Impact of incorporating greenhouse gas emission intensities in selection indexes for sow productivity traits

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Abstract

Genetic improvement programmes should incorporate emerging challenges about environmental concerns into breeding goals. The large volume of pig meat production implies important greenhouse gas (GHG) emissions despite its lower carbon footprint per animal in front of ruminant productions. The different breeding goals considered by swine industry depending on different purebred lines, or line crosses adapted to different market demands and production constraints, could mask the effect of incorporating GHG emissions into selection indexes for improving sow productivity traits in nucleus populations. This paper analysed this effect following a methodological approach consisting in augmenting existing selection indexes derived from profit functions. An index previously described in the literature including litter size at birth, piglet perinatal survival, piglet survival to weaning, age at first conception and weaning to conception interval, was employed. This index was expanded to include GHG emissions calculating the emission intensities per litter, assuming a finished pig market and different scenarios and financial costs of GHG emissions. Results indicated that the inclusion of GHG emissions diminished the economic weight of litter size and piglet survival *vs.* the age at first conception and the interval weaning to conception, but did not affect significantly the contributions of these traits in the selection indexes. The improvement of sow productivity traits diluted relevantly the GHG emissions per piglet produced, and so, per kg of pork produced. The approach used in this study, despite its limitations in front of bio-economic models, has shown to be a simple and flexible way to analyse the effect of incorporating GHG emissions into existing selection indexes.

***Keywords**:* Breeding goal; Economic weight; Litter size; Environmental impact; Pig production.

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Introduction

Sows productivity traits, such as litter size, have been the focus of pig breeding programs during the last three decades and have been effectively improved besides their low heritability (Kim et al., 2013). Nowadays, genetic programmes faces new challenges, and opportunities. One of them is greenhouse gas (GHG) emissions and the development of breeding goals that incorporate environmental concerns is both desirable and possible (Wall et al., 2010). Although carbon footprint from pig production is much lower than ruminant production, its large volume increases the environmental burdens (Merks et al., 2012).

If analyses of environmental impacts are performed at farm level it could be concluded that an increase in sow's productivity increases environmental costs, as the number of finished pigs and feed consumption per year also increase. However, increasing number of piglet per litter and year decreases GHG emissions per kg of meat produced as sow impacts could be allocated to a higher amount of meat produced (Reckmann and Krieter, 2015).

When sow productivity traits are considered together with pig feeding traits like feed conversion ratio it has been reported that considering GHG emissions for deriving economic values reduces the importance of sow efficiency traits (Ali et al., 2018). This was not surprising because as highlighted by different studies, feed conversion ratio is one of the most important parameters influencing environmental impacts (Reckmann and Krieter, 2015), but could lead to a not clear understanding of impact of considering environmental concerns on sows productivity traits, especially using complex methodological approaches.

GHG emissions could be incorporated into the calculation of economic values by using bio-economic models. Bio-economic models are more and more commonly used allowing the consideration of the biological and the economic complexities of livestock systems (Nielsen et al., 2104). They have already been used in the analysis of the incorporation of the cost of GHG emissions into the calculation of economic values in different species (Ali et al., 2018; Krupa et al., 2017; Wall et al., 2010; Åby et al., 2013). They are, undoubtedly, useful tools for analysing livestock production systems. Nevertheless, the implicit model's assumptions about the interacting factors in the model, and the need to reduce the level of complexity for an accurate and transparent calculation of the weighting for each individual traits, have led to propose other methodological approaches (Amer et al., 2018). Using the classic selection index approach based on profit functions, Amer et al. (2018) proposed to combine the marginal change in GHG emissions per unit of output that arises from a unit change in a trait, with the conventional economic values that make up an existing index that excludes GHG emissions. This approach could allow incorporating easily GHG emissions in profit functions such as the one described by Quinton et al. (2006) to derive economic values for sow productivity traits.

The objective of this paper was to evaluate whether important changes could be produced in economic weights of selection indexes for sow productivity traits when incorporating the cost of GHG emissions generated. Existing genetic selection indexes were expanded to account for the impact of changes in traits on GHG emissions.

Methods

Selection index for sow productivity traits excluding GHG emissions

The economic merit index for sow productivity traits defined for a finished pig market by Quinton et al. (2006) was considered for the analysis. Traits included in the index to be combined are perinatal survival, litter size at birth, survival to weaning, age at first conception and weaning to conception interval. The methods described by Quinton et al. (2006) take into account the existing negative correlation between litter size and piglet perinatal survival. In this study, we expanded this method taking into consideration the pig mortality from weaning to slaughter. The resulting expression of the net profit per litter and its partial derivatives are included in Supplementary Material.

