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Predicting piglet survival until weaning using birth weight and within-litter birth weight variation as easily measured proxy predictors

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ABSTRACT

Individual piglet birth weight (**BW0**) and within-litter birth weight variability (**BWvar**) strongly affect preweaning survival. Piglet mortality in commercial pig operations poses significant economic and ethical concerns, as well as animal welfare implications. The objective of this study was to evaluate the effects of BW0, BWvar and other potential sow and environmental factors, including parity, sex, litter size, year, season and farm, on piglet survival from birth to weaning age using a logistic regression approach. The study determined the critical threshold values for BW0 and BWvar, both separately and for a combined index to predict preweaning survival. This was done through a receiver operating characteristic (**ROC**) curve analysis. Data consisted of 68 394 piglet records from 1 661 sows obtained from two research farms; the Research Institute for Farm Animal Biology in Germany and Agroscope in Switzerland. The BW0 and BWvar significantly influenced piglet survival at birth, but their influence changed with piglet age and management interventions such as cross-fostering. The BW0 exerted the greatest effect on survival, with the probability of survival increasing with increasing BW0 following a curvilinear trend. A significant observation was that BWvar was more important than litter size in determining piglet survival at birth. The ROC analysis revealed that piglets below a BW0 cut-off value of 1.18 kg (accuracy = 0.73) had a lower survival probability at birth compared to their heavier counterparts. With a cut-off value of 0.277 g (accuracy = 0.50), the BWvar amongst total piglets born predicted survival less accurately. Piglets with low BW0 and born in litters with high BWvar had the lowest survival probabilities. Consequently, two novel indexes were developed, namely the birth weight-to-variation ratio and the birth weight-to-variation composite index, to offer a comprehensive assessment of piglet viability. The results suggest that using the derived indexes for predicting piglet survival was more informative (accuracy = 0.89) than relying solely on BW0 or BWvar. This study demonstrates a robust methodology for the identification of low-viability piglets using fundamental and easy-to-measure birth weight traits.

Implications

A BW cut-off value measured at birth serves as a proxy for preweaning piglet survival. Piglets weighing less than 1.18 kg are classified as low birth weight. Combining birth weight with within-litter birth variation into a birth weight-to-variation ratio and a composite index greatly enhances the accuracy of predicting neonatal mortality risk. Identifying at-risk piglets allows for timely and targeted interventions, such as monitoring colostrum intake and providing supplemental milk feeding, which can improve their chances of survival. These measures are crucial for reducing mortality and ensuring better welfare in piglets.

Introduction

High piglet mortality in commercial pig operations is of both economical and ethical relevance. In addition, the death of piglets may be associated with pain and/or suffering due to hypothermia, starvation, injury, disease or low birth weight, which is considered a welfare issue (Stygar et al., 2022). The greatest proportion of piglet mortality in commercial pig production occurs during the preweaning period. Out of the total number of piglets born (**TNB**), between 15 and 20% die either during the farrowing process or in early lactation (Farmer and Edwards, 2022). The success of

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the genetic selection of sows for larger litters over the years has led to hyper-prolific sows resulting in more piglets born but with low birth weight, a high proportion of intra-uterine growth retardation and lower physiological maturity at birth, all contributing to increased mortality (Wolf et al., 2008; Matheson et al., 2018). Other factors contributing to neonatal and postnatal piglet mortality, particularly in hyperprolific sows, and strategies to improve piglet survival have been extensively reviewed (e.g. Ward et al., 2020; Peltoniemi et al., 2021; Farmer and Edwards, 2022).

Piglets within the same litter vary considerably in birth weight (**BW0**). As litter size increases, the within-litter birth weight variation (**BWvar**) rises, with more low-birth-weight piglets being born in larger litters (Stange et al., 2020). When the BWvar is high, the direct competition for functional and productive teats may become a limiting factor for the survival of light littermates during the suckling period (Milligan et al., 2001). The heavy piglets are better able to compete for milk and to effectively stimulate the sow teats to produce milk (Peltoniemi et al., 2021). Littermate weight may affect the performance of low-birth-weight piglets due to increased time intervals between birth and first suckling and direct competition for access to a functional teat (Tuchscherer et al., 2000; Andersen et al., 2011; Nuntapaitoon et al., 2019). Given other relevant traits influencing piglet mortality, such as foetal maturity, the role of BW0 remains a convenient proxy (Knap et al., 2023). Data on BW0 are also easy to routinely record for management and genetic evaluation purposes.

