# Response to a selection index including environmental costs and risk preferences of producers[1]

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**ABSTRACT:** Genetic improvement of animals plays an important role in improving the economic and environmental sustainability of livestock production systems. This paper proposes a method to incorporate mitigation of environmental impacts and risk preferences of producers into a breeding objective via economic values (**EV**s). The paper assesses the effects of using these alternative EVs of breeding goal traits on discounted economic response to selection and on environmental impacts at commercial farm level. The application focuses on a Brazilian pig production system. Separate dam- and sire-line breeding programs that supply parents in a 3-tier production system for producing crossbreds (fattening pigs) at commercial level were assumed. Using EVs that are derived from utility functions by incorporating risk aversion increases the cumulative discounted economic response to selection in sire-line selection (6%) while reducing response in dam-line selection (12%) compared with the use of traditional EVs. The use of EVs that include environmental costs increases the cumulative discounted social response to selection in both dam-line (5%) and sire-line (10%) selections. Emission of greenhouse gases, and excretion of nitrogen and phosphorus can be reduced more with genetic improvements of production traits than reproduction traits for the typical Brazilian farrow-to-finish pig farm. Reductions in environmental impacts do not, however, depend on the use of the different EVs (i.e., with and without taking into account environmental costs and risk). Both environmental costs and risk preferences of producers need to be considered in sire-line selection, and only environmental costs in dam-line selection to improve, at the same time, the economic and environmental sustainability of the Brazilian pig production system.

**Key words:** economic value, environmental impact, pigs, risk aversion, selection index



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## INTRODUCTION

Livestock production currently occupies 30% of ice-free terrestrial land (Steinfeld et al., 2006) and uses one-third of global cereal production to feed animals (Cassidy et al., 2013). It causes major environmental impacts through its dependence on scare resources (e.g., cropland, fossil fuel, and water), and emission of pollutants to air, water, and soil (Steinfeld et al., 2006; De Vries and De Boer, 2010). Besides technological advancements in nutrition and management practices, genetic improvement of animals also plays an important role in reducing the environmental impacts of livestock production systems (Wall et al., 2010; Bell et al., 2013; Van Middelaar et al., 2014). Groen et al. (1997) noted that the genetic merit of animals should be improved through selection to fulfill the economic, ecological, and social requirements of future livestock production systems (e.g., ensuring

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the growing demand for animal protein while minimizing environmental impacts). In multitrait economic selection indices, economic values (**EVs**) guide the direction and emphasis of selection in the overall breeding objective by providing a measure of the relative importance of each trait (Hazel, 1943). A breeding objective describes the traits that the breeder aims to improve through selection. Pig breeding programs have been focusing on the genetic improvement of economically important traits such as litter size, growth rate, feed efficiency, and lean meat with little attention to traits with noneconomic or little economic importance (e.g., environmental sustainability) (Olesen et al., 2000; Kanis et al., 2005). However, there is a growing public concern about the undesirable side effects of production systems (e.g., environmental impacts) and breeders need to consider these in their breeding objectives in addition to economic improvement. Mitigation of environmental impacts in breeding objectives on the basis of correlated traits can be achieved by the use of EVs that incorporate environmental costs (Wall et al., 2010; Ali et al., 2018a). As Kanis et al. (2005) noted, more selection emphasis should be given to efficiency traits (e.g., feed efficiency) as these traits have environmental (and societal) values that are not represented when selection is based solely on economic aspects.

Current breeding programs define their breeding objectives with risk neutral producers in mind. These traditional breeding objectives are defined based on EVs derived from profit equations or bioeconomic models that do not account for risk and the risk preferences of producers (i.e., they implicitly assume that producers are risk neutral). However, previous studies provide abundant evidence that agricultural producers are risk averse (e.g., refer to Moschini and Hennessy (2001) for an overview). Accordingly, models that do take risk into consideration provide better predictive power of producers' behavior than those that do not. Therefore, risk should be incorporated when deriving EVs since farmers' decisions (e.g., the adoption of new genetics) and thereby farm profitability depends on their risk preferences. Ali et al. (2018a) proposed a method for integrating environmental costs and risk preferences of producers into the derivation of EVs of traits using a mean-variance utility function. They derived EVs for sow efficiency and production traits by accounting for environmental costs and risk preferences of farmers for a pig production system. Responses to selection (i.e., genetic gains, economic returns, and environmental impact reductions) depend on the values of the EVs used to define breeding objectives.

The use of incorrect EVs reduces efficiency of selection (e.g., Smith (1983)) and may even result in selection in the wrong direction (Cottle and Coffey, 2013). The use of incorrect genetic parameters can also reduce efficiency of selection (e.g., Harris, 1963). Cottle and Coffey (2013), for example, reported that a 10% underestimation of the relative EV of protein for UK Holstein cows would result in a loss of financial genetic gain of £0.17 per cow per year. Although the figure looks very small, given the fact that genetic improvement produces permanent and cumulative change in performance, the accrued financial loss becomes substantial if it is computed for UK Holstein cow population over a given investment period (e.g., 20 yr). Vandepitte and Hazel (1977) also reported that large errors (>50%) in the EV of feed efficiency of pigs can lead to a 76% loss in relative efficiency of a selection index. To the best of our knowledge, no study to date has focused on the impact of risk preferences and environmental costs simultaneously when deriving EVs on the efficiency of selection.

In light of the foregoing discussion, the objective of this study was, therefore, to assess the effect of using EVs of pig breeding goal traits that account for environmental costs and risk preferences of producers on response to selection. Genetic gains of breeding goal traits, cumulative discounted economic returns, and environmental impact reductions were predicted by the gene flow method (McClintock and Cunningham, 1974; Brascamp, 1978). The effects are illustrated by applying it to a Brazilian pig production system. The results of the study are useful for breeding companies that need to update their breeding objectives to meet the growing demand for sustainable products and to properly acknowledge their customers' (i.e., risk averse producers) risk preferences.

## MATERIALS AND METHODS

The first subsection introduces the gene flow method, which is used to calculate the flow of genetic superiorities from nucleus to commercial herds in a 3-tier production system. Then, the multitrait selection index method for the Brazilian pig production system is applied to assess the effect of using EVs that account for environmental costs and risk aversion on selection response.

### *The Gene Flow Method*

Pig production systems often consist of 3 production levels: nucleus, multiplier, and commercial herds. The nucleus herd is used to select parents for the multiplier herd (and for the commercial herd). The multiplier herd supplies parents for the commercial herd where fattening pigs are finished for slaughter. Monetary gains over a given investment period from 1 round of selection of parents can be computed by using the gene flow method. Not all traits in the breeding objective are expressed with the same frequency, nor at the same point in time. As a result, genetic superiority is transferred with different frequencies and involves time delays that depend on the production system and the crossbreeding scheme (Wolfová et al., 2001). As McClintock and Cunningham (1974) outlined, the true weights of traits in multitrait selection indices should be the products of the EVs of traits and their respective number of discounted expressions (i.e., expressions of genetic superiority discounted by a given interest rate within a defined investment period). The use of EVs weighted by discounted expressions enables selection of animals based on their discounted aggregate genetic values in monetary units. In the present study, the gene flow method outlined by McClintock and Cunningham (1974) was used to calculate the number of discounted expressions of traits. Since genetic improvements of some traits (e.g., growth rate) require shorter time period to be realized than some other traits (e.g., litter size), the number of discounted expressions is different among traits.

Monetary gains are defined as expressed genetic gains in the nucleus, multiplier, and commercial levels following 1 round of selection. Suppose an age-class is a period of $k$ years. Suppose $m_t$ is a vector representing gene frequencies per sex in an age class in a particular season $t$ (where a season is also $k$ years). Then, it can be calculated as follows (Brascamp, 1978):

$$m_t = Rn_{t-1} + Pm_{t-1} \tag{1}$$

where $R$ is a matrix defining gene transmission through reproduction, $P$ is a matrix defining gene transmission through reproduction and aging, and

$$n_t = Qn_{t-1} \tag{2}$$

where $n$ is a vector with gene frequencies per sex in the age classes, and $Q$ is a matrix defining aging. Genetic superiorities of selected parents are used for $m_0$ and $n_0$. Then, the discounted cumulative genetic gains in monetary units ($R_M$) can be calculated as follows (Brascamp, 1978):

$$R_M = \sum_{t=1}^{T} m'(t)h\left(\frac{1}{1-r}\right)^t \tag{3}$$

where $m$ is a vector with gene frequencies in defined age classes in all tiers by sex subclasses originating from the selected parents, $h$ is an incidence vector describing the expression of a trait, which is equal to the product of the EV of the trait and the number of animals that expressed the trait in each sex-age class, and $r$ is the discount rate.

### *Application to Brazilian Pig Production System*

***Definition of breeding objective and choice of selection index traits.*** In this study, the multitrait selection index method (Hazel, 1943) is used to define the breeding objective. The selection index method has long been used in the livestock industry to select animals based on multiple traits by weighting estimated breeding values (**EBVs**) of traits with their respective EVs (e.g., Groen (1990), Wolfová et al. (2007), Dube et al. (2013), and Ochsner et al. (2017)).