From the partial derivatives, both the economic values and the economic weights were derived. It should be noticed that the use of economic values and economic weights is sometimes confusing in the literature. In this work, following Amer et al. (2001), we defined, and calculated, economic values and economic weights as:

- Economic values were defined as the expected increase in profit equation from a unit increase in a trait, and were calculated from partial derivatives considering for all traits their mean value (μ), and average costs and prices:

$$EVx = \frac{\partial T}{\partial x} \mid_{\mu}$$

- Economic weights were defined as the relative importance of each trait in the selection index. They allow a better comparison of the economic importance of one trait versus another, or among different breeds and different studies (Krupa et al., 2017), and were obtained multiplying economic values by the genetic standard deviation of the trait (Supplementary Table S1):

$$EWx = EVx \times \sigma_{g_x}$$

Economic values and weights were computed for different scenarios considering values from Supplementary Table S1 and litter size as variable; values considered for total litter size at birth, including stillborn, but excluding mummified piglets were 8, 12, 16 and 20 (as in Quinton et al., 2006).

GHG emission intensity

The GHG emission intensity per litter was computed as a function of the daily emissions for each pig class (starter, grower, finisher, lactating sow and dry sow), and the number of animals and length of each phase (see Supplementary Material for details).

Daily emissions were considered to depend on the daily feed intake, the volatile solid excretion and the protein content in feed. The expression of GHG emission intensity (EI) and its partial derivatives are included in Supplementary Material. From the partial derivatives, both the GHG intensity values and weights were derived:

- GHG intensity values were defined as the expected change in GHG emissions from a unit change in a trait, and were calculated from partial derivatives considering for all traits their mean value (μ) (Supplementary Tables S1 and S2):

$$IVx = \frac{\partial EI}{\partial x} \mid_{\mu}$$

- GHG intensity weights were defined as the relative importance of each trait in the selection index, and were obtained multiplying GHG intensity values by the genetic standard deviation of the trait (Supplementary Table S1):

$$IWx = IVx \times \sigma_{g_x}$$

GHG intensity values and weights were computed for different scenarios considering values from Supplementary Table S2 that correspond to low and high emissions of data reported by Little et al. (2008) for Canadian provinces.

Selection index for sow productivity traits including GHG emissions

Once economic and GHG intensity values were computed, they were integrated following Amer et al. (2018) proposal and using the expression:

$$H = \sum_{i=1}^{n} (EV_i + \beta \times \gamma \times IV_i) \times BV_i$$

where:

- H is the expanded economic value that considers GHG emission intensity,

- BV_i are the breeding values of the i traits that should be combined,
- EV_i are their economic values,
- IV_i are their GHG intensity values,
- β quantifies the financial implication associated with a change in emissions intensity,
- γ is a coefficient to arbitrarily change the relative weighting given to GHG intensity values in the expanded index.

For the financial implication associated with change in emission intensity, a shadow price for kg of CO_2 equivalent of 0.04 €/kg was considered (β=0.04; following Ali et al. (2018): 0.045 $/kg). Different arbitrary values in the relative weighting given to GHG intensity values (γ = 0, 0.5, 1) were also considered. It should be noticed that the scaling factor in the original expression of Amer et al. (2018) to convert the units of product for which emissions intensities are calculated to units employed to derive economic values, was taken as the unity because both, economic and GHG emission were computed per litter. Expanded economic weights were also derived as: $HWx = Hx \times \sigma_{g_x}$

Changes in expanded values and weights due to litter size, GHG emission level and relative weighting given to GHG intensity values were analysed holding other factors constant to some reference values. Scenarios analysed are summarised in Table 1.

Results and discussion

When GHG emissions were not considered, results obtained for economic values and economic weights were very similar to those obtained by Quinton et al. (2006) (Table 2), that showed the considerable impact of population average litter size on the weighting of sow productivity traits. This result was expected, because the values of parameter involved (Supplementary Table S1) were very similar to those of Quinton et al. (2006). Unfortunately, economic values and weights were not equally defined in this work and that of Quinton et al. (2006). In the paper of Quinton et al. (2006) their tables 2 and 4 show economic values and weights, respectively, if the definition made in the present article is taken into account.

Per kg of carcass weight GHG emissions estimated ranged from 3.2 to 3.6 kg CO_2 equivalent, similar to those reported by Gill et al. (2010) and McAuliffe et al. (2017);

these figures correspond to CO_2 emissions that did not consider energy used on-farm, neither off-farm CO_2 and N_2O emissions from supply of inputs of feed, and fuel. Accounting for GHG emissions affected significantly profit per litter, in a dependent manner from average population litter size, and weighting of the financial implication associated with emissions intensity (Figure 1). The dilution of GHG emissions per piglet produced when litter size increases is also observed in Figure 1: emissions of a litter producing 8 piglets is almost half of the emissions of a litter producing 20 piglets.

However, taking into consideration GHG emissions per litter did not seems to affect considerably the selection indexes for sow productivity. When GHG emissions were considered at its maximum value (scenario with high GHG emission intensity adjusted for a standard feed diet and considering a maximum relative weighting) economic weights for litter size, perinatal survival and survival to weaning were lower, increasing weights for age at first conception and weaning to conception interval (Table 3). Changes are relevant in absolute terms, especially for litter size, but traits were not re-ranked when GHG emissions were considered. As expected according to these results, other scenarios of GHG emission intensity (low, high emissions dues to production system; high or standard feed digestibility), showed small differences among economic values and weights (Table 4). These results indicates that the implication of incorporating GHG emissions is expected to be little affected by differences into emissions among countries, feeding characteristics, and assumptions made on daily pig emissions of CH_4 and N_2O emissions and its conversion to equivalent kg of CO_2.