There is no clear definition of when a BW0 is low in human and domestic mammal species (Mugnier et al., 2022). In pigs, studies have defined ≤ 1.25 kg as low-birth-weight piglets (Douglas et al., 2014). Declerck et al. (2016) classified piglets < 1.00 kg as very low BW0 and between 1 and 1.2 kg as low BW0. The definition of low-birth-weight piglets has also been based on litter weight distribution, such as having a BW0 below the 10th percentile of the mean litter birth weight (De Vos et al., 2014), weighing at least 300 g less than the litter's mean birth weight, or weighing 200 – 300 g less than the litter's mean birth weight and at least 100 g less than the immediate larger member of the litter (Robert et al., 1995). However, definitions of low-birth-weight piglets that solely rely on BW distribution in the litter or in the farm may not necessarily reflect a functional relationship to maturity, survival and growth.

Therefore, in this study, cut-off values for individual piglet BW0 and within-litter BWvar were determined with a functional link to predict preweaning piglet survival. A receiver operator characteristics (**ROC**) curve analysis was used to provide a more objective method for determining cut-off values that can predict piglet survival at a given time point. The underlying assumption of ROC analysis is that a diagnostic predictor is used to discriminate between two mutually exclusive states of tested animals (Greiner et al., 2000). The technique allows cut-off values to be optimised with regard to maximising both sensitivity (i.e. probability of a true positive event) and specificity (probability of a true negative event) with the least possible trade-off between sensitivity and specificity (Greiner et al., 2000). The ROC curve analysis has been used to estimate the cut-off values for birth and weaning BW of piglets that would reach a given target slaughter weight at 22 weeks of age (Camp Montoro et al., 2020). By applying a ROC analysis, Patterson et al. (2020) determined the BW0 cut-off value for predicting piglet mortality within 4 days after birth.

The first objective of this study was to use historical data from two research farms with different pig genotypes and management conditions to evaluate the effects of BW0, BWvar and other potential sow and environmental factors, including parity, sex, litter size, year, season and farm, on piglets' survival probability from birth to weaning at days 0, 3, 7, 14 and 28 of age using a logistic regression approach. The second objective was to use piglet BW0 and within-litter BWvar as easy-to-measure diagnostic indicators of survival during the suckling period and to establish functional cut-off values with predictive capabilities. The ROC curve analysis was also used to test the plausibility of the combined use of BW0 and BWvar into an index.

Material and methods

Study design

The study design was observational with data obtained from farm databases of sow reproductive performance. The observational unit for piglet weights was the individual piglets and for the BWvar was the sow litter.

Data

Data were obtained from two pig research farms, namely the Research Institute for Farm Animal Biology (**FBN**) in Dummerstorf, Germany, and Agroscope in Posieux, Switzerland (Agroscope). In both farms, piglets are routinely bred and raised, not only for experimental purposes. The FBN data covered the period from 2012 to 2021 for the German Landrace breed. There were 90 458 individual piglet records for BW measurements collected at four time periods: at birth (BW0), d14 (BW14), d21 (BW21) and d28 (BW28). This yielded 28 242 piglet records, as not all of the four BW records were always available. Records were only retained if the BW0 was recorded within the first day (24 h) after birth. Animals with a missing date of birth and unknown sex were excluded from the analysis. After data editing, there were records of 27 901 TNB piglets (i.e. born dead or alive) from 748 sows. The Agroscope dataset consisted of the Swiss Large White breed for the period from 2005 to 2021. Incomplete records and litters from ovariectomised sows, piglets with unknown sex, hermaphrodites as well as animals indicated as euthanised were excluded. After this data editing, 40 493 records for TNB piglets from 913 sows were retained. In both farms, animals used in an experiment and stillborn piglets were accounted for in TNB but removed in the survival analysis for later time points. If a sow gives birth to more piglets than the functional teats she has, the surplus piglets are typically cross-fostered. In this study, fostering management was different on the two research farms. At FBN, the smaller piglets were fostered out, whereas at Agroscope, the larger piglets were fostered out. Analysis with cross-fostering effect considered the foster sow.

Statistical analysis of data

The TNB piglets represent the sum of the total number of piglets born alive (**TBA**) and the stillborn piglets. The BWvar was described as the sample SD of individual piglets' birth weights within a litter. As the mean birth weight differs significantly between the sexes (Wittenburg et al., 2011), the BWvar was calculated separately for males and females and then pooled using the following equation:

$$S_p = \frac{(m-1)S_x + (f-1)S_y}{(m+f)-2}$$

where m is the number of male piglets; f is the number of female piglets; S_x is the SD of male piglets; and S_y is the SD of female piglets. As the BWvar of available piglets changes with postpartum deaths, the variation for the total number of piglets born (**BWvar_TNB**) was only considered when estimating survival at birth, while the variation for the total number of piglets born alive (**BWvar_TBA**) was used when estimating survival thereafter (until weaning). The elimination of stillborn piglets in BWvar for postpartum survival estimates is a logical consequence that ensures a relevant consideration of BWvar for survival estimates for the remaining piglets.