Pig breeding programs include separate dam- and sire-lines. Dam-lines are mainly selected for reproduction traits (e.g., litter size), whereas sire-lines are selected for production traits (e.g., growth rate). However, dam-lines are also used to select for production traits. Number of piglets born alive per litter (**NBA**), preweaning mortality rate (**PWM**), weaning-estrus interval (**WOI**), and average daily gain (ADG) are assumed to be in the dam-line breeding objective for the Brazilian production system. In the dam-line breeding objective, a desired-gain approach (see Kanis et al. (2005) for an overview) is followed for ADG in addition to obtaining maximum response in the reproduction traits. Following the desired gains approach, the genetic gain of ADG is set close to zero by changing the EV of ADG such that response in ADG will be close to zero. The traits ADG and feed conversion ratio (**FCR**) during the growing-finishing stage are assumed to be in the sire-line breeding objective (Ali et al., 2018a). The dam-line ($H_1$) and sire-line ($H_2$) breeding objectives are defined as follows:

$$\begin{aligned} H_1 = EV_{ADG} \times EBV_{ADG} + EV_{NBA} \times EBV_{NBA} \\ + EV_{PWM} \times EBV_{PWM} + EV_{WOI} \times EBV_{WOI} \end{aligned} \tag{4a}$$

$$H_2 = EV_{ADG} \times EBV_{ADG} + EV_{FCR} \times EBV_{FCR} \tag{4b}$$

where $EV_i$ is the economic value of trait $i$, $EBV_i$ is the BLUP estimated breeding value of trait $i$, and the rest as defined above.

Ali et al. (2018a) proposed a method for integrating environmental costs and risk preferences of producers into the derivation of EVs of traits using a mean-variance utility function. They derived EVs for sow efficiency and production traits by accounting for environmental costs and risk preferences of farmers for Brazilian pig production system. Breeding objectives, which account for environmental costs and risk preferences of producers, are defined by using the EVs that incorporate environmental costs and risk preferences of producers (Table 1). Table 1 also provides the economic weights (relative EVs) of dam- and sire-line breeding objective traits. The first 2 cases (**RN_NGHG** and **RN_GHG**, Table 1) are for a risk neutral producer excluding and including greenhouse gases (**GHGs**) emission costs, respectively. The first case (RN_NGHG) refers to the traditional EVs, which are commonly used in breeding programs (and derived from a bioeconomic model). Cumulative response to selection derived from EVs that incorporate GHGs emission costs (RN_GHG) implies social returns (i.e., economic return minus environmental cost). The third and fourth cases (**RA_NGHG**, **RA_GHG**; Table 1) are EVs that are derived from a mean-variance utility function by accounting for risk and risk aversion (Ali et al., 2018a). Cumulative response to selection derived from EVs that account for risk and risk aversion (RA_NGHG) implies change in utility. The fourth case (RA_GHG, Table 1) gives the EV that breeders should use for defining their breeding objectives as it accounts for emission of GHGs while serving risk averse producers.

In addition to the economically important traits (i.e., ADG, NBA, PWM, and WOI) that are included in the breeding objective, the traits 21-d litter weight (**21LW**), piglet birth weight (**PBW**), and gestation length (**GL**) are included in the dam-line selection index. Breeders commonly use the trait 21LW for selection as it has favorable genetic correlations with other economically important traits. The trait PBW influences piglet survival and growth performance (Beaulieu et al., 2010). Selection for litter size needs to be accompanied by selection for reducing PWM due to the negative genetic correlation between NBA and piglet survival (Lund et al., 2002). Rydhmer et al. (2008) reported that selection for longer GL increases piglet survival since the genetic correlation between GL and number of piglets that die after birth is negative. Moreover, the genetic correlations among GL, PBW, and piglet growth rate are positive (Rydhmer et al., 2008).

Although there is no carcass-quality-based payment system in Brazil, backfat thickness (**BF**) is included in the sire-line selection index as selection against BF increases lean meat and reduces feed cost (and environmental impacts). Residual feed intake (**RFI**) is also included in the index as this results in better response than including ratios such as FCR or feed efficiency (Gilbert et al., 2007; Cai et al., 2008). Saintilan et al. (2015) showed that in addition to the traditional feed efficiency traits (i.e., FCR or RFI), pig growth model parameters (i.e.,



**Table 1.** Economic values (US$) and economic weights (%, in brackets) of breeding goal traits[1] for Brazilian pig production system with and without considering environmental costs and risk preferences of producers (adapted from Ali et al., 2018a)

| Traits[2] | RN_NGHG[3] | RN_GHG[3] | RA_NGHG[3] | RA_GHG[3] |
|---|---|---|---|---|
| Reproduction traits (US$ per sow per farrowing) | | | | |
| ADG, g/d[4] | 0.064 (10.106) | 0.067 (10.101) | 0.058 (11.093) | 0.061 (10.910) |
| NBA, piglets per litter | 20.854 (67.590) | 21.806 (67.474) | 17.243 (67.689) | 18.378 (67.461) |
| PWM, % | −2.979 (16.092) | −3.131 (16.147) | −2.007 (13.131) | −2.208 (13.508) |
| WOI, d | −1.725 (6.212) | −1.826 (6.278) | −1.854 (8.087) | −1.991 (8.121) |
| Production traits (US$ per finished pig) | | | | |
| ADG, g/d | 0.065 (56.111) | 0.070 (55.383) | 0.069 (56.215) | 0.073 (55.254) |
| FCR, kg/kg | −17.149 (43.889) | −19.022 (44.617) | −18.128 (43.785) | −19.941 (44.746) |

[1]The economic weight for breeding goal trait $i$ is calculated as follows: $Economic\,weight_i = 100 \times \frac{\sigma_{gi} \times EV_i}{\sum_{i=1}^{n} \sigma_{gi} \times EV_i}$, where $i,\ldots,n$ refers to breeding goal traits, $EV_i$ is the economic value of trait $i$, and $\sigma_{gi}$ is the genetic standard deviation of trait $i$.

[2]NBA = number of piglets born alive per litter; PWM = preweaning mortality rate of piglets; WOI = weaning-estrus interval; ADG = average daily growth during the growing-finishing stage; FCR = feed conversion ratio during the growing-finishing stage (kg feed/kg gain).

[3]RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

[4]Following a desired gain approach for ADG, the economic value of ADG is set to ensure that ADG is not deteriorating while selecting for reproduction traits (the actual economic value of ADG is large). It is set to make genetic gain of ADG close to zero for obtaining maximum possible genetic gains in the reproduction traits.

mean protein deposition [**PD**], net energy intakes at 50 [**FI50**], and 100-kg body weights [**FI100**]) can also be included in the selection criteria since they have moderate to strong genetic correlations with respect to feed intake and feed efficiency. The use of these parameters in breeding programs might reduce the cost and difficulty of data recording for feed intake. Given the lack of accurate measures for feed intake throughout the life cycle of a pig, recording feed intake at 50- and 100-kg body weights might be a better alternative.

To reduce environmental impacts, the EVs that were derived by incorporating GHGs emission costs from feed production and manure (Table 1) were used in the breeding objective (and indirectly in the selection index). For the dam- and sire-lines, the selection indices are defined as, respectively, follows:

$$I_1 = b_{ADG} \times EBV_{ADG} + b_{NBA} \times EBV_{NBA} + b_{PWM} \times EBV_{PWM} + b_{WOI} \times EBV_{WOI} + b_{GL} \times EBV_{GL} + b_{PBW} \times EBV_{PBW} + b_{21LW} \times EBV_{21LW} \quad (5a)$$

$$I_2 = b_{ADG} \times EBV_{ADG} + b_{RFI} \times EBV_{RFI} + b_{PD} \times EBV_{PD} + b_{FI50} \times EBV_{FI50} + b_{FI100} \times EBV_{FI100} + b_{BF} \times EBV_{BF} \quad (5b)$$

where $I_1$ and $I_2$ are the selection indices for the dam- and sire- lines, respectively; $b_i$ is index weight of trait *i*, $EBV_i$ is the estimated breeding value of trait *i,* and the rest as defined before.

Phenotypic (co)variances are calculated from phenotypic correlations between traits and SDs. Genetic (co)variances are calculated from genetic SDs and genetic correlations between traits. The phenotypic SDs, heritabilities, and phenotypic and genetic correlations between traits are extracted from the literature and are presented in Table 2. Since the Brazilian production system is also based on modern technologies such as high potential imported breeds and concentrated feed, the estimates used from the literature, which are mainly from European and North American production systems, are expected to hold. Here we assumed that there are no genotype by environment interactions (i.e., a given genotype is assumed to perform equally in Europe or in North America and in Brazil).

The deterministic simulation computer program SelAction (Rutten et al., 2002) was used to estimate response to selection in trait units (genetic superiorities of selected parents) for the breeding goal traits, accounting for the reduction in variance due to selection and also corrects selection intensities for finite population sizes. The estimated genetic gains of breeding goal traits are used as genetic superiorities of selected parents (in nucleus herd) that can be transferred to the commercial level over a 10-yr investment period in the gene flow method. The total discounted economic response per year in monetary units is estimated as described in the following subsection by using the gene flow method.