The relative weighting to GHG emission intensity had a significant effect on economic values and weights of different traits that define sow productivity (Table 5), reducing the weighting of litter size and piglet survival, and increasing, although only weakly, age at first conception and weaning to conception interval. Nevertheless, contributions to selection index showed small changes (Figure 2). This result was not surprising because financial cost of GHG emissions reduces the net revenue from the sale of a market pig reducing the contribution of litter size at weaning, and increases the cost of unproductive days of sows, increasing the contribution of age at first conception and the interval weaning to conception. However, in a market scenario that assure net revenues even including financial costs of GHG results indicated that very weakly changes are expected in the contributions of traits, independently of average litter size population value.

As indicated by Ali et al. (2018) there are few studies that analyse the implications of considering GHG emission costs in the derivation economic values for pig breeding goal traits by monetizing these emissions. Following a different approach, these authors analysed the effect of incorporating environmental cost on economic values of pig breeding goal traits considering sow efficiency and production traits. Sow efficiency traits considered were number of piglets born alive per litter, preweaning mortality rate, and weaning-oestrus interval. If these sow traits are considered exclusively when interpreting their results, it can be concluded that no relevant changes are produced in the relative economic weights of sow efficiency traits after the inclusion of GHG costs, as in this study. No a re-ranking of traits for both sow efficiency and production traits after the inclusion of GHG emission costs were found. The costs of GHG emissions are diluted in a similar way on the traits defining sow productivity, affecting very little their contributions to the selection index.

The main conclusion that may be drawn from this limited study, which aimed to analyse the effect of including GHG emission budens in economic weights of sow productivity traits, is that GHG emissions have not a great impact on weighting of sow productivity traits in selection indexes in pigs. These results are valid for the production system and market characteristics analysed, but could differ for other systems, average livestock performances, market requirements and GHG emissions assessment. However, this study demonstrated a flexible and simple tool to combine the marginal change in GHG emissions with the conventional economic values of an existing index that do not account yet for GHG emissions.

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Table 1 - Summary of scenarios analysed.

Parameter	Values
Litter size (number of total piglets born)	8, 12, 16, 20
GHG intensity values	High[1] / Standard feed diet[2]; High[1] / Highly digestive feed diet[2]; Low[1] / Standard feed diet[2]; Low[1] / Highly digestive feed diet[2].
Relative weighting given to GHG intensity values (γ)	0, 0.5, 1

[1] See Supp. Table 2.

[2] Adjustment coefficient for volatile solid excretion: 1 for standard feed diet, 0.95 for highly digestible feed diet.

Table 2 - Economic values and weights calculated for sow productivity traits excluding GHG.

	Economic values				Economic weights			
Trait	8 pigs	12 pigs	16 pigs	20 pigs	8 pigs	12 pigs	16 pigs	20 pigs
Litter size at birth	30.6	27.5	22.0	13.8	30.3	27.3	21.7	13.7
Perinatal survival	2.6	4.0	5.3	6.6	8.0	12.0	16.0	19.9
Survival to weaning	2.7	4.0	5.1	5.9	3.4	5.0	6.3	7.3
Age at first conception	-0,2	-0,2	-0,2	-0,2	-2.2	-2.2	-2.2	-2.2
Weaning to conception interval	-0,6	-0,6	-0,6	-0,6	-2.1	-2.1	-2.1	-2.1

Table 3 - Expanded economic values and weights calculated for sow productivity traits including GHG in the scenario that considers higher emissions (High GHG emission intensity adjusted for a standard feed diet and maximum relative weighting, $\gamma=1$).

	Economic values				Economic weights			
Trait	8 pigs	12 pigs	16 pigs	20 pigs	8 pigs	12 pigs	16 pigs	20 pigs
Litter size at birth	23.6	21.3	17.0	10.9	23.4	21.1	16.8	10.6
Perinatal survival	2.0	3.1	4.1	5.1	6.2	9.2	12.3	15.4
Survival to weaning	2.1	3.1	4.0	4.6	2.6	3.8	4.9	5.67
Age at first conception	-0,2	-0,2	-0,2	-0,2	-2.4	-2.4	-2.4	-2.4
Weaning to conception interval	-0,6	-0,6	-0,6	-0,6	-2.3	-2.3	-2.3	-2.3

Table 4 - Expanded economic values and weights calculated for sow productivity traits including GHG in different scenarios of GHG emission intensity (litter size=16 and relative weighting $\gamma=1$).

