EVALUATION OF THE IMPACT OF REPRODUCTIVE TECHNOLOGIES ON THE GENETIC IMPROVEMENT AND PROFIT OF PIG PRODUCTION SYSTEMS

BY

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DISSERTATION

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ABSTRACT

Boar utilization efficiency and fertility play a significant role on the productivity and profitability of the U.S. pig industry. The impact of artificial insemination technique, semen preparation, and selection for semen traits on profitability and complementary financial indicators was evaluated under a comprehensive range of productive and reproductive circumstances. Net profit was 2.2% to 2.6% higher in intra-uterine and deep intra-uterine relative to conventional artificial insemination with fresh semen and slightly higher with frozen semen. The differences in net profit between fresh and frozen semen were driven by differences in variable costs and ranged from -5.3% (conventional AI) to -24.7% (deep intra-uterine AI). Overall, insemination technique and semen preparation had a non-linear effect on profit.

A subsequent study evaluated the impact of boar selection strategies including four semen traits in addition to standard paternal and maternal traits on genetic improvement and profit of the enterprise. A first-in-kind derivation of the economic weight of semen traits was undertaken. Genetic gains for paternal and maternal traits were higher in the four and three-way schemes, respectively. The selection strategy including the four semen traits is recommended because this approach enables genetic gains for these traits without compromising the genetic gains for maternal traits and with minimal losses in genetic gains for paternal traits. Three boar semen collections per week offered the highest return on investment. The selection strategy including semen traits had higher net profit (P-value < 0.0001) than the traditional strategy. Intra-uterine insemination allowed a further reduction on the number of boars maintained, lowered total cost, and increased net profit relative to conventional insemination. These studies demonstrate the potential genetic and financial benefits derived from efficient boar use through combination of reproductive techniques and collection frequencies; and selection strategies including semen traits.

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CHAPTER I: Literature review

1.1 Background, genetic structure, and gene flow

Background

Global pork production in 2013 was 113 million metric tons. The U.S. is one of the world's leading pig producing countries and pork exporters. In fact, the U.S. is second only to China in terms of pig population and pig meat production (FAOSTAT, 2015). The U.S. accounts for 9.3 % of the worldwide pork production behind China (47%, FAOSTAT, 2015). Since 1995, the U.S. exports more pig meat than import (**Figure 1.1**, USDA, 2015). Even though Japan is the top importer of U.S. pork (23% to 31% of the total pig exports), other countries including Mexico, China, and South Korea are rapidly increasing their U.S. imports (USDA, 2015). In the U. S., the major producing states are Iowa, North Carolina, Minnesota, and Illinois (**Figure 1.2**, FAO, 2015; NASS, 2015). The steady increase in pig production in the U.S. is supported by two major changes: i) concentration of production (fairly constant number of hogs on fewer yet larger farms), and, ii) farm specialization, moving away from the traditional farrow-to-finish operations (which encompass the entire life cycle of hogs from birth to harvest) in favor of farms dedicated to a single phase of the production cycle. The latter situation has also been accompanied by a rise in the use of contracts (Key and McBride, 2007).

Genetic structure

Pig production can be divided into two distinct periods, breeding (reproduction) and growing. This division is based on the different inputs of each period and because of the benefit of segregating younger from older animals for disease control purposes (Pitcher and Springer, 1997). Also, both periods have substantial differences in the costs associated with both periods labor, facility, and feed requirements. The reproduction or farrow-to wean period starts when the young females (gilts) reach breeding age (at 200 to 220 days of age), followed by successful insemination, farrowing (114 days post insemination), and the offspring reaching weaning age (21 days of age, Omtvedt et al., 1965; Schukken et al., 1994; PigCHAMP, 2012; Knox, 2013). After weaning, sows return to estrus and are bred within 7 to 10 days (Sterning et al., 1998; Knox, 2000). In the U.S., a sow produces on average 2.3 litters / year with an average of 11.87 pigs/litter (Knox, 2000; PigCHAMP, 2012). The growing or farrow-to-finish period can be divided into distinct phases including farrow-to-wean (production of breeding sows, farrowing, and selling of weaning pigs), farrow-to-feeder pigs (in addition to farrow-to-wean, the offspring are sold at 60 pounds to a finishing operation), and feeder pig-to-finish (weaned or feeder pigs are grown to harvest at approximately 250 pounds, Schaeffer et al., 2008).

Gene flow

Traditional livestock breeding programs are hierarchical in nature and a three-tier structure is commonly observed (Shepherd, 1997). The structure of pig production systems is a good example. The structure to produce commercial crossbred pigs has a pyramidal hierarchy (**Figure 1.3**, Dekkers, 2007). The breeding nucleus is located at the top of the pyramid (first tier), and the genetic material flows from this first top tier, through the multiplier tier, to the base, third tier or commercial tier. Hybrids cross sows between two purebred pigs in the first tier are mated. The maternal line at the commercial level is usually an F1 crossbred to exploit the reported heterosis associated with reproductive traits. Management and breeding decisions are dominated by the goal to maximize genetic improvement of the traits of interest in the first tier (Shepherd, 1997). At the second tier, the decisions are dominated by the goal to produce the maximum number of breeding sows with highest genetic merit. At the third tier, decisions are dominated by the goal of maximizing profit (Bichard, 1977; Faust et al., 1992; Harris, 2000).

The commercial herds produce pigs for market (Merks, 2000; Bidanel, 2010). The sow and boar at the commercial levels originate from different breeding programs (Smith, 1964; Moav, 1966). Crossbred sows reach puberty earlier; have higher conception rate, slightly greater ovulation rate and better embryo/fetal survival rates and farrow larger litters than purebred sows (Bidanel, 2011). Crossbred males also reach puberty earlier; have larger testes size, and higher sperm production compared with purebred boars (Buchanan, 1987). However, heterosis has limited effects on carcass traits, and direct and maternal heterosis effects on meat quality traits are also relatively small (Ciobanu et al., 2011). This is the main reason why the terminal boars are purebred from lines selected for growth, carcass and meat quality traits.

1.2. Animal breeding

Selection within lines or breeds and crossbreeding are two animal breeding strategies that can be used alone or in combination to augment the profit of an enterprise through improved production and wellbeing, (Goddar, 2000; Webb, 2000).

1.2.1 Crossbreeding

In livestock, crossbreeding is used to produce individuals with higher mean performance for the trait of interest than their parents. Terminal crossbreeding systems are common in pig production (Cassady et al., 2002). In the pig industry, a common practice is to use maternal and paternal lines. The maternal lines selected for reproductive traits (prolificacy and maternal ability) are crossed to obtain F1 hybrid sows that have better reproductive performance than each maternal line of progenitors. The hybrid sows are in turn mated to purebred boars from a terminal line that has been selected for fast growth and superior carcass traits (Moav, 1966; McLaren et al., 1987, Bidanel, 2011). A typical three-breed terminal crossbreeding system should use 100% of the available heterosis, have a less variable product, and take better advantage of the complementarity of breeds (Kuhlers et al., 1994).

Crossbreeding justification is based on the fact that the progeny from a cross of purebred parents express 100% of available heterosis (Dickerson, 1973). Also, progeny would again express 100% of available heterosis if one or both parents are crossbred and parents are of different breeds or lines. Heterosis is particularly important for reproductive traits. These traits tend to have low-to-moderate heritabilities, especially fertility and prolificacy that are the results of complex interaction among sows, boar, and embryos or piglet genotypes. Therefore, the genetic improvement of these traits through selection is challenging. Crossbreeding in the third tier is used because the new allelic combinations in the pigs tend to increase growth, daily feed intake, and carcass length, while decreasing backfat. Therefore crossbred pigs grow more rapidly than purebred pigs (Cassady et al., 2002).

1.2.2. Selection index

The selection of the purebred lines or breeds in the nucleus relies on selection indices that combine the economic and genetic value of the traits of interest (Enns, 2010). An economic selection index is a linear function of the genetic merit of the animal for each trait weighted by the relative economic value of the trait (Hazel, 1943).

The additive genetic values of the traits for an individual conform the aggregate genotype (Hazel, 1943). Assuming that the relationship among the traits in the breeding objective is linear then the aggregate genotype is:

$H = v_1a_1 + v_2a_2 + \ldots + v_na_n$

where

H= aggregate genotype

a_i= additive genetic value of the i^{th}trait

v_i=economic value of genetically improving the i^{th}trait (partial economic weight)

In practices, additive genetic values are usually unknown, so the phenotypic records are used to approximate and estimate the aggregate genotype. These are combined into an index value (Hazel 1943):

$I = b_1y_1 + b_2y_2 + \ldots + b_my_m$

where

I = selection index of the animal

$\hat{a}$ = estimated breeding value

b_i = selection index coefficient (or weight) for the i^{th} trait

y_i = observation of the i^{th} source of information expressed as deviation from mean

(contemporary group mean for the trait)

The challenge is to estimate the selection index coefficient (b_i) such that the selection of individuals on their selection index value (I) maximizes response in the aggregate genotype (H) and allows I to be an unbiased predictor of H.

1.2.2.1 Properties of b_i

Maximizing the response in aggregate genotype. Using the standard selection theory the expected response in aggregate genotype is

$$R_H = b_{H,I}\left(\mu_{I_s} - \mu_I\right) \qquad (1)$$

where

R_H = expected response in aggregate genotype

$b_{H,I}$= regression of aggregate genotype on index value

μ_{I_s}= mean of index value of the selected animals or groups of animals

μ_I = mean index values of all animals in the population

And because the i of selection is defined as the deviation of average of selected individuals from average all individuals in standard deviation units

$$i = \frac{(\mu_{I_s} - \mu_I)}{\sigma_I}$$

Where

σ_I= standard deviation of index values

Then

$$\left(\mu_{I_s} - \mu_I\right) = i\sigma_I \qquad (2)$$

Then substitutes (2) in (1)

$$R_H = b_{H,I} i\sigma_I \qquad (3)$$

For the standard regression theory

$$b_{H,I} = \frac{\sigma_{H,I}}{\sigma_I^2} \qquad (4)$$

where

$\sigma_{H,I}$= covariance H and I

σ_I^2 = variances of I

Then substitutes (4) in (3)

$$R_H = \left(\frac{\sigma_{H,I}}{\sigma_I^2}\right) i\sigma_I \qquad (5)$$

Then simplifying (5)

$$R_H = \left(\frac{\sigma_{H,I}}{\sigma_I}\right) i$$

where

R_H = expected response in aggregate genotype

i = selection intensity

$\sigma_{H,I}$= covariance H and I

σ_I = standard deviation of I

Then for a given i the response in H maximized when

$$R_H = \left(\frac{\sigma_{H,I}}{\sigma_I}\right) i$$

Unbiased predictor. In addition, I should be an unbiased predictor of the aggregate genotype (H). This property can be represented:

$$E\left(u_{I_s} - u_I\right) = u_{H_s} - u_H$$

Given the condition of multivariate normality, this equality is achieved when $b_{H,I} = 1$.

1.2.2.2 Estimating b_i

The variance of the index is:

$$\sigma_I^2 = b_1^2\sigma_{y1}^2 + b_2^2\sigma_{y2}^2 + \cdots + 2b_1b_2\sigma_{y_{12}} + 2b_1b_3\sigma_{y_{13}} + \cdots$$

where

$\sigma_{y_{12}}$= phenotypic covariance of observation from the kth and lth observation of traits in the index

σ_{y1}^{2} = variances

Then this formula could be written in summation notation as:

$$\sigma_I^2 = \sum_{k=1}^{m}\sum_{l=1}^{m} b_k b_l \sigma_{y_{kl}} \ (6)$$

The covariance between H and I is:

$$\sigma_{H,I} = b_1 v_1 \sigma_{y_1 a_1} + b_1 v_2 \sigma_{y_1 a_2} + \cdots + b_m v_n \sigma_{y_m a_n}$$

where

$\sigma_{y_m a_n}$= additive covariance of kth observation in the index and the ith traits in the aggregate genotype. Then in summation notation

$$\sigma_{H,I} = \sum_{k=1}^{m}\sum_{i=1}^{n} b_k v_i \sigma_{y_k a_i} \qquad (7)$$

To maximize the ratio $M = \left(\frac{\sigma_{H,I}}{\sigma_I}\right)$,

$logM = log\sigma_{H,I} - log\sigma_I$ equivalent to $logM = log\sigma_{H,I} - (\frac{1}{2})log\sigma_I^2$ (8)

Then substituting (7) and (6) in (8)

$$logM = \log\left(\sum_{k=1}^{m}\sum_{i=1}^{n} b_k v_i \sigma_{y_k a_i}\right) - (\frac{1}{2})log\left(\sum_{k=1}^{m}\sum_{l=1}^{m} b_k b_l \sigma_{y_{kl}}\right)$$

The final goal is to maximize M, and this is accomplished by differentiating $logM$ with respected each our index coefficients:

$$\frac{\delta logM}{\delta b_k} = 0$$

Then, the partial derivative of each b_k for k=1 is set to m

Thus, M is maximum when

$$\sum_{l=1}^{m} b_l \sigma_{y_{kl}} = \left(\frac{\sigma_I^2}{\sigma_{H,I}}\right) \sum_{i=1}^{n} v_i \sigma_{y_k a_i} \quad (9)$$

I is unbiased when $b_{H,I} = 1$

Then $\frac{\sigma_I^2}{\sigma_{H,I}} = 1$ and also

$$\sum_{l=1}^{m} b_l \sigma_{y_{kl}} = \sum_{i=1}^{n} v_i \sigma_{y_k a_i} \quad (10)$$

The equation in (10) is known as the set of normal equations.

Expanding these equations:

$$\begin{aligned}
b_1\sigma_{y1}^2 \; + \; \ldots + b_m\sigma_{y_{1m}} &= \; v_1\sigma_{y_1 a_1} + \; \ldots + v_n\sigma_{y_1 a_n} \\
b_1\sigma_{y21} + \; \ldots + b_m\sigma_{y_{2m}} &= \; v_1\sigma_{y_2 a_1} + \; \ldots + v_n\sigma_{y_2 a_n} \\
\vdots \qquad \vdots \qquad \vdots \qquad & \qquad \vdots \qquad \vdots \qquad \vdots \\
b_1\sigma_{y21} + \; \ldots + b_m\sigma_{y_m} &= v_1\sigma_{y_m a_1} + \; \ldots + v_n\sigma_{y_m a_n}
\end{aligned}$$

In matrix notation these equation are rewritten as: $\mathrm{Pb} = \mathrm{Gv}$

where

P = symmetric mxm matrix of phenotypic co-variances of the m observed traits

G = mxn matrix of co-variances among m observed traits and n traits in the aggregate genotype

b = is the mx1 vector of m index coefficients

v = is the nx1 vector of n economic weights for the n traits in the aggregate genotype

Then selection index weights are calculated as $\mathrm{b} = \mathrm{P}^{-1}\mathrm{Gv}$.

When b is obtained then the variances of the index ($\sigma_I^2 = b'Pb$), the response to selection ($R_H = \frac{b'Gv}{\sqrt{b'Pb}} i$) and the accuracy ($r_{H,I} = \frac{b'Gv}{\sqrt{(b'Pb)(v'Gv)}} i$) could be estimated.

The maximum gain from selection is obtained by using the previously demonstrated selection index (Hazel, 1943; Henderson, 1963; Cunningham, 1975). An index permits the simultaneous consideration of multiple traits. Different selection indices need to be used when selecting within each of the three purebred lines in a three-breed crossbred pig production system. The same selection index fundamentals and traits can be applied to all indices. Different weights (including zero) allow for vastly different genetic improvement profiles among lines.

1.2.3 Common breeds in U.S.

Pig breeds in the world fluctuate around 200-300 (Porter, 1993; Jones, 1998). Breeds were often created by mixing diverse pigs of local types with different production levels and genetic backgrounds. The three main countries of breed development are England, China and the U.S. (Jones, 1998). The geographical distribution of pig breeds differs depending on the population under consideration, however breeds like Large White, Landrace, Hampshire, and Duroc, have been extraordinarily successful mainly due to their uses in modern intensive systems (Amills et al., 2010).

The five main breeds of pigs in the US are Berkshire, Hampshire, Landrace, Yorkshire, and Duroc. The last four of these, represent more than 80 percent of the purebred hog registrations in US, and serve as a foundation for commercial hog production (**Figure 1.4**, NSR, 2012). The fifth breed, Berkshire, is also common with a high census in Iowa, Illinois, Indiana, Minnesota, and Wisconsin (Welsh et al., 2010). The Duroc and Hampshire are considered top meat and eating quality breeds and the recommended terminal sire lines. Duroc are regarded as the fastest growing hogs available to commercial producers for terminal breeds and is the second most recorded breed of swine in the U.S., while Hampshire is the fourth (Langlois and Minvielle, 1989; NSR, 2012). Yorkshires (the most recorded breed of swine in the US and Canada) and Landrace (the fifth most recorded in US) are the recommended maternal lines. The crossbred sow Yorkshire x Landrace has a superiority in reproductive performance compared with the purebred (Langlois and Minvielle, 1989; NSR, 2012).

The U.S. pig breeding industry has two major players: 1) multinational swine genetics companies such as Pig Improvement Company (PIC, http://www.pic.com/USA) and, 2) independent domestic breeders such as Whiteshire/Hamroc (http://www.whiteshirehamroc.com/), Waldo farms (http://www.waldogenetics.com/), and The Maschhoffs (http://www.themaschhoffs.com/; NSR, 2012). The U.S. PIC is a subsidiary of the biotechnology company Genus plc. Genus plc is a United Kingdom-based company engaged in applying quantitative genetics and biotechnology to animal breeding in the bovine and porcine sectors. PIC works closely with third party breeders/multipliers, producers and farmers to crossbreed animals possessing desirable traits and genes. PIC generates revenue through the sale of breeding animals and semen, and custom improvement programs for customers (PIC, 2012). Whiteshire/Hamroc is first in sow productivity data contribution for Yorkshire and Landrace breeds and second for Duroc and Hampshire in the U.S. The Maschhoffs is first in post-weaning data contribution for Landrace, while Waldo Farms is the first contributor for Duroc, and Whiteshire/Hamroc is first for Hampshire and Yorkshire breeds (NSR, 2012).

1.3. Traits

Two major groups of traits can be recognized in pig production systems, production traits (growth and carcass characteristic) and reproduction traits (fertility and longevity of sows, Smith, 1964). Production traits including growth rate, food conversion, and carcass fatness are traditional targets of selection in paternal lines (McPhee and MacBeth, 2000; Kanis et al., 2005; Houška, et al., 2010). The second group of traits are typically the target of selection in maternal lines and include maternal and reproduction traits (Merks, 2000; Merks et al., 2000). Sow longevity is an example of survival or time-to-event data and plays an important role in piglet production (Beckova and Václavková, 2008). The length of productive life of sow is directly related to the number of piglets produced during a sow´s productive lifetime (Serenius and Stalder, 2006). Sow longevity can be defined as "stayability" or length of productive herd life-the number of days between a beginning event, such as date of birth or date of first farrowing and culling of a sow (Serenius and Stalder, 2004). Sow longevity impacts profit and herds with high prevalence of sows with high longevity associated with less economic risk than herds with low longevity (Rodriguez-Zas et al., 2003).

Other selection criteria that impact profit and have low heritability (i.g. 0.17) is number of pigs born alive (Johnson et al., 1999). The means of number born alive in U.S. for Yorkshire, Duroc, Hampshire and Landrace were 10.6 piglets/litter, 9.2 piglets/litter, 9.5 piglets/litter and 10.4 piglets/litter, respectively (Chen et al., 2002). Selection to increase litter size should include number and pigs weights, especially since these traits are related with piglet survival (Rosendo et al., 2007). Birth weight (1.5 kg/pig) is an important trait, particularly average birth weight which has high heritability (0.15 to 0.39) and is associated with the survival of the piglets and is correlated with weaning weight (7 kg) (Hermesch et al., 2000; Damgaard et al., 2003; Rosendo et al., 2007, Su et al., 2008; Kapell et al., 2011).

A third group of traits, usually absent from selection decisions, that play an important role in the efficiency and productivity of the pig industry are semen traits (Rothschild, 1996; Smital et al., 2005; Ruiz-Sanchez et al., 2006). Semen traits are associated with the sperm quality of the boars and include: ejaculate volume (VOL, mL), sperm concentration (CON, 10^3 spermatozoa/mm^3), percentage of motile sperm (MOT, %), and morphologically abnormal cells (ABN, %), among others measurements. These traits are routinely assessed as semen quality measurements and are helpful indicators of the boar's fertility (Flower, 1997; Gadea, 2005; Foxcroft et al., 2008). Traits like CON influence the amount of doses that can be obtained from one ejaculate and has a direct economic impact on the boar stud and AI efficiency (Camus et al., 2011). Similarly, MOT is considered a viability parameter with a minimum threshold established by the industry (Sancho and Vilagran, 2013). The evaluation of morphology or ABN offers information on sperm quality and give insight on seminiferous tubule functionality and epididymal maturation that could be linked to the collection frequency program (Rutten et al., 2000; Gadea, 2005). Additionally, heritability estimates for VOL, CON, MOT, and ABN range from 0.14 to 0.25, 0.13 to 0.26, 0.05 to 0.18, and 0.04 to 0.12, respectively (Grandjot et al., 1997a; Wolf, 2009, 2010). These estimates suggest that selection can improve semen traits leading to recommendations of inclusion in selection strategies for terminal sires (Flowers, 2009). Considering that currently in the U.S., 90% of the sows that are housed in specialized indoor production facilities are bred using AI (Flowers, 2015), financial benefits could be derived of selection strategies that incorporate semen traits relative to traditional selection strategies in the pig industry.

Both crossbreeding and selection strategies require successfully mating boars with a sow. The reproductive technology used will play a critical role on the boar:sow ratio and thus on the intensity by which animals with superior genetic merit are used.

1.4. Reproductive technologies

Reproduction is the process that ensures the maintenance and growth of a species (Bidanel, 2011). In livestock species, this process can be manipulated using artificial insemination (Verberckmoes et al., 2004). Artificial insemination (AI) facilitates the fertilization of the female egg by ensuring the presence of an adequate number of male sperm proximal to the fertilization site (Allen et al., 1985). This technique which was introduced in livestock for sanitary reasons has become a tool necessary for a profitable pig production (Knox, 2000; Verberckmoes et al., 2004).

Artificial insemination in pigs was initiated in the early 1900s (Ivanov, 1907; Ivanov, 1922). This technique rapidly spread to U.S. (McKenzie, 1931), Japan (Ito et al., 1948; Niwa, 1958), and Western Europe (Polge, 1956). In countries with intensive pig production (e.g. Western Europe) more than 90% of the sows have been bred by AI for more than two decades (Gerrits et al., 2005; Vyt, 2007). When compared with natural mating, AI is a useful alternative that allows: a) rapid genetic improvement through the use of proven boars, b) optimum use of the boar (one ejaculate can inseminate several sows), c) prevention of the transmission of venereal diseases; d) ease of transportation and distribution of semen, e) removal of males from the herd, thus eliminating maintenance costs; f) use of intrauterine and deep intrauterine insemination techniques; g) use of frozen-thawed semen, and h) implementation of synchronization programs and crosses (Knox, 2000; Maes et al., 2008). Effective use of AI requires training on the technique, consideration of estrus detection (Sterle and Safranski, 1997), semen preparation, insemination technique, and sex-sorting options.

1.4.1 Artificial insemination using fresh semen preparation

Fresh boar semen (FRE) is the most popular preparation used with AI and this trend is widespread within the pig industry (Riesenbeck, 2011). From a total of 31 high pig producing, 11 countries have more than 90% of their sows mated using FRE AI. In Denmark, Chile, Norway and Netherlands more than 98% of the sows are mated using FRE AI (Riesenbeck, 2011).

The storage time of FRE to maintain a high percentage of viable and motile sperm is from 3 to 7 days for use with AI (Johnson et al., 1988; Levis, 2000). Because the viability of sperm decreases daily, the majority of FRE AI occurs during the first, second or third day following collection (Levis, 2000; Gerrits et al., 2005).

The popularity of FRE relative to FRO may be linked to the current economic models that are more concerned about the additional costs for FRO, instead of the aggregate values offered by this tool. For example, training costs, and management time for FRO are prioritized relative to boar supply and maintenance costs (Smith, 1983; Maes et al. 2008).

1.4.2 Artificial insemination using frozen semen preparation

Following the success of frozen bull sperm in the dairy industry the next logical step was to freeze boar sperm (Foote, 1996). However, due to the characteristics of the boar sperm plasmatic membrane (one of the lowest in cholesterol phospholipid proportion (0.26) and highest contain of unsaturated phospholipids) from maturation in the epididymis, the boar sperm is particularly sensitive to cryopreservation processes with poor frezability (Nikolopoulou et al., 1985; Parks and Lynch, 1992; Maxwell and Johnson, 1997; Cerolini et al., 2001; Maldjian et al., 2005). This situation has deterred wide-spread use of FRO AI (Johnson, 1985; Roca et al., 2011). Reports concluded that FRO was less suitable than FRE AI at the commercial pig level because of lower litter size, farrowing rate, and the need to double the sperm concentration resulting in fewer sows served per ejaculate (Wagner and Thibier, 2000). Nevertheless, FRO AI has been advocated for specialized genetic transfer applications (Gerrits et al., 2005).

An important and commonly used measure of sow herd reproductive performance is farrowing rate which is defined as the proportion of females served that farrow (Dial et al., 1992; Koketsu et al., 1997). It is generally accepted that farrowing rate of 85% is an appropriate target under commercial condition (Gadea et al., 2004). Farrowing rates for FRO AI ranged between 50-60% and are 20 to 30% lower than FRE in the literature (Johnson, 1985; Johnson, 1998). However, 72% to 82% farrowing rates have been reported for FRO AI in purebred and crossbred sows, respectively (Eriksson et al., 2002). Likewise, when using deep intrauterine insemination, the farrowing rates for FRO and FRE were 70% and 84%, respectively (Roca et al., 2003).

The reproductive efficiency of FRO relative to FRE has been associated with other factors that need to be considered at the time of AI. First, the lifespan of FRO sperm post-AI in the female tract is reduced (Waberski et al., 1994; Wongtawan et al., 2006). Second, there is a season effect on the fertility of FRO and this is more pronounced in sows than gilts. However, this effect has not been reported in FRE (Eriksson et al., 2002). Lastly, the reproductive performance of FRO could be improved through the selection of boars for high fertility (Almlid and Hofmo, 1996).

1.4.3 Artificial insemination using sex-sorted semen

Sex-sorting semen allows the selection of the sex of the offspring with 95% accuracy and requires separation of X- from the Y-chromosome bearing spermatozoa (Vazquez et al., 2009). Most domestic livestock species have a difference of 3.6 to 4.2% in DNA content between X- and Y-chromosome bearing spermatozoa. This difference allows the use of flow cytometric sorting for separating the two populations (Johnson, 1991; Johnson and Welch, 1999). Concerns about lower fertility, lower survival after cryopreservation and limitations on the speed of separation process makes the use of sex-sorting semen in the commercial tier of pig production unfeasible (Johnson, 1991; Johnson and Welch, 1999; Johnson et al., 2000; Gerrick et al., 2005; Wheeler et al., 2006). However, as low-dose insemination techniques such as intrauterine AI move forward, the practical application of sexing may follow and could be expected to have a tremendous impact on pig production worldwide (Roca et al., 2011).

Advantages of sex-sorting semen in pig production include: i) improvement of reproductive management in pig production because of the ability to plan matings for male or female lines, ii) production of offspring with the desired gender at the different tier, iii) unnecessary discussion on castration ban (especially important in Europe), and iv) eliminate males as a by-product of production (Vazquez et al., 2009).

1.4.4 Artificial inseminations techniques

Artificial insemination techniques differ on the location where the sperm is deposited, thus impacting the reproductive performance (Roca et al., 2006a; Vazquez et al., 2008). An average boar during natural mating deposits (replicated by conventional AI) around 50-70 $\times 10^9$

sperm in the cervical canal of the sow. Of these, most are lost due to the back flow, the inflammatory process, while a small percentage of the original sperm reach the reservoir to fertilize the oocytes (Steverink et al., 1998; Matthijs et al., 2000; Matthijs et al., 2003; Vazquez et al., 2008). Therefore, reproductive techniques that place the sperm closer to the reservoir are expected to have higher reproductive performance than conventional AI (CON) for a given concentration of quality sperm. For lower concentrations of quality sperm (due to FRO or sex-sorting), insemination techniques that deposit the sperm closer to the oocyte grant reasonable reproductive performance. Insemination techniques that supersede CON in locating the sperm closer to the oocyte include intrauterine (IUI) and deep intrauterine (DUI) AI (**Figure 1.5**, Vazquez et al., 2008).

1.4.4.1 Conventional AI

Natural mating was replaced by CON AI in pig farms because it is an inexpensive, easy, quick and successful procedure. Conventional AI deposits sperm to create a functional sperm reservoir in the oviduct with the goal to fertilize all of the ovulated oocytes. In CON AI, the semen is deposited in the posterior portion of the cervical canal (**Figure 1.5**). The protocol includes $3x10^9$ sperm/dose in a volume of 80 to 100 mL with the standard catheter. During estrus, the sow will be inseminated at least two times. This protocol limits the number of doses that can be prepared from one ejaculate (Roca et al., 2006b; Vazquez et al., 2008).

Even though CON AI with FRE meets the pig industry requirements, other sperm technologies like FRO and sex-sorted semen could provide advantages if strategies to achieve successful fertilization using few spermatozoa are developed. Also decreasing the number of spermatozoa required for successful insemination impacts the fixed costs of a dose of high added-value semen, promoting the use of these new sperm biotechnologies (Johnson, 2000; Glossop, 2003; Martinez et al., 2005).

1.4.4.2 Intrauterine insemination

This AI technique deposits the sperm in the uterine body (Vazquez et al., 2008). This insemination technique allows a reduction in the number of sperm and volume of inseminating dose, and decreases backflow loss (Hancock, 1959, Mezalira et al., 2005; Vazquez et al., 2008). The main obstacle to the IUI insemination is the cervical canal, characterized by the presence of the cervical folds. The protocol described includes $1x10^9$ sperm/dose in a volume of 30 mL with a device 15-20 cm longer than a conventional catheter, which is able to traverse the cervix and deposit the spermatozoa in the uterine body or posterior horn of sows (Vazquez et al., 2008).

Fields trials corroborated similar farrowing rates however, litter size with at least 2 piglets less with IUI compared to CON could occur (Watson and Behan, 2002; Rozeboom et al., 2004; Mezalira et al., 2005; Roberts and Bilkei , 2005; Sumransap et al., 2007). This decreased in litter size is associated directly to the reduction in the amount of sperm but could also be due to improper insemination because of lack of training of technicians in the handling of the IUI insemination device (Roberts and Bilkei, 2005). Others factors, like aged sperm, improper semen handling or insemination-ovulation interval can cause these results (Rozeboom et al. 2004).

Careful attention should be paid to proper insemination technology to minimize the incidence of cervical and uterine damage, since the semi-rigid extended catheters can damage reproductive tissues (Vazquez et al., 2008).

1.4.4.3 Deep intrauterine insemination

In DUI, the sperm is deposited in the far depths of the uterine horns. In comparison with CON AI, a 20-fold reduction in the amount of sperm needed, and at least an 8 to 20-fold reduction in the dose volume can be achieved using DUI without affecting farrowing rate and litter size (Martinez et al., 2001; Vazquez et al., 2005). The protocol included 150 to 600 $x10^6$ spermatozoa in a volume of 20 mL with a device that had 1.80 m length, 4 mm outer diameter, and 1.80 mm diameter of the inner tubing. Several trials confirmed that is possible to insert the catheter into one uterine horn in more than 90% of the sows, taking approximately 3 to 4 min per insemination (Martinez et al., 2005; Vazquez et al., 2005; Roca et al., 2006b).

Studies comparing DUI and CON AI in commercial insemination programs using 0.15 $x10^9$ sperm/dose were conducted in Spain and the U.S. (Vazquez et al., 2001; Day et al., 2003). Pregnancy rates and litter sizes were similar between DUI and CON AI in the Spanish trial. However, significant differences (2.4 piglets/litter) between the techniques were reported in the U.S. trial. This result was associated with the high incidence of unilateral fertilization in DUI (Day et al., 2003; Martinez et al., 2006).