***Population structure, selection strategy, and gene flow.*** In a 3-tier production system, we assumed that the nucleus herd is used to select parents for the multiplier herd and fathers for the commercial herd. The multiplier herd supplies dams for the commercial herd where fattening pigs are finished for slaughter. Assume there are 2 breeds/lines (A and B) in the nucleus herd to produce 1,500,000 crossbred pigs at commercial level per season, and assume a season is equal to 6 mo. The structure of selection groups in the 2-way crossing system (B × A) that follows from these assumptions is given in Table 3. The first column of Table 3 shows the lines of dams and sires that are used to produce parents for the 3 tiers. Line A is used to produce replacement sows and sires for the nucleus and multiplier tiers, and sows for the commercial tier. Line B is used to produce replacement sows and sires for the nucleus herd and sires for the commercial tier. The crossbred pigs (fattening pigs) are the crosses of sire B and sow A (crosses of groups 17 and 18, Table 3). Breed A, a dam-line, consists of 2,000 sows (half 12 and half 18 mo old) and 50 boars (half 12 and half 18 mo old) at the nucleus herd to produce replacements for the nucleus tier. Breed B, a sire-line, consists of 1,000 sows (half 12 and half 18 mo old) and 40 boars (half 12 and half 18 mo old) at the nucleus herd to produce replacements for the nucleus tier. The 24-mo-old sows and boars of the nucleus herd are replaced by selected candidates in line A. The replacements of commercial sires (Sire B) are produced by mating the 40 sires in nucleus herd (24 and 30 mo old) with the 1000 sows (Sow B) in the nucleus herd (24 and 30 mo old). The number of sires and sows in each tier together with their respective length of productive life is summarized in Table 4. In line A, each boar is mated to 40 sows and in line B with 25 sows, resulting in 10 offspring per female per farrowing (5 males and 5 females).

In line A, the female parents are selected in 2 stages. In stage 1, the female candidates are tested for ADG (e.g., when they are 6 mo old) to select 6,000 candidates out of potential 10,000 candidates

**Table 2.** Phenotypic standard deviations ($\sigma_p$, first column), heritability (diagonal), genetic (above diagonal), and phenotypic (below diagonal) correlations between traits for dam-line (upper left corner) and sire-line (bottom right corner) selection

| Traits[1] | $\sigma_p$ | NBA | PWM | WOI | GL | PBW | 21LW | ADG | FCR | PD | FI50 | FI100 | RFI | BF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NBA, piglets per litter | 2.85[a] | **0.10**[a] | 0.34[b] | 0.15[c] | −0.60[d] | −0.35[b] | 0.07[b] | −0.20[c] | | | | | | |
| PWM, % | 4.74[a] | 0.04[b] | **0.10**[a] | 0.31[f] | −0.37[g] | −0.24[g] | −0.69[b] | −0.24[g] | | | | | | |
| WOI, d | 3.16[a] | 0.10[c] | −0.01[f] | **0.10**[a] | 0.00[h] | −0.05[e] | 0.43[i] | 0.10[c] | | | | | | |
| GL, d | 1.35[h] | −0.12[d] | −0.14[g] | 0.12[h] | **0.29**[h] | 0.12[g] | 0.03[j] | 0.00[a] | | | | | | |
| PBW, g | 353.01[l] | −0.32[b] | −0.28[g] | 0.00[e] | 0.15[g] | **0.26**[l] | 0.87[b] | 0.40[a] | | | | | | |
| 21LW, kg | 16.01[o] | 0.36[b] | −0.70[b] | 0.08[i] | 0.16[j] | 0.07[b] | **0.11**[b] | 0.13[k] | | | | | | |
| ADG, g/d | 86.00[m] | 0.00[c] | 0.04[g] | 0.00[c] | 0.00 | 0.42[a] | 0.03[k] | **0.26**[m] | −0.33[m] | 0.92[n] | 0.52[n] | 0.46[n] | 0.11[m] | 0.35[c] |
| FCR (kg/kg) | 0.23[m] | | | | | | | −0.41[m] | **0.32**[m] | −0.76[n] | 0.35[n] | 0.25[n] | 0.58[m] | 0.58[m] |
| PD, g/day | 13.00[n] | | | | | | | 0.93[n] | −0.74[n] | **0.40**[n] | −0.04[n] | 0.25[n] | −0.31[n] | −0.22[n] |
| FI50, MJ/d | 2.19[n] | | | | | | | 0.39[n] | 0.42[n] | 0.07[n] | **0.30**[n] | 0.30[n] | 0.49[n] | 0.74[n] |
| FI100, MJ/d | 3.10[n] | | | | | | | 0.57[n] | 0.16[n] | 0.33[n] | 0.19[n] | **0.56**[n] | 0.45[n] | 0.37[n] |
| RFI, g/d | 115.00[n] | | | | | | | 0.00[m] | 0.74[m] | −0.31[n] | 0.61[n] | 0.37[n] | **0.23**[m] | −0.04[m] |
| BF, mm | 3.59[n] | | | | | | | 0.30[c] | 0.33[m] | −0.13[n] | 0.33[n] | 0.25[n] | 0.00[m] | **0.45**[c] |

[1]NBA = number of piglets born alive; PWM = pre−weaning mortality rate; WOI = weaning-estrus interval; GL = gestation length; PBW = piglet birth weight; 21LW = 21-d litter weight; ADG = average daily gain; FCR = feed conversion ratio; PD = mean protein deposition; FI50 = net energy intake at 50-kg body weight; FI100 = net energy intake at 100-kg body weight; RFI = residual feed intake; BF = back fat thickness.

[a]Rydhmer (2000).

[b]Huby et al. (2003).

[c]Kanis et al. (2005).

[d]Hermesch (2001).

[e]Wallenbeck et al. (2016).

[f]ten Napel et al. (1998).

[g]Knol (2001).

[h]Hanenberg et al. (2001).

[i]Lundgren et al. (2014).

[j]Using 14-d litter weight instead of 21-d litter weight (Hermesch, 2001).

[k]Average of the first 3 parties (Tholen et al., 1996).

[l]Miar et al. (2014).

[m]Saintilan et al. (2013).

[n]Saintilan et al. (2015).

[o]Fundora (2015).

**Table 3.** Selection groups in a 2-way crossing system

| | | Nucleus | | | | Multiplier | | Commercial | |
|---|---|---|---|---|---|---|---|---|---|
| Tier | Breed | Sire A | Sow A | Sire B | Sow B | Sire A | Sow A | Sire B | Sow A |
| Nucleus | Sire A | 1 | 2 | | | | | | |
| | Sow A | 3 | 4 | | | | | | |
| | Sire B | | | 5 | 6 | | | | |
| | Sow B | | | 7 | 8 | | | | |
| Multiplier | Sire A | 9 | 10 | | | | | | |
| | Sow A | | | | | 11 | 12 | | |
| Commercial | Sire B | | | 13 | 14 | | | | |
| | Sow A | | | | | 15 | 16 | | |
| Fattening pigs | | | | | | | | 17 | 18 |

based on own performance and performance of 9 full sibs and 390 half sibs. In the second stage, the new generation of 1,000 females is selected out of the 6,000 candidates based on own performance and performance of 2 full sibs and 117 half sibs on NBA, PWM, WOI, GL, PBW, and 21LW. The 25 boar replacements are also selected in 2 stages. First, 800 boars are selected out of 10,000 males based on own performance and performance of 390 half sibs on ADG. In the second stage, the 25 boars are selected out of the 800 selection candidates based on performance of 1 female full sib and 117 half

**Table 4.** Productive seasons (1 season equals 6 mo, first progeny born when sires/sows are 12 mo old)

| Tier | Breed | No. of sires | No. of sows | Productive life of sires (in seasons) | Productive life of sows (in seasons) |
|---|---|---|---|---|---|
| Nucleus | A | 50 | 2,000 | 3 (24-mo-old 25 sires produce 25 boar replacements for multiplier) | 3 (24-mo-old 1,000 sows produce 1,000 sow replacements for multiplier) |
| | B | 40 | 1,000 | 4 (24- and 30-mo-old 40 sires produce 100 boar replacements for commercial) | 4 (24- and 30-mo-old 1,000 sows produce 100 boar replacements for commercial) |
| Multiplier | A | 75 | 5,000 | 3 | 5 |
| Commercial | B×A | 500 | 150,000 | 5 | 6 |

sibs on NBA, PWM, WOI, GL, PBW, and 21LW. For all traits, pedigree information (BLUP breeding values) is used. For line B, male selection candidates are tested for ADG, RFI, BF, PD, FI50, and FI100, whereas female selection candidates are tested for only ADG, BF, and PD. The new generations of 20 boars are selected out of 5,000 candidates based on own performance and performances of 9 full sibs and 240 half sibs for ADG, BF, and PD, and performances of 4 full sibs and 120 half sibs for RFI, FI50, and FI100. Similarly, the new generations of 500 gilts are selected out of 5,000 candidates based on own performance and performances of 9 full sibs and 240 half sibs for ADG, BF, and PD, and performances of 5 full sibs and 120 half sibs for RFI, FI50, and FI100. For all traits, pedigree information (BLUP breeding values) is used.

Monetary gains over a 10-yr investment period (20 seasons) from 1 round of selection of parents (selected before 6 mo old) are computed by using the gene flow method. A 5% annual discount rate is assumed. For the assumed production structure presented above, the *P*, *Q*, and *R* matrices that are used in the gene flow method can be found in Supplementary Material.

