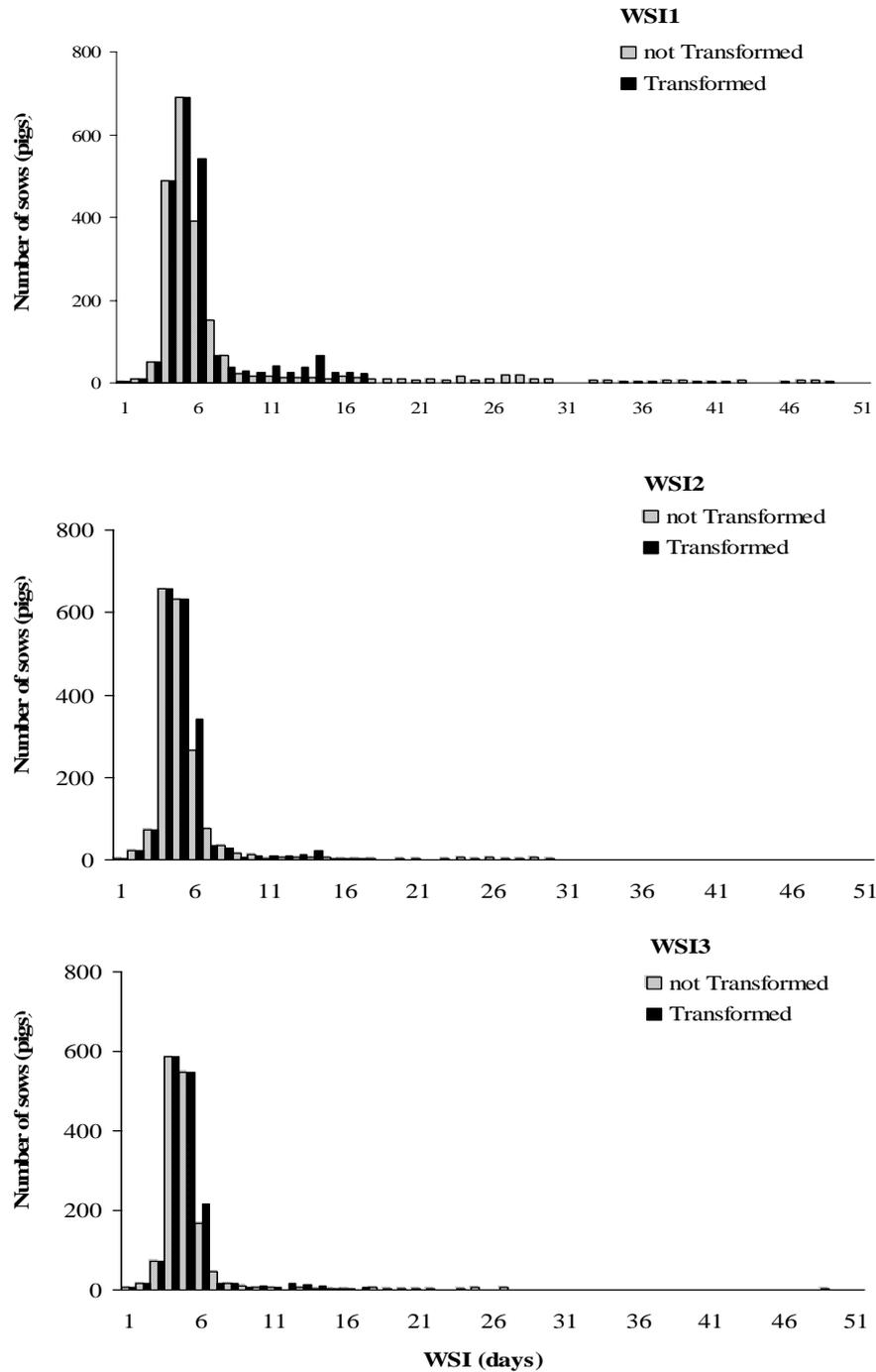
Appendix Figure 9 Genetic trends for number of stillborn piglets in first parity sows (SB1) calculated from model without (a) or with (b) genetic groups from 1993 to 2003.



Appendix Figure 10 Genetic trends for number of stillborn piglets in later parity sows (SB2+) calculated from repeatability model without (a) or with (b) genetic groups from 1993 to 2003.



Appendix Figure 11 Phenotypic trends for average daily gain (ADG), adjusted backfat thickness (BF), age at first conception (AFC), total number of piglets born in first to fourth parity (TB1-4) and weaning to first service interval after first to third litter (WSI1-3) from 1994 to 2003.



Appendix Figure 12 Frequency distributions of not transformed (1 to 50 days) and transformed weaning to first service interval for the first to third parity sows.

Note WSI1, WSI2 and WSI3 were weaning to first service interval after first, second and third litter.

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