The IUI and DUI procedures eliminate two major obstacles for routine application of FRO under commercial conditions: the large number of sperm/dose needed in each dose ($3x10^9$ sperm/dose CON AI, 1 to $1.5x10^9$ sperm/dose for IUI, and 0.15 to 0.6 $x10^9$ sperm/dose for DUI) and the low fertility achieved by FRO CON. Therefore, both procedures should be considered as practical insemination approaches that can be successfully used to produce piglets from FRO and sex-sorted sperm (Roca et al. 2003; Bathgate et al. 2005, Bolarin et al., 2006; Wongtawan et al. 2006).

Most studies of boar AI have evaluated either boar semen preparation or AI technique and focused on reproductive indicators (Vazquez et al., 1999; Martinez et al, 2001; Eriksson et al., 2002; Watson and Behan, 2002; Day et al., 2003; Roca et al., 2003; Rozeboom et al., 2004; Mezalira et al., 2005; Roberts and Bilkei, 2005). The objective of the proposed studies is to assess the impact of semen preparation and insemination techniques on financial indicators simultaneously. A production system under a wide range of conditions was simulated and the resulting output was used to evaluate the impact of semen preparation and insemination technique.

1.5. Evaluation of system

Return and costs converge in net profit of any production system (Skorupski, 1995). In livestock production systems, profits are the main driving force behind the breeding and selection objectives (Kluyts, 2004). To accomplish the goal of maximizing profit, the traits of economic importance that will be integrated in the breeding goal must be identified (Gjedrem, 1972). The evaluations of the breeding and selection programs consider three aspects: the improvement per unit time, the dissemination of genetic progress, and costs to profit ratio (Ollivier, 1988). One approach to evaluate breeding and selection programs is to survey production units and compare their performance. The challenge of pursuing this strategy is that few production units make their production and profit records publicly available. Another challenge is the availability of information across programs. Alternatively, the simulation of systems across a wide range of realistic scenarios based on real systems allows comprehensive assessment of the performance of systems while simultaneously considering different factors.

This simulation studies the expected genetic and economic gain response of the breeding strategies that must be made before investments are made (Wollny, 1995). Computer simulation is a useful tool for system analysis, especially when the real data is not available or limited (Nakimbugwe, 2005).

There are two simulation methods available that are suitable to design and evaluate breeding and selection programs: stochastic and deterministic. A stochastic simulation generates the inputs and outputs at an individual level and totals the indicators across the population where the variables are defined in ranges of values randomly selected. A deterministic simulation uses equations and population parameters (mechanisms are modeled explicitly) to calculate inputs and outputs at the system level (Gibson and Dekkers, 2009). Stochastic simulations are often used to validate deterministic simulations because the first ones tend to be easy to implement compared to the complete definition of the deterministic models, and because the stochastic nature reflects random sampling events (e.g. the best boar dies, or is culled due to lameness before producing offspring). However, stochastic programs can be computationally onerous because each animal in the population is individually identified and tracked (Gibson and Dekkers, 2009).

Some of the software packages available for deterministic calculation are ZPLAN (Willam et al., 2008), ZPLAN+ (Täubert et al., 2010), and SelAction (Rutten et al., 2002), and for stochastic ADAM (Pederson et al., 2009), EVA (Berg et al., 2006), and SixS (Kremer et al., 2006). However ZPLAN is the only comprehensive software package available that offers a detailed deterministic evaluation of complex breeding programs.

1.5.1 ZPLAN

The software ZPLAN allows users to combine the three components of livestock breeding and selection programs (Täubert et al., 2010). ZPLAN was developed in the 1980s at the University of Hohenheim, Germany (Niebel, 1974; Karras, 1993; Hill, 1974; Elsen and Mocquot, 1974; Brascamp, 1978). This program is written in Fortran and available open source, thus allowing the modification of existing subroutines (König et al., 2009; Okeno et al., 2013). ZPLAN encompasses gene-flow and selection index methodology and enables multitrait modeling, simulation of different breeding and selection plans in livestock species. ZPLAN can be applied for plans with several sub-populations, for populations used in a crossbreeding scheme and considers several tiers in the scheme such as nucleus, multiplier, and production or commercial levels (Willam et al., 2008). The outputs include response to selection for every trait, and tier, annual genetic gains for breeding objective traits and annual return on investment (Willam et al., 2008).

For the selection index, the information available to evaluate an animal candidate to be selected as parent of the next generation has to be defined by the number and type of relatives contributing to the index of an animal as well as records on an individual's own performance (Willam et al., 2002; Willam et al., 2008). Phenotypic (standard deviation for each trait, phenotypic correlation between each pair of traits and phenotypic correlations between the traits of relatives) and genetic information (heritable fraction of the variance in each trait and genetic correlation between each pair of traits) are also needed to construct the selection indexes. The modeling of breeding and selection programs by ZPLAN has two main steps: basic run and alternative runs for alternative breeding schemes. Alternative runs are calculated by varying certain parameters on the basic run to predict the outcome of each scheme using one or more output parameters (e.g. genetic gain per year, return, costs, profit). ZPLAN has some limitations (Willam et al., 2008). The software does not account for the changes in the genetic parameters during the period considered, nor returns from external sales (Dekker and Shook, 1990; Willam et al., 2008).

1.5.2 Programs prerequisites and definitions

The breeding and selection objectives and investment time are defined by the user in ZPLAN. Software inputs are the specification of both the traits to select for and the corresponding economic values. Additional inputs are the phenotypic standard deviation, phenotypic and genetic correlations and heritabilities of the traits. For each selection group (e.g. sows of sows, sows of boars, boars of sows and boars of boars within nucleus purebred line, and sows and boars of the F1 sows at the multiplier level), the available information sources and selection criteria must be defined (Künzi, 1976; Cunningham and Mahon, 1977; Willam et al., 2008).

Internal subroutines calculate the selection indices for each selection group, the numbers of selected animals, and the replacements and selection intensities of each selection group (Willam et al., 2008).

In breeding programs the process of discounting is that money spent or earned invested that generate an increase in its value over time. In evaluating a breeding program discounting factor is calculated:

$$d = \left(\frac{1}{1+r}\right)^{t}$$

d = is the discounting factor for financial value in year t

r = is the discount rate for the returns

The standard discounted expression (SDE) is specific to each selection group and each type of trait. The SDE is calculated weighting each selection group by the discounting factor (d). Two types of traits are defined by the user in ZPLAN, paternal and maternal traits. The SDE is calculated as follow (Nitter et al., 1994):

$$\mathrm{SDE}_{ij} = \sum_{t=1}^{T} h_i' m_{jt} d$$

were

T = is the time horizon of the investment

h_i' = $1xs$ vector (realization vector) for traits i where s is the number of sex/age class

m_{jt} = $sx1$ vector of gene proportions that the animal of the various sex-age classes carry from selection groups j at the time t.

The net present values of return and profit are calculated. The return is the monetary value of the genetic change expressed by improved animals over the time of investment (defined previously by the user). ZPLAN estimate the returns using elements calculated in the gene flow subroutine. The return minus the cost is the profit (Nitter et al., 1994).

The return from selecting for a single trait i in a selection group j (R_{ij}) and the total return for the selection group (R_i) are given by the equations (Nitter et al., 1994):

$$R_{ij} = \Delta G_{ij}.SDE_{ij}.v_i$$

$$R_j = \sum_{i=1}^{m} \Delta G_{ij}.SDE_{ij}.v_i$$

where ΔG_{ij} is the genetic superiority of the trait i in a selection group j, SDE is the standard discounted expression and v_i is the undiscounted economic values of the trait i , one of m traits contained in the breeding and selection objective.

The overall return from selection is obtained by summing all selection groups (k' groups considering all tiers) over all m traits (Nitter et al., 1994):

$$R_{overall} = \sum_{i=1}^{m} \sum_{j=1}^{k\prime} \Delta G_{ij}.SDE_{ij}.v_i.$$

Another input is the definition of the fixed and variable costs. The variable costs are costs per sow for each measurement or information source utilized in selection. These costs are specific together with their average time of occurrence, in years or semester (dependents of the species). Fixed costs are those incurred in the genetic improvement efforts that are independent of the number of sows involved. Such fixed costs are expressed per sow and per semester, cost of registration, data processing and other technical services. The overall cost of the investment in one round of selection is calculated as (Nitter et al., 1994):

$$C_{Overall} = \sum_{t=0}^{T^*} \frac{c_t}{(1 + r^*)^t}$$

where T^* is the time of one round of selection, c_t are cost applying in years t and r^* is the discount rate for cost.

The net present value of the returns from one round of selection or the overall profit is obtained by subtracting the overall cost from the overall returns (Nitter et al., 1994).

1.5.2.1 Gene flow

The software ZPLAN uses the gene flow method to assess the genetic improvement of the production system simulated. Gene flow method allows study of the flow of genes through a population, which in turn can be used to define the times at which genes are expressed, and by knowing the value of that expression and the number of animals involved, the economic value of that expression can be calculated. Discounting future profits and costs then allows cost-benefit analysis of a breeding program (Hill, 1974).

The gene flow technique is useful for: i) evaluating the economic costs-benefits of a particular selection or breeding decision, ii) derivation of discounted economic values for use in development of breeding goals, iii) economic evaluation and optimization of breeding programs, iv) study of genetic lags in multi-tier breeding programs (Gibson and Dekker, 2009). The gene flow method is used in ZPLAN for the calculation of the net present values of return (Nitter et al., 1994).

For the gene flow methodology the vector m'_0 defined the proportion of genes in each sex and age class in generation t that come from the original group of animals at time 0. The vector m_t has the length $h + k$ where h is the number of males classes and k the number of females classes. The elements of m_t are found by defining the flow of genes from each sex-age class at $\mathrm{t} - 1$ to each sex-age class at time t. Then $\mathrm{m}_t = P\mathrm{m}_{(t-1)}$

where P had the general for

$$\mathrm{P} = \begin{array}{cc} & \text{genes FROM} \\ \text{genes TO} & \left\{\begin{bmatrix} \mathrm{P}_{11} & \cdots & \mathrm{P}_{1,\mathrm{h+k}} \\ \vdots & \ddots & \vdots \\ \mathrm{P}_{\mathrm{h+k},1} & \cdots & \mathrm{P}_{\mathrm{h+k},\mathrm{h+k}} \end{bmatrix}\right. \end{array}$$

where P_{ij} is the proportion of genes in sex-age class i at time t which comes from sex-age class j at time t-1.

In P**,** the first row defines the origin of genes of males entering the population and row h + 1 defines the origin of genes of females entering the population. The sum of all rows is 1 so that all genes in each current age-sex class are accounted for. The matrix P represents several levels, from nucleus to commercial then the elements of P_{ij} are equal to groups and describes the proportion of genes appearing in group-age class i at time t that originate from group-age class j at time t-1.

The direct contributions to $\mathrm{m}_{(\mathrm{t})}$ from the original group of individuals (parents) should be excluded to considered the expression of the genes in their progeny. This can easily be accomplished by defining a new vector $\mathrm{m}^*_{(\mathrm{t})}$, which refers proportions of genes in each sex-age class at time t that originated from the original group of animals at time 0 through ageing alone. Thus, $\mathrm{m}^*_{(0)} = m_{(0)}$ and $\mathrm{m}^*_{(t)} = \mathrm{Q}\mathrm{m}^*_{(t-1)} = \mathrm{Q}^t m_{(0)}$ where Q is a transition matrix that describes ageing. This allow to defined the matrix R that consists of the reproduction rows and can be calculated: $\mathrm{R} = \mathrm{P} - \mathrm{Q}$. Then, the response (r_t) which is a vector of proportions of genes in each sex-age class at time t that originated from our group of interest in time 0 through descendants alone can be calculated :

$$\mathrm{r}_{(\mathrm{t})} = \mathrm{R}\mathrm{Q}^{\mathrm{t}-1}\mathrm{m}_{(0)} + \mathrm{P}\mathrm{r}_{(\mathrm{t}-1)}$$

where R is the reproduction matrix, $\mathrm{Q}^{\mathrm{t}-1}$is the is the transmission matrix of ageing, $\mathrm{m}_{(0)}$ is the mean of breeding values relative to unselected animals in the same age-sex class, P is the transmission matrix and $\mathrm{r}_{(\mathrm{t}-1)}$ the vector of response. The first term of the equation represents the production of progeny from the initial group of individuals, while the second term represents the ageing of and reproduction from their descendants and is the response. Thus, if selection is practiced in every time period, the cumulate response vector $R_{(t)}$ is:

$$R_{(t)} = r_t + r_{t-1} + \cdots + r_1$$

Let w be a vector of the economic benefits per one unit of genetic improvement of the trait for each sex-age group, across all animals that express the trait by sex-age group.

$$w = n'v$$

where n is a vector with numbers of animals by sex-age group that express the trait in each given time.

v is a vector with economic values per unit of genetic improvement for the trait in and per animal that expresses the trait in each sex-age group. With a single round of selection, the returns at time t of the genetic superiority created at time 0 is given by:

$$y^*_{(t)} = w'r_{(t)}$$

With a discount rate for time t of $d_{(t)}$, the present value of these returns is equal to:

$$y_t = d_{(t)}w'r_{(t)}$$

The present value of cumulative returns at time t from one round of selection at time 0 is equal to:

$$Y_{(t)} = \sum_{i=1}^{t} y_i$$

Discounted returns at time t if continuous selection is practiced are equal to:

$$y^C_{(t)} = d_{(t)}w'R_{(t)}$$

and present value of cumulate returns from continuous selection at time t are given by:

$$\mathrm{Y}_{(\mathrm{t})}^{\mathrm{C}} = \sum_{\mathrm{i}=1}^{\mathrm{t}} \mathrm{y}_{\mathrm{t}}^{\mathrm{c}}$$

The economic returns depend on the magnitude of the genetic change, genetic relationship of the descendants to the individuals in which the genetic change was created, and the timing of the expressions of the genetic change; returns received in the near future are more valuable than returns received in the more distant future (Gibson and Dekker, 2009).

1.6. Linear models

The evaluation of the impact of semen preparation and insemination techniques using simulation result in a series of financial outputs across biological scenarios (litter size and farrowing rate). Linear models were used to evaluate the statistical significance of the effect of semen preparation and insemination techniques while adjusting for biological scenarios.

The linear models describe the relationship between two types of variables as a function of linear in a set of parameters. The linear model relates the response variable y to the explanatory variable(s) x_i through a set of parameters, $b_0, b_{1,} b_{2,} \dots . b_i$ such that is linear in the set of parameters (Kuehl, 2000):

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_i x_i + e$$

where y is the response variable, b_i are the unknow parameters of the models, x_i the independent variables, and $e$is the random error. The random error is the variation associated of the observation and the expected value defined:

$$e = y - E[y]$$

$$E[e] = E\big[y - E[y]\big] = E[y] - E[y] = o$$

The expected value of the errors is 0.

The classification of the models according with the nature of the effects can be made as: fixed (all the effects are fixed), random (all the effects are random) and mixed (fixed and random effects).

An effect is included in the model as a fixed effect when the levels include all possible classes of interest, are reproducible, are small, and the same levels would be taken account if the experiment is repeated (Rodriguez-Zas, 2012).

The general notation of the fixed models is

$$y = Xb + e$$

where y is a column vector $nx1$ with the records, b is a column vector $px1$ with the unknown fixed parameters, e is the residual column $nx1$ random vector, and X is the incidence matrix nxp that relates the records in y with the parameters in b.

The expecting value $E[y] = Xb$, the variance $Var[y] = Var[e]$

The solution to the system is $\hat{b} = (X'X)^{-1}X'y \;\; Var[b] = (X'X)^{-1}\sigma_e^2$

When the effect is included in the model as random, the results are (co)variances and refers to all possible levels, requires assumptions of the distributions of the random variables (normal distribution with mean cero, variances equal to 1, homogenous and independent), and had large amount of levels (Rodriguez-Zas, 2012).

The mixed effects models in matrix notation:

$$y = X\beta + Zu + e$$

where y is a column vector $nx1$ with the records, b is a column vector $px1$ with the unknown fixed parameters, u is the vector of random effects $ax1$, e is the residual column $nx1$ random vector, X is the incidence matrix nxp that relates the records in y with the parameters in b, and Z is the incidence matrix nxa that relates the records in y with the parameters in u.

The expecting value $E[y] = Xb$, the variances are:

$Var[u] = G$, $Var[e] = R$, $Var[y] = ZGZ' + R$

The structure of G and R depends of the assumption made about the random effects.

Then if the random effects are assumed to have homogenous variance and independence the matrix of (co) variances are diagonals

$$G = \sigma_u^2 \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{axa} \qquad R = \sigma_e^2 \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}_{nxn}$$

The solution are obtained solving the equation systems (Rodriguez-Zas, 2012)

$$\begin{bmatrix} X'R^{-1}X & X'R^{-1}Z \\ Z'R^{-1}X & Z'R^{-1}Z + G^{-1} \end{bmatrix} \begin{bmatrix} b \\ u \end{bmatrix} = \begin{bmatrix} X'R^{-1}y \\ Z'R^{-1}y \end{bmatrix}$$

Then $\hat{b} = \left(X'\hat{V}^{-1}X\right)^{-1} X'\hat{V}^{-1}y \;\; Var(b) = \left(X'\hat{V}^{-1}X\right)^{-1}$

$\hat{u} = \hat{G}Z'\hat{V}^{-1}(y - X\hat{b})$

The solution for the fixed effects are used to test the null hypothesis (using t or F test or likelihood ratio or approach for model comparison) associated with the differences of the means of the levels of the effects. The solution of the random effects are used to compute the random effects variances and tested using likelihood ratio test or approach for models comparison like Akaike or BIC. The GLM and MIXED procedures of SAS could be used for the estimation of the solutions of fixed and mixed models, respectively (Rodriguez-Zas, 2012).

In sum, a comprehensive study of the impact of insemination technology, semen preparation (and additional reproductive technologies) on the financial indicators of a three-tier, crossbred pig production system will be undertaken. A deterministic simulation including selection indices encompassing production and reproduction traits and applied to multiple sub-populations will be considered. Linear models will be used to assess the statistical significance of the technologies and preparations across biological scenarios.

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1.8. Figures

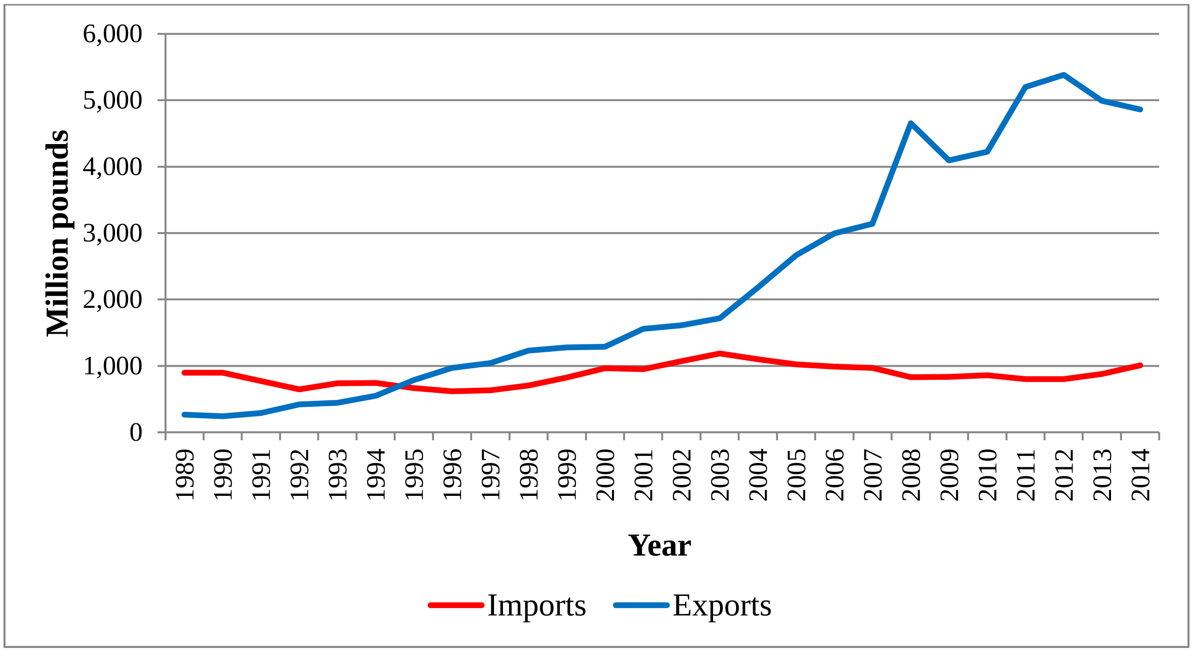

Figure 1.1. US imports and export pork meat trade (Source: USDA, 2015).

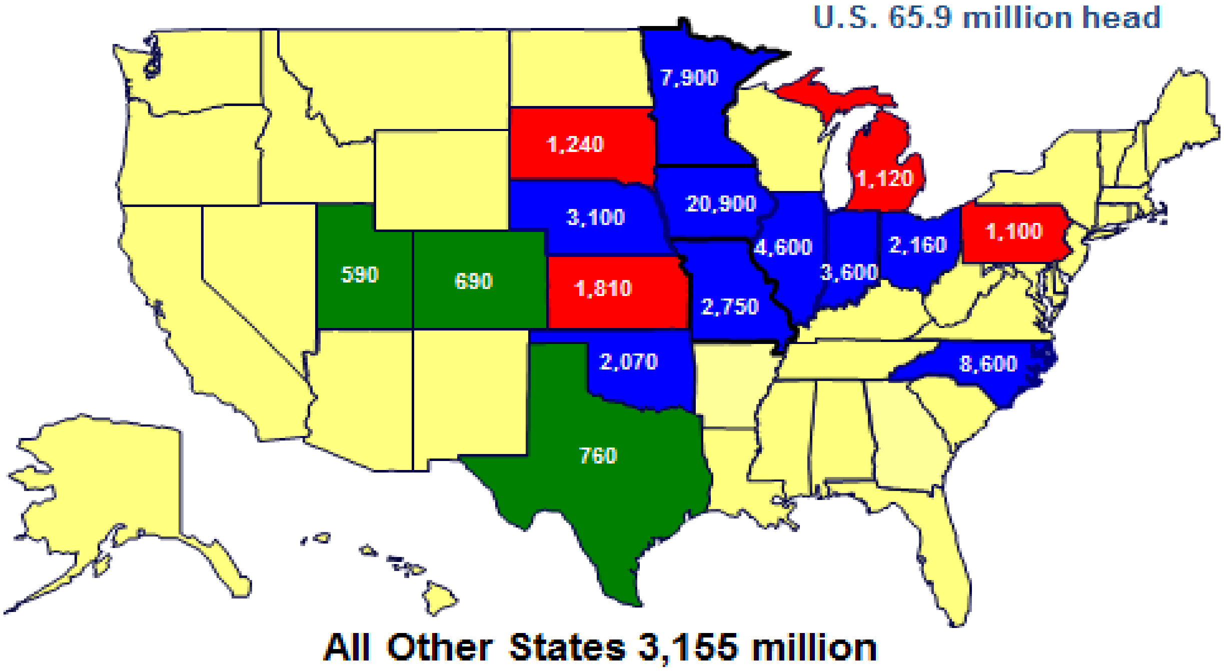

Figure 1.2. Total hogs and pigs inventory (1,000 head) December 1, 2014. Source National Agricultural Statistic Service (NASS, 2015).

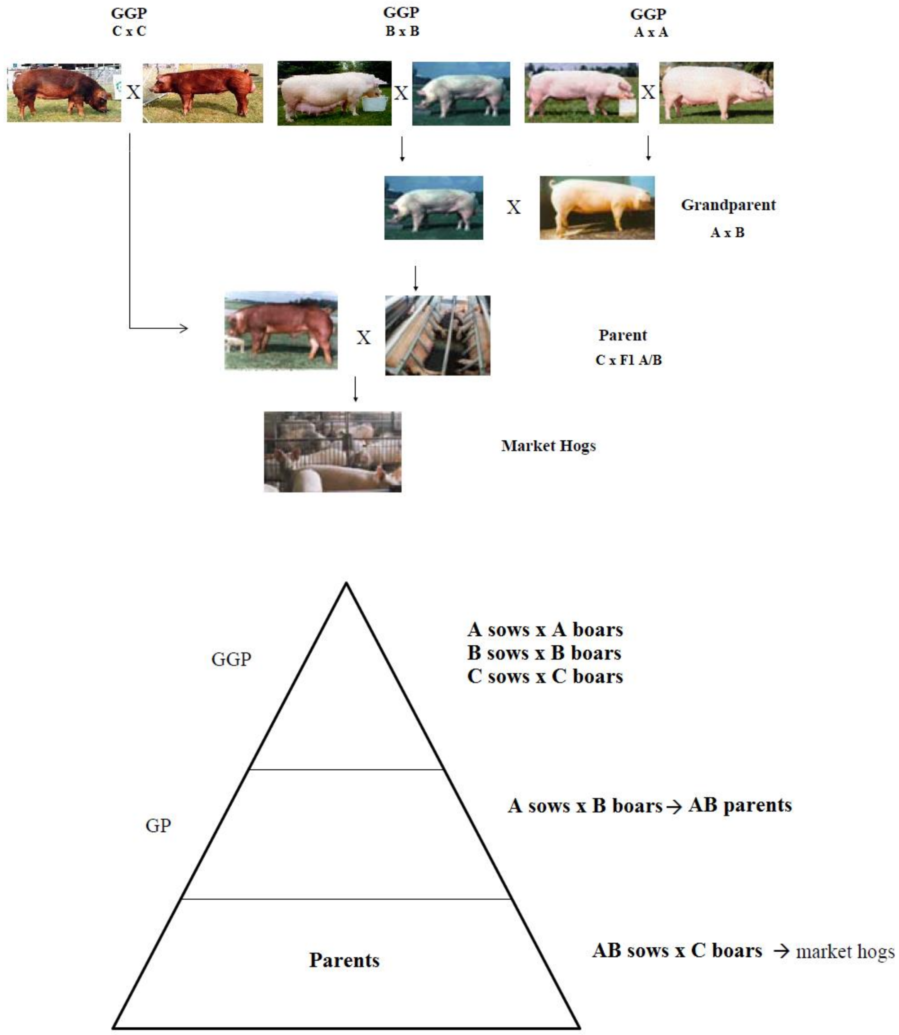

Figure 1.3. The three-tier crossbred pigs and the equivalent position in the pyramidal structure

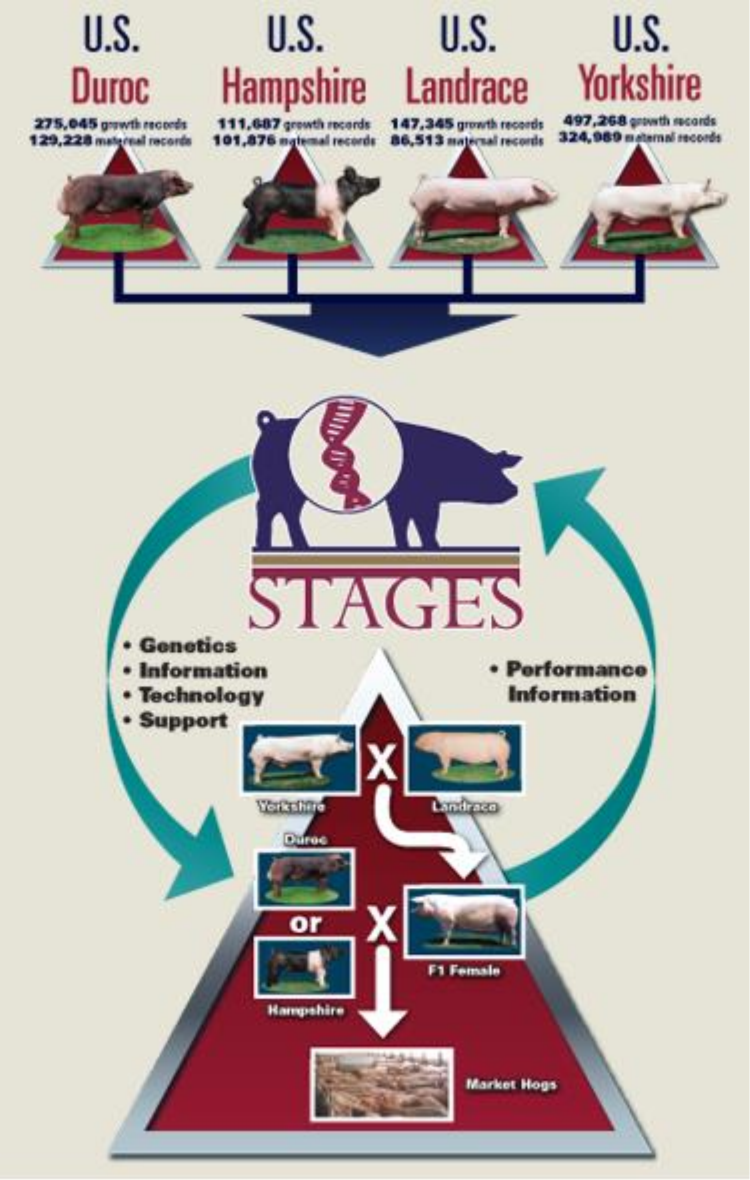

Figure 1.4. Breeds and combinations and information flows in the NSR (retrieved from NRS website)

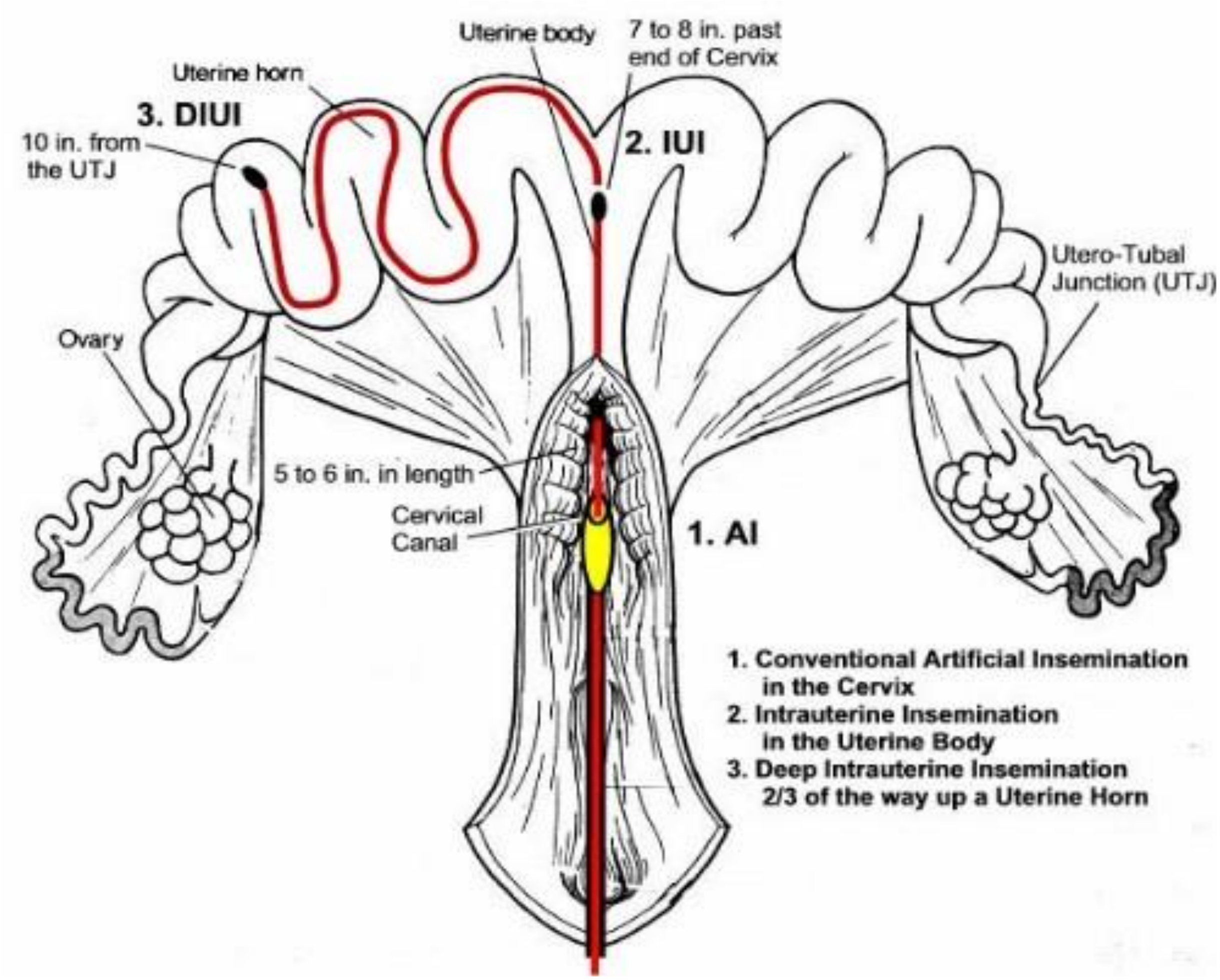

Figure 1.5. Reproductive tract of a sow showing the site of deposition of sperm with CON, IUI, and DUI AI techniques.