***Environmental impacts at commercial farm level.*** Based on a bioeconomic model for a typical Brazilian farrow-to-finish commercial pig farm (Ali et al., 2018b), the effects of using the different EVs to select parents (Table 1) on commercial farm level emission of GHGs (kg $CO_2$-equivalent), nitrogen excretion (**N**, kg), and phosphorus excretion (**P**, kg) are assessed. As described in Ali et al. (2018b), the typical farm is assumed to own 1,500 sows and finishes about 33,500 fattening pigs per farm per year with a constant slaughter weight of 115.5 kg each. The number of sows and slaughter weights was assumed to be fixed. Reductions in emissions of GHGs, and excretions of N and P are calculated at commercial level for this typical pig farm that uses selected parents (based on the breeding structure described above in subsection Population structure, selection strategy, and gene flow).

The derivation of these environmental impacts is as follows. First, using the bioeconomic pig farm model (Ali et al., 2018b), the effects of a 1 unit genetic change of a trait (i.e., genetic superiorities of selected parents, Table 5) on emissions of GHGs, and excretions of N and P per finished pig for production and per sow for reproduction traits are derived. We refer to Ali et al. (2018a) for details regarding the effects of genetic changes of traits on environmental impacts for the Brazilian farrow-to-finish pig production system. Second, taking into account the time delay and transfer of genes from selections carried out in the nucleus herd in the current period, the cumulative reductions of environmental impacts at commercial farm level over a 10-yr period are simulated using the gene flow method. Using the environmental impact reductions as EVs in the gene flow method (e.g., reduction in emission of GHGs in kg $CO_2$-eq due to a 1 unit genetic superiority of parents for a given trait), the environmental impact reductions over a 10-yr investment period are derived for each trait.

## RESULTS

### *Genetic Gains of Breeding Goal Traits*

Genetic superiority of selected parents from 1 round of selection, obtained from SelAction, for production and reproduction traits in line A, and for production traits in line B is summarized in Table 5 for the different breeding goal traits. Following the desired gain approach, genetic gains in ADG are kept close to zero in the dam-line breeding objective. As expected, selection within the dam-line resulted in higher genetic response for reproductive traits in females than males, whereas selection within the sire-line resulted in higher responses in production traits in males than in females. The optimal dam-line breeding objectives resulted in unfavorable effects for PWM and WOI. This implies that the economic return of selection for increased NBA outweighs the combined economic losses associated with increased PWM and WOI. As expected, accuracy of selection is higher for the sire-line breeding objective than for the dam-line breeding objective

**Table 5.** Simulated genetic superiorities of selected parents (in trait units) from 1 round of selection in separate dam-line and sire-line selections (using SelAction)

| | RN_NGHG[1] | | RN_GHG[1] | | RA_NGHG[1] | | RA_GHG[1] | |
|---|---|---|---|---|---|---|---|---|
| Traits | Male | Female | Male | Female | Male | Female | Male | Female |
| **Dam-line objective** | | | | | | | | |
| ADG, g/d[2] | 1.106 | 2.352 | 1.102 | 2.353 | 1.105 | 2.325 | 1.103 | 2.333 |
| NBA, piglets per litter | 0.214 | 0.270 | 0.214 | 0.270 | 0.214 | 0.271 | 0.214 | 0.270 |
| PWM, % | 0.116 | 0.138 | 0.115 | 0.137 | 0.129 | 0.154 | 0.127 | 0.152 |
| WOI, d | 0.010 | 0.012 | 0.009 | 0.011 | 0.000 | 0.000 | 0.000 | 0.000 |
| Variance of index | 13.914 | 50.704 | 15.201 | 55.389 | 9.825 | 35.837 | 11.111 | 40.516 |
| Variance of breeding goal | 278.381 | 278.381 | 304.371 | 304.371 | 190.918 | 190.918 | 216.761 | 216.761 |
| Accuracy of index | 0.224 | 0.427 | 0.223 | 0.427 | 0.227 | 0.433 | 0.226 | 0.432 |
| **Sire-line objective** | | | | | | | | |
| ADG, g/d | 24.836 | 15.889 | 24.627 | 15.765 | 24.865 | 15.906 | 24.590 | 15.744 |
| FCR, kg/kg | −0.068 | −0.032 | −0.070 | −0.033 | −0.068 | −0.032 | −0.070 | −0.033 |
| Variance of index | 3.759 | 3.332 | 4.492 | 3.967 | 4.217 | 3.741 | 4.912 | 4.335 |
| Variance of breeding goal | 13.898 | 13.898 | 16.497 | 16.497 | 15.612 | 15.612 | 18.015 | 18.015 |
| Accuracy of index | 0.520 | 0.490 | 0.522 | 0.490 | 0.520 | 0.489 | 0.522 | 0.491 |

Refer to Table 2 for abbreviations of traits.

[1]RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

[2]Based on a desired genetic gain, it is set close to zero.

(among others due to higher heritability of production traits than reproduction traits).

Genetic gains of NBA are similar across the 4 cases implying that the inclusion of environmental costs and risk aversion does not affect response to selection for NBA (in trait units). Compared with the traditional breeding objective (RN_NGHG), genetic gains of PWM worsens (i.e., PWM increased) when derived from EVs that take into account risk aversion (12%; Table 5). For the sire-line breeding objective, the genetic superiority of selected parents decreases for ADG (by about 1%) with the inclusion of both environmental costs and risk aversion (RA_GHG), whereas it increases for FCR (by about 3%). The accuracy of selection has increased with the inclusion of environmental costs and risk aversion by about 1% for the dam-line, whereas it remained the same for the sire-line breeding objectives.

### *Cumulative Discounted Economic Returns*

The genetic superiority of selected parents of purebred lines A and B in nucleus herds is transferred to crossbred animals in the commercial level. For the Brazilian production system, the number of discounted expressions over 20 seasons from 1 round of selection is summarized in Supplementary Table A1. The discounted expressions are from 1 unit of genetic superiority, and assuming 1 unit of economic value and a 5% annual discount rate. As expected, in the dam-line selection, the number of expressions of production traits (ADG) is greater than the expressions of reproduction traits (e.g., NBA). Reproduction traits are expressed only on females, whereas ADG is expressed on both sexes. Moreover, the timing of expression for production traits is shorter than reproduction traits; therefore, the cumulative number of discounted expressions for ADG is greater than the expressions for reproduction traits. The expressions of reproduction traits start after 3 seasons, whereas it starts after 2 seasons for production traits in the nucleus tier. In the multiplier tier, expression of production traits from selections carried out in the dam-line starts after 4 seasons, whereas it starts after 5 seasons for reproduction traits. The expressions of production traits from selection in the sire-line are zero as line B is not used in the multiplier tier. In the dam-line selection, the expression of genetic superiorities of production traits (ADG) starts after 6 seasons, whereas it starts after 7 seasons for reproduction traits at commercial production level. In the sire-line selection, however, the expressions of genetic superiorities for production traits start after 4 seasons at commercial level.

The discounted economic returns (farm returns) and social returns (i.e., economic returns minus environmental costs) are computed from the genetic superiorities of parents for each breeding goal trait (Table 5) by accounting for the number of discounted expressions (Supplementary Table A1). The discounted response to selection (in US$) is summarized in Table 6 for the 4 breeding objectives (RN_NGHG, RN_GHG, RA_NGHG, and RA_GHG). When the EVs that were derived by accounting for risk and risk aversion are used for deriving response to selection in monetary units (RA_NGHG, Table 1), response to selection implies change in mean-variance utility. On the other hand, when the EVs that were derived by accounting for environmental costs are used for deriving response to selection in monetary units (RN_GHG, Table 1), response to selection implies social returns. The use of EVs that are derived by incorporating risk and risk aversion (RA_NGHG; Table 6) increases the cumulative discounted utility in sire-line selection (by about 6%) while reducing in dam-line selection (by about 12%) compared with the use of traditional EVs (RN_NGHG; Table 6). The use of EVs that are derived by incorporating environmental costs (RN_GHG; Table 6) increases the cumulative discounted social return in both dam-line (about 5%) and sire-line (about 10%) selections compared with response to selection based on the traditional EVs (RN_NGHG; Table 6). The EVs that are derived by accounting for environmental cost are greater than the traditional EVs (Table 1). For example, in the sire-line, this resulted in greater genetic gain in FCR and lower genetic gain in ADG compared with the use of traditional EVs (Table 5). The aggregate social return in the sire-line (about US$ 7.2 million; Table 6) is greater when EVs that account for environmental costs are used than the purely economic return from traditional EVs (about US$ 6.6 million; Table 6) since an improvement in FCR reduces both feed cost and environmental costs associated with feed. The results show that the use of EVs that account for environmental costs increases both farm economic returns (Supplementary Table A2) and social returns (Table 6). This implies that the incorporation of mitigation of environmental impacts in breeding goals via EVs, which were derived by accounting for environmental costs, does not result in a decrease in farm productivity (Supplementary Table A2).