	Economic values				Economic weights			
Trait	High/ Stand	High/ Diges	Low/ Stand	Low/ Diges	High/ Stand	High/ Diges	Low/ Stand	Low/ Diges
Litter size at birth	17.0	17.0	17.8	17.9	16.8	16.9	17.7	17.7
Perinatal survival	4.1	4.1	4.3	4.3	12.3	12.4	13.0	13.0
Survival to weaning	4.0	4.0	4.2	4.2	4.9	4.9	5.2	5.2
Age at first conception	-0.2	-0.2	-0.2	-0.2	-2.4	-2.4	-2.4	-2.4
Weaning to conception interval	-0.6	-0.6	-0.6	-0.6	-2.3	-2.3	-2.3	-2.3

[1] High/Stand: High GHG emission intensity / Standard feed diet (Supp. Table S2);
High/Diges: High GHG emission intensity / Highly digestive feed diet (Supp. Table S2);
Low/Stand: Low GHG emission intensity / Standard feed diet (Supp. Table S2);
Low/Diges: Low GHG emission intensity / Highly digestive feed diet (Supp. Table S2).

Table 5 - Expanded economic values and weights calculated for sow productivity traits including GHG with different relative weighting (γ=0, 0.5, 1) (litter size=16 and high GHG emission intensity adjusted for a standard feed diet).

	Economic values			Economic weights		
Trait	$\gamma=0$	$\gamma=0.5$	$\gamma=1$	$\gamma=0$	$\gamma=0.5$	$\gamma=1$
Litter size at birth	22.0	19.5	17.0	21.7	19.3	16.8
Perinatal survival	5.3	4.7	4.1	16.0	14.1	12.3
Survival to weaning	5.1	4.6	4.0	6.3	5.6	4.9
Age at first conception	-0.2	-0.2	-0.2	-2.2	-2.3	-2.4
Weaning to conception interval	-0.6	-0.6	-0.6	-2.1	-2.2	-2.3

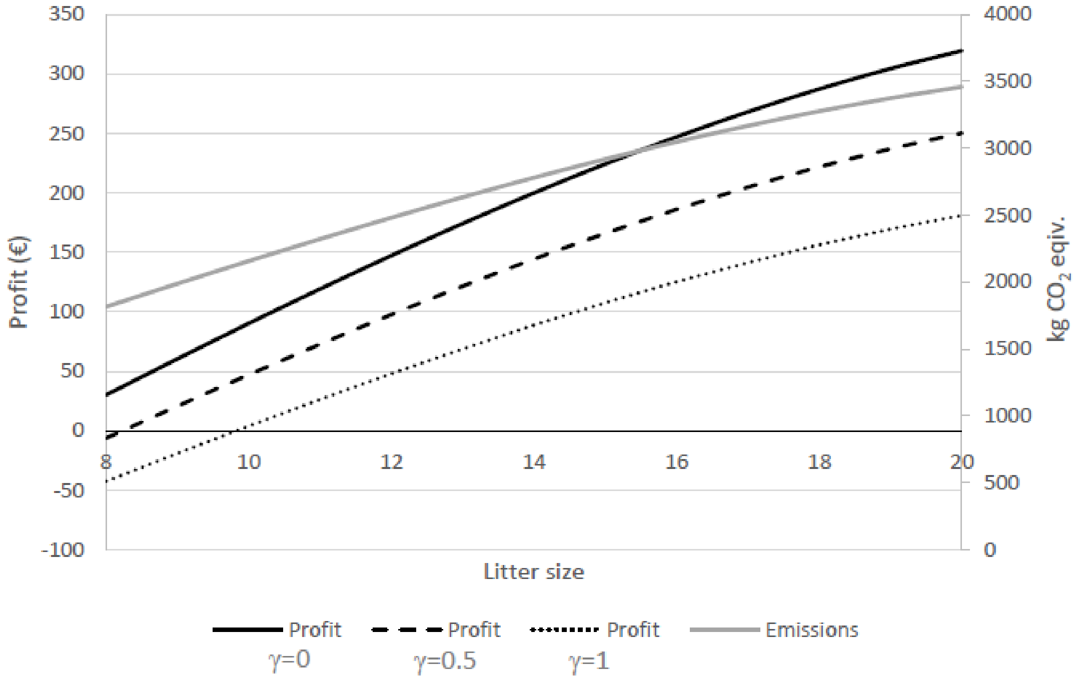

Figure 1 - Evolution of GHG emission intensity and profit, when different weighting was given to GHG intensity values in the expanded index, with litter size (high GHG emission intensity was considered).