CHAPTER II: Impact of pig insemination technique and semen preparation on profitability[1]

D. Gonzalez-Pena, R.V. Knox, J. Pettigrew, and S.L. Rodriguez-Zas

2.1. Abstract

Artificial insemination (AI) technique and semen preparation impact boar utilization efficiency, genetic dissemination, and biosecurity. Intrauterine (IUI) and deep intrauterine (DUI) AI techniques require lower number of spermatozoa per dose compared to conventional (CON) AI. Frozen semen (FRO) has been associated with lower reproductive performance compared to fresh (FRE) preparation. The combined effects of three AI techniques (CON, IUI, and DUI) and two semen preparations (FRE and FRO) on the financial indicators of a pig crossbreeding system were studied. A three-tier system was simulated in ZPLAN and the genetic improvement in a representative scenario was characterized. The cross of nucleus lines B and A generated 200,000 BA sows at the multiplier level. The BA sows were inseminated (CON, IUI, or DUI) with FRE or FRO semen from line C boars at the commercial level. Semen preparation and AI technique were represented by distinct sow:boar ratios in the C x BA cross. A range of farrowing rates (60% to 90%) and litter sizes (8 to 14 liveborn pigs) were tested. Genetic improvement per year for number born alive, adjusted 21-day litter weight, days to 113.5 kg, backfat, average daily gain were 0.01 pigs per litter, 0.06 kg, -0.09 days, -0.29 mm, and 0.88 g respectively. On average, the net profit for FRE (FRO) increased (P-value < 0.0001) from CON to IUI and DUI

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by 2.2% (3.2%) and 2.6% (4%), respectively. The differences in profit between techniques were driven by differences in costs. Differences in fixed costs between IUI and DUI relative to CON were -2.4% (-5.2%) and -3.4% (-7.4%), respectively. The differences in total costs between FRE and FRO were lower than -5%. The difference in variable costs between FRE and FRO ranged from -5.3% (CON) to -24.7% (DUI). Overall, insemination technique and semen preparation had a non-linear effect on profit. The average relative difference in profit between FRE and FRO was less than 3% for the scenarios studied.

2.2. Introduction

The use of frozen-thawed boar semen (FRO) in artificial insemination (AI) could augment the genetic progress, reduce biosecurity hazards, reduce the cost of boar maintenance, and enable the creation of gene banks relative to fresh semen (FRE) preparation (Knox, 2011). These advantages could be overshadowed by the lower viable spermatozoa, average farrowing rate (FR between 35% and 85%), and litter size of FRO relative to FRE observed in some studies (Almlid et al., 1987; Eriksson et al., 2002; Roca et al., 2003; Bolarin et al., 2006, 2009; Wongtawan et al., 2006). Other studies have reported non-significant differences in litter size (LS) between FRO and FRE (Eriksson et al., 2002; Roca et al., 2003; Bathgate et al., 2008). Reservations about the fecundity and limited expertise on effective FRO preparation has resulted in wide-spread use of FRE. Artificial insemination with FRE is used in the 31 major pork producing countries and 11 of them breed more than 90% of the sows with this technique (Riesenbeck, 2011).

Intrauterine (IUI) and deep intrauterine (DUI) insemination techniques that deposit sperm closer to the oviduct relative to conventional (CON) AI augment the fecundity of boar semen (Roca et al., 2006; Vazquez et al., 2008). Most studies have evaluated boar semen preparation or

AI techniques and focused on reproductive indicators (Eriksson et al., 2002; Day et al., 2003; Roca et al., 2003). A comprehensive evaluation of the potential interaction between AI technique and semen preparation on the profit of pig production systems is needed. The main objective of this study was to characterize the simultaneous impact of boar semen preparation (FRE and FRO) and insemination technique (CON, IUI, and DUI) utilized at the commercial level of the production system on financial indicators. Supporting aims include the simulation of a three-tier system under a comprehensive range of productive and reproductive circumstances, consideration of realistic biological and financial scenarios, characterization of the genetic change on a representative scenario, and evaluation of complementary financial indicators.

2.3. Materials and Methods

The simultaneous impact of boar semen preparation (FRE and FRO) and AI technology (CON, IUI, and DUI) on the financial indicators of a system were studied. The comparison of the preparation-technique combinations (FRE-CON, FRE-IUI, FRE-DUI, FRO-CON, FRO-IUI, and FRO-DUI) on the financial indicators was implemented using ZPLAN (Willam et al., 2008). This software supports the assessment of financial and genetic progress in a deterministic framework using selection indexes and gene flow methodology.

A three-tier, three-way crossbreeding scheme was simulated and the selection objective encompassed nine traits that were weighted differently across selection groups. The three-tier classic pyramid system included: a) a nucleus level containing 500 sows for each of the three lines, maternal lines A and B selected for reproductive traits and paternal line C selected for growth-carcass traits; b) a multiplier level that generates F1 sows from B boars and A sows; and c) a commercial level that sells pigs obtained from the cross between BA sows and C boars. The mating scheme resulted in a transmission matrix including 16 selection groups (**Table 2.1**; Wünsch et al., 1999). Each nucleus line population had four selection groups (boars to produce boars, boars to produce sows, sows to produce boars, and sows to produce sows) totaling 12 (3 x 4) groups. Nucleus A and B pigs produced selection groups 13 and 14 respectively. Nucleus C produced selection group 15 boars. Sows and boars from groups 13 and 14 were mated to produce group 16 (F1 BA sows). The impact of semen preparation and insemination technique was tested on the service of group 16 sows by group 15 boars. Group 16 sows were artificially inseminated (using CON, IUI, or DUI techniques) with boar C group 15 semen (prepared using FRO or FRE) and generated the market pigs that were sold for profit (**Table 2.1**).

Selection criteria

In this study, genetic selection does not interact with semen preparation and insemination technique because the latter ones are applied in the third tier of the system. Nevertheless, genetic selection impacts the overall financial indicators of the system and is hereby described. Two types of traits, growth-carcass (hereby denoted as growth traits) and reproductive traits were considered in the selection indices. Growth traits included days to 113.5 kg (D113), backfat (BF), average daily gain (ADG), feed efficiency (FE), and lean carcass % (LEAN). The ADG and D113 were included in the index because average daily gain encompasses the period between 27 to 113 kg weight meanwhile D113 encompasses the days between birth and 113 kg weight. Reproductive traits included: number of pigs born alive (NBA), litter birth weight (LBW), adjusted 21-day litter weight (A21), and number at 21 days (N21). The maternal lines are usually line crosses to exploit the heterosis of the reproductive traits that typically have lower heritability (Bidanel, 2011).

Table 2.2 lists the traits included in the selection indices, and economic values ($ per unit), phenotypic standard deviations, heritabilities, and genetic and phenotypic correlations (NSIF, 2002). Seven selection indices were created using this information and records from the pig, ancestors (boar, sow, paternal boar, paternal sow, maternal boar, and maternal sow) and half-sibs. The seven indices were applied to generate replacement boars and sows in each of the three nucleus groups and to generate multiplier sows BA inseminated with line C (2 indices (male and female) x 3 nucleus + 1 terminal level = 7).

The relative economic weight for each trait in the selection indices was the product of the economic value by the standard discount expression (SDE) to adjust for interest rate across time, expressed relative to the genetic standard deviation of each trait (Wünsch et al., 1999). One round of selection (selection only based on parental and half-sib information) was used and thus the effects of inbreeding, lower genetic variation due to selection, and return from breeding product sales were assumed negligible (Willam et al., 2008).

Biological and technological input parameters

The biological, technological, and financial input parameters used in the simulation were based on a literature review (**Tables 2.3** and **2.4**). Sow stayability was kept constant during the period studied and ranged from 1 year (nucleus sows) to 3 years (commercial sows) and involuntary culling annual rate was approximately 32% (Rodriguez-Zas et al., 2003; 2006; Knox et al.; 2008; Knox et al., 2013). For comparison purposes and set barn capacity, all scenarios were simulated to result in 225,000 farrowings at the commercial level every six months and a profit horizon of 10 years (Weller, 1994). This farrowing number adjusted by the 2.25 expected farrowings per year (2.25 / 2) correspond to 200,000 sows per cycle. For the set farrowing target, the number of sows in the multiplier and commercial levels varied depending on the FR and LS scenario simulated. In addition to the number of sows, the boar utilization varied across scenarios through the sow:boar ratio. The fixed cost per six months (also referred to as semester in this study) of labor for the previously described production system was estimated to be approximately $7.8 million. This cost resulted from multiplying the number of sows (200,000) by the hourly labor wage ($15) by the hours of labor per week (40 hours) and by the number of weeks of labor in a semester (26 weeks), and dividing this total by the sow:worker ratio (400). The fixed costs also included insurance cost (1% of the building and equipment costs) and maintenance and repair cost (2.5% of the building and equipment costs). Published building and equipment costs were assumed (Dhuyvetter et al., 2009). The following example demonstrates the calculation of the building and equipment costs. Consider a nucleus herd including 1,500 sows. The herd was divided into two groups assuming that at any one time 15% of the sows are farrowing and thus assigned to the farrowing building and the remaining 85% of the sows are in the gestation building. The building and equipment costs per sow were $2,508 and $1,150, respectively in the farrowing building and $600 and $235, respectively in the gestation building. Thus, the total building and equipment costs (220*2,508 + 220*1,150 + 1,280*600 + 1,280*235) amount of $1,837, 560. Insurance and maintenance costs were applied to the result of the previous calculation.

The variable costs per sow were comprised of the cost associated with the reproductive technique and other variables costs directly related to performance and pedigree records at the nucleus level. The variable costs associated with reproductive technique included standard catheter cost, labor time and wage listed in **Table 2.4**. The variable costs related to performance included \$3 per production measurement and \$5 per reproduction measurement (Levis et al., 2001; Martinez et al., 2010; Wünsch et al., 1999).

The differences in reproductive efficiency between FRE and FRO and among CON, IUI, and DIU were simulated through differences in the sow:boar ratio (**Table 2.4**). For the calculations, an average of 80 to 120 billion sperm cells per collection value was assumed (Bidanel, 2011). Distinct sperm counts for each of the three AI techniques evaluated: $3x10^9$ sperm per dose for CON, $1x10^9$ sperm per dose for IUI, and $0.150x10^9$ sperm per dose for DUI, 2.1 semen doses per estrus, 2.25 farrowings per year, and 50 collections per boar per year were assumed (**Table 2.4**, Levis et al., 2001; Roca et al., 2006; Safranski, 2008). This strategy permitted the evaluation of the same range of FR and LS among preparation (FRE and FRO) and AI technology (CON, IUI, and DUI).

Financial input parameters and system outputs

A summary of the input values used in the simulation was listed in **Tables 2.3** and **2.4** (Rodriguez-Zas et al., 2003; 2006; Knox et al.; 2008; Dhuyvetter et al., 2009; Knox et al., 2013**).** A FRO:FRE costs ratio equal to three was considered based on standard catheter cost, labor cost and labor time (Levis et al., 2001; Martinez et al., 2010). A demonstration of the computation in **Table 2.4** is provided for FR = 90% and a sow:boar ratio = 258:1 resulting in \$12.04 per sow. Assuming 2.1 doses of semen used per estrus and 2.25 farrowings per sow and year, then the number of doses used in a year would be 4.725. Assuming 27 doses were produced per ejaculate and 50 ejaculates per boar and year, then a boar annually produces 1350 doses. From these numbers, the number of sows needed per boar for a FR = 90% is (1350 / 4.725)*0.9 = 257.14. Thus, 258 sows per boar would be needed. Assuming 2.25 farrowings per year (1.125 per six months), 225,000 / 1.125 = 200,000 farrowing sows would be required every 6 months. These sows, at a FR = 90% will require 222,222.22 inseminations. Furthermore, assuming the costs of: \$0.17 per catheter, \$10 per insemination labor hour, 4 minutes per insemination event, and \$10 per processed semen, then the total cost would be (0.17 * 222,222.22) + (((222,222.22 * 4) / 60) * 10) + (222,222.22 * 10) = \$2,408,148.15. Lastly, 2,408,148.15 /y 222,222.22 = \$12.04 per sow.

The impact of preparation and insemination technique on financial outputs was evaluated. Financial outputs included net profit, gross return and total costs (fixed costs and variables costs, Nitter et al., 1994; Wünsch et al., 1999; Willam et al., 2008). Briefly, profit was return minus cost and return was the monetary value of the sow over the time of investment and thus was adjusted for the profit horizon using SDE. Total costs included variable and fixed costs that are dependent and independent of the size of the operation, respectively. For example, variable costs related to performance and pedigree recording, and fixed costs included overhead cost to maintain the breeding program (Wünsch et al., 1999).

Analysis of financial impact and sensitivity analysis

A representative scenario was defined. Artificial insemination using FRE preparation and CON technique is the most common practice in pig industry and was used in an estimated 60% of swine breed herds in the US in 2000 (Knox, 2000). A large scale survey found that 90% of all the hand-mated sows were artificially inseminated (USDA, 2007). Under these conditions the median LS was approximately 10 liveborn pigs per litter and, the average FR in the US was estimated at 82.7% (Knox et al., 2013; PigCHAMP, 2011). Thus, the representative scenario in this study was characterized by the FRE-CON combination, a LS of 10 liveborn pigs per litter, and a FR of 85%.

The genetic improvement along the three-tier system was evaluated for a representative scenario. The genetic progress at the nucleus and multiplier levels was unaffected by semen preparation or insemination technique because these practices were tested solely on the production of market pigs at the commercial level. The study of the impact of the preparation-techniques at the commercial third tier of the system enabled the profiling of the financial trends without confounding with genetic changes throughout the nucleus and multiplier tiers. In the first stage of the study the genetic improvement and financial indicators were estimated for the representative scenario across all tiers. Subsequent stages evaluated the impact of the six preparation-technique combinations on the financial indicators.

A sensitivity analysis was implemented based on the evaluation of a grid of FR ranging from 60% to 90% (by 5%), and LS ranging from 8 to 14 liveborn pigs per litter (one pig increments). Under these boundaries, the worst scenario was characterized by a FR equal to 60% and a LS equal to 8 liveborn pigs per litter and the best scenario was characterized by FR equal to 90% and LS equal to 14 liveborn pigs per litter. An average FR equal to 75% and LS equal to 11 liveborn pigs per litter were considered and variation within symmetric upper and lower bounds was evaluated. Realistic upper boundaries were considered to ensure that the study will remain relevant in the short term. Farrowing rate above 85% and LS equal to 14 had been frequently reported for several years (Love et al., 1995; Young et al., 2010; Klindt, 2003).

The financial outputs from the simulation were analyzed using the model:

$$y_{ijkl} = \mu + P_i + T_j + PT_{ij} + \beta_1\left(F_{ijk} - \bar{F}\right) + \beta_2(F_{ijk} - \bar{F})^2 + \beta_3\left(L_{ijkl} - \bar{L}\right) + \beta_4(L_{ijkl} - \bar{L})^2 + \varepsilon_{ijkl}$$

where y_{ijkl} denoted the value of net profit, gross return, total costs, fixed costs, variable costs, or sows population size, μ is the overall mean, P_i denoted the fixed effect of preparation type with two levels (FRE and FRO), T_j denoted the fixed effect of the insemination technique with three levels (CON, IUI, and DUI), PT_{ij} denoted the interaction between preparation and insemination technique, $\beta_1$and β_2 denoted the regression coefficients for the covariate FR (F 60 to 90%) linear and quadratic, respectively, $\beta_3$and β_4 denoted the regression coefficients for the covariate LS (L, 8 to 14 pigs per litter), respectively, and ε_{ijkl} denoted the residual associated with y_{ijkl}. Analysis was implemented using the MIXED procedure of SAS (SAS Institute, Cary, NC). Orthogonal contrasts among the preparation by technique interaction levels were evaluated and Scheffé multiple comparison adjustments were used (Kuehl, 2000). The preparation and technique trends within the interaction were tested using the SLICE option in the GLM procedure (SAS Institute, Cary, NC). The evaluation of the impact of semen preparation on various indicators was expressed in relative difference terms. Relative difference was defined as the difference in the indicator between FRE and FRO, relative to the recorded maximum value between FRE and FRO. The use of a relative value enabled the assessment of the impact protected from specific absolute values, and the use of observed maximum value supported a conservative calculation.

2.4. Results and Discussion

Genetic and financial trends using fresh conventional insemination on a representative scenario

In the first stage of the study the genetic improvement and financial indicators were evaluated for the representative scenario characterized by the FRE-CON preparation-technique combination for FR equal to 85% and LS equal to 10 pigs per litter **(Table 2.5)**. This information offered a characterization of the simulated system, unaffected by the semen preparation or AI technique used at the commercial tier.

The genetic gain for the reproductive traits (NBA, LBW, A21, and N21) was similar between the maternal lines A and B selected for reproductive traits, and higher than line C. The relative gain of the average of A and B relative to C (calculated as average the (A,B)-C/ maximum[average(A,B),C]) for NBA, LBW, A21, and N2 were 85%, 82%, 99% and 77%, respectively. On the other hand, the genetic gain in the paternal line C selected for growth traits (D113, BF, FE, ADG, and LEAN) was higher than for the average of lines A and B. The relative gain of C relative to the average of A and B or D113, BF, FE, ADG, and LEAN was 141%, 75%, 93%, 134%, and 118%, respectively.

The genetic trends observed in the simulated representative scenario (**Table 2.5**) were consistent with previously reported (Wünsch et al., 1999). The reported genetic trends for D113, BF, NBA, A21, and number of pigs weaned in Yorkshire, Duroc, Hampshire and Landrace were:-0.40 d, -0.39 mm, 0.018 pigs per litter, 0.114 kg, and 0.004 pigs, respectively (Chen et al., 2002; 2003). The estimated annual genetic trends for ADG, FE, and carcass average BF thickness in French Large White pigs were 3.7 g/d, -0.014 kg/kg and -0.35 mm, respectively (Tribout et al., 2010). The annual genetic trend for European pig breeding programs for daily gain, lean meat % and LS were 20 g/d, 0.5% , and 0.2 pigs per litter, respectively (Merks, 2000).

Table 2.6 summarizes the discounted economic values and associated relative economic weights per trait and nucleus line. These values were applied to the nucleus lines and thus apply all the scenarios simulated. Consistent with the genetic progress, the weight of NBA were higher in the maternal lines A and B with values of 29.3% and 36.8%, respectively. For the paternal line, the relative economic weights were less than 1% for the reproductive traits and ranged from 3.1% to 42.4% for the growth traits (BF, FE, and ADG).

The monetary value of the genetic gain was \$11.36, \$11.30, and \$3.04 for the lines A, B, and C, respectively (**Table 2.5**). The difference in genetic gain between lines was due to the higher economic weight assigned to reproductive traits based on the lower expected heritabilities of these traits and impact of additional sold pigs resulting from reproductive trait improvement. The maternal lines A and B contributed the 57.19% and 33.41 % and the paternal line C contributed 9.39 % of the total return. The highest contribution of line A that produced BA sows was due to the direct selection of the sows and their replacement for the reproductive traits; whereas, only males were indirectly selected in line B to produce boars of BA sows. In a previous simulation study, the growth and carcass traits contributed more to the return than the reproductive traits and the boar line had higher monetary gain (Wünsch et al., 1999). The differences between studies can be attributed to the single round of selection simulated in the present study compared to the two-stage selection in the boar line including information from crossbred offspring in the previous study. The single round of selection used in this study used only progenitor and half-sib information to select offspring.

Impact of semen preparation and insemination techniques on financial indicators

The second phase of the study evaluated the impact of FRE-CON, FRE-IUI, FRE-DUI, FRO-CON, FRO-IUI, and FRO-DUI preparation-techniques on the financial indicators. Sensitivity analysis of the different preparation-technique combinations across FR and LS levels permitted the contextualization of the results. The study of the impact of the preparation-techniques at the commercial third tier of the system enabled the profiling of the financial trends without confounding with genetic changes in the first and second tiers.

The P-values of the main effects of semen preparation, insemination technique, and their interaction on profit, return, total costs, fixed costs, variable costs and sow population size were summarized in **Table 2.7**. Minimum statistical and financial thresholds were used to identify significant differences on biological and financial indicators across preparation- technique combinations. A stringent P-value threshold (P-value < 0.005) was used for the multiple testing across financial indicators. The minimum threshold for indicating a financially significant difference was set at 2%, equivalent to the average interest rate of Treasury note (US Treasury, 2013). The interaction between preparation and technique had a significant impact on all the financial indicators considered across the FR and LS levels evaluated. No quadratic association between FR level and the financial indicators was observed. No linear or quadratic association between LS level and variable costs and no quadratic association with the other financial indicators except for sow population size was observed.

The outputs of the simulation, including financial indicator and sow population size estimates (least square means), grouped by preparation-technique were summarized in **Table 2.8**. Across the FR and LS levels studied, the indicators differed across preparation-technique combinations. Sow population size exhibited an interesting pattern across preparations and techniques. The numbers of sows in the FRO-DIU, FRE-DUI and FRE-IUI scenarios were similar. This result can be explained by the effect of the insemination technique on the reproductive efficiency, and thus the sow population size. Fewer boars were needed to serve the same amount of sows using IUI and DUI relative to CON and therefore less sow replacements were needed to produce these boars, resulting in a lower sow population size. The impact of semen preparation and insemination technique on sow population size was first investigated due to the major role on all financial indicators.

Impact of semen preparation and insemination technique in sow population size

The relative differences in sow population size across insemination techniques within preparation failed to surpass the 2% threshold (**Table 2.8**). Note that sow population size are consistent with the amount of sows needed year to produce 225,000 farrowing in 1 according to each technique used and the range of FR and LS considered. Within FRE preparation, the highest sow population size was observed with the CON technique. However, higher FR and LS were associated with less difference between CON and the other techniques, therefore with FR equal to 90% and LS equal to 14 pigs per litter, fewer sows were needed compared with CON in the worst scenario. Within FRO, the trends across insemination techniques were similar to FRE. In the worst FR-LS reproductive scenario, CON had highest sow population size (1.35% higher than IUI and 1.92% higher than DUI) and in the best FR-LS reproductive scenario CON had a lowest difference relative to the other techniques (0.94% higher than IUI and 1.33% higher than DUI for the best scenario). Thus, fewer sows were needed in IUI and DUI than in CON. The relative differences in sow population size between FRE and FRO were -1.13% for CON, -0.38% for IUI, and -0.06% for DUI in the worst reproductive scenario. Also, the relative differences between FRE and FRO in sow population size were -0.77% for CON (**Figure 2.1**), -0.28% for IUI, and -0.06% for DUI in the best reproductive scenario. The lower sow population required by FRE relative to FRO was due to the lower number of doses obtained from an ejaculate for FRO, and to the higher number of boar and thus semen doses required to serve the higher number of sows (Roca et al., 2006). The boar spermatozoa are sensitive to cryopreservation and usually no more than 50% of the spermatozoa in the ejaculate survive the cryopreservation process.

Impact of semen preparation and insemination technique in net profit

The relative difference in net profit (expressed in $ per sow) between FRE and FRO was 2.88% for CON and lower than the 2% financial threshold for IUI and DUI (**Table 2.8**). The higher difference in net profit between FRE and FRO under CON was due to the higher population size required to achieve similar outputs. Within FRE (FRO), CON had 2.22% (3.19%) lower profit than IUI and 2.55% (3.98%) lower profit than DUI (**Table 2.8).** The relative differences in profit between FRE and FRO were 3.53% for CON, 2.48% for IUI, and 1.85% for DUI in the worst FR-LS reproductive scenarios. Also, the relative differences in profit between FRE and FRO were 2.34% for CON (**Figure 2.2**), 1.55% for IUI, and 1.15% for DUI in the best reproductive scenario.

The net profit increased more than 2% from CON to IUI and to DUI and these increments were slightly less than 2% higher in FRE than in FRO (**Table 2.8**). The average net profit across FR and LS scenarios in FRE (FRO) increased from CON to IUI and DUI by 2.22% (3.19%) and 2.55% (3.98%), respectively. The profit per sow and farrowing cycle for FRE across FR and LS scenarios ranged from $40.81 to $44.47 for CON, $41.99 to $45.27 for IUI, and $42.17 to $45.4 for DUI techniques. Likewise, the profit per sow for FRO across FR and LS scenarios ranged from $39.37 to $43.43 for CON, $40.95 to $44.57 for IUI and $41.39 to $44.88 for DUI techniques. These results demonstrate that the impact of insemination technique on net profit was higher in FRO than in FRE. Both, FRE and FRO had the lowest profit in the worst reproductive scenario and the higher profit in the best reproductive scenario.

The DUI technique had the highest net profit regardless of preparation. The profit of DUI relative to CON for FRE (FRO) ranged from 3.23% (4.88%) in the worst reproductive scenario to 2.05% (3.23%) in the best scenario, respectively. In general, IUI resulted in higher profit than CON regardless of preparation. The profit for FRE (FRO) semen preparation associated with IUI relative to CON ranged from 2.81% (3.86%) in the worst reproductive scenario to 1.77% (2.56%) in the best scenario respectively (**Figure 2.3** and **Figure 2.4** for FRE and FRO, respectively). The higher benefit of IUI relative to the CON technique for FRO preparation could be linked to the smaller dose required by the first technique that accommodates the lower spermatozoa counts obtained by FRO relative to the FRE preparation.

Net profit is an indicator that combines two other financial indicators, return and total costs (Nitter et al., 1994). A careful study of the differences between preparation and insemination techniques within profit components was undertaken to better understand the overall differences in profit.

Impact of semen preparation and insemination technique in gross return

The relative differences in gross return (expressed in $ per sow) between FRE and FRO within insemination technique were low (less than 1%) and did not surpass the 2% threshold (**Table 2.8**). These results suggest that the differences in profit between preparations and techniques were driven by differences in costs. A detailed analysis of total, fixed, and variable costs was undertaken. The average return for FRE (FRO) across FR and LS scenarios increased from CON to IUI and DUI by 0.33% (0.59%) and 0.50% (0.92%), respectively. These findings imply that the impact of insemination technique on return was higher in FRO than in FRE. Both FRE and FRO had the lowest return in the worst scenario and the higher return in the best scenario.

Impact of semen preparation and insemination technique on total costs

The relative differences in total costs (expressed in $ per sow) between FRE and FRO surpassed the 2% financial threshold in all three CON, IUI and DUI techniques (**Table 2.8**). The relative differences in total costs between FRE and FRO were -4.98% for CON (**Figure 2.5**), -4.09% for IUI, and -3.55% for DUI, in the worst FR-LS reproductive scenario. Also, the relative differences in total costs between FRE and FRO were -3.84% for CON (**Figure 2.5**), -3.02% for IUI, and -2.62% for DUI, in the best reproductive scenario.

The average total costs in FRE (FRO) across FR and LS scenarios decreased from CON to IUI and DUI by 3.8% (4.71%) and 4.04% (5.37%), respectively. The total cost for FRE ($ per sow) across FR and LS scenarios ranged from $21.35 to $19.27 for CON, $20.42 to $18.64 for IUI and $20.36 to $18.6 for DUI techniques. Likewise, the total cost for FRO ($ per sow) across FR and LS scenarios ranged from $22.47 to $20.04 for CON, $21.29 to $19.22 for IUI and $21.11 to $19.1 for DUI techniques. Across insemination techniques, the cost of FRE was lower than FRO. Both FRE and FRO had the highest total costs in the worst reproductive scenario and the lowest total costs in the best reproductive scenario. The higher total costs associated with the lower FR were due to the higher number of inseminations per pregnancy needed to have similar number of output market pigs. This, in turn leads to a higher required investment in materials, labor, and semen.

The DUI technique had the lowest total costs regardless of preparation. The total costs of DUI relative to CON using FRE (FRO) was -4.64% (-6.05%) in the worst reproductive scenario and -3.48% (-4.69%) in the best reproductive scenario, respectively. The total costs of IUI were lower than CON regardless of preparation. The total cost of IUI relative to CON using FRE was -4.36% (**Figure 2.6**) and using FRO was -5.25% (**Figure 2.7**) in the worst reproductive scenario and -3.27% **(Figure 2.6)** and using FRO was -4.09% (**Figure 2.7**) in the best reproductive scenario, respectively.

The majority of the indicators studied follow a constant trend. The local oscillations observed in some trends like the one depicted in **Figure 2.1** are the result of the individual simulation of the corresponding particular scenario. An unexpected drop (approximately 7%) in the total cost difference between IUI and CON was observed at 85% FR (**Figure 2.7**). The overall trend of lower total costs in IUI relative to CON was maintained however the tendency for lower differences in costs between the techniques with higher FR was not observed at 85% FR. The reason for this small oscillation was a slightly higher change in the denominator (total cost for CON) than the numerator (total cost difference between IUI and CON) that cause the relative indicator to dip.

The fixed costs were linearly correlated to the number of individuals in the breeding program and variable costs were defined in each selection group (Sitzenstock et al., 2013). Thus, both fixed and variable costs were expected to be distinctly affected by preparation and insemination technologies considered. Also, the higher differences in return and total costs between FRE and FRO in CON, relative to IUI and DUI can be understood by profiling the fixed and variable costs. An investigation on the impact of preparation and insemination technique on the two components of the total, variable and fixed costs was undertaken.

Impact of semen preparation and insemination technique in the variable costs

The relative differences in variable costs (expressed in $ per sow) between FRE and FRO within insemination technique were -5.42% for CON, -20.30% for IUI, and -24.57% for DUI, and were more extreme than the 2% financial threshold (**Table 2.8**). The relative differences in variable costs between FRE and FRO preparations were -5.88% for CON, -23.87% for IUI, and -27.63% for DUI in the worst reproductive scenarios. Also, the relative differences in variable costs between FRE and FRO were -4.73% for CON, -18.94% for IUI, and -22.07% for DUI, in the best reproductive scenario. The substantial increase in variable cost differences between FRE and FRO from CON to IUI and DUI is due to the requirements of the techniques in catheter costs, labor costs and labor time. These differences in variable costs do not translate into total costs due to the relative higher impact of fixed costs.

The average variable costs in FRE across FR and LS scenarios decreased from CON to IUI and DUI by 16.38% and 9.15%, respectively. However, the average variable costs in FRO decreased from CON to IUI by 0.44% and changed the trend and increased by 12.42% for DUI related to CON. The IUI technique was associated with the lowest variable costs, despite that the lowest population size was observed in DUI. However the higher catheter costs, labor costs and labor time of DUI compared with IUI increased the variable costs for DUI compared to IUI. In FRE, the variable costs of DUI did not reach the values of CON because the reduction in variable costs had two sources; the reduction in sow population size, and the reduction in the boar maintenance costs. Thus, despite of the higher catheter costs, labor costs and labor time compared with CON, the variable costs decreased. The difference between IUI and CON in FRO was only $0.01. The weaker trend stems from the reduction in variable costs solely due to a reduction in sow population size. This reduction was insufficient to compensate the increased cost associated with the IUI and DUI techniques relative to CON.

The variable costs ($ per sow) for FRE across FR and LS scenarios ranged from $2.08 to $1.81 for CON, $1.69 to $1.54 for IUI and $1.86 to $1.66 for DUI techniques. The variable costs for FRO ($ per sow) across FR and LS scenarios ranged from $2.22 to $1.90 for CON, $2.21 to 1.90 for IUI and $2.57 to $2.13 for DUI techniques. Both, FRE and FRO had the highest variable costs in the worst reproductive scenario, and the lowest costs in the best reproductive scenario. The synergistic effect of preparation and technique costs was responsible for the different variable costs trends between FRE and FRO.