**Table 6.** Discounted response to selection (US$) over 20 seasons from 1 round of selection in a dam-line for reproduction traits (line A) and a sire-line for production traits (line B) in a 3-tier production system for the different cases (1 season = 6 mo)

| Breeding objective | Season | ADG, g/d | NBA, per litter | PWM, % | WOI, d | Dam-line subtotal | ADG, g/d | FCR, kg/kg | Sire-line sub-total | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| RN_NGHG[1] | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 656 | 8,076 | −601 | −30 | 8,101 | 225,224 | 145,908 | 371,132 | 379,233 |
| | 10 | 12,529 | 41,292 | −3,060 | −154 | 50,607 | 265,848 | 172,226 | 438,074 | 488,681 |
| | 15 | 16,309 | 88,278 | −6,613 | −332 | 97,642 | 251,360 | 162,840 | 414,200 | 511,842 |
| | 20 | 17,640 | 102,230 | −7,655 | −384 | 111,831 | 235,032 | 152,262 | 387,294 | 499,125 |
| | Cumulative | 203,349 | 986,050 | −73,667 | −3,697 | 1,112,035 | 4,001,040 | 2,592,013 | 6,593,053 | 7,705,088 |
| RN_GHG[1] | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 707 | 8,445 | −626 | −29 | 8,497 | 240,566 | 166,699 | 407,265 | 415,762 |
| | 10 | 13,526 | 43,177 | −3,191 | −148 | 53,364 | 283,957 | 196,767 | 480,724 | 534,088 |
| | 15 | 17,602 | 92,308 | −6,896 | −319 | 102,695 | 268,482 | 186,044 | 454,526 | 557,221 |
| | 20 | 19,037 | 106,897 | −7,983 | −370 | 117,581 | 251,041 | 173,958 | 424,999 | 542,580 |
| | Cumulative | 219,488 | 1,031,064 | −76,823 | −3,561 | 1,170,168 | 4,273,580 | 2,961,364 | 7,234,944 | 8,405,112 |
| RA_NGHG[1] | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 686 | 6,695 | −451 | 0 | 6,930 | 239,354 | 154,238 | 393,592 | 400,522 |
| | 10 | 13,105 | 34,238 | −2,298 | 0 | 45,045 | 282,527 | 182,058 | 464,585 | 509,630 |
| | 15 | 17,068 | 73,146 | −4,965 | 0 | 85,249 | 267,130 | 172,136 | 439,266 | 524,515 |
| | 20 | 18,467 | 84,709 | −5,747 | 0 | 97,429 | 249,777 | 160,954 | 410,731 | 508,160 |
| | Cumulative | 212,799 | 817,169 | −55,309 | 0 | 974,659 | 4,252,055 | 2,739,986 | 6,992,041 | 7,966,700 |
| RA_GHG[1] | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 737 | 7,117 | −489 | 0 | 7,365 | 250,516 | 174,753 | 425,269 | 432,634 |
| | 10 | 14,073 | 36,390 | −2,494 | 0 | 47,969 | 295,701 | 206,273 | 501,974 | 549,943 |
| | 15 | 18,324 | 77,796 | −5,385 | 0 | 90,735 | 279,586 | 195,032 | 474,618 | 565,353 |
| | 20 | 19,823 | 90,092 | −6,233 | 0 | 103,682 | 261,424 | 182,363 | 443,787 | 547,469 |
| | Cumulative | 228,469 | 868,976 | −59,997 | 0 | 1,037,448 | 4,450,334 | 3,104,435 | 7,554,769 | 8,592,217 |

Refer to Table 2 for abbreviations of traits.

[1]RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

Compared with cumulative economic returns from genetic improvement that are derived from the traditional EVs (RN_NGHG, Supplementary Table A2), cumulative economic returns following from genetic improvement that are derived from EVs which account for environmental costs are slightly higher (RN_GHG, Supplementary Table A2). In this case, the social return is decomposed into cumulative economic returns and cumulative reductions in environmental costs following from genetic improvement. Therefore, the figures for RN_GHG in Supplementary Table A2 refer to the amounts of economic returns in the social returns (RN_GHG, Table 6).

Cumulative discounted social return decreased by about 7% for dam-line selection, whereas it increased by 15% for sire-line selection when EVs that account both environmental costs and risk aversion (RA_GHG; Table 6) are used compared with discounted economic response to selection based on the traditional EVs (RN_NGHG; Table 6). For reproduction traits, RN_GHG case provides the highest cumulative discounted economic return (about US$ 1.2 million; Table 6). For production traits, RA_GHG case provides the highest cumulative discounted social return (about US$ 7.6 million; Table 6). The correlation between the traditional breeding objective (RN_NGHG) and the other breeding objectives that account for GHG emission costs and risk aversion is almost 1 (ranging between 0.998 for RA_NGHG in dam-line objective to 1.0 in RA_NGHG in sire-line breeding objective).

### *Environmental Impacts at Commercial Farm Level*

The cumulative reductions in emissions of GHGs (kg $CO_2$-equivalent), and excretions of N and P (kg) at commercial farm level following from the use of selected parents are presented in Table 7 for sire-line and in Table 8 for dam-line selections. The results for the sire-line show that the expressions of genetic superiorities start after 4 seasons at commercial level (Table 7), whereas for the dam-line expressions of genetic superiorities start after 5 seasons for production traits and after 7 seasons for reproduction traits (Table 8). For the sire-line selection, on average, emission of GHGs decreases by 35,360 kg $CO_2$-equivalent per year (i.e., the cumulative reduction in the emission of GHGs is 353,601 kg over 20 seasons; Table 7) when EVs that are derived by accounting for both environmental costs and risk aversion are used. Reductions in environmental impacts following from genetic improvement of traits of the dam-line objective are negligible compared with the results of sire-line breeding objective. Reductions in environmental impacts (in both lines) do not depend on the use of the different EVs (i.e., with and without taking into account environmental costs and risk aversion). Compared with the traditional breeding objective (RN_NGHG), the use of EVs that account for both environmental costs and risk aversion resulted in about 1% additional reduction in emission of GHGs, and excretions of N and P. However, the inclusion of other environmental costs (e.g. acidification, eutrophication, and GHGs emission from other stages of production) would further increase the differences among the different EVs and thereby these results might change.

## DISCUSSION

In pig breeding programs, dam-lines are selected for reproduction (and production) traits, whereas sire-lines are predominantly selected for production traits. In this study, a dam-line breeding objective with breeding goal traits ADG, NBA, PWM, and WOI, and a sire-line breeding objective with traits ADG and FCR were assumed. We followed a desired-gain approach for ADG in the dam-line breeding objective (by changing the EV of ADG such that response to selection for ADG is close to zero). The use of the actual EV of ADG in the dam-line breeding objective would result in deterioration of all reproduction traits for the Brazilian production system. However, the main target of dam-line selection is to improve reproduction traits. Therefore, in the dam-line breeding objective, we aimed at achieving the maximum possible improvement in reproduction traits without deteriorating ADG.

Although the effect of the use of EVs that account for environmental costs and risk aversion of producers on genetic superiorities (in trait units) seems to be small, its effect on cumulative discounted economic response to selection is large as genetic improvement results in permanent and cumulative changes in performance. For example, the genetic superiorities (in trait unit) of NBA in the dam-line breeding objectives are the same when genetic superiorities are derived based on EVs that account and do not account for environmental costs and risk aversion (Table 5). However, cumulative discounted economic returns for NBA increased by about 5% and decreased by about 17% when derived from EVs that account for GHG emission costs and risk aversion, respectively (Table 6), following from the increase

**Table 7.** Cumulative reductions in environmental impacts (kg per season) at commercial farm level over 20 seasons from 1 round of selection in sire-line (line B) for production traits for a typical Brazilian farrow-to-finish pig farm for the different breeding objectives (1 season = 6 mo)

| Traits | Breeding objective | Environmental impact | 1–3 | 4 | 5 | 10 | 15 | 20 | Cumulative |
|---|---|---|---|---|---|---|---|---|---|
| FCR | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −7,115 | −7,115 | −9,581 | −10,247 | −10,832 | −152,802 |
| | | N, kg | 0 | −144 | −144 | −194 | −208 | −220 | −3,101 |
| | | P, kg | 0 | −27 | −27 | −37 | −39 | −42 | −588 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | −7,328 | −7,328 | −9,868 | −10,554 | −11,157 | −157,386 |
| | | N, kg | 0 | −149 | −149 | −200 | −214 | −226 | −3,194 |
| | | P, kg | 0 | −28 | −28 | −38 | −41 | −43 | −606 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −7,115 | −7,115 | −9,581 | −10,247 | −10,832 | −152,802 |
| | | N, kg | 0 | −144 | −144 | −194 | −208 | −220 | −3,101 |
| | | P, kg | 0 | −27 | −27 | −37 | −39 | −42 | −588 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | −7,328 | −7,328 | −9,868 | −10,554 | −11,157 | −157,386 |
| | | N, kg | 0 | −149 | −149 | −200 | −214 | −226 | −3,194 |
| | | P, kg | 0 | −28 | −28 | −38 | −41 | −43 | −606 |
| ADG | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −9,349 | −9,349 | −12,591 | −13,466 | −14,234 | −200,799 |
| | | N, kg | 0 | −217 | −217 | −292 | −312 | −330 | −4,650 |
| | | P, kg | 0 | −39 | −39 | −53 | −56 | −60 | −842 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | −9,273 | −9,273 | −12,488 | −13,355 | −14,118 | −199,158 |
| | | N, kg | 0 | −215 | −215 | −289 | −309 | −327 | −4,612 |
| | | P, kg | 0 | −39 | −39 | −52 | −56 | −59 | −835 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −9,360 | −9,360 | −12,605 | −13,481 | −14,250 | −201,026 |
| | | N, kg | 0 | −217 | −217 | −292 | −312 | −330 | −4,655 |
| | | P, kg | 0 | −39 | −39 | −53 | −57 | −60 | −843 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | −9,260 | −9,260 | −12,470 | −13,336 | −14,098 | −198,872 |
| | | N, kg | 0 | −214 | −214 | −289 | −309 | −326 | −4,605 |
| | | P, kg | 0 | −39 | −39 | −52 | −56 | −59 | −834 |
| Sire-line subtotal | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −16,464 | −16,464 | −22,172 | −23,713 | −25,066 | −353,601 |
| | | N, kg | 0 | −361 | −361 | −486 | −520 | −550 | −7,751 |
| | | P, kg | 0 | −66 | −66 | −90 | −95 | −102 | −1,430 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | −16,601 | −16,601 | −22,356 | −23,909 | −25,275 | −356,544 |
| | | N, kg | 0 | −364 | −364 | −489 | −523 | −553 | −7,806 |
| | | P, kg | 0 | −67 | −67 | −90 | −97 | −102 | −1,441 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −16,475 | −16,475 | −22,186 | −23,728 | −25,082 | −353,828 |
| | | N, kg | 0 | −361 | −361 | −486 | −520 | −550 | −7,756 |
| | | P, kg | 0 | −66 | −66 | −90 | −96 | −102 | −1,431 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | −16,588 | −16,588 | −22,338 | −23,890 | −25,255 | −356,258 |
| | | N, kg | 0 | −363 | −363 | −489 | −523 | −552 | −7,799 |
| | | P, kg | 0 | −67 | −67 | −90 | −97 | −102 | −1,440 |