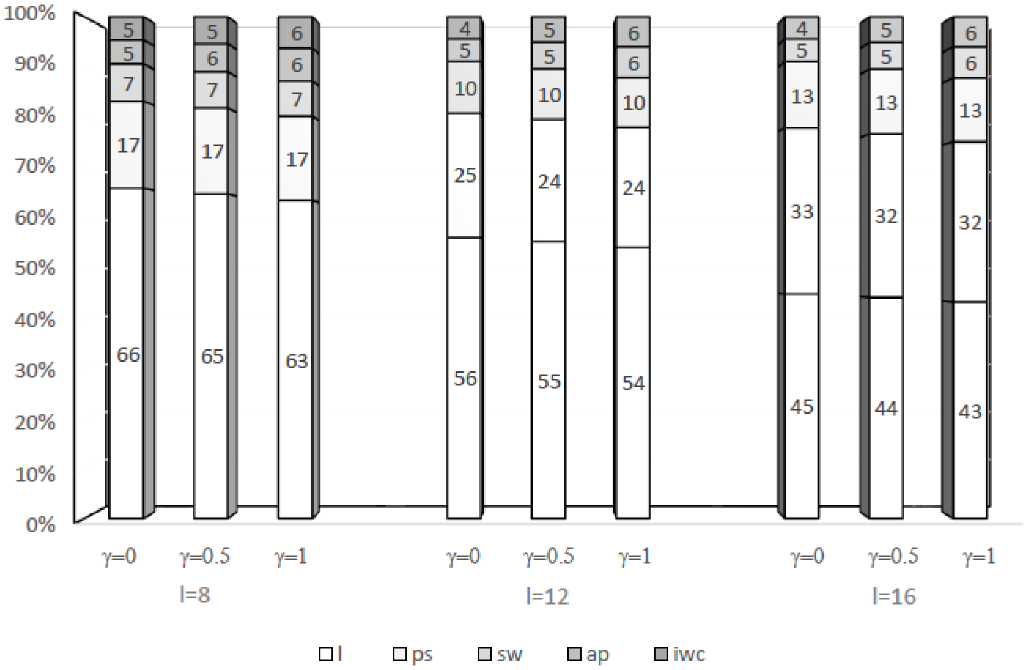

Figure 2 - Contribution (%) of litter size (l), perinatal survival (ps), survival until weaning (sw), age at first conception (ap) and interval weaning to conception (iwc) for different relative weighting of GHG emission intensity (γ=0, 0.5, 1) and average litter size population values (l=8, 12 and 16).

Supplementary Material

a) Derivation of selection index for sow productivity traits excluding GHG emissions

Net profit per litter

The net profit per litter (T) was computed as:

$$T = l \times ps(l) \times sw \times \big((mw \times p) - (dm \times cd)\big) \times (1 - m)$$

$$- \left(c_l + \frac{1}{t} \times \big(c_g + f_g \times ap\big) \times r \times z + \frac{(t-1)}{t} \times (c_s + f_s \times iwc) \times z\right)$$

where:

- l is the total litter size at birth, including stillborn, but excluding mummified piglets,
- $ps(l)$ is the perinatal survival rate from shortly before birth to the end of the neo-natal period (24 h), that was assumed to depend on constraints imposed by the total litter size at birth, being s_v survival not constrained by litter size, and a, b, c are quadratic equation parameters in litter size, $ps(l) = (s_v + a + b \times l + c \times l^2)$
- sw is the survival from the end of the neo-natal period to weaning,
- $\big((mw \times p) - (dm \times cd)\big)$ is the net revenue from the sale of a market pig, after accounting for costs from weaning to market, being mw = average market weight, p = price per kg, dm = days to market, and cd = cost per day,
- m is the pig mortality from weaning to slaughter, defined as the sum of pig mortality during pig starting, growing and finishing periods, m_{sp} , m_{gp} and m_{fp}, respectively.
- c_l is the cost of breeding plus the cost of sow feed and services during lactation,
- t is the total number of litters produced by a commercial sow in her lifetime,
- c_g is feed and service costs during gestation for a gilt,
- f_g is daily feed and service costs until breeding for a gilt,
- ap is the age at first conception (puberty),
- c_s is feed and service costs during gestation for a sow,
- f_s is daily feed and service costs from weaning to rebreeding for a sow,
- iwc is the interval from weaning to conception,
- r is the ratio of first to latter parity litter size,

- z is the weighting factor to the size of the second and subsequent litters, relative to the average litter size; $z = \frac{t}{r+(t-1)}$

Partial derivatives

Partial derivatives of net profit (T) expression with respect perinatal survival (ps), litter size at birth (l), survival to weaning (sw), age at first conception (ap) and weaning to conception interval (iwc) were:

$$\frac{\partial T}{\partial ps} = l \times sw \times \big((m \times p) - (dm \times cd)\big) \times (1 - m_{sp} - m_{gp} - m_{fp})$$

$$\frac{\partial T}{\partial l} = sw \times \big((m \times p) - (dm \times cd)\big) \times (1 - m_{sp} - m_{gp} - m_{fp}) \times (s_v + a + 2 \times b \times l + 3 \times c \times l^2)$$

$$\frac{\partial T}{\partial sw} = l \times (s_v + a + b \times l + c \times l^2) \times \big((m \times p) - (dm \times cd)\big) \times (1 - m_{sp} - m_{gp} - m_{fp})$$

$$\frac{\partial T}{\partial ap} = -\frac{1}{t} \times f_g \times r \times \left(\frac{t}{r + (t-1)}\right)$$

$$\frac{\partial T}{\partial iwc} = -\frac{(t-1)}{t} \times f_s \times \left(\frac{t}{r + (t-1)}\right)$$

b) Derivation of GHG emissions intensities

GHG emission intensity per litter

The GHG emission intensity (EI) per litter was computed as:

$$EI = \left(e_p \times gl\right) + \left(e_l \times ll\right) + \left(\frac{1}{t} \times e_g \times ap \times r \times z\right) + \left(\frac{(t-1)}{t} \times e_s \times iwc \times z\right) + \left(e_{sp} \times n_{sp} \times d_{sp}\right) + \left(e_{gp} \times n_{gp} \times d_{gp}\right) + \left(e_{fp} \times n_{fp} \times d_{fp}\right)$$

where:

- e_p is daily emissions during gestation,
- e_l is daily emissions during lactation,
- e_g is daily emissions until breeding for a gilt,
- e_s is daily emissions from weaning to rebreeding for a sow,
- e_{sp} is daily emissions of starting pigs (from weaning -7 kg- to 18 kg),
- e_{gp} is daily emissions of growing pigs (from 18 to 60 kg),
- e_{fp} is daily emissions of finishing pigs (from 60 to 100 kg),
- gl is the gestation length,
- ll is the lactation length,
- d_{sp} are days from weaning to 18 kg pig weight (starting),
- d_{gp} are days from 18 to 60 kg pig weight (growing),
- d_{fp} are days from 60 to 100 kg pig weight (finishing);
- n_{sp} is the number of weaning to 18 kg piglets, that depends on litter size, perinatal survival, survival to weaning and mortality (m_{sp}) during d_{sp}:

$$n_{sp} = l \times ps(l) \times sw \times \left(\frac{1 - m_{sp}}{2}\right)$$

- n_{gp} is the number of 18 to 60 kg pigs, that depends on n_{sp} and mortality (m_{gp}) during d_{gp}:

$$n_{gp} = l \times ps(l) \times sw \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)$$

- n_{fp} is the number of 60 to 100 kg pigs, that depends on n_{gp} and mortality (m_{fp}) during d_{fp}

$$n_{fp} = l \times ps(l) \times sw \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)$$

Remembering that $ps(l) = s_v + a + b \times l + c \times l^2$, and calling:

$$e_{mcorr} = \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right) + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

Partial derivatives

Partial derivatives of GHG emission intensity (EI) expression with respect perinatal survival (ps), litter size at birth (l), survival to weaning (sw), age at first conception (ap) and weaning to conception interval (iwc) were:

$$\begin{aligned}
\frac{\partial EI}{\partial ps} &= \frac{\partial\left[\,(e_{sp} \times n_{sp} \times d_{sp}) + (e_{gp} \times n_{gp} \times d_{gp}) + (e_{fp} \times n_{fp} \times d_{fp})\right]}{\partial ps} \\
&= e_{sp} \times d_{sp} \times l \times sw \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times l \times sw \\
&\quad \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right) + e_{fp} \times d_{fp} \times l \times sw \times \left(1 - m_{sp}\right) \\
&\quad \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right) \\
&= l \times sw \\
&\quad \times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right. \\
&\quad \left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)
\end{aligned}$$

$$\frac{\partial EI}{\partial l} = \frac{\partial\left[\,(e_{sp} \times n_{sp} \times d_{sp}) + (e_{gp} \times n_{gp} \times d_{gp}) + (e_{fp} \times n_{fp} \times d_{fp})\right]}{\partial l} =$$

$$
\begin{aligned}
& e_{sp} \times d_{sp} \times ps \times sw \times \left(\frac{1-m_{sp}}{2}\right) \\
&\qquad + e_{sp} \times d_{sp} \times l \times \frac{\partial ps}{\partial l} \times sw \times \left(\frac{1-m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times ps \times sw \\
&\qquad \times \left(1-m_{sp}\right) \times \left(\frac{1-m_{gp}}{2}\right) + e_{gp} \times d_{gp} \times l \times \frac{\partial ps}{\partial l} \times sw \times \left(1-m_{sp}\right) \\
&\qquad \times \left(\frac{1-m_{gp}}{2}\right) + e_{fp} \times d_{fp} \times ps \times sw \times \left(1-m_{sp}\right) \times \left(1-m_{gp}\right) \\
&\qquad \times \left(\frac{1-m_{fp}}{2}\right) + e_{fp} \times d_{fp} \times l \times \frac{\partial ps}{\partial l} \times sw \times \left(1-m_{sp}\right) \times \left(1-m_{gp}\right) \\
&\qquad \times \left(\frac{1-m_{fp}}{2}\right) =
\end{aligned}
$$

$$
\begin{aligned}
& ps \times sw \times \left(e_{sp} \times d_{sp} \times \left(\frac{1-m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1-m_{sp}\right) \times \left(\frac{1-m_{gp}}{2}\right) + e_{fp}\right. \\
&\qquad \left. \times d_{fp} \times \left(1-m_{sp}\right) \times \left(1-m_{gp}\right) \times \left(\frac{1-m_{fp}}{2}\right)\right) + l \times \frac{\partial ps}{\partial l} \times sw \\
&\qquad \times \left(e_{sp} \times d_{sp} \times \left(\frac{1-m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1-m_{sp}\right) \times \left(\frac{1-m_{gp}}{2}\right)\right. \\
&\qquad \left. + e_{fp} \times d_{fp} \times \left(1-m_{sp}\right) \times \left(1-m_{gp}\right) \times \left(\frac{1-m_{fp}}{2}\right)\right) =
\end{aligned}
$$