Impact of semen preparation and insemination technique on fixed costs

The relative differences in fixed costs (expressed in $ per sow) between FRE and FRO within insemination technique was -4.33% for CON and more extreme than the 2% financial threshold for IUI and DUI (**Table 2.8**). The relative differences in fixed costs between FRE and FRO were -4.89% for CON (**Figure 2.8**), -1.78% for IUI, and -0.27% for DUI, in the worst reproductive scenarios. Also, the relative differences in fixed costs between FRE and FRO were -3.75% for CON, -1.33% for IUI, and -0.18% for DUI, in the best reproductive scenario.

The average fixed costs across FR and LS scenarios for FRE (FRO) decreased from CON to IUI by 2.4% (5.16%) and from CON to DUI by 3.43% (7.4%). The fixed cost ($ per sow) for FRE across FR and LS scenarios ranged from $19.27 to $17.46 for CON, $18.73 to $17.09 for IUI and $18.50 to $16.94 for DUI techniques. Likewise, the fixed cost ($ per sow) for FRO across FR and LS scenarios ranged from $20.26 to $18.14 for CON, $19.07 to $17.32 for IUI and $18.55 to $16.97 for DUI techniques. The impact of insemination technique on fixed costs was higher in FRO than in FRE because of the higher costs associated with spermatozoa loss of the former preparation. A reduction of fixed costs could be achieved by augmenting the efficiency of the technique through a higher number of doses per boar (Glossop, 2003).

Regardless of the insemination technique, FRO returns per sow were on average $63.23 (compared to $63.08 for FRE) and FRO had higher fixed (2.1%) and variable (16.98%) costs than FRE. Therefore, FRO was 3.6% more costly and had 2.07% less net profit than FRE. Developments in the preparation and technologies could further diminish these differences. The present study considered tangible returns and costs in the comparison of the financial indicators of FRE and FRO when applied to the commercial level of a production system. Further studies will benefit from considering other benefits of FRO relative to FRE associated with biosecurity hazard, management logistics of boar maintenance, creation of a genetic bank, and use of FRO in the nucleus and multiplier levels that could lead to accelerated genetic improvement. The former considerations at a global plane and the latter considerations at an individual systems production level could offset some of the financial differences between FRO and FRE identified in this study.

In conclusion, insemination and semen preparation techniques have a non-additive effect on profit, return, total costs, fixed costs, variable costs, and sow population size. At a similar farrowing number in the commercial level, both IUI and DUI insemination techniques allowed a reduction in sow population size and an increase in the efficiency of boar use with the consequent reduction in fixed costs. The main differences between FRE and FRO in the profits were driven by differences in variable costs. The relatively small differences between FRE and FRO in sow population size (lower than -2% on average), return (lower than 1% on average), and profit (lower than 3% on average) must be weighted in consideration of the benefits of FRO in terms of efficiency of boar semen, dissemination of genetics, and biosecurity.

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2.6. Tables

Table 2.1. Transmission matrix denoting the relationship between the 16 pig population groups in the simulated three-tier, three-line crossbreed production system.

		Maternal Lines				Paternal Line		F1
		A		B		C		BA
Group		Boars	Sows	Boars	Sows	Boars	Sows	Sows
Nucleus Maternal Line A	Boars	1	2					
	Sows	3	4					
Nucleus Maternal Line B	Boars			5	6			
	Sows			7	8			
Nucleus Paternal Line C	Boars					9	10	
	Sows					11	12	
Multiplier	Sows		13[1]	14[2]				
Commercial						15[3]		16[4]

[1] Sows in group 13 were obtained from the cross among line A boars and sows (groups 1, 2, 3, and 4). [2] Boars in group 14 were obtained from the cross among line B boars and sows (groups 5, 6, 7, and 8). [3] Boars in group 15 were obtained from the cross among line C boars and sows (groups 9, 10, 11, and 12). [4] Sows in group 16 were obtained from the cross among groups 13 sows and group 14 boars. The sows in group 16 are inseminated with fresh or frozen semen from boars in group 15, using conventional, intrauterine or deep intrauterine techniques to produce pigs for the market.

Table 2.2. Economic values (EV), heritability (h^2), phenotypic standard deviations (σ_p), genetic (above diagonal) and phenotypic (below diagonal) correlations of the nine traits included in the selection indices applied to the nucleus and multiplier stages (NSIF, 2002).

	Parameter			Correlation								
Traits[1]	EV($)	h^2	σ_p	NBA	LBA	A21	N21	D113	BF	FE	ADG	LEAN
NBA	13.50	0.10	2.50	***1.00***	0.63	0.12	0.80	0.20	0	0	0	0
LBA	0.45	0.29	7.20	0.80	***1.00***	0.50	0.67	0	0	0	0	0
A21	0.50	0.15	16.00	0.20	0.66	***1.00***	0.60	0	0	0	0	0
N21	6.00	0.06	2.35	0.60	0.70	0.6	***1.00***	0	0	0	0	0
D113	0.12	0.30	13.00	0.10	0	0	0	***1.00***	0	0.60	-0.70	0.10
BF	15.00	0.40	0.20	0	0.10	0	0	-0.18	***1.00***	0.33	0.14	0.70
FE	13.00	0.30	0.25	0	0	0	0	0.50	0.25	***1.00***	-0.70	0.40
ADG	6.00	0.30	0.20	0	0.20	0	0	-0.50	0.20	-0.65	***1.00***	0.20
LEAN	1.10	0.48	1.50	0	0	0	0	0.10	0.70	0.30	0.10	***1.00***

[1] NBA = number born alive (pigs/litter); LBA = litter birth weight (kg); A21 = adjusted 21-day litter weight (kg); N21 = number of pigs per litter at 21 days (pigs/litter); D113 = days for pig to reach 113.5 kg (d); BF = backfat (mm); FE = feed efficiency (kg/kg), ADG = average daily gain (g/day), LEAN = lean carcass (%).

Table 2.3. Biological, technological and financial input values used in the simulation.

Variables	Input
Nucleus size (sows)	500
Involuntary culling	32 %
Boar:sow ratio (1st tier)	30
Boar:sow ratio (3st tier)	Variable (see Table 4)
Offspring reared (maternal lines A, B)	9.5
Offspring reared (paternal line C)	8.5
Offspring reared (multiplier sows BA)	10
Productive life of sows (1st pyramid tier)	1 year
Productive life of sows (2st pyramid tier)	2 years
Productive life of sows (3st pyramid tier)	3 years
Productive life of boars (1st pyramid tier)	1 year
Productive life of boars (2st pyramid tier)	1 year
Productive life of boars (3st pyramid tier)	1 year
Age of sows at the first litter	11 months
Age of boars at the first litter	12 months
Investment period	10 years
Interest ratio for returns	3 %
Interest rate for costs	2 %
Fixed cost per semester of labor	$ 7,800,000
Insurances cost	$ 18,735.6
Maintenance and repair cost	$ 46,839.0
Cost associated with the reproduction technology	Variable (see Table 4)
Cost of boar keeping (fresh semen preparation) per day	$ 0.75

Table 2.4. Input biological (sow:boar ratio) and financial (cost, \$/sow) parameters for the two semen preparations and three insemination technologies used at the third-tier commercial level of the production system across selected farrowing rates.

	Semen preparation[1]					
	FRE			FRO		
	Techniques[2]			Techniques[2]		
Farrowing Rate %	CON	IUI	DUI	CON	IUI	DUI
90	258(12.04)	772(13.47)	5143(24.44)	115(34.26)	343(35.69)	2286(46.67)
80	229(13.55)	686(15.15)	4572(27.50)	102(38.55)	305(40.15)	2032(52.50)
70	200(15.48)	600(17.32)	4000(31.43)	89(44.05)	267(45.89)	1778(60.00)
60	172(18.06)	515(20.21)	3429(36.67)	77(51.39)	229(53.54)	1524(70.00)

[1] FRE = fresh semen preparation; FRO = frozen semen preparation.

[2] CON = conventional AI; IUI = Intrauterine AI; DUI = deep intrauterine AI.

Table 2.5. Genetic gain per year for various biological and financial indicators, generation interval, return, cost, and profit for the fresh semen preparation (FRE) and conventional insemination technique (CON) on a representative scenario.

Parameter	Unit	Nucleus lines			Total
Genetic gain per year Traits[1]		A	B	C	
NBA	pigs/litter	0.02	0.02	0.003	
LBA	kg	0.13	0.13	0.02	
A21	kg	0.09	0.09	0.001	
N21	pigs/litter	0.01	0.01	0.003	
D113	days	0.54	0.67	-1.49	
BF	mm	-0.17	-0.12	-0.57	
FE	kg/kg	0.0004	0.0002	0.004	
ADG	g	-2.31	-3.08	8.03	
LEAN	%	-0.02	-0.03	0.14	
Mean generation interval	Years	1.17	1.17	1.17	
Monetary genetic gain per year	$	11.36	11.30	3.04	
Return for single trait	$				
NBA	$	16.80	9.72	0.002	26.52
LBA	$	8.33	4.88	0.03	13.24
A21	$	5.97	3.72	0.01	9.70
N21	$	4.96	2.87	0.02	7.85
D113	$	-0.26	-0.12	1.11	0.73
BF	$	0.45	0.14	2.10	2.69
FE	$	0.04	-0.02	0.60	0.62
ADG	$	-0.23	-0.11	1.11	0.77
LEAN	$	-0.08	-0.06	0.93	0.79
Return Total ($/sow)	$	35.98	21.02	5.91	62.91
Return %	%	57.19	33.41	9.39	
Cost total ($/sow)	$				20.32
Profit ($/sow)	$				42.59

[1] NBA = number born alive; LBA = litter birth weight; A21 = adjusted 21-day litter weight; N21 = number at 21 days; D113 = days for pig to 113.5 kg; BF = backfat; FE = feed efficiency; ADG = average daily gain; LEAN = lean carcass.

Table 2.6. Discounted economic values and relative economic weights of traits used in the selection indices applied to the maternal (A and B) and paternal (C) nucleus lines.

	Discounted economic values ($/sow)			Relative economic weights (%)		
	Nucleus Line			Nucleus Line		
Traits[1]	A	B	C	A	B	C
NBA	8.792	5.015	0.159	29.389	36.847	0.311
LBA	0.293	0.167	0.005	0.980	1.228	0.010
A21	0.326	0.186	0.006	1.088	1.365	0.012
N21	3.908	2.229	0.071	13.062	16.376	0.138
D113	0.057	0.020	0.173	0.189	0.151	0.339
BF	7.069	2.561	21.630	23.629	18.818	42.389
FE	6.126	2.220	18.746	20.479	16.309	36.737
ADG	2.828	1.025	8.652	9.452	7.527	16.956
LEAN	0.518	0.188	1.586	1.733	1.380	3.109

[1] NBA = number born alive; LBA = litter birth weight; A21 = adjusted 21-day litter weight; N21 = number at 21 days; D113 = days for pig to 113.5 kg; BF = backfat; FE = feed efficiency; ADG = average daily gain; LEAN = lean carcass.

Table 2.7. Impact (P-value) of semen preparation, insemination technique, farrowing rate and litter size on the output financial indicators.

	Effect[1]						
Indicator[2]	P	T	PT	F	FF	L	LL
Profit	<.0001	<.0001	<.0001	<.0001	<.0601	<.0001	<.0511
Return	<.0001	<.0001	<.0001	0.0116	0.1568	<.0001	<.0601
Total costs	<.0001	<.0001	<.0001	<.0001	<.0711	<.0001	0.9227
Fix costs	<.0001	<.0001	<.0001	0.0051	0.0666	<.0001	0.9101
Variables cost	<.0001	<.0001	<.0001	<.0001	<.0591	0.4538	0.9849
Population size	<.0001	<.0001	<.0001	0.0067	0.7213	<.0001	<.0001

[1] P = semen preparation type (FRE, FRO); T = insemination technique (CON, IUI, DUI); PT = interaction between preparation and technique; F = linear trend on farrowing rate; FF = quadratic trend on farrowing rate; L = linear trend on litter size; LL = quadratic trend on litter size.

[2] Profit, return, total cost, fix cost, and variable cost expressed in $/sow, population size expressed in number of sows.

Table 2.8. Absolute and relative comparison of the output biological and financial indicators across semen preparation and insemination techniques.

	Insemination technique[1]	Semen preparation[2]		SE[3]	RD[4]
Indicator		FRE	FRO		%
Population size (sows)	CON	236293.88^{c}	238512.25^{d}	159.61	-0.93
	IUI	235106.12^{b}	235853.06^{bc}	159.61	-0.32
	DUI	234587.76^{a}	234710.20^{ab}	159.61	-0.05
Profit ($/sow)	CON	42.78^{b}	41.55^{a}	0.02	2.88
	IUI	43.75^{e}	42.92^{c}	0.02	1.9
	DUI	43.90^{f}	43.27^{d}	0.02	1.44
Return ($/sow)	CON	63.05^{b}	62.76^{a}	0.003	0.46
	IUI	63.26^{d}	63.13^{c}	0.003	0.21
	DUI	63.37^{f}	63.34^{e}	0.003	0.05
Total costs ($/sow)	CON	20.28^{d}	21.21^{e}	0.01	-4.38
	IUI	19.51^{a}	20.21^{c}	0.01	-3.46
	DUI	19.46^{a}	20.07^{b}	0.01	-3.04
Variables costs ($/sow)	CON	1.92^{c}	2.03^{e}	0.01	-5.42
	IUI	1.61^{a}	2.02^{d}	0.01	-20.30
	DUI	1.75^{b}	2.32^{f}	0.01	-24.57
Fix costs ($/sow)	CON	18.35^{d}	19.18^{e}	0.01	-4.33
	IUI	17.91^{b}	18.19^{c}	0.01	-1.54
	DUI	17.72^{a}	17.76^{a}	0.01	-0.23

$^{a-f}$ Means within a indicator (across the 6 preparation-insemination techniques levels) with different superscript differ within row (P-values < 0.001).

[1] Insemination technique: conventional (CON), intrauterine (IUI), and deep intrauterine (DUI).

[2] Semen preparation: fresh (FRE) and frozen (FRO).

[3] standard error.

[4] RD = relative differences in columns between FRE and FRO (FRE-FRO/maximum ([FRE, FRO]).

2.7. Figures

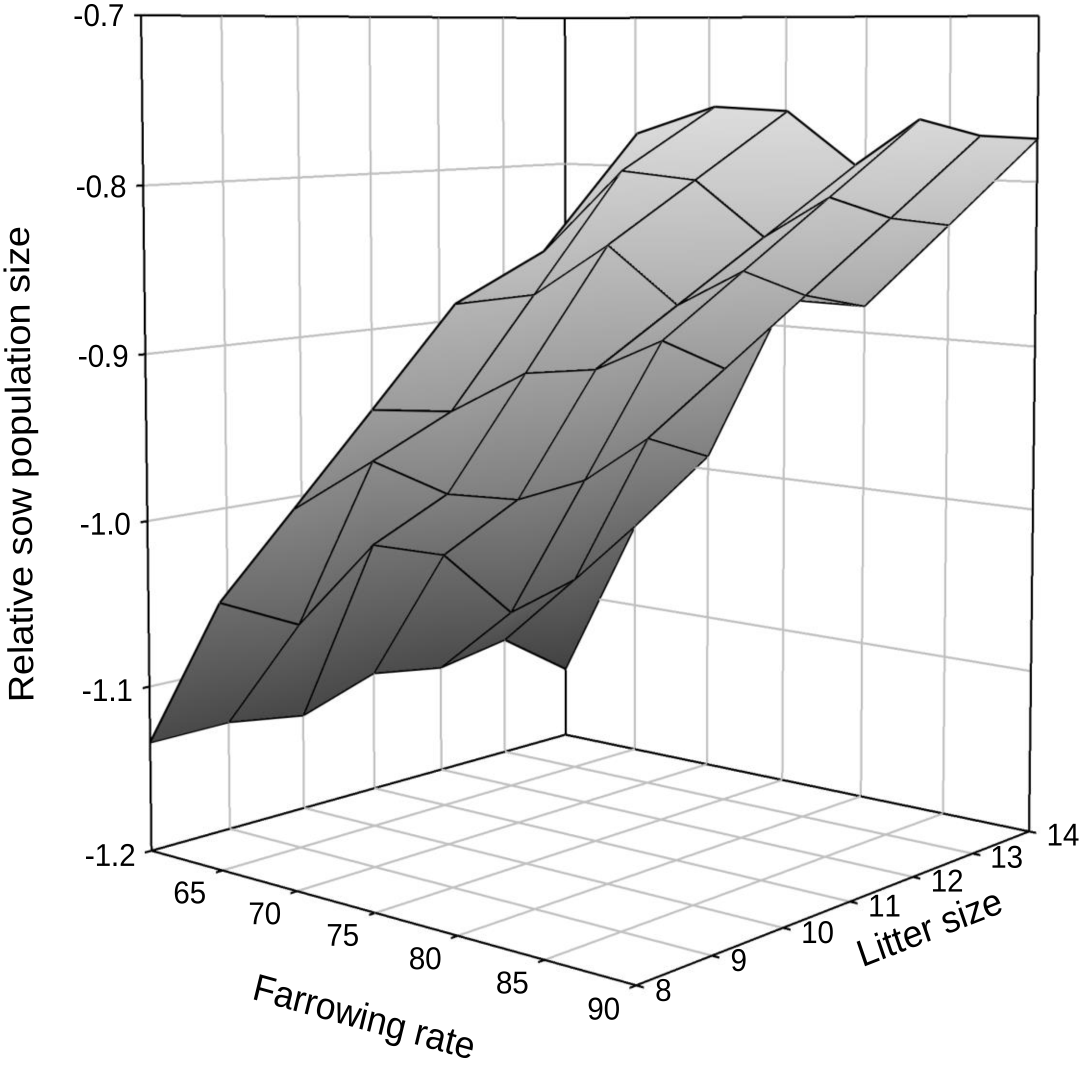

Figure 2.1. Relative difference between fresh (FRE) and frozen (FRO) semen preparation (FRE-FRO) / maximum ([FRE, FRO]) in sow population size for the conventional insemination technique (CON) across farrowing rate (%) and litter size (pigs/litter) levels.

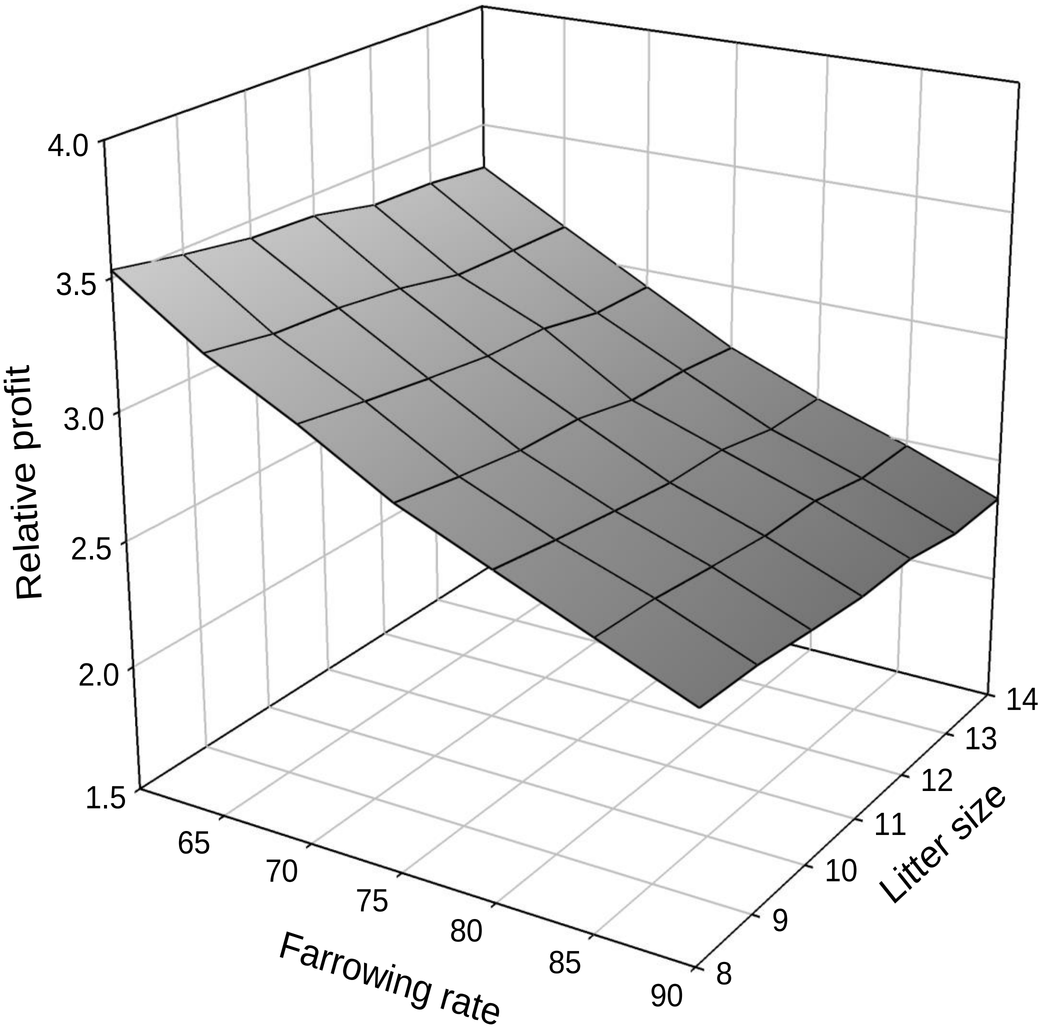

Figure 2.2. Relative difference between fresh (FRE) and frozen (FRO) semen preparation (FRE-FRO) /maximum ([FRE, FRO]) in net profit for the conventional insemination technique (CON) across farrowing rate (%) and litter size (pigs/litter) levels.

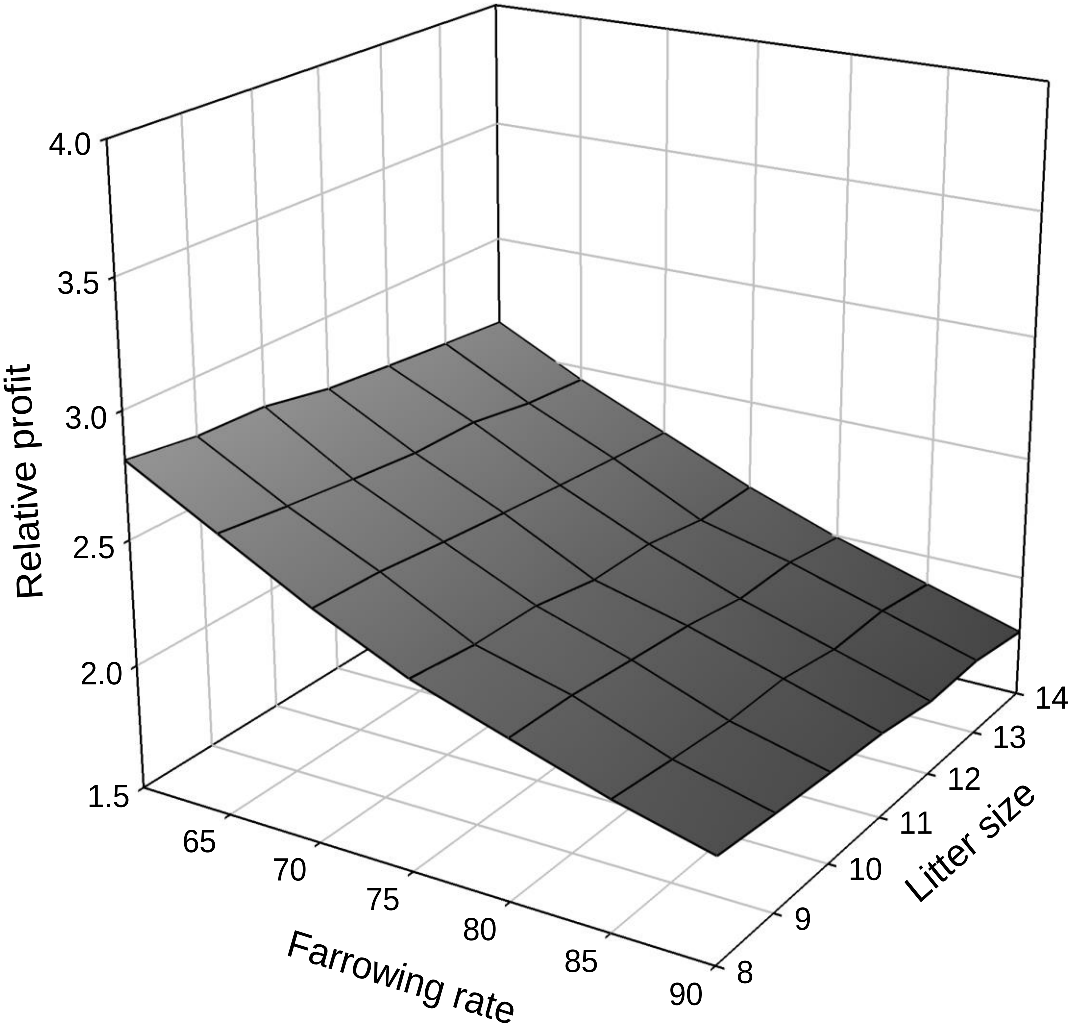

Figure 2.3. Relative difference between intrauterine (IUI) and conventional (CON) insemination technique (IUI-CON) / maximum ([IUI, CON]) in net profit for fresh (FRE) semen preparation across farrowing rate (%) and litter size (pigs/litter) levels.

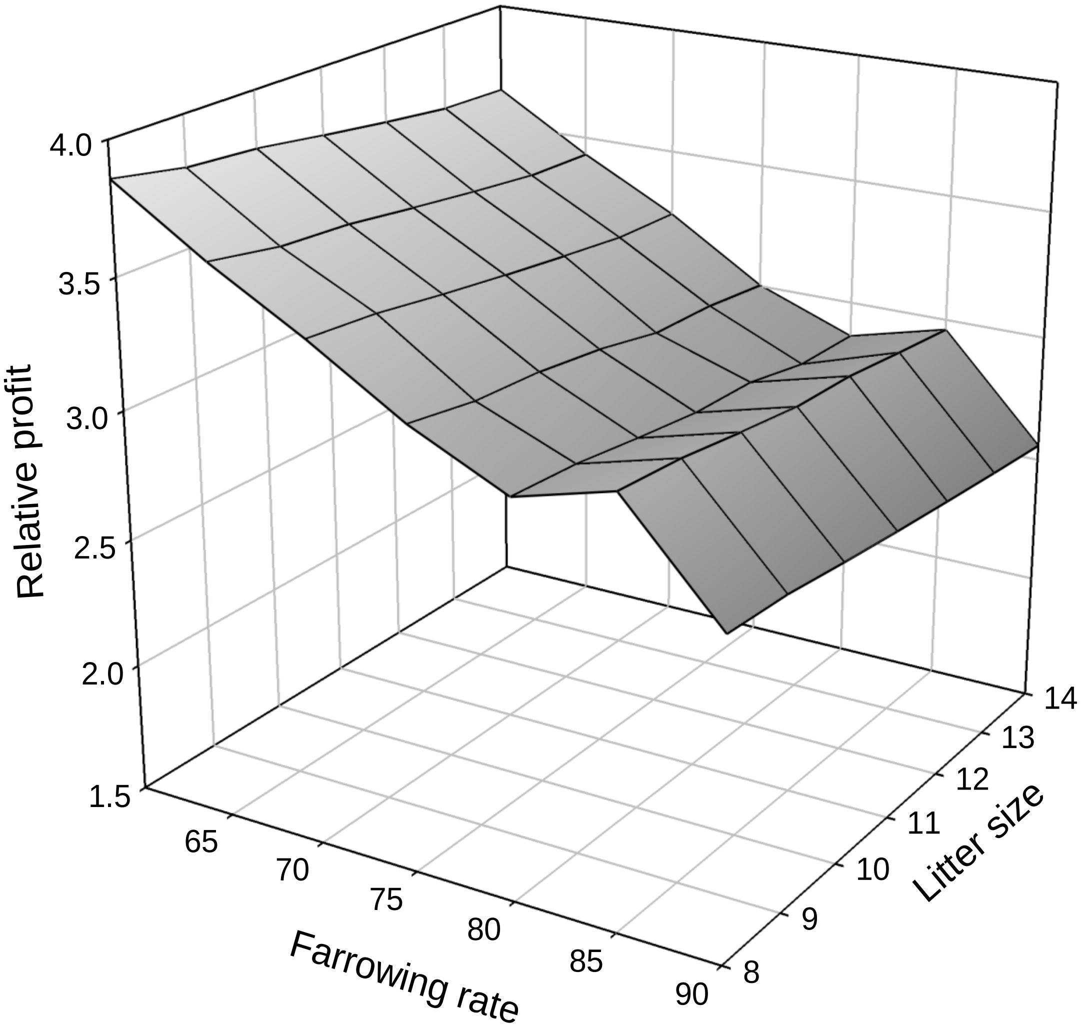

Figure 2.4. Relative difference between intrauterine (IUI) and conventional (CON) insemination technique (IUI-CON) / maximum ([IUI, CON]) in net profit for frozen (FRO) semen preparation across farrowing rate (%) and litter size (pigs/litter) levels.

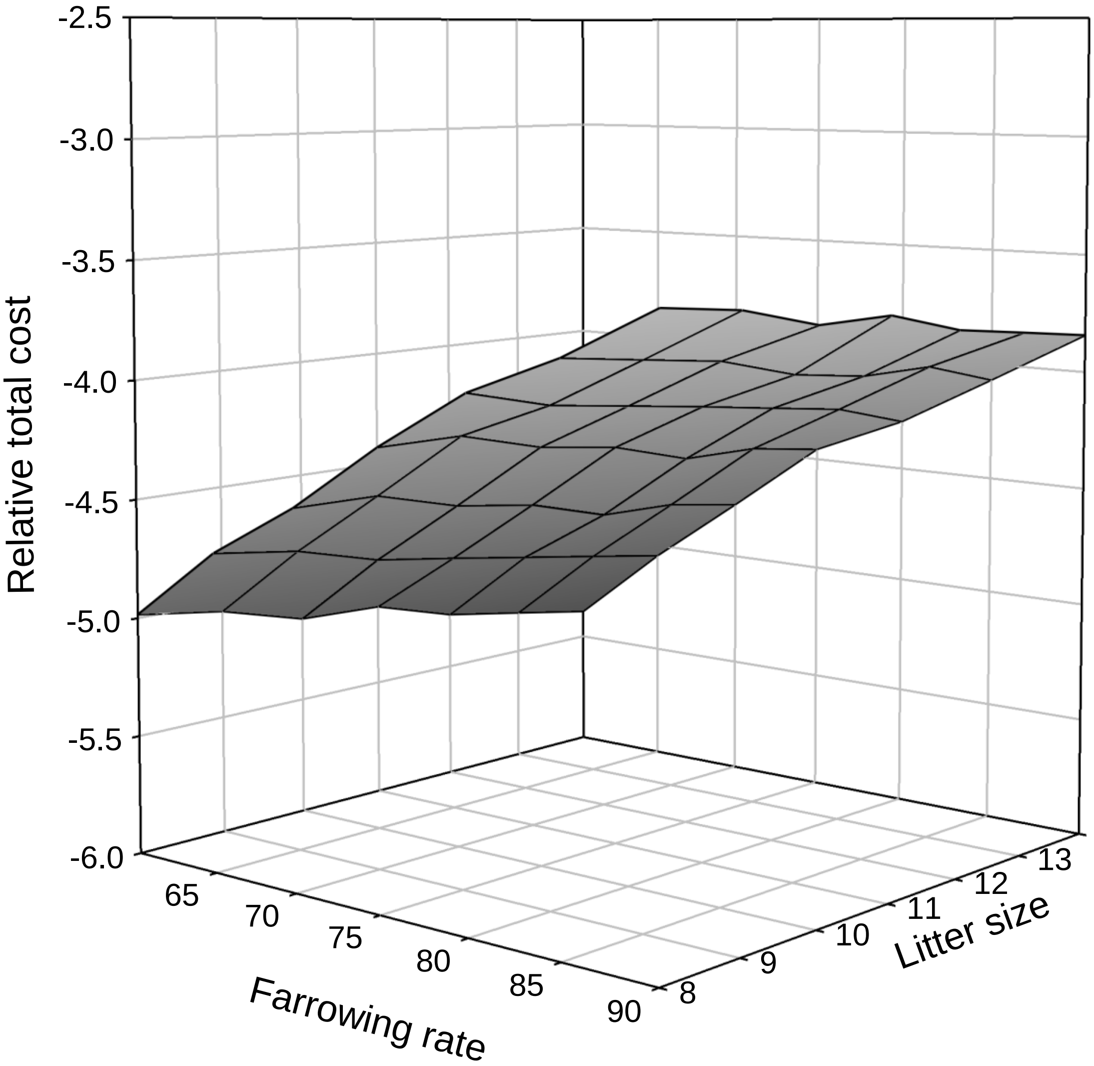

Figure 2.5. Relative difference between fresh (FRE) and frozen (FRO) semen preparation (FRE-FRO) / maximum ([FRE, FRO]) in total costs for the conventional insemination technique (CON) across farrowing rate (%) and litter size (pigs/litter) levels.