GHG = greenhouse gases (kg $CO_2$-equivalent per farm per season); N = nitrogen excretion (kg per farm per season); P = phosphorus excretion (kg per farm per season).

Refer to Table 2 for abbreviations of traits.

[1]RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

and decrease in EVs of NBA with GHG emission cost and risk aversion, respectively (Table 1). On the other hand, the genetic superiorities (in trait unit) of FCR in the sire-line breeding objectives increased by about 3%, 0%, and 3% when derived from EVs that account for environmental costs, risk aversion, or both, respectively (Table 5). The associated increases in cumulative discounted economic responses to selections are about 14%, 6%, and 20%, respectively (Table 6). The results of the present study are in line with the conclusion of Kanis et al. (2005) that mitigating environmental impacts requires more emphasis in selection given to efficiency traits (e.g., FCR) as these traits have environmental (and societal) values that are not captured by selection based solely on direct economic aspects.

The results of this paper showed that for reproduction traits, the use of EVs that incorporate

**Table 8.** Cumulative reductions in environmental impacts at commercial farm level over 20 seasons (kg per season) from 1 round of selection carried out in dam-line for production and reproduction traits for a typical Brazilian farrow-to-finish pig farm for the different breeding objectives (1 season = 6 mo)

| Traits | Breeding objective | Environmental impact | 1–5 | 6 | 10 | 15 | 19 | 20 | Cumulative |
|---|---|---|---|---|---|---|---|---|---|
| ADG | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −216 | −546 | −826 | −988 | −1,022 | −9,863 |
| | | N, kg | 0 | −5 | −13 | −19 | −23 | −24 | −228 |
| | | P, kg | 0 | −1 | −2 | −3 | −4 | −4 | −41 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | −216 | −546 | −826 | −987 | −1,021 | −9,856 |
| | | N, kg | 0 | −5 | −13 | −19 | −23 | −24 | −228 |
| | | P, kg | 0 | −1 | −2 | −3 | −4 | −4 | −41 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −214 | −541 | −819 | −980 | −1,014 | −9,779 |
| | | N, kg | 0 | −5 | −13 | −19 | −23 | −23 | −226 |
| | | P, kg | 0 | −1 | −2 | −3 | −4 | −4 | −41 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | −214 | −542 | −821 | −981 | −1,015 | −9,798 |
| | | N, kg | 0 | −5 | −13 | −19 | −23 | −24 | −227 |
| | | P, kg | 0 | −1 | −2 | −3 | −4 | −4 | −41 |
| NBA | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | −560 | −1,556 | −1,992 | −2,089 | −16,647 |
| | | N, kg | 0 | 0 | −3 | −9 | −12 | −12 | −98 |
| | | P, kg | 0 | 0 | −3 | −9 | −11 | −12 | −92 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | −560 | −1,556 | −1,992 | −2,089 | −16,647 |
| | | N, kg | 0 | 0 | −3 | −9 | −12 | −12 | −98 |
| | | P, kg | 0 | 0 | −3 | −9 | −11 | −12 | −92 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | −561 | −1,559 | −1,997 | −2,093 | −16,685 |
| | | N, kg | 0 | 0 | −3 | −9 | −12 | −12 | −98 |
| | | P, kg | 0 | 0 | −3 | −9 | −11 | −12 | −92 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | −560 | −1,556 | −1,992 | −2,089 | −16,647 |
| | | N, kg | 0 | 0 | −3 | −9 | −12 | −12 | −98 |
| | | P, kg | 0 | 0 | −3 | −9 | −11 | −12 | −92 |
| PWM | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +84 | +238 | +304 | +319 | +2,535 |
| | | N, kg | 0 | 0 | +1 | +2 | +3 | +3 | +27 |
| | | P, kg | 0 | 0 | 0 | +1 | +2 | +2 | +14 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +84 | +236 | +302 | +316 | +2,515 |
| | | N, kg | 0 | 0 | +1 | +2 | +3 | +3 | +26 |
| | | P, kg | 0 | 0 | 0 | +1 | +2 | +2 | +14 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +94 | +265 | +339 | +355 | +2,825 |
| | | N, kg | 0 | 0 | +1 | +3 | +4 | +4 | +30 |
| | | P, kg | 0 | 0 | +1 | +1 | +2 | +2 | +15 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +93 | +261 | +334 | +350 | +2,785 |
| | | N, kg | 0 | 0 | +1 | +3 | +4 | +4 | +29 |
| | | P, kg | 0 | 0 | +1 | +1 | +2 | +2 | +15 |
| WOI | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +3 | +8 | +11 | +11 | +90 |
| | | N, kg | 0 | 0 | 0 | 0 | 0 | 0 | +1 |
| | | P, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | +3 | +8 | +10 | +10 | +82 |
| | | N, kg | 0 | 0 | 0 | 0 | 0 | 0 | +1 |
| | | P, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | N, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | P, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | N, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | P, kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dam−line subtotal | RN_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −216 | −1,019 | −2,136 | −2,665 | −2,781 | −23,885 |
| | | N, kg | 0 | −5 | −15 | −26 | −32 | −33 | −298 |
| | | P, kg | 0 | −1 | −5 | −11 | −13 | −14 | −119 |
| | RN_GHG[1] | GHG, kg $CO_2$-eq | 0 | −216 | −1,019 | −2,138 | −2,667 | −2,784 | −23,906 |
| | | N, kg | 0 | −5 | −15 | −26 | −32 | −33 | −299 |
| | | P, kg | 0 | −1 | −5 | −11 | −13 | −14 | −119 |
| | RA_NGHG[1] | GHG, kg $CO_2$-eq | 0 | −214 | −1,008 | −2,113 | −2,638 | −2,752 | −23,639 |
| | | N, kg | 0 | −5 | −15 | −25 | −31 | −31 | −294 |
| | | P, kg | 0 | −1 | −4 | −11 | −13 | −14 | −118 |
| | RA_GHG[1] | GHG, kg $CO_2$-eq | 0 | −214 | −1,009 | −2,116 | −2,639 | −2,754 | −23,660 |
| | | N, kg | 0 | −5 | −15 | −25 | −31 | −32 | −296 |
| | | P, kg | 0 | −1 | −4 | −11 | −13 | −14 | −118 |

GHG = greenhouse gases (kg $CO_2$-equivalent per farm per season); N = nitrogen excretion (kg per farm per season); P = phosphorus excretion (kg per farm per season).

Refer to Table 2 for abbreviations of traits.

[1]RN_NGHG, for a risk neutral producer without including greenhouse gases emission costs; RN_GHG, for a risk neutral producer by including greenhouse gases emission costs; RA_NGHG, for a risk averse producer without including greenhouse gases emission costs; and RA_GHG, for a risk averse producer by including greenhouse gases emission costs.

environmental costs provides the highest cumulative discounted social return. For production traits, the use of EVs that incorporate both environmental costs and risk aversion provides the highest cumulative discounted social return. Therefore, breeding programs need to consider both environmental costs and risk preferences of producers in sire-line selection for improving both economic and environmental sustainability of Brazilian pig production systems. On the other hand, breeding companies should consider only environmental costs for improving reproduction traits in dam-line selection. The results of the current study are useful for Brazilian pig integrators, which control the entire pork production chain including pig breeding, to improve the sustainability of their production systems and to meet the growing demand for sustainable pork. As the results of this study show, the use of EVs that are derived by accounting for GHGs emission costs improves both economic and environmental sustainability of pig farming (Table 6). Therefore, policy makers may facilitate the design of a well-functioning carbon market for the agricultural sector or may impose taxes on farms for emission of GHGs or excretion of nutrients. A carbon market (e.g., the European Emission Trading System) allows agents (e.g., farmers) to trade emission allowances, and thereby environmental impacts become part of farming decisions via market forces (e.g., like feed cost). Similarly, producers might be obliged to pay taxes for emission of GHGs or excretion of nutrients. Policy makers may also provide incentives (e.g., arrange finance at a lower interest rate) to encourage breeding companies to update their breeding objectives by incorporating environmental costs and risk aversion.