Mixed models

Statistical analyses for the mixed models were conducted using the SAS software, Version 9.4 (SAS Institute Inc, 2023). Binary outcomes (dead or alive) for each piglet were modelled using the GLIMMIX procedure to identify factors influencing piglet survival at birth and the survival-to-weaning period. The denominator df were computed via Kenward-Rodger approximation to account for the unbalanced data across fixed effects (Kenward and Roger, 1997). The mixed model for piglet survival at birth was fitted as follows:

$$Y_{ijklmn} = F_i + P_j + FP_{ij} + LS_j + BW\,var\_TNB_j + Sex_k + BW0_k + yrs_l + A_m + e_{ijklmn}$$

where F_i is the farm effect (i = Agroscope, FBN); P_j is the parity (j = 1 – 5); FP_{ij} is the parity by farm interaction effect; LS_j is the litter size; $BW\,var\_TNB_j$ is the birth weight variation within the litter for the total number of piglets born (df = 1); Sex_k is the sex of the piglet (k = male, female); $BW0_k$ is the piglet birth weight (df = 1); yrs_l is the year-season effect (season within year) fitted as a random effect; and A_m is the random sow effect.

In order to account for cross-fostering effect, the model for survival after day 3 was fitted as:

$$Y_{ijklmno} = F_i + P_j + FP_{ij} + LS_j + BW\,var\_TBA_j + Sex_k + BW0_k + Foster_l + PFoster_{jl} + yrs_m + A_n + e_{ijklmno}$$

where $BW\,var\_NBA_j$ is the birth weight variation within litter for piglets born alive (df = 1),$Foster_l$ is the fostering effect (l = yes, no); $PFoster_{jl}$ is the fostering by parity interaction effect. Other model terms are as previously defined. All interaction effects were tested, and those found statistically significant were retained.

The random year-season effect accounts for the fact that herd management decisions are not necessarily consistent over years or seasons within years; it also accounts for changes in the size of the herd. The EFFECTPLOT statement in PROC PLM (PLM = post-linear modelling) was used to construct effect plots. An effect plot indicates the predicted response as a function of certain covariates while other covariates are held constant (SAS Institute Inc, 2023 Cary, NC, USA). The SAS code for this analysis is presented in the Supplementary Materials (Supplementary File).

Receiver operating characteristic curve analysis

The critical cut-off point values for piglet survival at birth were estimated using an receiver operator characteristics curve analysis (Greiner et al., 2000). Data were analysed using the *cutpointr* package version 1.1.2 of R (Thiele and Hirschfeld, 2021). To establish these cut-off values, BW0 or BWvar were treated as continuous variables. These variables were fitted to predict the binary outcome of survival (i.e. alive or dead). In a further step, the piglets with a high risk of preweaning mortality were identified as those piglets with a low individual BW0 and piglets from litters with large variations in birth weight. Consequently, piglets at this intersection are at an increased risk of preweaning mortality. Two indexes were developed and subjected to receiver operator characteristics analysis to take particular account of low birth weight piglets from litters with high variation in BW0. The first index was the birth weight-to-variation ratio (**BWVR**) calculated as follows: BW0 / BWvar_TNB. The next index was the birth weight-to-variation composite index (**BWVCI**) based on principle component analysis (**PCA**). The BWVCI was estimated using the 'compindPCA' package in R (Paul et al., 2023). The composite index was developed by assigning weights to BW0 and BWvar and combining the weighted variables. The PCA-derived weights for BW0 and BWvar were 0.52 and 0.48, respectively. The relationship between the index and both BW0 and BWvar is presented in Supplementary Fig. S1.

In the receiver operator characteristics curve analysis, sensitivity was defined as the proportion of piglets correctly classified as surviving at a given time point until weaning, and specificity as the proportion of piglets correctly classified as not surviving at that particular time point. The critical cut-off value was identified using the Youden Index (Youden, 1950), which is defined for all points of an receiver operator characteristics curve, and the maximum value of the index may be used as a criterion for selecting the optimum cut-off point when a diagnostic test yields a numeric result (The Youden's Index is calculated as follows: J = sensitivity + specificity – 1). The accuracy of the model was then assessed with the area under the curve (**AUC**) derived from the plot of sensitivity fitted against 1 - specificity. Values of AUC for diagnostic tests are classically interpreted as non-accurate (AUC = 0.5), less accurate (0.5 < AUC ≤ 0.7), moderately accurate (0.7 < AUC ≤ 0.9), highly accurate (0.9 < AUC < 1) and perfect (AUC = 1) according to Greiner et al. (2000). In addition, the optimal cut-off values for the indexes were identified by optimising the prediction accuracy because sensitivity and specificity contribute to the overall accuracy with different weights (accuracy = (tp + tn) / (tp + fp + tn + fn)). The R code for the receiver operator characteristics analysis is presented in the Supplementary Materials.