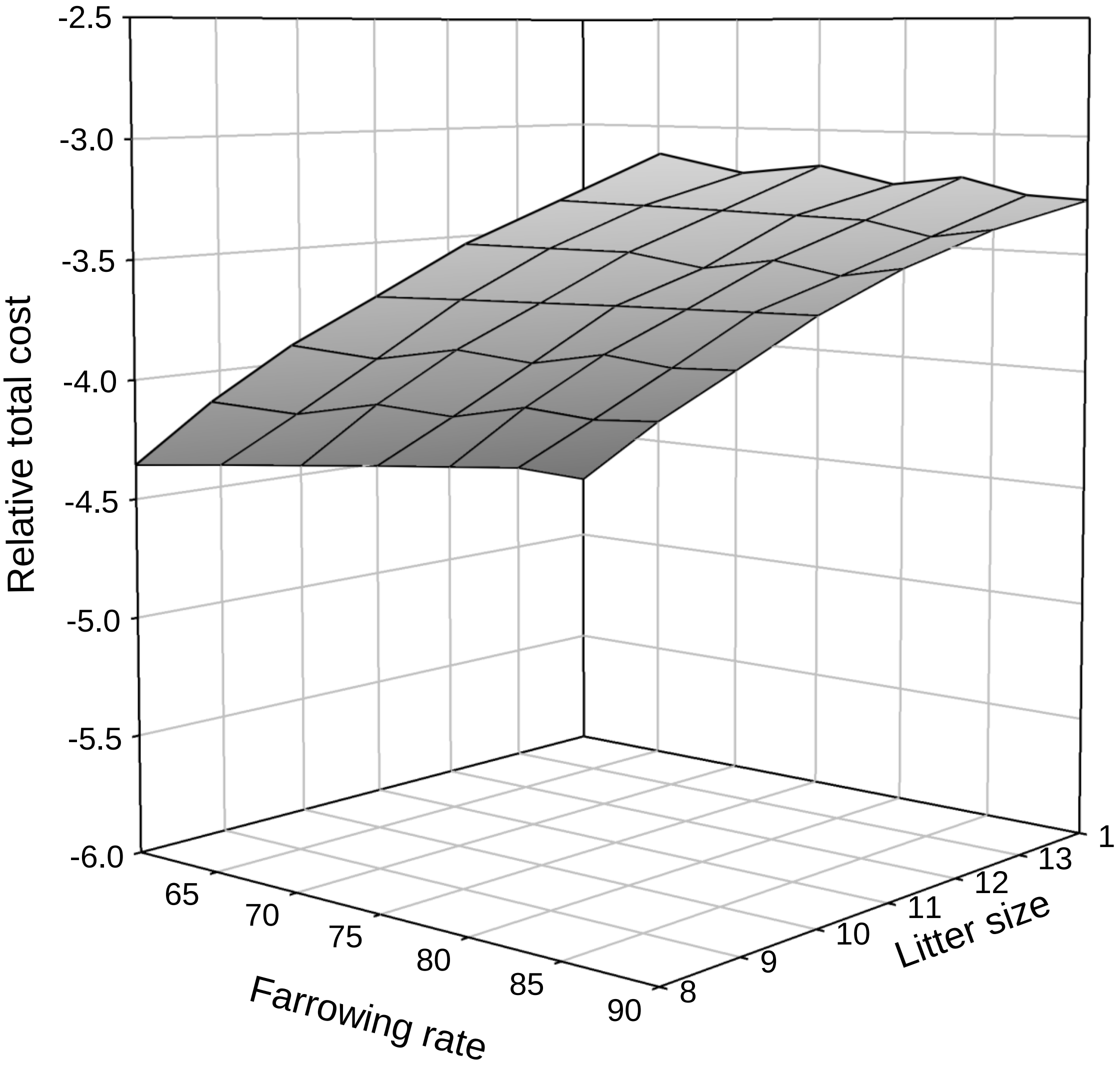

Figure 2.6. Relative difference between intrauterine (IUI) and conventional (CON) insemination technique (IUI-CON) / maximum ([IUI, CON]) in total costs for fresh (FRE) semen preparation across farrowing rate (%) and litter size (pigs/litter) levels.

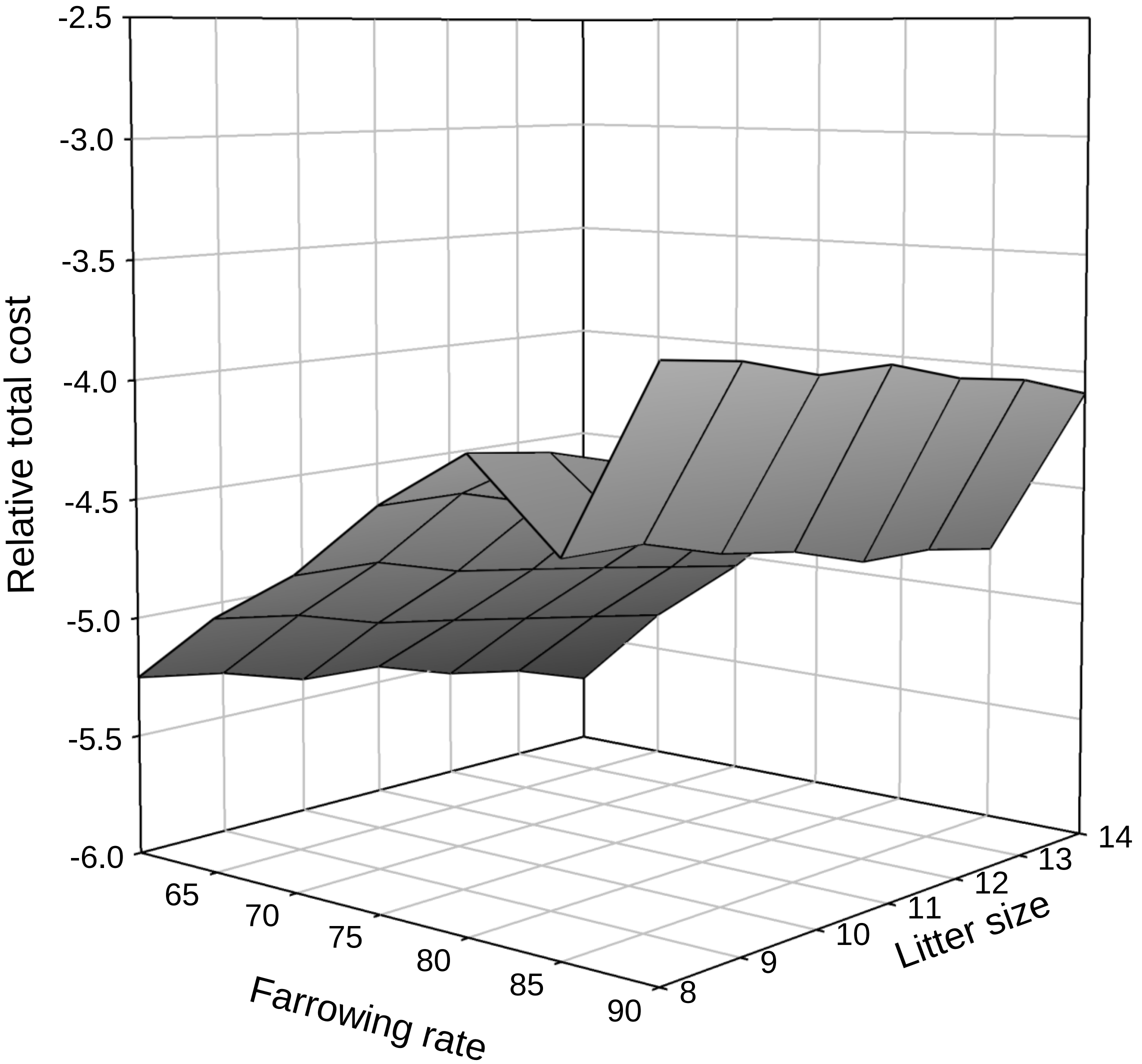

Figure 2.7. Relative difference between intrauterine (IUI) and conventional (CON) insemination technique (IUI-CON) / maximum ([IUI, CON]) in total costs for frozen (FRO) semen preparation across farrowing rate (%) and litter size (pigs/litter) levels.

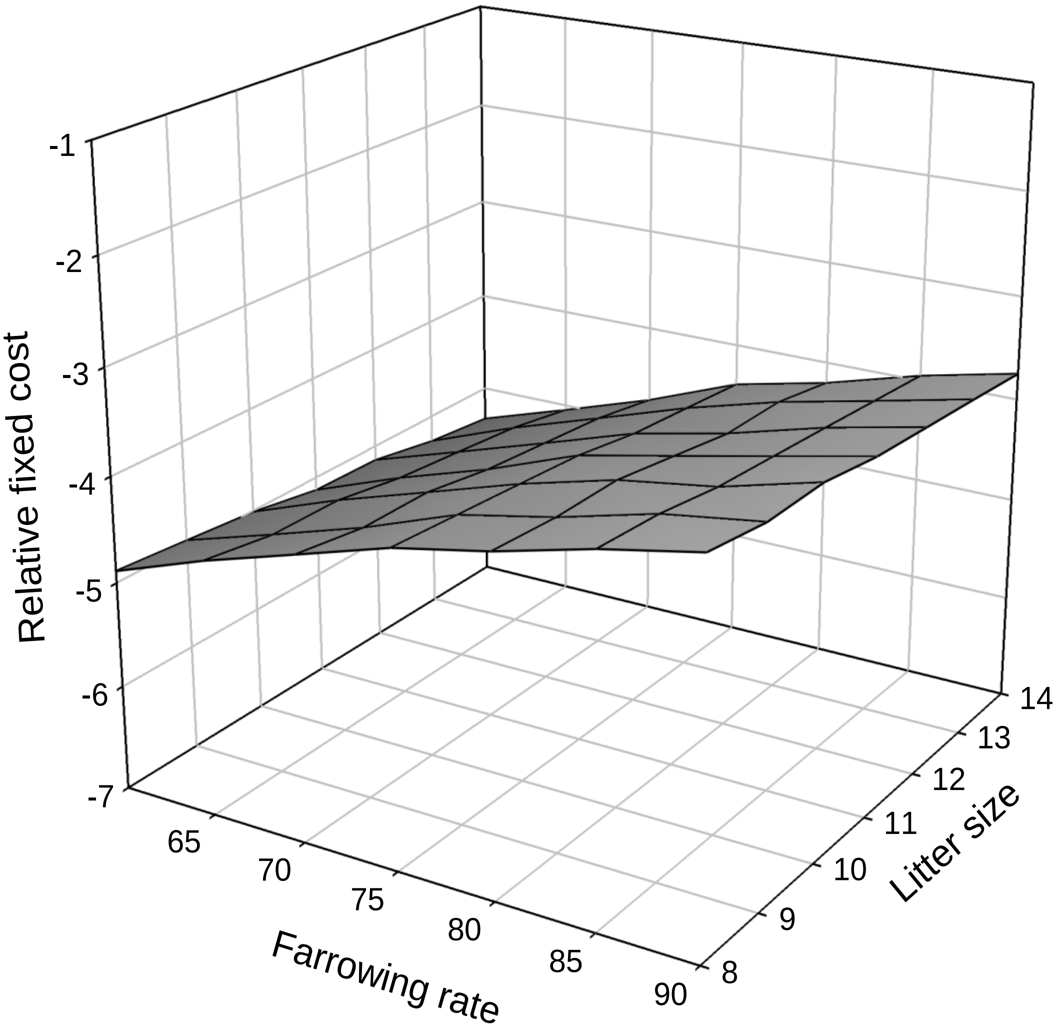

Figure 2.8. Relative difference between fresh (FRE) and frozen (FRO) semen preparation (FRE-FRO) / maximum ([FRE, FRO]) in fixed costs for the conventional insemination technique (CON) across farrowing rate (%) and litter size (pigs/litter) levels.

CHAPTER III: Genetic gain and economic values of selection strategies including semen traits in three- and four-way crossbreeding systems for swine production[2]

D. Gonzalez-Pena, R.V. Knox, M.D. MacNeil, and S.L. Rodriguez-Zas

3.1. Abstract

Four semen traits: volume (VOL), concentration (CON), progressive motility of spermatozoa (MOT), and abnormal spermatozoa (ABN) provide complementary information on boar fertility. Assessment of the impact of selection for semen traits is hindered by limited information on economic parameters. Objectives of this study were to estimate economic values for semen traits and to evaluate the genetic gain when these traits are incorporated into traditional selection strategies in a three-tier system of swine production. Three-way (maternal nucleus lines A and B and paternal nucleus line C) and four-way (additional paternal nucleus line D) crossbreeding schemes were compared. A novel population structure that accommodated selection for semen traits was developed. Three selection strategies were simulated. Selection Strategy I (baseline) encompassed selection for maternal traits: number of pigs born alive (NBA), litter birth weight (LBW), adjusted 21-d litter weight (A21) and number of pigs at 21 d (N21); and paternal traits: number of days to 113.5 kg (D113), backfat (BF), ADG, feed efficiency (FE), and carcass lean % (LEAN). Selection Strategy II included Strategy I and the number of usable semen doses per collection (DOSES), a function of the four semen traits. Selection Strategy III included Strategy I and the four semen traits individually. The estimated

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economic values of VOL, CON, MOT, ABN, and DOSES for 7 to 1 collections/wk ranged from \$0.21 to \$1.44/mL, \$0.12 to \$0.83/10^3 spermatozoa/mm^3, \$0.61 to \$12.66/%, -\$0.53 to -\$10.88/%, and \$2.01 to \$41.43/%, respectively. The decrease in the relative economic values of semen traits and DOSES with higher number of collections per wk was sharper between 1 and 2.33 collections/wk than between 2.33 and 7 collections/wk. The higher economic value of MOT and ABN relative to VOL and CON could be linked to the genetic variances and covariances of these traits. Average genetic gains for the maternal traits were comparable across strategies. Genetic gains for paternal traits, excluding semen traits, were greater in selection Strategy I than Strategies III and II. Genetic gains for paternal and maternal traits were greater in the four and three-way schemes, respectively. The selection strategy including the four semen traits is recommended because this approach enables genetic gains for these traits without compromising the genetic gains for maternal traits and with minimal losses in genetic gains for paternal traits.

3.2. Introduction

In crossbreeding systems for swine production, selection decisions tend to prioritize reproductive traits in maternal lines and growth and carcass traits in paternal lines. Although boar fertility play an important role in the efficiency and productivity of the system, semen traits are usually absent from selection decisions (Rothschild, 1996; Smital et al., 2005; Ruiz-Sanchez et al., 2006).

Most common semen traits include measurements of ejaculate volume (VOL, mL), sperm concentration (CON, 10^3 spermatozoa/mm^3), percentage of sperm motile (MOT, %), and morphologically abnormal cells (ABN, %). Heritability estimates for VOL, CON, MOT, and ABN range from 0.14 to 0.25, 0.13 to 0.26, 0.05 to 0.18, and 0.4 to 0.12, respectively (Grandjot et al., 1997a; Wolf, 2009, 2010). These estimates suggest that selection can improve semen traits of boars, leading to more units of usable semen (surpassing the minimum spermatozoa count for effective insemination) from an equal or reduced number of boars, potentially resulting in greater selection intensity and production efficiency in the swine industry (Smital et al., 2005; Oh et al., 2006; Foxcroft et al., 2008).

Despite genetic parameter estimates being available and the economic, health, and welfare benefits associated with the improvement of semen traits, no selection strategies that include semen traits have been developed; there has been no systematic study on the impact of selection programs that include these traits. Objectives of this study were to understand the impact of including semen traits in swine production systems and to identify the most effective integration of these traits into selection practices. Supporting aims were 1) to derive the economic values for the semen traits and 2) to evaluate the impact of including semen traits in three and four-way crossbreeding schemes within a three-tier system.

3.3. Materials and Methods

Economic values of four semen traits, VOL, CON, MOT, and ABN, and number of usable semen doses per collection (DOSES) were developed for three selection strategies that also included traditional maternal and paternal traits. These strategies were applied to simulated three- and four-way crossbreeding schemes used in swine production and the resulting genetic gains were compared. A conventional AI technique was assumed.

The trait VOL is the volume of the sperm-rich fraction, and ranges between 140 and 300 mL depending on the age and breed of the boar (Bidanel, 2011; Banaszewska and Kondracki, 2012).

The trait CON is the concentration of spermatozoa in the collection (CON, 10^3/mm^3). With variability associated with age, breed, and number of collections per wk or collection frequency; estimates range between 300 and 650 x 10^3 spermatozoa/mm^3 (Smital et al., 2005; Banaszewska and Kondracki, 2012). The trait MOT is the percentage of all spermatozoa that appear to be active and moving progressively in a forward direction (Broekhuijse et al., 2012). The trait ABN is the percentage of spermatozoa that appear to be abnormal (Dominiek et al., 2011). Following industry standards, ejaculates are used for insemination when MOT > 70% and ABN < 30% (Smital et al., 2005, Ruiz-Sanchez et al., 2006).

The trait DOSES is a function of the four semen traits and has been proposed as a single indicator of boar fertility and a possible trait for selection (Smital et al., 2005):

$$DOSES = \frac{[VOL \times CON/1{,}000] \times [MOT/100 \times (1-(ABN/100))]}{SPD},$$

where spermatozoa per dose (SPD) is the number of spermatozoa per dose recommended for successful insemination (usable dose). This study assumed SPD = 3.0 x 10^9 spermatozoa per dose following the industry standard for conventional insemination practices (Safranski et al., 2008).

Selection strategies

Three selection strategies were analyzed. Selection strategy I (baseline or traditional strategy) encompassed genetic selection for maternal and paternal traits (NSIF, 2002; Gonzalez-Peña et al., 2014). Maternal traits included: number of pigs born alive (NBA), litter birth weight (LBW), adjusted 21-d litter weight (A21) including linear and quadratic adjustments for litter age in d (litter weight*[2.218 - 0.0811(age) + 0.0011(age)^2], Wood et al., 1990) and number of pigs at 21 d (N21). Paternal traits included: number of days to 113.5 kg (D113), backfat (BF), ADG (from 60 lb to 250 lb equivalent to 27 kg to 113.5 kg), feed efficiency (feed:gain, FE), and lean carcass % (LEAN). ADG and D113 were both included in the index in consideration that a number of paternal line selection strategies tend to prioritize D113 meanwhile a number of maternal line selection strategies tend to prioritize ADG. Also, both traits span non-completely overlapping periods in the productive life of pigs. ADG encompasses the period between 27 kg and 113.5 kg of BW meanwhile D113 encompasses the period between birth and 113.5 kg of BW. Selection strategy II included the traits from Strategy I and DOSES. Selection strategy III included the traits from Strategy I and the four individual semen traits: VOL, CON, MOT, and ABN.

Table 3.1 lists the traits included in the selection indices, and the corresponding economic values ($/unit), phenotypic SD, heritability, and genetic and phenotypic correlation values. These values were compiled from a review of existing literature (NSIF, 2002; Smital et al., 2005). A selection index derived using the profit equation method that takes these covariations into account was utilized to maximize the genetic progress of all traits in the favorable direction. For example, reducing BF and increasing FE without undesirable negatively influences on ADG and LEAN.

Biological and technological input parameters

Biological, technological, and financial input parameters used in the simulation were based on a literature review. Inputs for the three-way crossbreeding scheme were obtained from previous studies of similar swine production systems (Rutten et al., 2000; Gonzalez-Peña et al., 2014). Similar methodology was adapted to compute the input parameters for the four-way crossbreeding scheme. Assumed input costs associated with boar maintenance and semen doses collected (e.g. facilities, management, collection costs) are presented in **Table 3.2** (Rutten et al., 2000; Dhuyvetter et al., 2009). The number of collection per wk considered in this study ranged from 1 to 7 (corresponding to 7d to 1d intervals between collections) assuming that the schedule of collection could be maintained during the year. This range considers the physiological limitation of a boar to produce more than 16 x 10^9 spermatozoa per d from both testes (Senger, 2005) and industry practices. Following previous studies of semen traits, a linear relationship between number of collections per wk and VOL, CON, ABN, MOT was assumed (Rutten et al., 2000). For comparison purposes and set barn capacity, all strategies were simulated to result in 225,000 farrowings at the commercial level every six months and a planning horizon of 10 year (Weller, 1994; Gonzalez-Peña et al., 2014). This farrowing number adjusted by the 2.25 expected farrowings/year (2.25/2) correspond to 200,000 sows/cycle in a system that uses conventional AI with liquid extended semen (fresh semen preparation), has an average farrowing rate of 85%, and produces on average 10 live pigs/litter (USDA, 2007; PigCHAMP, 2011; Knox et al., 2013).

Derivation of the economic values

A profit equation adapted from an established economic system was developed for the traits (Rutten et al., 2000; Smital et al., 2005). A profit function is an equation that models the change in net economic returns as a function of a series of biological and economic parameters. The economic value of a trait was computed as the first partial derivative of the financial indicator evaluated at the population mean for all traits. The use of partial derivatives of the profit function method circumvents double counting of traits (Dekkers, 2005). The net profit was:

$P = R - C,$

where P denotes the profit per boar space, R denotes the returns per boar space, C denotes the costs per boar space, and the terms were expressed on a per wk basis.

Returns per boar space depend on the number of semen doses (DOSES) corresponding to the number of collections per wk (*N*), and the semen sale price (*S*, $/dose)

$$R = DOSES \times S \times N$$

The costs per boar space were given by:

$C = F + CC \times N + CD \times N \times DOSES,$

where F denotes the fixed costs per boar space including facility, feed, utilities, and health management per wk, CC denotes the costs per collection including labor and laboratory supplies, and CD is the costs per dose including extender, equipment, and post evaluation labor (**Table 3.2**).

Partial derivatives of the profit function, taken with respect to each trait of interest (VOL, CON, MOT, ABN, or DOSES at the corresponding *N*) were used to compute the economic value for each semen trait. The partial derivative for VOL was:

$$\frac{\partial P}{\partial VOL} = \frac{CON \times MOT \times \left(1 - \left(\frac{ABN}{100}\right)\right) \times S \times N}{SPD \times 10^5} - \frac{CD \times CON \times MOT \times \left(1 - \left(\frac{ABN}{100}\right)\right) \times N}{SPD \times 10^5}$$

The partial derivative for CON was:

$$\frac{\partial P}{\partial CON} = \frac{VOL \times MOT \times \left(1 - \left(\frac{ABN}{100}\right)\right) \times S \times N}{SPD \times 10^5} - \frac{CD \times VOL \times MOT \times \left(1 - \left(\frac{ABN}{100}\right)\right) \times N}{SPD \times 10^5}$$

The partial derivative for MOT was:

$$\frac{\partial P}{\partial MOT} = \frac{VOL \times CON\left(1 - \left(\frac{ABN}{100}\right)\right) \times S \times N}{SPD \times 10^5} - \frac{CD \times VOL \times CON \times \left(1 - \left(\frac{ABN}{100}\right)\right) \times N}{SPD \times 10^5}$$

The partial derivative for ABN was:

$$\frac{\partial P}{\partial ABN} = \frac{CD \times VOL \times CON \times MOT \times N}{SPD \times 10^7} - \frac{VOL \times CON \times MOT \times S \times N}{SPD \times 10^7}$$

Assuming:

$P\ = DOSES \times S \times N - [F + CC \times N + CD \times N \times DOSES]$,

the partial derivative for DOSES was:

$$\frac{\partial P}{\partial DOSES} = S \times N - CD \times N$$

Crossbreeding schemes

The impact of the three selection strategies was evaluated for two crossbreeding schemes in a three-tier production system. These schemes included three and four crosses between swine lines or breeds. The three-way crossbreeding scheme included two maternal lines, A and B, and one paternal line C. In the three-tier system each nucleus line had 500 sows, the multiplier level produced F_1 sows from B boars and A sows, and at the commercial level, pigs obtained from the cross between F_1 BA sows and C boars were sold (Gonzalez-Peña et al., 2014). The four-way scheme encompassed the three-way scheme and an additional parental nucleus line D that had 500 sows. The multiplier level produced F_1 sows from B boars and A sows and F_1 DC boars from D boars and C sows, the commercial pigs obtained from the cross between F_1BA sows and F_1DC boars were sold. In both schemes all maternal and paternal traits were included in the selection indices. However, maternal lines were selected mainly for female reproductive traits, and paternal line C and D were selected mainly for growth-carcass and semen traits by means of selection index. Based on previous studies (Rutten et al., 2000; Smital et al., 2005), the number of semen collections per wk used to inseminate the F_1 sows considered in this study ranged from 1 to 7 collections/wk. The three-way scheme was simulated using a transmission matrix including 16 population groups (Gonzalez-Peña et al., 2014). A novel transmission matrix including 22 population groups was developed to simulate the four-way scheme (**Table 3.3**; Wünsch et al., 1998).

Evaluation of the genetic trend and the relative economic value

Genetic improvement that results from considering semen traits in breeding and selection decisions was evaluated across strategies (three strategies x two crossbreeding schemes = six combinations). The selection strategy (Strategy I, II or III) and crossbreeding scheme (three or four-way) combinations were denoted as I3, II3, III3, I4, II4, and III4. For the three-way scheme, selection indices were developed to select replacement boars and sows in the nucleus lines, and F_1 BA sows that were inseminated with line C semen. Additional selection indices were developed in the four-way scheme to select nucleus line D boars and sows, and F_1 DC boars. Meanwhile Strategy I includes maternal and paternal traits, Strategy II also includes DOSES and Strategy III includes all four semen traits. The economic values ($/unit) were based on National Swine Improvement Federation guidelines (NSIF, 2002). For the maternal lines, females at the nucleus level were selected based on the own performance for maternal traits and the parental and half sib performance for maternal traits; at the multiplier level females were selected based on the parental and half sib performance for maternal traits; and at the commercial level females were selected based on the parental performance for maternal traits. For the maternal lines, males at the nucleus level were selected based on the parental, full and half sib performance for maternal traits and the male’s own performance for paternal traits; at the multiplier level males were selected based on the parental performance for maternal and paternal traits and full and half sib performance for maternal traits; and at the commercial level males were selected based on the parental performance for all traits. For the paternal lines, females at the nucleus level were selected based on the parental and half sib performance for paternal traits and based on the female’s own performance for the maternal traits; at the multiplier level females were selected based on the parental performance for maternal and paternal traits and based on half sib performance for paternal traits; and at the commercial level females were selected based on the parental performance for paternal and maternal traits. For the paternal lines, males at the nucleus level were selected based on the male’s own performance for paternal traits and parental, full and half sib performance for all traits; at the multiplier level males were selected based on the parental performance for all traits and full and half sib performance for maternal traits; and at the commercial level males were selected based on the parental performance for parental traits.

The relative economic value for each trait in the selection indices within strategy-scheme combination was the product of the economic value multiplied by the standard discount expression (to adjust for interest rate across time) at discount factor 0.744, expressed relative to the genetic standard deviation of each trait (Nitter et al., 1994). One round of selection (selection based on own phenotype, parental, and half-sib information) was used and thus the effects of inbreeding, reduced lower genetic variation due to selection, and return from breeding product sales were assumed negligible (Wünsch et al., 1999; Willam et al., 2008; González-Peña et al., 2014). The economic values estimated for the semen traits were integrated into the selection strategies and applied to the three-tier system that was simulated using the software ZPLAN (Willam et al., 2008). This software supports the assessment of genetic and financial progress in a deterministic framework using selection indexes and gene flow methodology (Willam et al., 2008).

3.4. Results and Discussion

Seedstock producers at the nucleus level of a three-tier swine production system traditionally select boars for maternal (mostly sow fertility) or paternal (mostly growth, carcass and meat quality) traits. However, superior genetics for maternal or paternal traits are ineffective when boars cannot produce usable semen in adequate quantity to transmit the favorable genes to the offspring. Despite the positive correlation between boar fertility and the rate of genetic improvement, semen traits associated with boar fertility are usually omitted from selection decisions (Rothschild, 1996; Robinson and Buhr, 2005; Foxcroft et al., 2008).

In addition to being key for achieving high selection intensity, semen traits provide information on reproductive performance complementary to pregnancy rate and litter size born (Robinson and Buhr, 2005; Foxcroft et al., 2008). Significant correlations between semen motility and morphology and farrowing rates and litter size have been reported (Waberski et al., 2011; Broekhuijse et al., 2012; Kummer et al., 2013). Heritability estimates for VOL, CON, and MOT from three German genetic lines ranged from 0.14 to 0.18, 0.17 to 0.26, and 0.05 to 0.18, respectively (Grandjot et al., 1997a). Similar heritability values for VOL, CON, and MOT ranging from 0.14 to 0.25, 0.13 to 0.23, and 0.06 to 0.16, respectively, were estimated from seven crossbred pig populations in the Czech Republic (Wolf, 2009). In Czech Large White and Landrace populations, the heritability estimates for VOL, CON, MOT, and ABN were between 0.20 and 0.25, 0.18 and 0.18, 0.08 and 0.12, and 0.10 and 0.12, respectively (Wolf, 2010). Greater heritability estimates for VOL, CON, MOT, and DOSES (0.58, 0.49, 0.38, 0.34, and

0.40, respectively) were obtained in a data set derived from 19 purebred and crossbred populations using mean values per boar instead of individual ejaculate measurements (Smital et al., 2005). Estimates of genetic correlations between NBA and VOL, CON, MOT, and ABN ranged from -0.07 to -0.22, -0.02 to 0.11, 0.04 to 0.24, and -0.24 to -0.06, respectively (Grandjot et al., 1997b; Smital et al., 2005; Wolf, 2010). Although the heritability estimates imply that selection for semen traits will result in genetic gains for these traits, the limited understanding of how to integrate these traits with traditional maternal and paternal traits in selection decisions has hampered genetic progress. This study provided insights on two major components of genetic improvement for semen traits: economic values and genetic gains from strategies incorporating four semen traits or number of semen doses, a function of the previous traits. Additional insights were gained from the consideration of two crossbreeding schemes and a range of semen collection frequencies per wk.

The impact of the different selection schemes on the traits is due to the indirect relationships between traits. **Table 3.1** shows that the semen traits are only related to number born alive (NBA) and number at 21 d (N21). Since D113 is correlated to NBA, only changes in NBA directly influences D113. However, other traits such ADG are not correlated to NBA but are correlated to D113. This results in a relatively higher indirect response in D113 compared to ADG in the selection strategies involving semen traits.

Economic values of semen traits

Economic values are listed in **Table 3.4**. Economic values and relative economic values for a range of semen collections per wk were estimated based on reported boar semen trait averages (VOL = 237.2 mL, CON = 412.6 x $10^3/mm^3$, MOT = 80.5%, ABN =7.6%; Smital et al., 2005) and associated costs (**Table 3.4**). The economic values for VOL, CON, MOT, ABN, and DOSES increased in absolute terms with decreasing collection frequency from \$0.21 to \$1.44/mL, \$0.12 to \$0.83/(10^3/mm^3), \$0.61 to \$12.66/%, \$-0.53 to \$-10.88/%, and \$2.01 to \$41.43/dose. The trend of more extreme economic values for VOL, CON, MOT, ABN and DOSES with higher number of collections per wk can be explained by changes in the quantity of usable semen available (**Table 3.4**). The greater number of collections per wk decreased the number of doses per ejaculate and resulted in reduced economic values. These results are consistent with reports that more frequent semen collections are associated with fewer spermatozoa being accumulated in the epididymal reserves (Rutten et al., 2000; Frangež et al., 2005). Consistent with the assumed relationship between semen traits and number of collections per wk, the economic value of these traits was more extreme with fewer collections per wk associated with the lower number of usable doses (above the minimum number of spermatozoa) per wk (Rutten et al., 2000). Limited report on genetic and economic considerations of boar semen traits contribute to the variability in the economic values and impact the robustness of the profit equation (Knap, 2005). The derivation and estimation of economic values for semen traits constitute an initial effort towards understanding the impact of including semen traits in selection decisions.