The largest contributors to environmental loads (e.g., emissions of GHGs and excretions of N and P) in the pig production chain are feed production and manure management (Cherubini et al., 2015). Genetic improvement of efficiency traits contributes towards reductions of environmental impacts. As illustrated using a typical Brazilian farrow-to-finish commercial farm (Table 7), emissions of GHGs and excretions of N and P can be reduced substantially with genetic improvements of production traits (in sire-line selection). Environmental impacts can further be reduced by about 1% by using EVs that are derived by incorporating GHG emission costs and risk aversion compared with the use of traditional EVs. Risk is an integral part of agricultural production (e.g., due to production variability and price volatility). Models that take into account risk preferences have a better predictive power of the behavior of farmers (and hence farm profit which are the basis for deriving EVs) than those that do not (Moschini and Hennessy, 2001). The results of the present study also showed that selection indices (and thereby response to selections) are different with and without considering risk preferences.

Generation interval affects cumulative discounted economic return through genetic gains of traits and discounting. A lengthy generation interval delays the expressions of genetic superiorities at the commercial production level, thereby reducing the cumulative number of expressions within a given investment period (Brascamp, 1978). Furthermore, the present value of the monetary gains from the delayed expressions of genetic superiorities is lower because of the effect of time on the present value of money (via discounting). As the generation interval and discount rate used in this study are the same across the 4 breeding objectives (with and without accounting environmental cost and risk aversion), the comparisons of results are not affected between the objectives.

The discount rate also affects the cumulative discounted response to selection. In this study, a 5% annual discount rate is assumed. The 2017 annual interest rate for Brazilian 10-yr government bond was about 7% (based on bloomberg.com). A social discount rate needs to be used when animal breeding program investments should be considered as public projects (Smith, 1978). Bird and Mitchell (1980) suggested the use of social discount rates between 2% and 5% in breeding program investment appraisals. In the case of the present study, governments have leading roles to play in reducing environmental impacts of livestock production systems and in arranging technologies for risk-averse producers.

The cost of running the breeding programs is not considered in the present study. However, as the cost remains the same across the different breeding objectives, it does not undermine the comparisons of discounted returns among the different breeding objectives. For the assumed production system, the use of EVs that account for GHG emission costs and risk aversion results in a discounted return of more than US$ 887,130 over 10 yr (compared with the traditional system that does not take into account GHG emission and risk).

The results of the present study are not directly comparable with other studies as the production systems, assumed breeding structures, and breeding goals are different across studies. For a 2-trait beef production system (ADG, kg/d and average daily dry matter intake [ADDMI; fractional change in kg/d]), Kulak et al. (2003) assessed the effect of using EVs that account for risk aversion on response to selection using a linear selection index based on own performance. Their results showed that genetic superiorities decreased from 0.079 to 0.077 for ADG and from 0.012 to 0.009 for ADDMI when EVs that account for risk aversion are used compared with the use of traditional EVs (for a fixed fattening period). In our study, response to selections in the sire-line (selection in males) marginally increased from 24.84 to 24.87 for ADG (g/d), and FCR (kg feed/kg gain) remained constant at −0.068 (for fixed output per farm per year) when risk aversion is considered. In Kulak et al. (2003), total economic response to selection (US$/animal) decreased from 20.68 to 5.68. In our study, total discounted cumulative economic response (US$/farm) increased from 6.59 million to 6.99 million in sire-line selection over 10 yr. As described in Ali et al. (2018a), an improvement in ADG decreases duration of fattening and thereby feed consumption decreases (for a constant output). An improvement in FCR directly results in a reduction in feed consumption. Both these improvements result in a decrease in the variance of feed cost (due to the reduction in feed consumption while the variance of output is constant), which results in higher profit and utility. For Kulak et al. (2003), response to selection derived from EVs that account for risk aversion is lower compared with the traditional response to selection, as output is not fixed (they fixed fattening duration). Improvement in ADG and increase in ADDMI result in increased output. The increase in output results in increase in revenue but also increased variability of revenue (due to the variability of beef prices) and the increase in revenue is outweighed by the increase in the variability of profit. For Kulak et al. (2003), accuracy of selection decreased slightly from 54.1% to 53.8%, whereas in the present study accuracy of selection does not change with the use of EVs derived by accounting for risk aversion. The correlation between the 2 breeding objectives (using EVs with and without accounting for risk aversion) was 99.7% in Kulak et al. (2003), whereas it is 99.9% in the present study for the sire-line breeding objectives.

Van Middelaar et al. (2014) measured the effect of genetic improvements of milk yield and longevity for Dutch dairy production system on emissions of GHGs at chain level. For a labor income maximizing breeding objective, an improvement in milk yield and longevity by 1 genetic SD unit resulted in a reduction of GHGs emission ($CO_2$-equivalent) of 247 and 210 kg per cow per year, respectively. When the breeding objective is to minimize emission of GHGs per kg of milk while maintaining labor income and milk production at least at the level before the genetic change in a trait, emission of GHGs can be reduced by 453 and 441 kg per cow per year for milk yield and longevity, respectively. Bell et al. (2013) reported that a 1-unit increase in survival and decreases in milk volume, live weight, dry matter intake, somatic cell count, and calving interval in Australian dairy production system would increase net income while reducing emissions of GHGs per cow and per kg of milk produced.

## CONCLUSIONS

This study assessed the effect of using EVs that account for GHGs emission costs and risk preferences of producers on response to selection in terms of genetic gains of breeding goal traits, cumulative discounted economic returns, and cumulative reductions in environmental impacts. The approach was applied to a Brazilian pig production system. Compared with traditional EVs, the use of EVs that account for both GHGs emission cost and risk aversion results in a decrease in genetic superiority for ADG (1%), an increase for FCR (3%), whereas NBA is not affected. The use of EVs that take into account risk aversion increases the cumulative discounted economic return in sire-line selection (6%) while reducing in dam-line selection (12%) compared with the use of traditional EVs. On the other hand, the use of EVs that account for environmental costs increases the cumulative discounted social return in both dam-line (5%) and sire-line (10%). Emission of GHGs, and excretion of N and P can be reduced more with genetic improvements of production traits than reproduction traits for the typical Brazilian farrow-to-finish pig farm. Reductions in environmental impacts do not, however, depend on the use of the different EVs (i.e., with and without taking into account GHGs emission costs and risk aversion). To improve both economic and environmental sustainability of the Brazilian pig production system, breeding companies need to consider both environmental costs and risk preferences of producers in sire-line selection. For dam-line selection, only environmental costs need to be considered.

## SUPPLEMENTARY DATA

Supplementary data are available at *Journal of Animal Science* online.

## LITERATURE CITED

Ali, B. M., P. B. M. Berentsen, J. W. M. Bastiaansen, and A. Oude Lansink. 2018a. A stochastic bio-economic pig farm model to assess the impact of innovations on farm performance. Animal 12:819–830. doi:10.1017/S1751731117002531

Ali, B. M., Y. de Mey, J. W. M. Bastiaansen, and A. G. J. M. Oude Lansink. 2018b. Effects of incorporating environmental cost and risk aversion on economic values of pig breeding goal traits. J. Anim. Breed. Genet. 135:194–207. doi:10.1111/jbg.12331

Beaulieu, A. D., J. L. Aalhus, N. H. Williams, and J. F. Patience. 2010. Impact of piglet birth weight, birth order, and litter size on subsequent growth performance, carcass quality, muscle composition, and eating quality of pork. J. Anim. Sci. 88:2767–2778. doi:10.2527/jas.2009-2222

Bell, M. J., R. J. Eckard, M. Haile-Mariam, and J. E. Pryce. 2013. The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. J. Dairy Sci. 96:7918–7931. doi:10.3168/jds.2012-6289

Bird, P. J., and G. Mitchell. 1980. The choice of discount rate in animal breeding investment appraisal. Anim. Breed. Abstr. 48:499–505.

Brascamp, E. W. 1978. Methods on economic optimization of animal breeding plans. Report B-134. Res. Inst. Anim. Husb., Zeist, The Netherlands.

Cai, W., D. S. Casey, and J. C. Dekkers. 2008. Selection response and genetic parameters for residual feed intake in Yorkshire swine. J. Anim. Sci. 86:287–298. doi:10.2527/jas.2007-0396

Cassidy, E. S., P. C. West, J. S. Gerber, and J. A. Foley. 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environ. Res. Lett. 8:034015. doi:10.1088/1748–9326/8/3/034015

Cherubini, E., G. M. Zanghelini, R. A. F. Alvarenga, D. Franco, and S. R. Soares. 2015. Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. J. Clean Prod. 87:68–77. doi:10.1016/j.jclepro.2014.10.035

Cottle, D. J., and M. P. Coffey. 2013. The sensitivity of predicted financial and genetic gains in Holsteins to changes in the economic value of traits. J. Anim. Breed. Genet. 130:41–54. doi:10.1111/j.1439-0388.2012.01002.x

De Vries, M., and I. J. de Boer. 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest. Sci. 128:1–11. doi: 10.1016/j.livsci.2009.11.007.