$$\left(ps + \left(l \times \frac{\partial ps}{\partial l}\right)\right) \times sw$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

$$= \left(s_v + a + b \times l + c \times l^2 + \left(l \times \frac{\partial(s_v + a + b \times l + c \times l^2)}{\partial l}\right)\right) \times sw$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

$$= \big(s_v + a + b \times l + c \times l^2 + (l \times (b + 2 \times c \times l)\big) \times sw$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

$$= (s_v + a + b \times l + c \times l^2 + b \times l + 2 \times c \times l^2) \times sw$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right) =$$

$$= (s_v + a + 2 \times b \times l + 3 \times c \times l^2) \times sw$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

$$\frac{\partial EI}{\partial sw} = \frac{\partial\left[\,(e_{sp} \times n_{sp} \times d_{sp}) + (e_{gp} \times n_{gp} \times d_{gp}) + (e_{fp} \times n_{fp} \times d_{fp})\right]}{\partial sw}$$

$$= \; e_{sp} \times d_{sp} \times l \times (s_v + a + b \times l + c \times l^2) \times \left(\frac{1 - m_{sp}}{2}\right) + \; e_{gp} \times d_{gp}$$

$$\times\, l \times (s_v + a + b \times l + c \times l^2) \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right) + \; e_{fp} \times d_{fp}$$

$$\times\, l \times (s_v + a + b \times l + c \times l^2) \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right)$$

$$\times \left(\frac{1 - m_{fp}}{2}\right)$$

$$= l \times (s_v + a + b \times l + c \times l^2)$$

$$\times \left(e_{sp} \times d_{sp} \times \left(\frac{1 - m_{sp}}{2}\right) + e_{gp} \times d_{gp} \times \left(1 - m_{sp}\right) \times \left(\frac{1 - m_{gp}}{2}\right)\right.$$

$$\left. + \, e_{fp} \times d_{fp} \times \left(1 - m_{sp}\right) \times \left(1 - m_{gp}\right) \times \left(\frac{1 - m_{fp}}{2}\right)\right)$$

$$\frac{\partial EI}{\partial ap} = \frac{1}{t} \times e_g \times r \times \left(\frac{t}{r + (t - 1)}\right)$$

$$\frac{\partial EI}{\partial iwc} = \frac{(t - 1)}{t} \times e_s \times \left(\frac{t}{r + (t - 1)}\right)$$

Summarizing:

$$\frac{\partial EI}{\partial ps} = l \times sw \times e_{mcorr}$$

$$\frac{\partial EI}{\partial l} = \; (s_v + a + 2 \times b \times l + 3 \times c \times l^2) \times sw \times \; e_{mcorr}$$

$$\frac{\partial EI}{\partial sw} = \; l \times (s_v + a + b \times l + c \times l^2) \times e_{mcorr}$$

$$\frac{\partial EI}{\partial ap} = \; \frac{1}{t} \times e_g \times r \times \left(\frac{t}{r + (t - 1)}\right)$$

$$\frac{\partial EI}{\partial iwc} = \; \frac{(t - 1)}{t} \times e_s \times \left(\frac{t}{r + (t - 1)}\right)$$

Calculus of GHG daily emissions

The missions due to enteric CH_4 and manure derived CH_4 and N_2O where considered when calculating daily GHG emissions per pig. For simplicity, other sources like CO_2 emissions from energy used on-farm, and off-farm CO_2 and N_2O emissions from supply of inputs of feed, and fuel (Bonesmo et al., 2012) were not considered. CO_2 produced during respiration neither was considered because it is assumed that it is compensated during photosynthesis by plants used as feed (Philippe and Nicks, 2014).

The CH_4 and NO_2 emissions were computed per pig and day according the following equations (Little et al., 2008):

1) enteric CH_4 (kg CO_2-equivalent/pig/day):

$$CH_{4\,enteric}(CO_2 eqiv) = 25 \times \frac{1.5}{365} = 0.103$$

being 25 the conversion factor to CO_2-equivalent, and 1.5 emission per pig and year (kg),

2) manure derived CH_4 (kg CO_2-equivalent/pig/day):

$$CH_{4\,manure}(CO_2 eqiv) = 25 \times 0.064 \times VS \times FI = 1.6 \times VS \times FI$$

being 25 the conversion factor to CO_2-equivalent, 0.064 the product of the methane capacity production (assumed 0.48) by a conversion factor from volume to mass (assumed 0.67) and a conversion factor based on handling and season of application (assumed 0.20), VS the volatile solid excretion (kg/kg feed), and FI daily feed intake per pig (kg),

3) manure derived N_2O (kg CO_2-equivalent/pig/day):

$$N_2O_{manure}(CO_2 eqiv) = 298 \times \frac{44}{28} \times \frac{0.7 \times FI \times CP}{6.25} \{0.005 + 0.045\}$$
$$= 2.622 \times FI \times CP$$

being 298 the conversion factor to CO_2-equivalent, 44/28 the conversion factor from N_2O-N to N_2O, 0.7 one minus the protein retained rate (kg/kg)), 6.25 the conversion from dietary protein to dietary N, 0.005 the emission N_2O-N factor (kg N_2O-N per kg N), 0.045 the product of volatilization fraction by the emission factor (assuming no leaching emissions), and CP the protein content in feed (kg/kg).