Genetic gains for maternal, paternal and semen traits

The average genetic gain (**Table 3.5**) for the maternal traits NBA, LBW, A21, and N21 remained fairly constant across Strategy-scheme combinations. Inclusion of boar semen traits in the selection indices, individually or combined in DOSES, had minor impact on the genetic gains for maternal traits. The difference in genetic gain between selection Strategy I that excluded semen traits and the average of Strategies II and III (including semen traits or DOSES, respectively) ranged from 5.4 to 7.7%. The low impact of including boar semen traits in the selection indices on the genetic gain for maternal traits is due to the low genetic correlation between these traits and the relatively low weight on semen traits in the indices used for the maternal lines.

Inclusion of semen traits in the selection indices impacted the genetic gain on the paternal traits. On average, genetic gains for paternal traits were greater in selection Strategy I followed by strategies III and II across crossbreeding schemes (**Table 3.5**). Deterioration in genetic gains for paternal traits relative to Strategy I was substantially less (25 to 66%) in Strategy III (including individual semen traits) than in Strategy II including DOSES. For example, the greater improvement in BF occurred in selection Strategy I, followed by Strategy III and Strategy II for both crossbreeding schemes. Expressing the difference in BF gain between strategies relative to the gain in Strategy I [(II3 - I3)/I3, (III3-I3)/I3, (II4 - I4)/I4 or (III4-I4)/I4], the genetic gain for II3, III3, II4, and III4 was 59, 26, 68, and 32%, respectively. These gains reflect the complex indirect relationships between semen traits and paternal traits due to the genetic correlations. Following the genetic correlations in **Table 3.1**, most semen traits are negative correlated to NBA, NBA is positively correlated to D113, D113 is negatively correlated to ADG, and ADG is positively correlated to BF. The only difference between selection strategies is the semen traits, thus the negative genetic correlation between NBA and most semen traits resulted in decreased genetic gain for BF when using semen traits in an index. Similar trends were observed for D113, ADG and LEAN.

The reduced impact of selection for boar semen traits on the genetic gain for paternal traits in the four-way relative to the three-way scheme was associated with the distribution of the effects between two parental lines (C and D) in four-way scheme relative to the concentration of the effects in one parental line (C) in the three-way scheme (**Table 3.5**). Similarly, the reduced impact of selection for boar semen traits on genetic gain for paternal growth in the selection Strategy III relative to II could be due to the distribution of the effects between four traits in Strategy III relative to the concentration of the effects in one trait (DOSES) in Strategy II.

The results summarized in **Table 3.5** suggest that selection to improve semen traits could be implemented in maternal nucleus lines without substantial loss in genetic gain for the other traits. Also, selection for semen traits had less effect on the genetic gains for paternal traits when the four traits are included in the selection index relative to DOSES and in a four-way scheme relative to a three-way crossbreeding scheme. Simulation increasing the selection intensity as the result of the improvement of the semen traits and the efficient production of doses will be needed.

Results for standard maternal and paternal traits across scenarios were consistent with the ranges reported by other studies for most traits (**Table 3.5**). The genetic trends for BF, ADG, NBA and LBW in female Large White pigs were -0.239 mm, 0.255 g, 0.028 pigs/litter, and 0.023 kg, respectively (de Almeida Torres Jr. et al., 2005). The genetic trends for FE, BF, and ADG in male Large White pigs were -0.012 kg, -0.235 mm, and 1.591 g, respectively (de Almeida Torres Jr. et al., 2005).

Genetic trends per year in Pietrain for ADG and FE were 1.33 and -0.011, respectively (Habier et al., 2009). An annual genetic trend in Large White pigs for NBA was 0.038 (Canario et al., 2005). The approximate annual genetic progress for NBA in American Yorkshire swine between 1983 and 1999 was reported at approximately 0.028 meanwhile the annual genetic trend for BF (cm) between 1994 and 1999 was -0.078 (See et al., 2001). Across studies and within study, across scenarios, genetic gain depends on the traits, selection and culling practices, genetic parameters, and weights considered (Rodriguez-Zas et al., 2003; 2006). For the selection strategies evaluated, genetic gains for maternal traits (**Table 3.5**) were not affected by the inclusion of semen traits. However, genetic gains for paternal growth and carcass traits were reduced when semen traits were included in the selection indices. The rationale for this trend is that selection was based on their own phenotype, parental and half-sib information and in the paternal lines, the boars have more direct information for semen traits that compete with information from the paternal traits in the selection index. Our results demonstrated that simultaneous genetic gains for semen traits are possible without detrimental effects on the genetic gains for maternal traits.

Relative economic values of maternal, paternal and semen traits

The relative economic value for each trait was computed as the product of the economic value multiplied by the standard discount expression (to adjust for interest rate across time), expressed relative to the genetic standard deviation of each trait (%). The relative economic values for each Strategy-scheme combination are presented in **Tables 3.6** and **3.7** for 1 (weekly collection), 2.33 (one collection every 3 d) and 7 (daily collection) collections/wk. These values measure the relative importance of each trait in the selection index (Wünsch et al., 1999; Gonzalez-Peña et al., 2014). The trait NBA dominated the index for the maternal lines (A and B) and BF and FE dominated the index for the paternal lines.

The relative economic values of paternal (e.g. growth, feed efficiency) and maternal (e.g. litter size) traits dominate those for semen traits. A comparison of the behavior of the four semen traits relative to DOSES was undertaken. The sum of the relative economic values for the four semen traits in Strategy III was 70% (maternal nucleus lines) to 78% of the economic value for

DOSES in Strategy II across crossbreeding schemes (**Tables 3.6** and **3.7**). However, the relationship between the sum of relative economic values for the four semen traits and the economic value for DOSES was not linear across number of semen collections per wk. The decrease in the relative economic values of semen traits and DOSES with higher number of collections per wk was sharper between 1 and 2.33 collections/wk than between 2.33 and 7 collections/wk. This nonlinear pattern is also observed in the sharper increase in total number of usable doses per wk between 1 and 2.33 collections/wk than between 2.33 and 7 collections/wk (**Table 3.2**). This suggests that the changes in economic values are dominated by the number of usable doses per wk primarily through the *CD* relative to the *CC*.

The relationship between maternal and paternal sum of relative economic value within nucleus line was consistent across strategies within collection per wk schedule (**Tables 3.6** and **3.7**). The ratio between maternal and paternal sum of relative economic values was consistent for lines A, B (three and four-way scheme) and D (four-way scheme) across collection schedules. The maternal:paternal trait relative economic value ratio for lines A, B, and D in the four-way scheme averaged 0.71, 1.29, and 0.008, respectively, and for lines A and B in the three-way scheme averaged 0.80 and 1.26. However, the maternal:paternal relative economic value ratio in line C increased with number of collections per wk from 0.010 to 0.017 and from 0.005 to 0.01 in the four-way and three-way scheme, respectively. The slight increase in maternal:paternal relative economic value ratio associated with higher collection schedules in line C that was not observed in line D could be due to the slightly lower relative economic values that the maternal traits received in line D relative to line C in the three- and four-way schemes.

Consistent with the trends presented in **Table 3.4**, the relative economic value of the semen traits and DOSES in the selection indices decreased with increasing collection frequency across crossbreeding schemes and strategies. On average, the relative economic value of the semen traits (sum of four traits or DOSES) increased 6.3 fold from 7 to 2.33 collections/wk and 1.9 fold from 2.33 to 1 collections/wk and these trends were consistent across crossbreeding schemes (**Tables 3.6** and **3.7**). The trends for maternal lines were slightly higher and for paternal lines slightly lower than the average.

Simultaneous considerations of the trends in semen traits or DOSES relative economic values across collection schedules and across strategies offer insights into the interaction between these components (**Tables 3.6** and **3.7**). Despite the higher relative economic value of DOSES in Strategy II relative to the sum of the relative economic values of the four semen traits in Strategy III, the relative economic values of the four traits and DOSES exhibited a similar negative trend with number of collections per wk across strategies. The relative economic values reported in **Table 3.7** also place the values presented in **Table 3.4** in perspective. The range of economic values in **Table 3.7** demonstrates that, when considered in the context of all the traits studied, the relative economic value of the semen traits are modest and commensurate to the objectives of each line.

In both crossbreeding systems the economic values for the semen traits VOL and CON remained low across number of collections per wk; however the economic value of MOT and ABN increased with lower collections per wk, relative to the weight of paternal and maternal traits. The relative emphasis on MOT and ABN relative to traditional maternal and paternal traits at low number of semen collections per wk could be associated with two phenomena. First, MOT and ABN have an increasing large positive impact on profitability with fewer semen collections per wk but the low estimates of heritability and phenotypic standard deviation for MOT and ABN are low (**Table 3.1**). Under these conditions the economic value increases as the number of semen collections per wk decreases. Second, MOT and ABN had low genetic correlation with any other maternal, paternal or semen trait. Thus, the relative emphasis ensures progress on these traits with limited genetic variation on the time horizon considered with minimum negative impact on any of the other traits.

The relative economic values of the semen traits (Strategy III) in the nucleus population for the three and four-way crossbreeding are presented in **Figures 3.1** and **3.2**. Consistent with the semen trait values assumed for all lines, the relative economic value of these traits in the selection indices remained constant across lines. The relative similarities between lines in the semen trait weights are in agreement with the planned line purpose. The values in paternal line C (and D) are slightly more similar to those in maternal line A than B. Congruent with the estimated economic values listed in **Table 3.4**, the absolute economic value of the semen traits is higher for one semen collection per wk relative to seven collections per wk. This trend is consistent with the economic principle of assigning more weight to more rare events and the expectation that, for the range considered in this study, for more intense collection schedules to result in higher total number of usable doses. The amount of useable doses per collection must be considered in relationship to the boar's physiology and the resting periods in semen collection. In practice collection frequencies between 2.33 and 1.75/wk are favored based on total profitability (Rutten et al., 2000; Knox et al., 2008).

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3.6. Tables

Table 3.1. Economic value (EV), and heritability (h^2), phenotypic standard deviation (σ_p), genetic (above diagonal) and phenotypic (below diagonal) correlation values assumed for the traits included in the selection indices used in the nucleus and multiplier stages*.

	Parameter			Correlation													
Traits[1]	EV($)	h^2	σ_p	NBA	LBW	A21	N21	D113	BF	FE	ADG	LEAN	VOL	CON	MOT	ABN	DOSES
NBA	13.50	0.10	2.50	***1.00***	0.63	0.12	0.80	0.20	0	0	0	0	-0.07	-0.02	0.04	-0.24	-0.10
LBW	0.45	0.29	7.20	0.80	***1.00***	0.50	0.67	0	0	0	0	0	0	0	0	0	0
A21	0.50	0.15	16.00	0.20	0.66	***1.00***	0.60	0	0	0	0	0	0	0	0	0	0
N21	6.00	0.06	2.35	0.60	0.70	0.6	***1.00***	0	0	0	0	0	-0.04	-0.02	-0.06	-0.15	0
D113	-0.12	0.30	13.00	0.10	0	0	0	***1.00***	0	0.60	-0.70	0.10	0	0	0	0	0
BF	-15.00	0.40	0.20	0	0.10	0	0	-0.18	***1.00***	0.33	0.14	0.70	0	0	0	0	0
FE	-13.00	0.30	0.25	0	0	0	0	0.50	0.25	***1.00***	-0.70	0.40	0	0	0	0	0
ADG	6.00	0.30	0.20	0	0.20	0	0	-0.50	0.20	-0.65	***1.00***	0.20	0	0	0	0	0
LEAN	1.10	0.48	1.50	0	0	0	0	0.10	0.70	0.30	0.10	***1.00***	0	0	0	0	0
VOL	TBE	0.25	91.86	0	0	0	0	0	0	0	0	0	***1.00***	-0.68	-0.04	-0.09	-
CON	TBE	0.18	144.92	0	0	0	0	0	0	0	0	0	-0.5	***1.00***	0.12	0.13	-
MOT	TBE	0.12	4.31	0	0	0	0	0	0	0	0	0	0.01	0.04	***1.00***	-0.48	-
ABN	TBE	0.10	5.75	0	0	0	0	0	0	0	0	0	-0.01	0.03	-0.20	***1.00***	-
DOSES	TBE	0.40	10.70	0	0	0	0	0	0	0	0	0	x	x	x	***x***	***1.00***

[1] NBA = number born alive (pigs/litter); LBW = litter birth weight (lb; 1 lb = 2.2046 kg); A21 = adjusted 21-d litter weight, adjusted for the age of the litter (lb); N21 = number of pigs per litter at 21 days (pigs/litter); D113 = days for pig to reach 113.5 kg (d); BF = backfat (in; 1 in = 25.4 mm); FE = feed efficiency (lb feed/lb gain), ADG = average daily gain (lb/day) between 60 lb and 250 lb, LEAN = carcass lean (%),VOL = semen volume (mL), CON = semen concentration (10^3 spermatozoa/mm^3), MOT = progressive motion of spermatozoa (%) , ABN = abnormal spermatozoa (%), DOSES = number of usable semen doses per collection.

* Values were compiled from NSIF (2002) and Smital et al. (2005)

\- not applicable.

TBE = to be estimated.

Table 3.2. Costs and financial input values assumed*.

Variables	Input
Interest rate	2.00%
Insurance costs	$ 24,039.80
Maintenance and repair costs	$ 60,099.00
Cost associated with the reproduction technology	$ 12.75
Cost of boar maintenance and semen processing per collection frequency	
Fixed costs/boar space/wk	
Facilities	$ 6.30
Feed	$ 3.00
Utilities	$ 0.20
Miscellaneous health costs	$ 0.40
Cost/collection	
Labor	$ 6.30
Laboratory supplies	$ 5.50
Semen sale price	$ 6.00
Cost/semen dose	
Semen extender	$ 0.20
Bags and equipment	$ 0.20
Labor (post semen evaluation)	$ 0.17
Boar costs per semester assuming:	
7.00 collections/wk; (17.6 usable doses/collection)	$ 4230.82
3.50 collections/ wk (19.2 usable doses/collection)	$ 2327.10
2.33 collections/ wk (23.5 usable doses/collection)	$ 1785.90
1.75 collections/ wk (25.3 usable doses/collection)	$ 1450.46
1.40 collections/ wk (25.7 usable doses/collection)	$ 1220.14
1.17 collections/wk (26.2 usable doses/collection)	$ 1068.33
1.00 collection/wk (27.3 usable doses/collection)	$ 968.79

*Values were compiled from Rutten et al. (2000) and Dhuyvetter et al. (2009).

Table 3.3. Transmission matrix depicting the relationship between the 22-pig selection groups in the simulated three-tier, four-way crossbreeding production system

		Maternal Lines				Paternal Lines				F1	F1
		A		B		C		D		DC	BA
Tier and Group		Boars	Sows	Boars	Sows	Boars	Sows	Boars	Sows	Boars	Sows
Nucleus Maternal	Boars	1	2								
Line A	Sows	3	4								
Nucleus Maternal	Boars			5	6						
Line B	Sows			7	8						
Nucleus Paternal	Boars					9	10				
Line C	Sows					11	12				
								13	14		
								15	16		
Multiplier	Boars						17[3]	18[4]			
Multiplier	Sows		19[1]	20[2]							
Commercial										21[5]	22[6]

[1] Sows in group 19 are the offspring of line A boars and sows (groups 1, 2, 3, and 4).

[2] Boars in group 20 are the offspring of line B boars and sows (groups 5, 6, 7, and 8).

[3] Sows in group 17 are the offspring of line C boars and sows (groups 9, 10, 11, and 12).

[4] Boars in group 18 are the offspring of line D boars and sows (groups 13, 14, 15, and 16).

[5] Boars in group 21 are the offspring of group 17 sows and group 18 boars.

[6] Sows in group 22 are the offspring of group 19 sows and group 20 boars. The sows in group 22 were inseminated using conventional insemination technique with fresh semen from boars in group 21 to produce pigs for the market.

Table 3.4. Economic value from partial derivatives of the profit for the individual semen traits volume, concentration, motility and abnormalities, and DOSES per wk by collection schedule.

Traits[1]	Collections/wk						
	7	3.5	2.33	1.75	1.4	1.17	1.00
VOL ($/mL)	0.21	0.41	0.62	0.82	1.03	1.23	1.44
CON ($/x$10^3$spermatozoa /mm^3)	0.12	0.24	0.35	0.47	0.59	0.71	0.83
MOT ($/%)	0.61	3.62	5.43	7.23	9.04	10.85	12.66
ABN ($/%)	-0.53	-2.63	-4.38	-6.04	-7.67	-9.28	-10.88
DOSES($/dose)	2.01	10.00	16.67	23.00	29.20	35.34	41.43

[1] VOL = semen volume, CON = semen concentration, MOT = progressive motion of spermatozoa, ABN = abnormal spermatozoa, DOSES = number of usable insemination doses per collection.

Table 3.5. Annual genetic gain for individual traits by selection strategy and crossbreeding scheme.

Trait[1]	Unit	Strategy and crossbreeding scheme[2]					
		I3	II3	III3	I4	II4	III4
NBA	pigs/litter	0.013	0.013	0.015	0.009	0.009	0.010
LBW	lb	0.229	0.249	0.236	0.194	0.220	0.192
A21	lb	0.143	0.132	0.139	0.123	0.110	0.121
N21	pigs/litter	0.009	0.009	0.008	0.008	0.007	0.008
D113	days	-0.103	0.153	0.093	-0.552	-0.091	-0.210
BF	in	-0.011	-0.005	-0.008	-0.016	-0.005	-0.011
FE	lb/lb	0.004	0.002	0.002	0.004	0.002	0.002
ADG	lb	0.002	-0.003	0.002	0.008	-0.0001	0.003
LEAN	%	0.032	0.005	0.013	0.068	0.020	0.042
DOSES	doses	-	1.229	-	-	1.846	-
VOL	mL	-	-	2.060	-	-	3.488
CON	x10^3spermatozoa/mm^3	-	-	-0.477	-	-	-0.652
MOT	%	-	-	0.023	-	-	0.030
ABN	%	-	-	0.013	-	-	0.005

[1] NBA = number born alive; LBW = litter birth weight (1 lb = 2.2046 kg); A21 = adjusted 21-d litter weight; N21 = number at 21 days; D113 = d for pig to 113.5 kg; BF = backfat (1 in = 25.4 mm); FE = feed efficiency; ADG = average daily gain; LEAN = carcass lean, VOL = semen volume, CON = semen concentration, MOT = progressive motion of spermatozoa, ABN = abnormal spermatozoa, DOSES = number of usable insemination doses per collection.

[2] Strategy: I = baseline; II = baseline + *DOSES*; III = baseline + *VOL* + *CON* + *MOT* + *ABN*; Crossbreeding scheme: 3 = three; 4 = four-way crossbreeding scheme.

- not applicable.

Table 3.6. Relative economic values* of the traits in the selection indices used in the maternal (A and B) and paternal (C) nucleus lines in the three-way crossbreeding scheme for selected number of semen collections per wk (7 = daily collection; 2.33 = 1 collection every 3 d; and 1 = weekly collection) by selection strategy.

Trait[1]	7 collections/wk by Strategy[2]								
	I3			II3			III3		
	A	B	C	A	B	C	A	B	C
NBA	29.39	36.86	0.30	28.49	35.96	0.28	28.73	36.20	0.29
LBW	0.98	1.23	0.01	0.95	1.20	0.01	0.96	1.21	0.01
A21	1.09	1.37	0.01	1.06	1.33	0.01	1.06	1.34	0.01
N21	13.06	16.38	0.13	12.66	15.98	0.13	12.77	16.09	0.13
D113	0.19	0.15	0.34	0.18	0.15	0.32	0.18	0.15	0.33
BF	23.63	18.81	42.40	22.90	18.34	40.12	23.09	18.47	40.71
FE	20.48	16.30	36.74	19.85	15.90	34.77	20.01	16.00	35.28
ADG	9.45	7.52	16.96	9.16	7.34	16.05	9.24	7.39	16.28
LEAN	1.73	1.38	3.11	1.68	1.35	2.94	1.69	1.35	2.99
DOSES	-	-	-	3.07	2.46	5.38	-	-	-
VOL	-	-	-	-	-	-	0.32	0.26	0.57
CON	-	-	-	-	-	-	0.18	0.15	0.33
MOT	-	-	-	-	-	-	0.94	0.75	1.66
ABN	-	-	-	-	-	-	0.82	0.65	1.44
	2.33 collections/wk by Strategy								
	A	B	C	A	B	C	A	B	C
NBA	29.38	36.83	0.46	23.26	30.46	0.31	25.11	32.44	0.35
LBW	0.98	1.23	0.02	0.78	1.02	0.01	0.84	1.08	0.01
A21	1.09	1.36	0.02	0.86	1.13	0.01	0.93	1.20	0.01
N21	13.06	16.37	0.21	10.34	13.54	0.14	11.16	14.42	0.16
D113	0.19	0.15	0.34	0.15	0.12	0.23	0.16	0.13	0.26
BF	23.64	18.83	42.29	18.72	15.57	28.77	20.21	16.58	32.43
FE	20.49	16.32	36.65	16.22	13.49	24.93	17.51	14.37	28.11
ADG	9.45	7.53	16.92	7.49	6.23	11.51	8.08	6.63	12.97
LEAN	1.73	1.38	3.10	1.37	1.14	2.11	1.48	1.22	2.38
DOSES	-	-	-	20.80	17.30	31.97	-	-	-
VOL	-	-	-	-	-	-	0.84	0.69	1.34
CON	-	-	-	-	-	-	0.47	0.39	0.76

Table 3.6 (Cont.)

MOT	-	-	-	-	-	-	7.31	6.00	11.74
ABN	-	-	-	-	-	-	5.90	4.84	9.47
	1 collection/wk by Strategy								
	A	B	C	A	B	C	A	B	C
NBA	29.39	36.86	0.75	17.78	24.26	0.35	20.89	27.85	0.44
LBW	0.98	1.23	0.03	0.59	0.81	0.01	0.70	0.93	0.01
A21	1.09	1.37	0.03	0.66	0.90	0.01	0.77	1.03	0.02
N21	13.06	16.38	0.33	7.90	10.78	0.15	9.29	12.38	0.19
D113	0.19	0.15	0.34	0.11	0.10	0.16	0.13	0.11	0.20
BF	23.63	18.81	42.10	14.30	12.38	19.47	16.80	14.21	24.42
FE	20.48	16.30	36.49	12.39	10.73	16.87	14.56	12.32	21.16
ADG	9.45	7.52	16.84	5.72	4.95	7.79	6.72	5.68	9.77
LEAN	1.73	1.38	3.09	1.05	0.91	1.43	1.23	1.04	1.79
DOSES	-	-	-	39.49	34.19	53.77	-	-	-
VOL	-	-	-	-	-	-	1.61	1.36	2.34
CON	-	-	-	-	-	-	0.93	0.79	1.35
MOT	-	-	-	-	-	-	14.18	11.99	20.61
ABN	-	-	-	-	-	-	12.18	10.31	17.71

Relative economic value = economic value * standard discount expression expressed relative to the genetic standard deviation.

[1] NBA = number born alive; LBW = litter birth weight; A21 = adjusted 21-day litter weight; N21 = number of pigs per litter at 21 days; D113 = days for pig to reach 113.5 kg; BF = backfat; FE = feed efficiency, ADG = average daily gain, LEAN = carcass lean, VOL = semen volume, CON = semen concentration, MOT = percentage of all spermatozoa that are active with progressive motion, ABN = percentage of abnormal spermatozoa, DOSES = number of usable insemination doses per collection.

[2] Strategy: I = baseline; II = baseline + DOSES; III = baseline + VOL + CON + MOT + ABN.

[-] Not applicable.

Table 3.7. Relative economic values* of the traits in the selection indices used in the maternal (A and B) and paternal (C and D) nucleus lines for the four-way crossbreeding scheme for selected number of semen collections per wk (7 = daily collection; 2.33 = 1 collection every 3 d; and 1 = weekly collection) by selection strategy.

Trait[1]	7 collections/wk by Strategy[2]											
	I4				II4				III4			
	A	B	C	D	A	B	C	D	A	B	C	D
NBA	27.40	37.13	0.68	0.53	26.51	36.22	0.64	0.50	26.75	36.46	0.65	0.51
LBW	0.91	1.24	0.02	0.02	0.88	1.21	0.02	0.02	0.89	1.22	0.02	0.02
A21	1.01	1.38	0.03	0.02	0.98	1.34	0.02	0.02	0.99	1.35	0.02	0.02
N21	12.18	16.50	0.30	0.24	11.78	16.10	0.28	0.22	11.89	16.21	0.29	0.23
D113	0.20	0.15	0.34	0.34	0.19	0.15	0.32	0.32	0.19	0.15	0.32	0.32
BF	24.91	18.64	42.15	42.25	24.11	18.18	39.90	39.98	24.32	18.30	40.48	40.57
FE	21.59	16.15	36.53	36.62	20.89	15.76	34.58	34.65	21.08	15.86	35.08	35.16
ADG	9.97	7.45	16.86	16.90	9.64	7.27	15.96	15.99	9.73	7.32	16.19	16.23
LEAN	1.83	1.37	3.09	3.10	1.77	1.33	2.93	2.93	1.78	1.34	2.97	2.98
DOSES	-	-	-	-	3.23	2.44	5.35	5.36	-	-	-	-
VOL	-	-	-	-	-	-	-	-	0.34	0.26	0.57	0.57
CON	-	-	-	-	-	-	-	-	0.19	0.15	0.32	0.32
MOT	-	-	-	-	-	-	-	-	0.99	0.74	1.65	1.65
ABN	-	-	-	-	-	-	-	-	0.86	0.65	1.43	1.43
	2.33 collections/wk by Strategy[2]											
	A	B	C	D	A	B	C	D	A	B	C	D
NBA	27.39	37.13	0.94	0.53	21.45	30.76	0.64	0.36	23.23	32.74	0.72	0.41
LBW	0.91	1.24	0.03	0.02	0.71	1.03	0.02	0.01	0.77	1.09	0.02	0.01
A21	1.01	1.38	0.03	0.02	0.79	1.14	0.02	0.01	0.86	1.21	0.03	0.02
N21	12.17	16.50	0.42	0.24	9.53	13.67	0.29	0.16	10.32	14.55	0.32	0.18
D113	0.20	0.15	0.34	0.34	0.16	0.12	0.23	0.23	0.17	0.13	0.26	0.26
BF	24.92	18.64	41.98	42.25	19.52	15.44	28.63	28.75	21.14	16.44	32.25	32.41
FE	21.60	16.15	36.39	36.61	16.91	13.38	24.81	24.92	18.32	14.24	27.95	28.09
ADG	9.97	7.45	16.79	16.90	7.81	6.18	11.45	11.50	8.45	6.57	12.90	12.96
LEAN	1.83	1.37	3.08	3.10	1.43	1.13	2.10	2.11	1.55	1.21	2.37	2.38
DOSES	-	-	-	-	21.69	17.16	31.81	31.95	-	-	-	-
VOL	-	-	-	-	-	-	-	-	0.87	0.68	1.33	1.34

Table 3.7 (Cont.)

CON	-	-	-	-	-	-	-	-	0.49	0.38	0.75	0.76
MOT	-	-	-	-	-	-	-	-	7.65	5.95	11.68	11.73
ABN	-	-	-	-					6.17	4.80	9.42	9.46
	1 collection/wk by Strategy[2]											
	A	B	C	D	A	B	C	D	A	B	C	D
NBA	27.40	37.11	1.13	0.53	16.23	24.50	0.52	0.24	19.18	28.10	0.66	0.31
LBW	0.91	1.24	0.04	0.02	0.54	0.82	0.02	0.01	0.64	0.94	0.02	0.01
A21	1.01	1.37	0.04	0.02	0.60	0.91	0.02	0.01	0.71	1.04	0.02	0.01
N21	12.18	16.50	0.50	0.24	7.21	10.89	0.23	0.11	8.52	12.49	0.29	0.14
D113	0.20	0.15	0.33	0.34	0.12	0.10	0.16	0.16	0.14	0.11	0.19	0.20
BF	24.91	18.65	41.86	42.25	14.76	12.31	19.41	19.50	17.44	14.12	24.33	24.46
FE	21.59	16.16	36.28	36.61	12.79	10.67	16.83	16.90	15.11	12.23	21.09	21.20
ADG	9.97	7.46	16.74	16.90	5.90	4.92	7.77	7.80	6.98	5.65	9.73	9.79
LEAN	1.83	1.37	3.07	3.10	1.08	0.90	1.42	1.43	1.28	1.04	1.78	1.79
DOSES	-	-	-	-	40.76	33.99	53.62	53.85	-	-	-	-
VOL	-	-	-	-	-	-	-	-	1.67	1.36	2.34	2.35
CON	-	-	-	-	-	-	-	-	0.96	0.78	1.35	1.35
MOT	-	-	-	-	-	-	-	-	14.72	11.91	20.54	20.65
ABN	-	-	-	-	-	-	-	-	12.65	10.24	17.65	17.74

Relative economic value = economic value * standard discount expression expressed relative to the genetic standard deviation.

[1] NBA = number born alive; LBW = litter birth weight; A21 = adjusted 21-day litter weight; N21 = number of pigs per litter at 21 days; D113 = days for pig to reach 113.5 kg; BF = backfat; FE = feed efficiency, ADG = average daily gain, LEAN = carcass lean, VOL = semen volume, CON = semen concentration, MOT = percentage of all spermatozoa that are active with progressive motion, ABN = percentage of abnormal spermatozoa, DOSES = number of usable insemination doses per collection.

[2] Strategy: I = baseline; II = baseline + DOSES; III = baseline + VOL + CON + MOT + ABN.

[-] Not applicable.

3.7. Figures

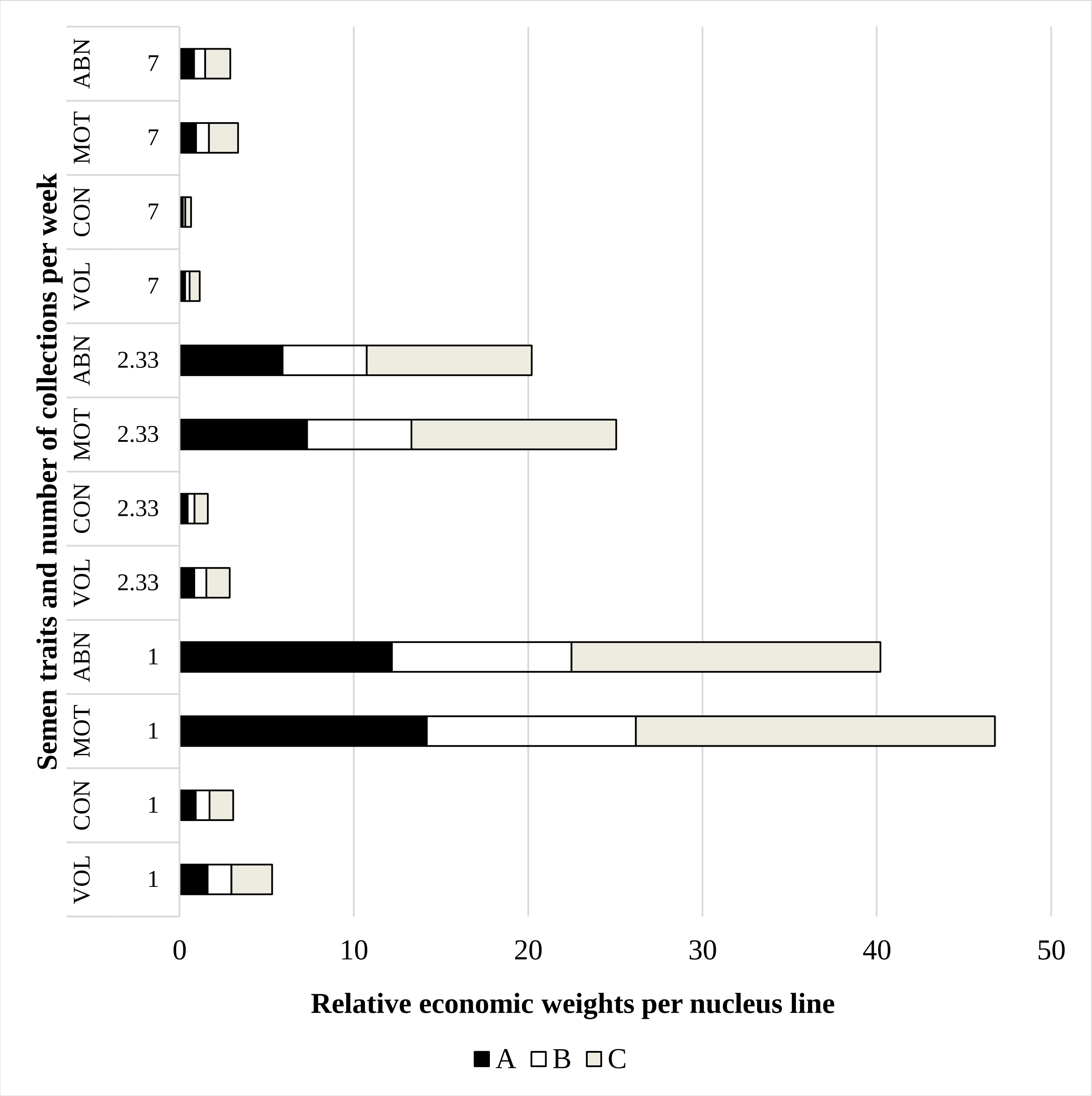

Figure 3.1. Relative economic values (%) of the 4 semen traits (VOLume, CONcentration, MOTility, and ABNormal) used in the selection indices for the maternal (A and B) and paternal (C) nucleus lines in Strategy III (baseline Strategy I + VOL + CON + MOT + ABN) for the three-way crossbreeding scheme with 7, 2.33, and 1 semen collections/wk.