Dube, B., S. D. Mulugeta and K. Dzama. 2013. Evaluating breeding objectives for sow productivity and production traits in large white pigs. Livest. Sci. 157:9–19. doi: 10.1016/j.livsci.2013.06.018

Fundora, D. G. 2015. Evaluation of the impact of reproductive technologies on the genetic improvement and profit of pig production systems. PhD Diss. Univ. Illinois, Urbana, United States.

Gilbert, H., J. P. Bidanel, J. Gruand, J. C. Caritez, Y. Billon, P. Guillouet, H. Lagant, J. Noblet, and P. Sellier. 2007. Genetic parameters for residual feed intake in growing pigs, with emphasis on genetic relationships with carcass and meat quality traits. J. Anim. Sci. 85:3182–3188. doi:10.2527/jas.2006-590

Groen, A. F. 1990. Influences of production circumstances on the economic revenue of cattle breeding programmes. Animal Sci. 51:469–480. doi: 10.1017/S0003356100012502

Groen, A. F., T. Steine, J. J. Colleau, J. Pedersen, J. Pribyl, and N. Reinsch. 1997. Economic values in dairy cattle breeding, with special reference to functional traits. Report of an EAAP-working group. Livest. Prod. Sci. 49:1–21. doi:10.1016/S0301-6226(97)00041-9

Hanenberg, E. H. A. T., E. F. Knol, and J. W. M. Merks. 2001. Estimates of genetic parameters for reproduction traits at different parities in Dutch Landrace pigs. Livest. Prod. Sci. 69:179–186. doi:10.1016/S0301-6226(00)00258-X

Harris, D. L. 1963. The influence of errors of parameter estimation upon index selection. In: W. D. Hanson and H. F. Robinson, editors, Proceedings of statistical genetics and plant breeding. NAS-NRC publication 982, Washington, DC. pp. 491–500.

Hazel, L. N. 1943. The genetic basis for constructing selection indexes. Genetics 28:476–490.

Hermesch, S. 2001. Avenues for genetic improvement of litter size and litter mortality. Proc. AGBU Pig Gen. Workshop:7–8, November 2001, Armidale, p. 36–43.

Huby, M., L. Canario, T. Tribout, J. C. Caritez, Y. Billon, J. Gogué, and J. P. Bidanel. 2003. Genetic correlations between litter size and weights, piglet weight variability and piglet survival from birth to weaning in large white pigs. Proc. 54th Annu. Meet. Eur. Assoc. Anim. Prod., Roma, Italy. Wageningen Pers, Wageningen, The Netherlands, p. 362.

Kanis, E., K. H. De Greef, A. Hiemstra, and J. A. van Arendonk. 2005. Breeding for societally important traits in pigs. J. Anim. Sci. 83:948–957. doi:10.2527/2005.834948x

Knol, E. F. 2001. Genetic aspects of piglet survival. PhD Diss. Wageningen Univ. Res., Wageningen, The Netherlands.

Kulak, K., J. Wilton, G. Fox, J. Dekkers. 2003. Comparisons of economic values with and without risk for livestock trait improvement. Livest. Prod. Sci. 79:183–191. doi:10.1016/S0301-6226(02)00155-0

Lund, M. S., M. Puonti, L. Rydhmer, and J. Jensen. 2002. Relationship between litter size and perinatal and pre-weaning survival in pigs. Animal Sci. 74:217–222. doi:10.1017/S1357729800052383

Lundgren, H., W. F. Fikse, K. Grandinson, N. Lundeheim, L. Canario, O. Vangen, D. Olsen, and L. Rydhmer. 2014. Genetic parameters for feed intake, litter weight, body condition and rebreeding success in primiparous Norwegian landrace sows. Animal 8:175–183. doi:10.1017/S1751731113002000

McClintock, A. E., and E. P. Cunningham. 1974. Selection in dual purpose cattle populations: defining the breeding objective. Animal Sci. 18:237–247. doi:10.1017/S0003356100022418

Miar, Y., G. Plastow, H. Bruce, S. Moore, G. Manafiazar, R. Kemp, P. Charagu, A. Huisman, B. van Haandel, C. Zhang, et al. 2014. Genetic and phenotypic correlations between performance traits with meat quality and carcass characteristics in commercial crossbred pigs. PLoS ONE 9:e110105. doi:10.1371/journal.pone.0110105

Moschini, G., and D. A. Hennessy. 2001. Uncertainty, risk aversion, and risk management for agricultural producers. Handb. Agric. Econ. 1:87–153. doi:10.1016/S1574-0072(01)10005–8

Ochsner, K. P., M. D. MacNeil, R. M. Lewis and M. L. Spangler. 2017. Economic selection index development for Beefmaster cattle I: terminal breeding objective. J. Anim. Sci. 95:1063–1070. doi:10.2527/jas.2016.1231

Olesen, I., A. F. Groen, and B. Gjerde. 2000. Definition of animal breeding goals for sustainable production systems. J. Anim. Sci. 78:570–582. doi:10.2527/2000.783570x

Rutten, M. J., P. Bijma, J. A. Woolliams, and J. A. van Arendonk. 2002. Selaction: software to predict selection response and rate of inbreeding in livestock breeding programs. J. Hered. 93:456–458. doi:10.1093/jhered/93.6.456

Rydhmer, L. 2000. Genetics of sow reproduction, including puberty, oestrus, pregnancy, farrowing and lactation. Livest. Prod. Sci. 66: 1–12. doi:10.1016/S0301-6226(99)00170-0

Rydhmer, L., N. Lundeheim, and L. Canario. 2008. Genetic correlations between gestation length, piglet survival and early growth. Livest. Sci. 115:287–293. doi:10.1016/j.livsci.2007.08.014

Saintilan, R., L. Brossard, B. Vautier, P. Sellier, J. Bidanel, J. van Milgen, and H. Gilbert. 2015. Phenotypic and genetic relationships between growth and feed intake curves and feed efficiency and amino acid requirements in the growing pig. Animal 9:18–27. doi:10.1017/S1751731114002171

Saintilan, R., I. Mérour, L. Brossard, T. Tribout, J. Y. Dourmad, P. Sellier, J. Bidanel, J. van Milgen, and H. Gilbert. 2013. Genetics of residual feed intake in growing pigs: relationships with production traits, and nitrogen and phosphorus excretion traits. J. Anim. Sci. 91:2542–2554. doi:10.2527/jas.2012-5687

Smith, C. 1978. The effect of inflation and form of investment on the estimated value of genetic improvement in farm livestock. Animal Sci. 26:101–110. doi:10.1017/S0003356100039507

Smith, C. 1983. Effects of changes in economic weights on the efficiency of index selection1. J. Anim. Sci. 56:1057–1064. doi:10.2527/jas1983.5651057x

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, C. D. Haan. 2006. Livestock's long shadow: environmental issues and options. Food Agric. Organ. United Nations, Rome, Italy.

ten Napel, J., T. H. Meuwissen, R. K. Johnson, and E. W. Brascamp. 1998. Genetics of the interval from weaning to estrus in first-litter sows: correlated responses. J. Anim. Sci. 76:937–947. doi:10.2527/1998.764937x

Tholen, E., K. L. Bunter, S. Hermesch, and H. U. Graser. 1996. The genetic foundation of fitness and reproduction traits in Australian pig populations. 2. Relationships between weaning to conception interval, farrowing interval, stayability, and other common reproduction and production traits. Aust. J. Agric. Res. 47:1275–1290. doi:10.1071/AR9961261

Vandepitte, W. M., and L. N. Hazel. 1977. The effect of errors in the economic weights on the accuracy of selection indexes. Ann. Genet. Sel. Anim. 9:87–103. doi:10.1051/1297-9686-9-1-87

van Middelaar, C. E., P. B. Berentsen, J. Dijkstra, J. A. van Arendonk, and I. J. de Boer. 2014. Methods to determine the relative value of genetic traits in dairy cows to reduce greenhouse gas emissions along the chain. J. Dairy Sci. 97:5191–5205. doi:10.3168/jds.2013-7413

Wall, E., G. Simm, and D. Moran. 2010. Developing breeding schemes to assist mitigation of greenhouse gas emissions. Animal 4:366–376. doi:10.1017/S175173110999070X

Wallenbeck, A., L. Rydhmer, H. Röcklinsberg, M. Ljung, E. Strandberg, and T. Ahlman. 2016. Preferences for pig breeding goals among organic and conventional farmers in Sweden. Organic Agric. 6:171–182. doi:10.1007/s13165-015-0125-3

Wolfová, M., G. Nitter, J. Wolf, and J. Fiedler. 2001. Impact of crossing system on relative economic weights of traits in purebred pig populations. J. Anim. Breed. Genet. 118:389–402. doi:10.1046/j.1439-0388.2001.00304.x

Wolfová, M., J. Wolf, and J. Pribyl. 2007. Impact of milk pricing system on the economic response to selection on milk components. J. Anim. Breed. Genet. 124:192–200. doi:10.1111/j.1439-0388.2007.00656.x