Summarising, total daily emissions (e_i) were calculated for each pig class (i: starter, grower, finisher, lactating sow and dry sow) as a function of their corresponding daily feed intake (FI_i), volatile solid excretion (VS_i) and protein content in feed (CP_i) (values in Supplementary Table S2) using the resulting expression:

$$e_i = 0.103 + FI_i \times (1.6 \times VS_i + 2.622 \times CP_i)$$

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Table S1 - Mean value traits, costs and prices, and genetic standard deviations assumed for the selection index computation for sow productivity traits excluding GHG

Trait	Abrev.	Value
Independent term for prediction of perinatal survival constrained by litter size [1]	*a*	-0.048
Linear term for prediction of perinatal survival constrained by litter size [17]	*b*	0.01243
Quadratic term for prediction of perinatal survival constrained by litter size [1]	*c*	-0.0008
Perinatal survival not constrained by litter size [2]	*sv*	0.93
Survival from the end of the neo-natal period to weaning [2]	*sw*	0.90
Total number of litters produced by a commercial sow in her lifetime [1]	*t*	4
Daily feed and service costs until breeding for a gilt (€)[1]	*fg*	0.72
Ratio of first to latter parity litter size [1]	*r*	0.92
Daily feed and service costs from weaning to rebreeding for a sow (€)[1]	*fs*	0.75
Pig mortality during starting period [3]	pm_s	0.01
Pig mortality during growing period [3]	pm_g	0.02
Pig mortality during finishing period [3]	pm_f	0.03
Average market weight of finishing pigs (kg)[1]	*m*	100
Price per kg of finishing pig (€)[4]	*p*	1.23
Days to market [5]	*dm*	150
Cost per day and finishing pig (€)[6]	*cd*	0.56
Cost of breeding plus the cost of sow feed and services during lactation (€)[7]	*cl*	83
Feed and service costs during gestation for a gilt (€)[7]	*cg*	82
Feed and service costs during gestation for a sow (€)[7]	*cs*	86
Gestation length (days)	*gl*	115
Lactation length (days)	*ll*	28
Age at first conception (days)	*ap*	250
Interval from weaning to conception (days)	*iwc*	9
Genetic standard deviation for litter size at birth [1]	σg_l	0.99
Genetic standard deviation for perinatal mortality [1,8]	σg_{sv}	0.32
Genetic standard deviation for mortality to weaning [1,8]	σg_{sw}	0.17
Genetic standard deviation for age at first conception [1]	σg_{ap}	13.02
Genetic standard deviation for weaning to conception interval [1,8]	σg_{iwc}	1.13

[1] Quinton et al. (2006)

[2] Lund et al. (2002)

[3] Maes et al. (2001)

[4] Corresponds to a cost of 1.40 € per carcass kg (Hoste, 2017) and a 10% of net profit.

[5] $dm = d_{sp} + d_{fp} + d_{fp}$ = (45 + 60 + 45)

[6] Corresponds to a cost of 0.9 € per kg of live weight during fattening (Hoste, 2017)

[7] Quinton et al. (2006) (transformed to €, 1€=0.8$)

[8] Values for traits in the transformed scale employed by Quinton et al. (2006). The economic weights of a single unit change on a transformed scale were calculated by dividing by the rate of change of the transformed values on the original value: -0.1059, -0.1297 and 0.3047 for perinatal mortality, mortality to weaning and interval weaning to conception, respectively.

Table S2 - Daily feed intake, protein content in feed, and volatile solid excretion for each pig class considered, respectively, for calculating High and Low GHG emission intensities.

Pig class	Daily feed intake (kg/pig)[1]	Volatile solid excretion (kg/kg feed) [1]	Protein content in feed (kg/kg)[1]
Starter	0.7 / 0.65	0.1292 / 0.0985	0.220 / 0.210
Grower	2 / 2	0.1539 / 0.1034	0.180 / 0.175
Finisher	3 / 2.8	0.1539 / 0.1034	0.155 / 0.135
Sow-lactating	6.11 / 5.85	0.1321 / 0.0712	0.200 / 0.185
Sow-dry	2.55 / 2.45	0.1321 / 0.0712	0.145 / 0.135

[1] Values reported for Saskatchewan and Ontario Canadian provinces, respectively, by Little et al. (2008). Number of days assumed for each pig class were 45 for starter, 60 for grower, 45 for finisher, 28 for sow-lactating and 125 for sow-dry.

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