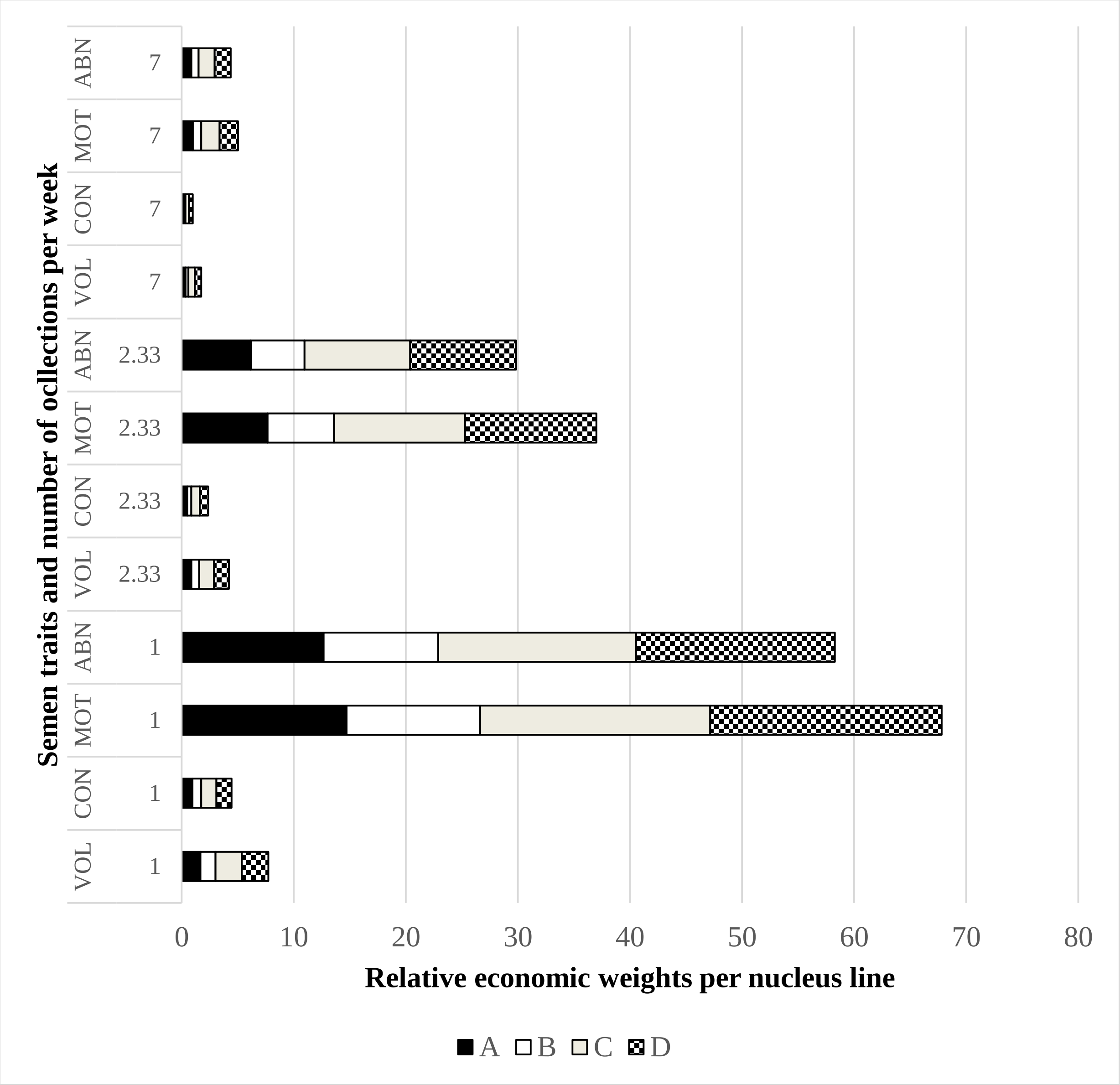

Figure 3.2. Relative economic values (%) of the 4 semen traits (VOLume, CONcentration, MOTility, and ABNormal) used in the selection indices for the maternal (A and B) and paternal (C and D) nucleus lines in Strategy III (Strategy I baseline + VOL + CON + MOT + ABN) for the four-way crossbreeding scheme with 7, 2.33, and 1 semen collections/wk.

CHAPTER IV: Contribution of semen trait selection, AI technique and semen dose to the profitability of pig production systems[3]

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4.1. Abstract

The economic impact of selection for semen traits on pig production systems and potential interaction with AI technique and semen dose remains partially understood. The objectives of this study were to compare the financial indicators (gross return, net profit, cost) in a three-tier pig production system under one of two selection strategies: a traditional strategy including nine paternal and maternal traits (S9) and an advanced strategy that adds four semen traits (S13). The five maternal traits included: number of pigs born alive, litter birth weight, adjusted 21-day litter weight, and number of pigs at 21 days and the four paternal traits included: days to 113.5 kg, backfat, average daily gain, feed efficiency, and carcass lean percentage. The four semen traits included: volume, concentration, progressive motility of spermatozoa, and abnormal spermatozoa. Simultaneously, the impact of two AI techniques and a range of fresh refrigerated semen doses including: cervical AI with $3x10^9$ (CAI3) and $2x10^9$ (CAI2) sperm cells/dose, and intrauterine AI with $1.5x10^9$ (IUI1.5), $0.75x10^9$ (IUI0.75), and $0.5x10^9$ (IUI0.5) sperm cells/dose were evaluated. These factors were also evaluated using a range of farrowing rates (60% to 90%), litter sizes (8 to 14 liveborn pigs), and a selected semen collection frequency. The financial impact of the factors was assessed through simulation of a three-way crossbreeding system (maternal nucleus lines A and B and paternal nucleus line C) using

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[3] This chapter has been submitted to be published as an open-access manuscript in Theriogenology on April 17, 2015.

ZPLAN. The highest return on investment (profit/cost) of boars was observed at 2.33 collections/wk (comparable to 3 periods of 24 h between collections). Under this schedule, a significant (P-value < 0.0001) interaction between selection strategy and AI technique-dose combination was identified for gross return; meanwhile significant (P-value < 0.0001) additive effects of selection strategy and AI technique-dose were observed for net profit. The highest gross return was obtained under S13 with IUI0.75 and IUI0.5. The net profit of S13 was 34.37% higher than the traditional S9 (P-value < 0.0001). The net profit favored IUI0.5 with relative differences of 4.13%, 2.41%, 1.72%, and 0.43% compared to CAI3, CAI2, IUI1.5, and IUI0.75, respectively. The advanced selection strategy proposed including four semen traits is recommended based on the higher profitability relative to the traditional strategy.

4.2. Introduction

Considerable genetic variation in sperm production and quality among boars has been reported, leading to recommendations for inclusion of semen traits in selection strategies for terminal sires (Flowers, 2009). In addition to genetic variability, economic, health, and welfare benefits associated with genetic improvement of semen traits have been noted (Smital et al., 2005; Oh et al., 2006; Foxcroft et al., 2008). Semen traits such as: ejaculate volume, sperm concentration, percentage of motile sperm, and morphologically abnormal cells are routinely measured and are helpful indicators of the boar’s fertility (Flowers, 1997; Gadea, 2005; Foxcroft et al., 2008). Simulation studies suggest that strategies including semen traits in addition to traditional paternal (growth) or maternal (reproductive) traits can enable the maintenance or improvement of the former traits without compromising the genetic gains for the latter traits (Safranski, 2008; Gonzalez-Pena et al., 2014b).

Studies of selection strategies including semen traits necessitate the simultaneous consideration of alternative AI techniques and associated semen dose required. Semen deposition close to the oviduct using post cervical AI instead of the conventional cervical requires lesser sperm and consequently fewer number of boars (Roca et al., 2006; Vazquez et al., 2008). Thus, AI techniques that require lower doses and boars could potentially enable greater selection intensity, production efficiency, gross return, and net profit for the pig industry (Smital et al., 2005; Oh et al., 2006; Foxcroft et al., 2008; Williams et al., 2011). The simultaneous impact of selection for semen traits, AI technique and semen dose on the financial indicators of a pig production system remains partially understood.

The objective of this study was to compare the economic impact of incorporating semen traits into a selection strategy relative to a traditional selection strategy under two AI techniques (cervical and intrauterine) that use fresh refrigerated semen across a number of sperm doses. Supporting aims were: 1) to evaluate the return on investment for a number of semen collection frequencies, and 2) to evaluate a set of complementary financial indicators under a range of productive and reproductive scenarios.

4.3. Materials and Methods

The simultaneous economic impact on a crossbreeding pig production system of two selection strategies: traditional with nine traits (S9) and advanced adding four semen traits (S13); two AI techniques: cervical (CAI) or intrauterine (IUI); and a number of sperm doses: two doses for CAI and three doses for IUI, was studied. A range of semen collection frequencies were considered and the results were evaluated for a range of farrowing rate (FR) and litter size (LS) scenarios.

Selection strategies

A three-tier, three-way crossbreeding scheme system was simulated using ZPLAN (Willam et al., 2008). Briefly, the crossbreeding scheme included maternal lines A and B and paternal line C. Each nucleus line included 500 sows, the multiplier level produced F_1 sows from B boars and A sows, and at the commercial level, pigs obtained from the cross between BA sows and C boars were sold (Gonzalez-Pena et al., 2014a).

The traditional selection strategy studied (NSIF, 2002) encompassed five maternal traits: number of pigs born alive (NBA), litter birth weight (LBW), adjusted 21-day litter weight (A21), and number of pigs at 21 days (N21), and four paternal traits: days to 113.5 kg (D113), backfat (BF), average daily gain (ADG), feed efficiency (FE), and carcass lean % (LEAN). The advanced selection strategy proposed added four semen traits: ejaculate volume, sperm concentration, percentage of motile sperm, and morphologically abnormal cells to the traditional strategy.

AI techniques and doses

The minimum fresh refrigerated semen dose required varies with the AI technique used. Thus, the economic impact of the selection strategy was studied for five combinations of AI technique and semen dose. The AI technique-dose (expressed in sperm cells/dose) combinations evaluated included: CAI and 3×10^9 (CAI3), CAI and 2×10^9 (CAI2), IUI and 1.5×10^9 (IUI1.5), IUI and 0.75×10^9 (IUI0.75), and IUI and 0.5×10^9 (IUI0.5).

A range of semen collection frequencies was considered. The average usable doses per collection frequency assumed for CAI3 are listed in **Table 4.1** (Rutten et al., 2000). The CAI3 was considered baseline and the values were multiplied by the standard sperm cells/dose ($3x10^9$, Safranski, 2008) in a semen dose and then divided by the amount of sperm cells/dose to be used (e.g. 2, 1.5, 0.75, and 0.5). The AI technique-dose combinations simulated in this study have been previously referred and used in field trials with refrigerated fresh semen preparation and ensured suitable fertility outcomes (Watson and Behan, 2002; Olesen and Hansen, 2009; Hernandez-Caravaca et al., 2012).

For financial comparison purposes the simulation assumed 2.1 semen doses per estrus, 2.25 farrowings/y, 225,000 farrowings at the commercial level every six months and a profit horizon of 10 years (Weller, 1994; Levis et al., 2001; Roca et al., 2006; Safranski, 2008). For the set farrowing target, the number of sows in the multiplier and commercial levels varied depending on the FR and LS scenario simulated. In addition to the number of sows, the boar utilization varied across scenarios through the reproductive and dose combinations. This selection strategy permitted the evaluation of the same range of FR and LS among selection strategy (S9 and S13) and AI technique-dose combinations (CAI3, CAI2, IUI1.5, IUI0.75, and IUI0.5).

Biological and technological input parameters and financial outputs

Biological, technological, and financial input parameters used in the simulation were based on a literature review. Inputs for the three-way crossbreeding scheme were obtained from previous studies of similar pig production systems (Rutten et al., 2000; Gonzalez-Pena et al., 2014a).

The financial outputs studied included net profit, gross return, and total cost (Nitter et al., 1994; Wünsch et al., 1999; Willam et al., 2008). Briefly, net profit was computed as gross return minus total cost and gross return was the monetary value of the sow over the time of investment. Total cost included variable and fixed costs that are dependent and independent of the size of the operation, respectively (Wünsch et al., 1999; Gonzalez-Pena et al., 2014a).

Costs associated with boar maintenance and semen doses including facilities, management, and collection are presented in **Table 4.2** (Rutten et al., 2000; Dhuyvetter et al., 2009). Using the information in **Table 4.2**, the cost and the return per boar were simulated according to the collection frequencies per wk (**Table 4.3**). A demonstration of the calculations in **Table 4.3** is provided for IUI1.5 with a collection frequency of 2.33/wk (3 resting days between collections). Assuming \$9.90/wk of facilities and management costs, plus a collection cost equal to \$11.8/collection in labor and laboratory supplies (total cost = \$11.8 * 7/3 = \$27.49), plus \$0.57/dose cost and 51 usable/wk (from **Table 4.1**, total cost = \$0.57 * 51 * 7/3 = 67.83), then the boar costs equals \$105.26/wk. The return was calculated in a similar manner. Continuing with the previous example, for 51 doses at the sale price of \$6.00/dose and 2.33 collections/wk, the return is \$714.00/boar/wk. This information was used to compute the return on investment [(return of one boar – boar weekly costs) / boar weekly costs] and to identify the collection frequencies with highest return on investment.

Analysis of financial outputs

A sensitivity analysis was implemented to understand the association between financial indicators, selection strategy, and AI technique-dose combination within a grid of FR (60% to 90%, in 5% increments) and LS (from 8 to 14 liveborn pigs/litter, in one pig increments). Within these boundaries, the least favorable scenario was characterized by a FR equal to 60% and a LS equal to 8 liveborn pigs/litter and the most favorable scenario was characterized by a FR equal to 90% and a LS equal to 14 liveborn pigs/litter. An average FR equal to 75% and LS equal to 11 liveborn pigs/litter were considered and deviations within the symmetric upper and lower bounds were evaluated. Realistic upper boundaries were considered to ensure that the study will remain relevant in the short term. Farrowing rate above 85% and LS equal to 14 liveborn pigs/litter has been frequently reported for several years (Love et al., 1995; Klindt, 2003; Young et al., 2010; Hernandez-Caravaca et al., 2012).

The financial outputs from the simulation were analyzed using the model:

$$\mathrm{y_{ijkl}} = \mu + \mathrm{S_i} + \mathrm{T_j} + \mathrm{ST_{ij}} + \beta_1\left(\mathrm{F_{ijk}} - \bar{\mathrm{F}}\right) + \beta_2(\mathrm{F_{ijk}} - \bar{\mathrm{F}})^2 + \beta_3\left(\mathrm{L_{ijkl}} - \bar{\mathrm{L}}\right) + \beta_4(\mathrm{L_{ijkl}} - \bar{\mathrm{L}})^2 + \varepsilon_{\mathrm{ijkl}}$$

where $\mathrm{y_{ijkl}}$ denoted the value of net profit, gross return, total cost, and variable cost, μ is the overall mean, S_i denoted the fixed effect of selection (levels S9 and S13), T_j denoted the fixed effect of the AI technique-dose combinations (levels CAI3, CAI2, IUI1.5, IUI0.75, and IUI0.5), ST_{ij} denoted the interaction between selection and AI technique-dose combinations, β_1 and β_2 denoted the linear and quadratic regression coefficients for the covariate FR (F), respectively, β_3 and β_4 denoted the linear and quadratic regression coefficients for the covariate LS (L), respectively, and ε_{ijkl} denoted the residual associated with y_{ijkl}. Analysis was implemented using the MIXED procedure of SAS (SAS Institute, Cary, NC). Orthogonal contrasts among the selection strategies and AI technique-dose combination levels were evaluated and Scheffé multiple comparison adjustment was used (Kuehl, 2000). The selection strategies and AI technique-dose combinations trends within the interaction were tested using the SLICE option in the GLM procedure (SAS Institute, Cary, NC). The evaluation of the impact of selection on various indicators was expressed in relative difference terms. Relative difference was defined as the difference in the indicator between S9 and S13, relative to the recorded maximum value between S9 and S13. The use of a relative value enabled the assessment of the impact protected from specific absolute values, and the use of observed maximum value supported a conservative calculation.

4.4. RESULTS

Study of collection frequency

The highest return on investment occurred at 2.33 collections/wk corresponding to resting periods of 3 days between semen collections (**Figure 4.1**). The frequency 1.75 collections/wk was a close second in return on investment and both frequencies (2.33 and 1.75) were optimal across all AI technique-dose combinations studied. The lowest return on investment was expected at 1.0 collection/wk. However, the minimum occurred at 1.17 collections/wk due to a small oscillation in the average of doses obtained per collection by boar. Subsequent analyses assume a frequency of 2.33 collections/wk.

Impact of selection strategy and AI technique-dose combination on the financial indicators

The impact of selection strategy and AI technique-dose combination on the financial indicators were evaluated across FR and LS scenarios at 2.33 collections/wk.

The significance P-values of the main effects of selection strategy, AI technique-dose combination, and their interaction on net profit, gross return, total cost, and variable cost are summarized in **Table 4.4**. Minimum statistical and financial thresholds were used to identify significant differences on biological and financial indicators across selection strategy-AI technique-dose combinations. A stringent P-value threshold (P-value < 0.005) was used in recognition of the multiple testing across financial indicators. The minimum threshold to designate a financially significant difference was set at 2%, equivalent to the average interest rate of the Treasury note (US Treasury, 2013). The gross return exhibited a significant association with the multiplicative interaction between selection strategy and AI technique-dose combination. The remaining financial indicators exhibited significant additive associations with selection strategy and AI technique-dose combination. Therefore, the main effects selection strategy and AI technique-dose combination will be evaluated across the FR and LS levels assessed. No quadratic association between FR level and the financial indicators was observed. No linear or quadratic association between LS level and variable and total cost and no quadratic association with the other financial indicators were found.

Characterization of the significant association between gross return and interaction is depicted by the least square mean estimates by combination of selection strategy and AI technique-dose presented in **Table 4.5.** Gross return is the income before deduction of total cost. Therefore, gross return was further investigated.

Impact selection strategy and AI technique-dose combination on gross return

The interaction between selection strategy and AI technique-dose combination had a statistical significant impact on gross return (expressed in $/ sow, **Table 4.4**). However, this impact was below the minimum 2% financial threshold considered (**Table 4.5**). The combination S13-IUI0.5 presented the highest gross return and stayed constant across FR levels; meanwhile the gross return for combination S13-IUI0.75 increased until paring with S13-IUI0.5 at 70% FR.

The gross return for combinations S13-IUI150 and S13- CAI2 reached a plateau at 75% and 85% FR, respectively with oscillations less than 0.001 units thereafter. On average, the relative difference in gross return between S13 and S9 was approximately 27% across AI technique-dose combinations (**Table 4.5**). The relative difference in gross return between AI technique-dose combinations within selection strategies was less extreme. These results indicate that the difference in gross return was dominated by the main effect selection strategy.

Characterization of the significant association between net profit, totals cost, variable cost, and the main effects of selection strategy and AI technique-dose combination are summarized in **Table 4.6**. The impact of selection strategy and AI technique-dose combination on net profit was further investigated.

Impact selection strategy and AI technique-dose combination on net profit

The relative difference in net profit (expressed in $/sow) between S9 and S13 was -34.37%; clearly superseding the minimum 2% financial threshold established. The IUI0.5 exhibited the highest net profit with relative differences of 4.12%, 2.41%, 1.72%, and 0.43% compared to CAI3, CAI2, IUI1.5, and IUI0.75, respectively (**Table 4.5**). Within S13 the relative differences in net profit between CAI3 compared to CAI2, IUI1.5, IUI0.75, and IUI0.5 were -2.27%, -3.19%, -4.79%, and -5.31%, respectively in the least favorable FR-LS scenario. Also, the relative differences in net profit between CAI3 compared to CAI2 (**Figure 4.2**), IUI1.5 (**Figure 4.3)**, IUI0.75, and IUI0.5 were -0.97%, -1.33%, -2.03%, and -2.26%, respectively in the most favorable FR-LS scenario. A notable finding was that the differences between selection strategy-dose combinations were more marked in the least favorable scenario.

Other notable comparisons of net profit were: CAI2 vs. IUI1.5, CAI2 vs. IUI0.75, and CAI2 vs. IUI0.5. The relative differences in net profit between CAI2 and IUI1.5 failed to surpass the minimum 2% financial threshold with values ranging between -0.94% and -0.36% in the least and most favorable FR-LS scenarios, respectively. The relative difference in net profit between CAI2 vs. IUI0.75 surpassed the 2% minimum financial threshold for FR lower than 70%. However, for FR equal or higher than 70% regardless of LS level, the relative difference between CAI2 and IUI0.75 ranged from -1.87% at 70% FR to -1.07% at 90% FR (best scenario). The same pattern was observed for the relative difference in net profit between CAI2 vs. IUI0.5 albeit at a slightly higher change point (75% FR). Beyond 75% FR and regardless of LS level, the relative differences between CAI2 and IUI0.5 ranged from -1.96% at 75% FR to -1.30% at 90% FR. In conclusion, for production systems with a minimum 75% FR that use S13, CAI2 results in similar or slightly less net profit than IUI for the doses considered in this study.

The net profit per sow for S13 across FR and LS scenarios ranged from \$56.84 to \$63.09 for CAI3, \$58.16 to \$63.71 for CAI2, \$58.71 to \$63.94 for IUI1.5, \$59.70 to \$64.40 for IUI0.75, and \$60.03 to \$64.55 for IUI0.5 combination. All the AI technique-dose combinations had the lowest net profit in the least favorable FR-LS scenario and the highest net profit in the more favorable FR-LS scenario. Also, the impact of the AI technique-dose combination on the net profit was weaker in the most favorable FR-LS scenario relative to the least favorable scenario. Net profit is the result of the gross return minus total cost (Nitter et al., 1994). A careful study of the differences in total and variable cost was undertaken.

Impact selection strategy and AI technique-dose combinations on total cost

The relative differences in total cost (expressed in $/sow) between S9 and S13 surpassed the 2% minimum financial threshold established (**Table 4.5**). The AI technique-dose combination that had lower total cost was IUI0.5 with relative differences compared to CAI3, CAI2, IUI1.5, and IUI0.75 of 8.25%, 4.98%, 3.63%, and 0.93% respectively. Within S13, the relative differences in total cost between CAI3 and CAI2, IUI1.5, IUI0.75, and IUI0.5 were 4.52%, 6.40%, 9.81%, and 10.92% in the least favorable FR-LS scenario, respectively. A similar trend yet less significant was observed in the relative differences in total cost between CAI3 and CAI2 (**Figure 4.4**), IUI1.5 (**Figure 4.5)**, IUI0.75, and IUI0.5 at 2.50%, 3.56%, 5.38%, and 6.01% in the most favorable FR-LS scenario.

Within the S13, the relative differences between CAI2 and. IUI0.75 or IUI0.5 in the least favorable FR-LS scenario were 5.54% and 6.70%, respectively; and 2.95% and 3.60%, respectively in the most favorable scenario. The relative difference in total cost between CAI2 vs. IUI1.5 in the least and most favorable scenarios were 1.97% and 0.98%, respectively thus failing to surpass the 2% minimum financial threshold. Total cost is an indicator that combines fixed and variable cost. Fixed cost is associated with the size of the operations and is linearly correlated with the number of animals. Therefore, this type of cost behaves as a constant across the two selection strategies. Variable cost, on the other hand, is expected to be affected by the AI technique-dose combination and selection strategy. Thus, an investigation on the impact of these factors on the variable cost was undertaken.

Impact selection strategy and AI technique-dose combination on variable cost

The relative differences in variable cost (expressed in $/sow) between selection strategies S9 and S13 surpassed the 2% financial threshold (**Table 4.5**). Similar to the trends observed for total cost, IUI0.5 had the lower variable cost with relative differences compared to CAI3, CAI2, IUI1.5, and IUI0.75 of 25.89%, 16.84%, 12.82%, and 3.57%, respectively. Within S13 the relative differences in variable cost in the least favorable FR-LS scenario between CAI3 and CAI2, IUI1.5, IUI0.75, and IUI0.5 were 11.97%, 16.70%, 25.65%, and 28.57%, respectively. The relative differences in variable cost in the most favorable FR-LS scenario between CAI3 and CAI2, IUI1.5, IUI0.75, and IUI0.5 were 7.78%, 10.43%, 16.30%, and 18.21%, respectively. For the least favorable scenario, the relative differences in variable cost between CAI2 and IUI1.5, IUI0.75 and IUI0.5 were 37%, 15.54%, and 18.86%, respectively surpassing the 2% financial threshold. Similarly, for the most favorable scenario, the relative differences in variable cost between CAI2 and IUI1.5, IUI0.75 and IUI0.5 were 2.87%, 9.24%, and 11.31%, respectively.

4.5. DISCUSSION

Considerations about semen collection frequency

The study of the impact of selection strategy and AI technique-semen dose combination on the financial indicators of a three-tier pig production system required the consideration of the frequency of semen collection. Frequency of semen collection affects both, sperm quality and fertility (Pruneda et al, 2005; Smital, 2009). Reducing the resting periods between collections from 10 to 2 days resulted in marked decreases in concentration and a reduction in semen volume (Wolf and Smital, 2009). Increasing the interval between collections increases the sperm concentration until 10 days and a plateau is reached thereafter (Wolf and Smital, 2009). Also, beyond this interval, motility tends to decrease. Optimum collection interval to maximize the total output of quality sperm ranges from 2 to 5 days (Smital, 2009). In the present study, 2.33 collections/wk offered the highest return on investment and was used in subsequent evaluations (**Figure 4.1**). This collection frequency is favorable from an economic and a physiological perspective, allowing the boar to recover the epididymal reserves. Our finding was consistent with usual practices in Europe and North America with frequencies between 3 and 7 days of resting between collections (Rutten et al., 2000; Knox et al., 2008; Broekhuijse et al., 2012).

Return of investment increased when the AI technique-dose allowed a reduction of the sperm concentration per dose. Techniques that required lower sperm per dose can increase the amount of doses and therefore, the cost of doses processing per collection. The beneficial decrease in the numbers of boars required and associated cost compensated the relative increase in the cost of the technique. Therefore, an efficient use of the boars due to a reduction on the required sperm concentration appropriate to the AI technique can increase the returns on investment, utilization efficiency, selection intensity and profitability of the system by reducing the boar cost (Rutten et al., 2000; Roca et al., 2006; Williams et al., 2011). Our study evaluated the effect of selection strategy and AI technique on the main financial indicators.

Impact of selection strategy and AI technique-dose combination on the financial indicators

Two selection strategies, a traditional strategy and an advanced strategy that added four semen traits were considered using 2.33 collections/wk. The financial indicators gross return, net profit, total cost, and variable cost were significantly impacted by selection strategy (**Table 4.4**) confirming previous reports that selection for semen traits plays a role in enterprise inputs and outputs (Rothschild, 1996). Despite this confirmation, boar semen traits are usually omitted from selection decisions (Rothschild, 1996; Flowers, 1997; Ruiz-Sanchez et al., 2006). Traits like sperm concentration influence the amount of doses that can be obtained from one ejaculate and this has a direct economic impact on the boar stud and AI efficiency (Camus et al., 2011). Similarly, ejaculate volume is considered a viability indicator with a minimum threshold established by the industry (Sancho and Vilagran, 2013) and is critical for efficient use of lower-dose insemination techniques (Broekhuijse et al., 2012). The evaluation of morphology or percentage of morphologically abnormal cells offers information on sperm quality and gives insight on seminiferous tubule functionality and epididymal maturation that could be linked to the collection frequencies (Rutten et al, 2000; Gadea, 2005). The previous semen traits are traditionally used in semen quality evaluation enabling the detection of male reproductive disorders that could result in low fertility (Holt, 2005; Gillan et al., 2005). Also, their inclusion in the selection decision allowed genetic gains for semen traits without compromising the genetic gains for other traits (Gonzalez-Pena et al., 2014b). Our study offers a glimpse of the possible effect of inclusion of these or similar traits in a selection program and demonstrate that selection for these semen traits impacts a number of financial indicators. Integration of information from additional semen traits indicators of boar fertility such as chromatin damage, presences of sperm membrane proteins, or seminal plasma proteins in the selection strategy needs to be evaluated (Foxcroft et al., 2008). Identification and inclusion in the selection index of semen traits involved in successful fertilization events could further contribute to higher net profit.

Impact selection strategy and AI technique-dose combination on gross return

A synergistic interaction between selection strategy and AI technique-dose combination on gross return was observed. Furthermore, considering selection strategy alone, our results demonstrate that S13 resulted in higher gross return (27% on average) across AI technique-dose combinations compared to S9 (**Table 4.5**). This trend can be explained by the inclusion of economically important traits in livestock selection strategies that are expected to increase gross return (Wünsch et al., 1998). The effect of the statistically significant interaction between selection strategy and AI technique-dose combination on gross return was below the minimum 2% financial threshold and was dominated by the effect of selection strategy. The highest gross return was obtained under S13 with IUI0.75 and IUI0.5 AI.

Impact selection strategy and AI technique-dose combination on net profit

Selection strategy and AI technique-dose combination acted in an independent additive fashion on net profit and were both, statistically and economically significant (**Table 4.6**). The net profit of S13 was higher than S9 indicating that the inclusion of the semen traits in selection strategies increased gross return without a comparable increase in cost (Wünsch et al., 1999). This is consistent with previous recommendations to include boar semen traits in selection strategies due to the influence of these traits on the amount of doses that could be obtained (Smital et al., 2005; Camus et al., 2011) and ultimately on net profit.

The AI technique-dose combination had less impact on the net profit than selection strategy. Across strategies, IUI0.5 presented the highest net profit and, the difference relative to IUI0.75 and IUI1.5 were lower than the minimum 2% financial threshold (**Table 4.6**). Our results confirm previous reports that production systems that use IUI can be as profitable as those that use CAI, under specific conditions (Roca et al., 2006).

The ranking of AI technique-dose combination in terms of net profit depended on the FR and LS. This dependency is consistent with prior reports on the impact of management practices and AI techniques (Levis et al., 2001). **Figures 4.2** and **4.3** demonstrate that the least favorable FR-LS scenario (lower x- and z-axes values) had the lowest net profit and exhibited the largest relative differences in net profit (more negative y-axis value) between AI techniques-dose compared. In comparison, **Figures 4.2** and 4.**3** also demonstrate that smaller relative differences in net profit (less negative y-axis value) were found in the comparison between AI techniques-dose combinations under the most favorable FR-LS scenario (highest x- and z-axes values). The relative differences in net profit between CAI3 and CAI2 or IUI1.5 were lower than the 2% minimum economical thresholds beyond 65% FR (**Figure 4.2**) and 75% FR (**Figure 4.3**), respectively. Additionally, relative differences in net profit at any FR and LS combination of IUI0.75 and IUI0.5 relative to CAI3 were highest than the 2% threshold. These results illustrate the importance of selecting the optimal combination of AI techniques-dose for each scenario to maximize net profit.

Impact selection strategy and AI technique-dose combinations on total and variable cost

Further analysis of the impact of selection strategy and AI technique-dose combination on the financial components indicated that the behavior of net profit was driven by the total cost. Selection strategy and AI technique-dose combination acted in an independent additive fashion on the total cost. Interestingly, S13 presented higher variable and total cost compared to S9; however, S13 also presented higher gross return and net profit (**Table 4.6**).

Among AI technique-dose combinations, CAI3 exhibited the highest variable and total cost (**Table 4.6**) and IUI0.5 exhibited the lowest variable and total cost. The relative difference in total cost between CAI3 and IUI1.5 was 4.8%. Reduction of 0.8% and 1.33% in total cost of CAI3 compared to IUI1.5 and IUI1.0 were reported in Europe (Hernandez-Caravaca et al., 2012). These results further confirm the value of careful selection of the optimal technique-dose combination to reduce the number of boars needed and associated costs (Rozeboom et al, 2004; Levis et al., 2001; Roca et al.,2006; Vazquez et al., 2008; Williams et al., 2011).

Furthermore, the results indicate that the optimal technique-dose combination depends on the FR-LS scenario considered (**Figure 4.4 and 4.5**). The comparison between CAI3 and CAI2 or IUI1.5 had the largest differences in total cost in the least favorable FR-LS scenario amounting to 4.5% (**Figure 4.4**) and 11% (**Figure 4.5**), respectively. With higher FR and LS the differences in total costs were less marked with the lowest differences between CAI3 and CAI2 or IUI1.5 amounting to 2.5% (**Figure 4.4**) and 6.0% (**Figure 4.5**), respectively at the most favorable scenario. This trend of larger total cost with more unfavorable FR-LS scenarios was observed for all AI techniques-dose combination comparisons.

Despite the higher cost of catheter and labor, and labor time of IUI compared to CAI that was assumed in this study, the variable cost was lower for IUI compared to CAI. The beneficial reduction in boar maintenance cost and sow population size required to market a set number of pigs due to higher fertility using IUI relative to CAI compensated the cost of IUI. These trends resulted in higher net profit when IUI was used.

In conclusion, selection strategy and AI technique-dose combination had a statistically significant non-additive effect on gross return although this effect was below the minimum 2% threshold. On average, the advanced strategy S13 including the four semen traits had 34.37%

higher net profit relative to the traditional strategy S9 that only includes paternal and maternal traits. At FR levels comparable to the current industry settings, S13 and IUI0.5 and IUI0.75 exhibited the highest efficiency of boar utilization with the consequent reduction in variable cost. In addition, the integration of S13 and conventional AI technique CAI2 with a minimum 75% FR offered a net profit similar to IUI at any of the doses combinations considered in this study. The AI technique-dose combinations IUI0.75 and IUI0.5 required fewer boars decreasing total cost and increasing net profit.

Challenges associated with the introduction a new technology, retraining of personnel, higher risk of injury associated with the catheter passing through the cervix, and recommendations of IUI for females with at least one parity (Levis et al., 2001; Olesen and Hansen, 2009) need to be considered together with reduction in total cost and increase in net profit. Also, challenges associated with the impact of lower semen dose on FR need to be considered and evaluated. Lower doses such as $1x10^9$ sperm cells/dose could reduce the FR if conventional AI is used (Watson and Behan, 2002). However, adequate levels of FR have been reported using doses as low as $0.5x10^9$ sperm cells/dose with intrauterine technique (Mezalira et al., 2005). Also, wide variation in FR have been reported with low doses, regardless of the AI technique used (Willenburg et al., 2012). Our results reflect the potential financial benefits when the dose is optimized to maximize FR according to the insemination technique used.

Our study demonstrated the financial benefits of advanced selection strategy incorporating semen traits relative to traditional selection strategy in a pig production system. Furthermore, our results lead to recommend the integration of the advanced selection strategy including maternal, paternal and semen traits together with the AI techniques-semen dose combinations that offered optimal (IUI) and proximal sub-optimal benefits (CAI) for the FR and LS scenario considered.

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4.6. References

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4.7. Tables

Table 4.1. Number of doses simulated across collection frequency (CF) levels according to the AI technique and associated dose concentration required

	AI technique-dose combination[1]				
CF[2]	CAI3	CAI2	IUI1.5	IUI0.75	IUI0.5
7	19.6	29.4	39.2	78.4	117.6
3.5	21.2	31.8	42.4	84.8	127.2
2.33	25.5	38.3	51.0	102.0	153.0
1.75	27.3	41.0	54.6	109.2	163.8
1.4	27.7	41.6	55.4	110.8	166.2
1.16	25.2	37.8	50.4	100.8	151.2
1	29.3	44.0	58.6	117.2	175.8

[1] CAI3 = cervical AI with $3x10^9$ sperm cells/dose [14]; CAI2 = cervical AI with $2x10^9$ sperm cells/dose; IUI1.5 = intrauterine AI with $1.5x10^9$ sperm cells/dose; IUI0.75 = intrauterine AI with $0.75x10^9$ sperm cells/dose; IUI0.5 = intrauterine AI with $0.5x10^9$ sperm cells/dose.

[2] CF = collection frequency per wk, 7 = one 24 h period between collections; 3.5 = two 24 h periods between collections; 2.33 = three 24 h periods between collections; 1.75 = four 24 h periods between collections; 1.4 = five 24 h periods between collections; 1.16 = six 24 h periods between collections, 1 = seven 24 h periods between collections (one collection per wk)

Table 4.2. Cost and financial input values assumed*

Variables	Input
Fixed cost per semester of labor	$ 7,800,000
Insurance costs	$ 18,735.60
Maintenance and repair costs	$ 46,839.00
Cost of boar maintenance and semen processing per collection frequency	
Fixed costs/boar space/wk	
Facilities	$ 6.30
Feed	$ 3.00
Utilities	$ 0.20
Miscellaneous health costs	$ 0.40
Cost/collection	
Labor	$ 6.30
Laboratory supplies	$ 5.50
Cost/dose	
Semen extender	$ 0.20
Bags and equipment	$ 0.20
Labor (post semen evaluation)	$ 0.17
Sale price/dose	$ 6.00

*Based on Rutten et al. (2012) and Dhuyvetter et al. (2012).

Table 4.3. Initial cost ($) and return ($, between parenthesis) per boar and wk across semen collection frequency (CF) levels

	AI technique-dose combination[1]				
CF[2]	CAI3	CAI2	IUI1.5	IUI0.75	IUI0.5
7	170.70 (823.20)	209.81 (1234.80)	248.91 (1646.40)	405.32 (3292.80)	561.72 (4939.20)
3.5	93.49 (445.20)	114.64 (667.80)	135.79 (890.40)	220.38 (1780.80)	304.96 (2671.20)
2.33	71.35 (357.00)	88.37 (536.20)	105.26 (714.00)	173.09 (1428.00)	240.92 (2142.00)
1.75	57.78 (286.65)	71.45 (430.50)	85.01 (573.30)	139.48 (1146.60)	193.94 (1719.90)
1.4	48.52 (232.68)	59.62 (349.44)	70.63 (465.36)	114.84 (930.72)	159.05 (1396.08)
1.16	40.42 (176.40)	48.80 (264.60)	57.18 (352.80)	90.70 (705.60)	124.21 (1058.40)
1	38.40 (175.80)	46.78 (264.00)	55.10 (351.60)	88.50 (703.20)	121.91 (1054.80)

[1] CAI3 = cervical AI with $3x10^9$ sperm cells/dose [14]; CAI2 = cervical AI with $2x10^9$ sperm cells/dose; IUI1.5 = intrauterine AI with $1.5x10^9$ sperm cells/dose; IUI0.75 = intrauterine AI with $0.75x10^9$ sperm cells/dose; IUI0.5 = intrauterine AI with $0.5x10^9$ sperm cells/dose.

[2] CF = collection frequency per wk, 7 = one 24 h period between collections; 3.5 = two 24 h periods between collections; 2.33 = three 24 h periods between collections; 1.75 = four 24 h periods between collections; 1.4 = five 24 h periods between collections; 1.16 = six 24 h periods between collections, 1 = seven 24 h periods between collections (one collection per wk)

Table 4.4. P-value of selection strategy, AI technique-dose combination, farrowing rate and litter size on the output financial indicators

Indicator[2]	Effect[1]						
	S	T	ST	F	FF	L	LL
Gross return	<.0001	<.0001	<.0001	0.0082	0.0490	<.0001	0.0091
Net profit	<.0001	<.0001	0.8000	<.0001	0.0061	<.0001	0.0079
Total cost	<.0001	<.0001	0.1025	<.0001	0.0053	0.0155	0.9727
Variable cost	<.0001	<.0001	0.0781	<.0001	0.0051	0.2316	0.9940

[1] S = selection strategy (S9, S13); T = AI technique-dose combination (CAI3, CAI2, IUI1.5, IUI0.75; IUI0.5); ST = interaction between selection strategy and AI technique-dose combination; F = linear trend on farrowing rate; FF = quadratic trend on farrowing rate; L = linear trend on litter size; LL = quadratic trend on litter size.

[2] Net profit, gross return, total cost, and variable cost expressed in \$/sow.

Table 4.5. Absolute and relative comparison of gross return ($/sow) between selection strategies and AI technique-dose combinations

AI technique-dose[1]	Selection strategy[2]		SE[3]	RD[4]
	S9	S13		%
CAI3	63.23[h]	86.42[c]	0.0019	-26.84
CAI2	63.28[g]	86.44[b]	0.0019	-26.79
IUI1.5	63.30[f]	86.44[b]	0.0019	-26.77
IUI0.75	63.34[e]	86.45[a]	0.0019	-26.73
IUI0.5	63.36[d]	86.46[a]	0.0019	-26.72

[a-f] Means with different superscript differ within row (P-values < 0.0001).

[1] CAI3 = cervical AI with 3x10^9 sperm cells/dose [14]; CAI2 = cervical AI with 2x10^9 sperm cells/dose; IUI1.5 = intrauterine AI with 1.5x10^9 sperm cells/dose; IUI0.75 = intrauterine AI with 0.75x10^9 sperm cells/dose; IUI0.5 = intrauterine AI with 0.5x10^9 sperm cells/dose.

[2] Selection strategy (S9, S13).

[3] Standard error.

[4] RD = relative differences in columns between S9 and S13 (S9-S13/maximum ([S9, S13]).

Table 4.6. Absolute and relative comparison of net profit and total and variable cost ($/sow) between selection strategies and AI technique-dose combinations

	Selection strategy[1]		SE[2]	RD[3]	Combination[4]	Mean	SE[2]	RD[5]
Indicator	S9	S13		%				%
Net Profit	40.47	61.67	0.0163	-34.37	CAI3	49.83^{e}	0.0259	-4.12
					CAI2	50.73^{d}		-2.41
					IUI1.5	51.08^{c}		-1.72
					IUI0.75	51.75^{b}		-0.43
					IUI0.5	51.98^{a}		
Total cost	22.83	24.77	0.0161	-7.84	CAI3	24.99^{e}	0.0254	8.25
					CAI2	24.13^{d}		4.98
					IUI1.5	23.79^{c}		3.63
					IUI0.75	23.15^{b}		0.93
					IUI0.5	22.93^{a}		
Variable cost	5.00	6.93	0.0154	-27.99	CAI3	7.02^{a}	0.0244	25.89
					CAI2	6.25^{b}		16.84
					IUI1.5	5.97^{c}		12.82
					IUI0.75	5.39^{d}		3.57
					IUI0.5	5.20^{e}		

[a-e] Means with different superscript differ within row (P-values < 0.0001).

[1] Selection strategy (S9, S13).

[2] Standard error.

[3] RD = relative difference between S9 and S13 (S9-S13/maximum ([S9, S13]).

[4] Combinations: CAI3 = cervical AI with 3x10^{9} sperm cells/dose [14]; CAI2 = cervical AI with 2x10^{9} sperm cells/dose; IUI1.5 = intrauterine AI with 1.5x10^{9} sperm cells/dose; IUI0.75 = intrauterine AI with 0.75x10^{9} sperm cells/dose; IUI0.5 = intrauterine AI with 0.5x10^{9} sperm cells/dose.

[5] RD = relative difference between IUI0.5 and the rest of the AI technique-dose combinations (IUI05-the rest of the AI technique-dose combinations)/maximum ([IUI05, the rest of the AI technique-dose combinations]).

4.8. Figures

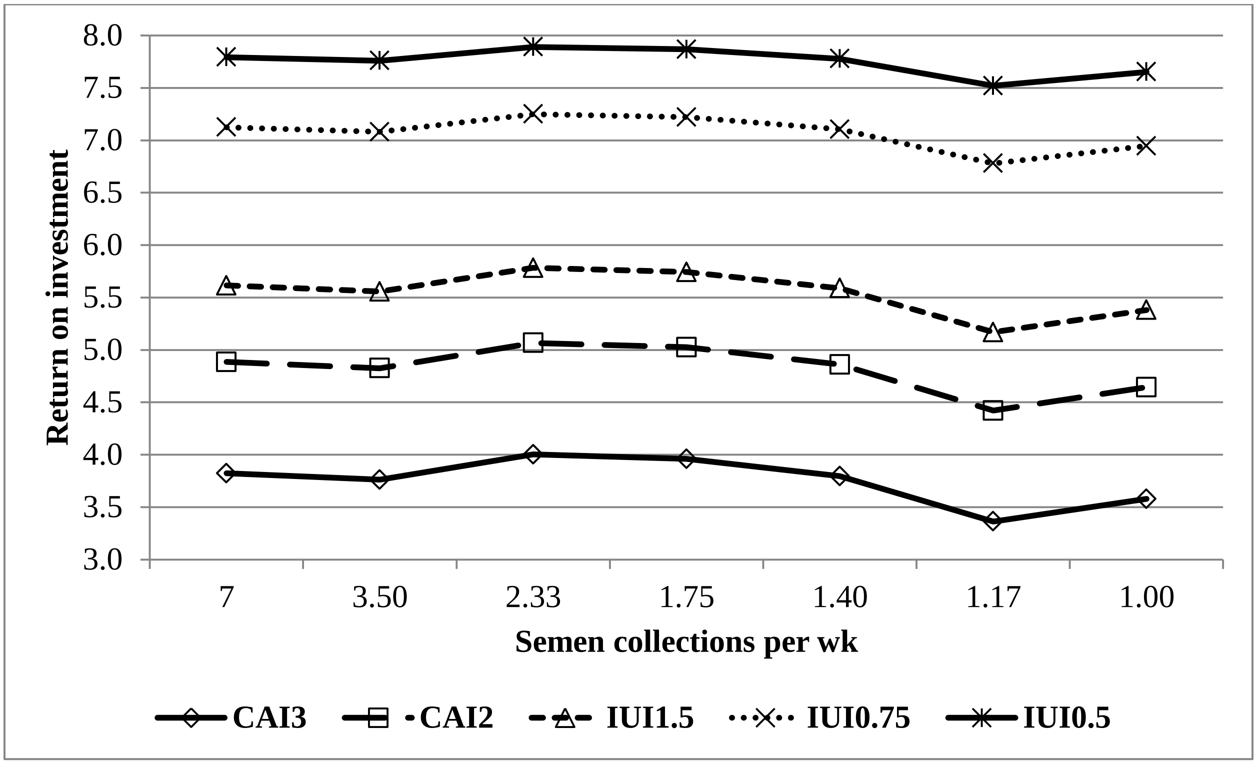

Figure 4.1. Return on investment [(return of one boar – boar weekly costs)/boar weekly costs] across semen collections per wk using fresh refrigerated semen for five AI technique-semen dose combinations: cervical with $3x10^9$ sperm cells/dose (CAI3); cervical with $2x10^9$ sperm cells/dose (CAI2); intrauterine with $1.5x10^9$ sperm cells/dose (IUI1.5); intrauterine with $0.75x10^9$ sperm cells/dose (IUI0.75), and intrauterine with $0.5x10^9$ sperm cells/dose (IUI0.5).

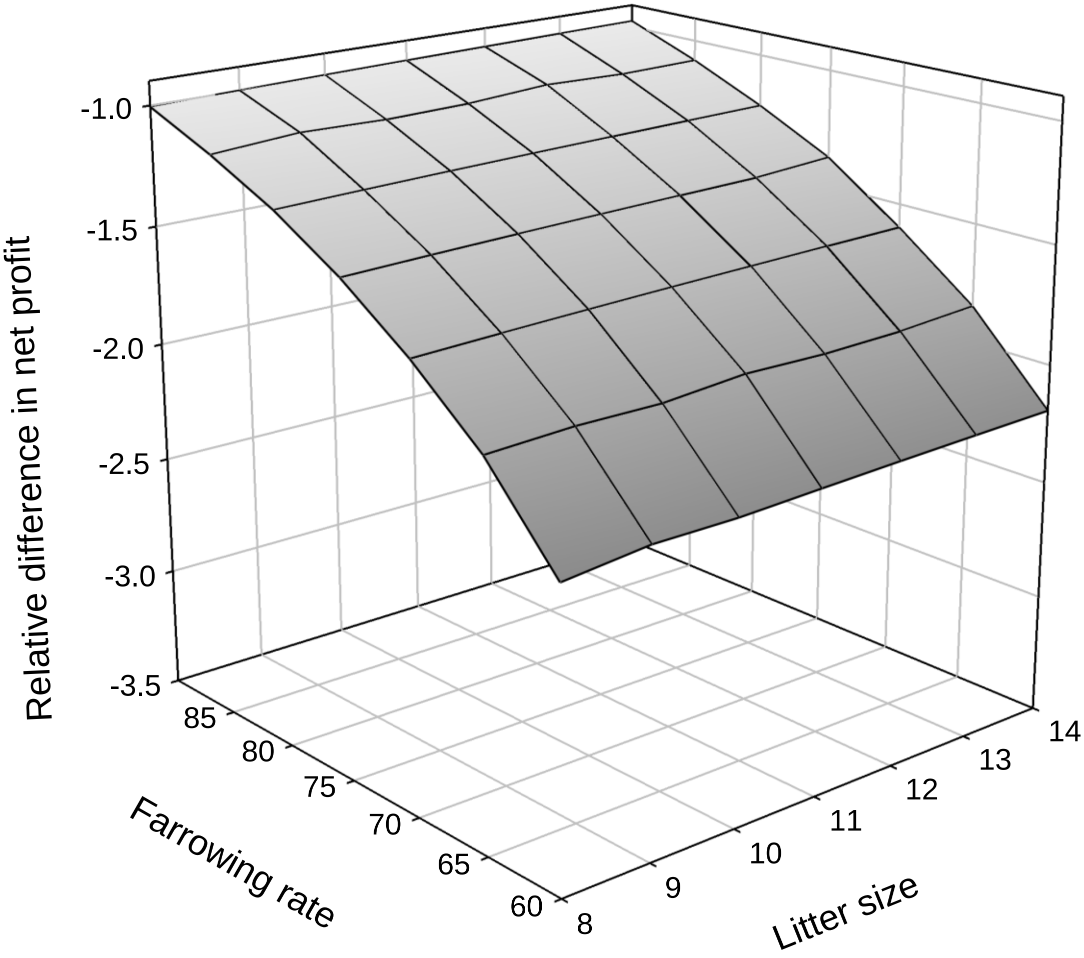

Figure 4.2. Relative difference in net profit using cervical AI (CAI) between 3x10^9 sperm cells/dose (CAI3) and 2x10^9 sperm cells/dose (CAI2) computed as (CAI3-CAI2) /maximum ([CAI3, CAI2]) for the advanced selection strategy including semen traits (S13) across farrowing rate (%) and litter size (pigs/litter) levels.

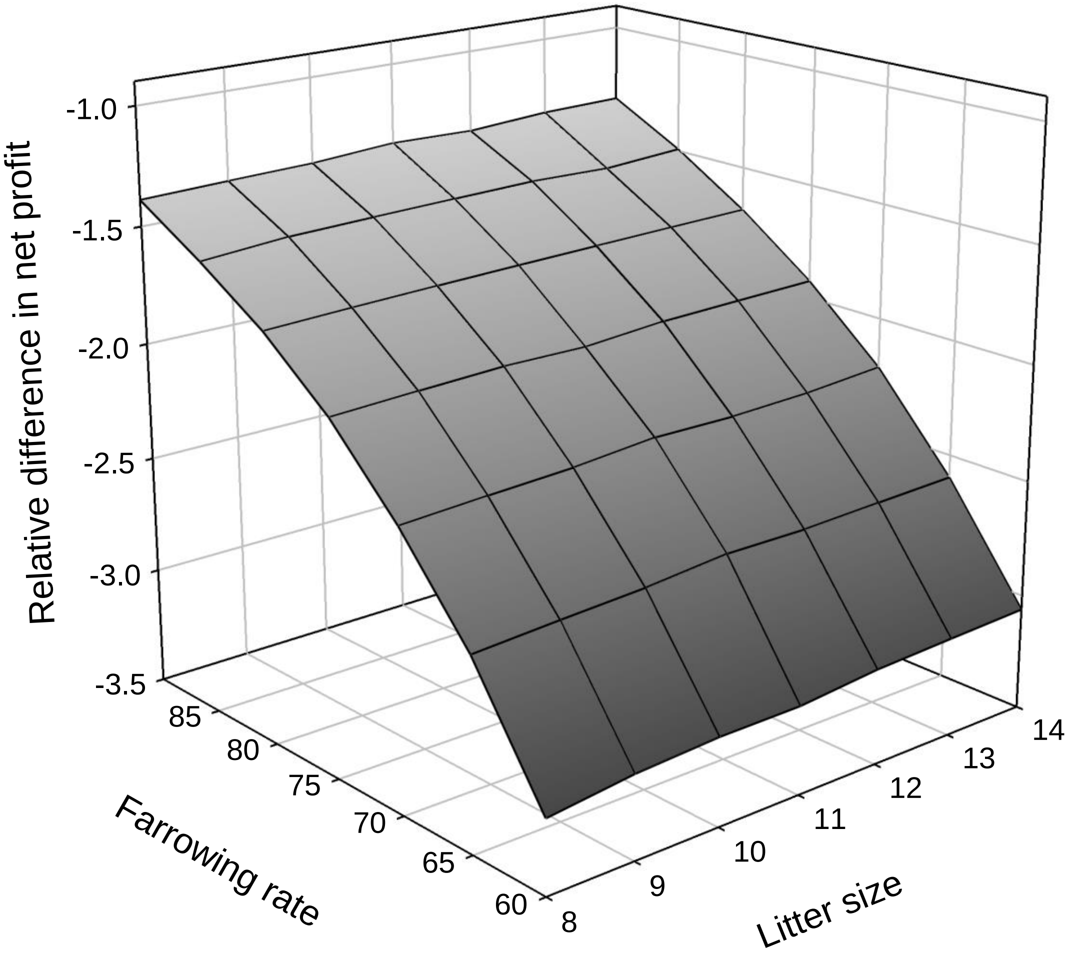

Figure 4.3. Relative difference in net profit between intrauterine insemination with $1.5x10^9$ sperm cells/dose (IUI1.5) and cervical AI with $3x10^9$ sperm cells/dose (CAI3) computed as (CAI3- IUI1.5) /maximum ([CAI3, IUI1.5]) for the advanced selection strategy including semen traits (S13) across farrowing rate (%) and litter size (pigs/litter) levels.

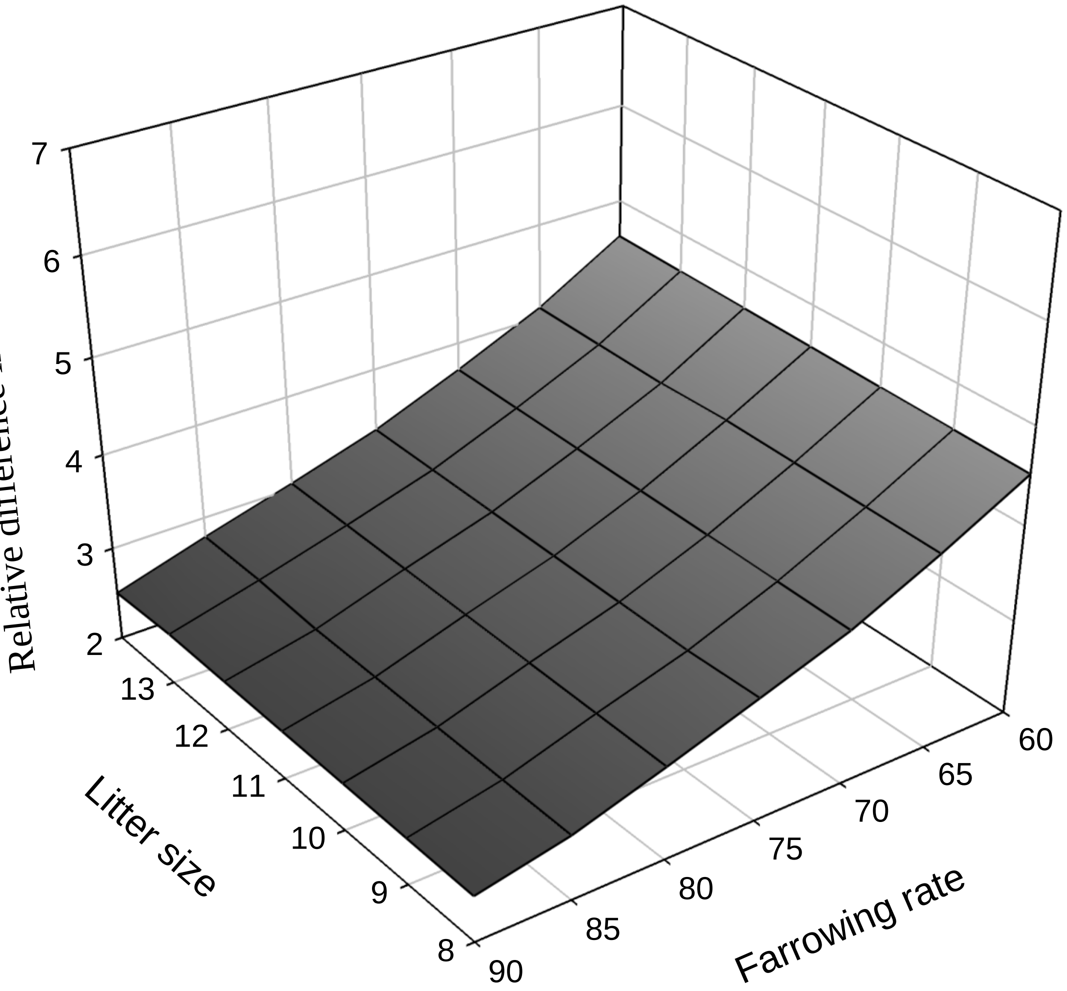

Figure 4.4. Relative difference in total costs using cervical AI (CAI) between $3x10^9$ sperm cells/dose (CAI3) and $2x10^9$ sperm cells/dose (CAI2) computed as (CAI3-CAI2) /maximum ([CAI3, CAI2]) for the advanced selection strategy including semen traits (S13) across farrowing rate (%) and litter size (pigs/litter) levels.

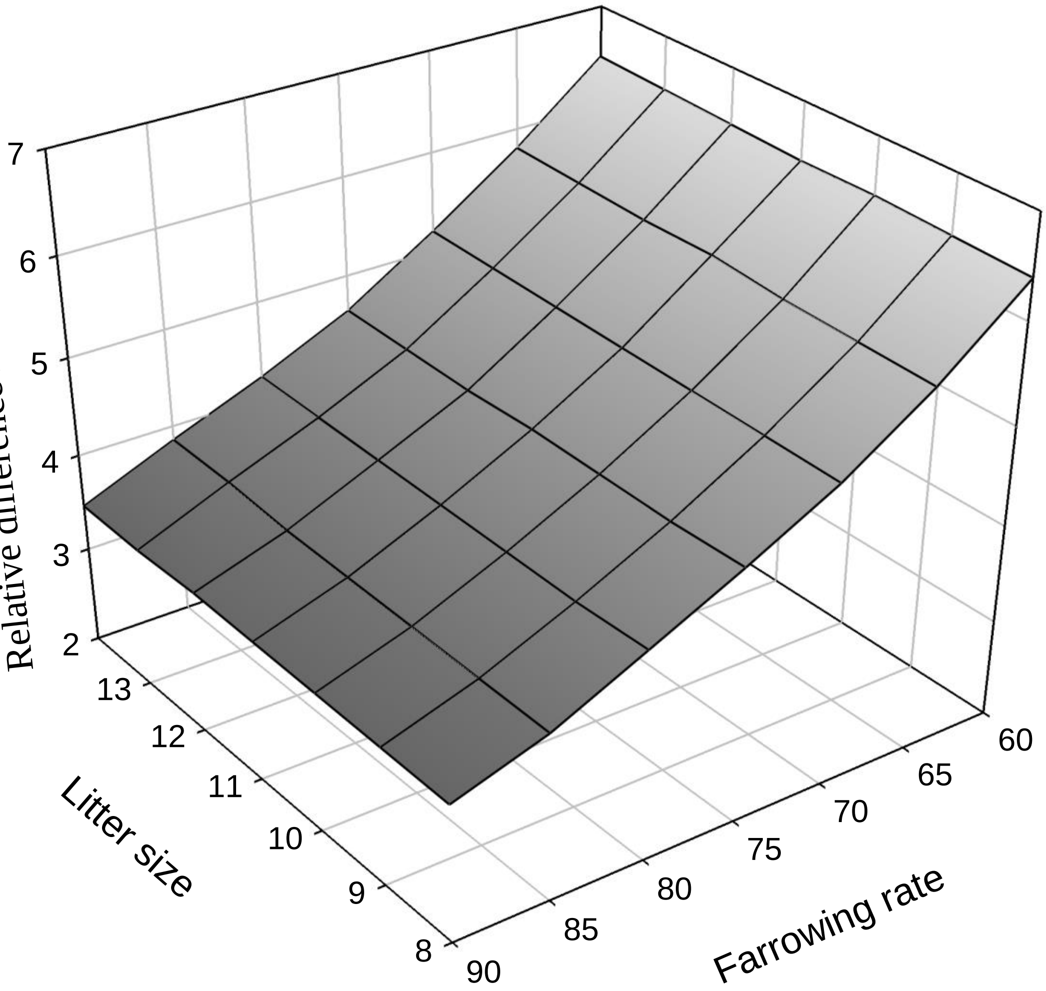

Figure 4.5. Relative difference in total costs between intrauterine insemination with $1.5x10^9$ sperm cells/dose (IUI1.5) and cervical AI with $3x10^9$ sperm cells/dose (CAI3) computed as (CAI3- IUI1.5) /maximum ([CAI3, IUI1.5]) for the advanced selection strategy including semen traits (S13) across farrowing rate (%) and litter size (pigs/litter) levels.

CHAPTER V: General conclusions

Insemination and semen preparation techniques have a non-additive effect on profit, return, total costs, fixed costs, variable costs, and sow population size. At a similar farrowing number in the commercial level, both intrauterine and deep intrauterine insemination techniques allowed a reduction in sow population size and an increase in the efficiency of boar use with the consequent reduction in fixed costs.

The main differences between fresh and frozen semen preparation in the profits were driven by differences in variable costs. The relatively small differences between fresh and frozen in sow population size (lower than -2% on average), return (lower than 1% on average), and profit (lower than 3% on average) must be weighted in consideration of the benefits of frozen in terms of efficiency of boar semen, dissemination of genetics, and biosecurity.

Selection strategy including the four semen traits enables genetic gains for these traits without compromising the genetic gains for maternal traits and with minimal losses in genetic gains for paternal traits.

Selection strategy including the four semen traits had higher net profit relative to the traditional strategy that only includes paternal and maternal traits. At farrowing rate levels comparable to the current industry settings, intrauterine insemination exhibited the highest efficiency of boar utilization with the consequent reduction in variable cost. In addition, the integration of the selection strategy proposed with conventional artificial insemination and a reduction in the semen doses offered a net profit similar to intrauterine.