Results

Descriptive statistics

The descriptive statistics for the litter size, BW0 and within-litter BWvar for the two farms are presented in Table 1. Out of the total piglets born, 87.5 and 92.8% were born alive at Agroscope and FBN respectively. Piglet mortality was highest within the first 3 days of life (Supplementary Fig. S2). Of the piglets born alive, 86.6 and 85.2% at Agroscope and FBN, respectively, survived the third day. The survival rate at weaning was 81.1 and 81.4%, respectively. The average litter size of TNB increased slightly from 12.9 ± 2.8 in 2005 to 15.3 ± 3.1 in 2021 at Agroscope (Fig. 1a). The litter size in the FBN research farm exhibited an increasing trend, from an average of 15.3 ± 3.2 in 2012 to 17.2 ± 3.4 in 2021. The TBA at Agroscope rose from 12.5 ± 2.7 in 2005 to 13.4 ± 3.0 in 2021 and at FBN from 13.7 ± 2.8 in 2012 to 15.6 ± 3.1 in 2021 (Supplementary Fig. S3). At Agroscope, the BW0 remained almost constant, at 1.4 3 ± 0.36 kg in 2005 and 1.45 ± 0.37 kg in 2021. At FBN, a downward trend in BW0 from 1.43 ± 0.38 kg in 2014 to 1.26 ± 0.35 kg in 2021 could be observed (Fig. 1b). The mean BWvar_TNB at Agroscope remained relatively constant at 0.278 ± 0.086 kg in 2005 and 0.275 ± 0.087 kg in 2021 (Fig. 1c). With the declining birth weight at FBN, there was also a slight decrease in the BWvar_TNB. The BWvar averaged 0.290 ± 0.077 kg in 2012 and 0.272 ± 0.067 kg in 2021, a decline of 18 g. If the proportion of postpartum deaths was not accounted for, the within-litter variation was lower for the TBA than for the TNB (Table 1).

Influence of the fixed effects on piglet survival

Several factors, including season, sow parity, litter size, BW0, BWvar, piglet sex, farm and parity by farm interaction influenced the survival of piglets at birth and were, therefore, included in the logistic regression models. For survival after day 3, there were also significant parity by farm and parity by fostering interactions ($P < 0.05$). The statistically significant ($P < 0.05$) variables influencing piglet survival at birth (day 0) and at day 3 are presented in

Table 1
Descriptive statistics (mean ± SD) of average litter size, piglet birth weight and within-litter birth weight variation for the two research farms.

Variable	Agroscope		FBN	
	N	Mean ± SD	N	Mean ± SD
Litter size, TNB	40 493	14.7 ± 3.39	27 901	15.7 ± 3.21
Litter size, TBA	40 493	12.9 ± 3.32	27 901	14.5 ± 2.97
Piglet birth weight (kg)	40 493	1.43 ± 0.37	27 901	1.35 ± 0.36
BWvar for males (kg)	40 475	0.287 ± 0.112	27 841	0.283 ± 0.101
BWvar for females (kg)	40 351	0.274 ± 0.110	27 817	0.272 ± 0.100
BWvar for TNB (kg)	40 493	0.284 ± 0.086	27 901	0.279 ± 0.079
BWvar for TBA (kg)	40 493	0.265 ± 0.086	27 901	0.272 ± 0.078

Abbreviations: BWvar = within-litter birth weight variation; FBN = Research Institute for Farm Animal Biology; TBA = total number of piglets born alive; TNB = total number of piglets born.

Table 2. It was observed that piglets from younger sows had higher survival probabilities compared to those from older sows (Supplementary Table S1). This was likely related to the increase in stillborn piglets with increasing parity (9.5% in parity 1 gilts compared to 14.9% in older sows in parity 5). The effect of farm on survival was significantly different ($P < 0.05$) at birth and at day 3 of age but was not significant from day 7 of age to weaning. The probability of surviving beyond birth was negatively associated ($P = 0.003$) with the litter size of total piglets born (litter size_TNB; Fig. 2a) and BWvar_TNB (Fig. 2b). A significant observation from the F-values was that BWvar_TNB was more important than litter size_TNB in determining survival at birth.

In the statistical tests, BW0 had the greatest effect (F-values, Table 2) on survival. At higher birth weights, there was no significant difference ($P < 0.05$) between males and females in the probability of survival. The predicted probabilities for BW0 at different time points fitted by sex are as shown in Fig. 3 and Supplementary Fig. S4. For survival at birth, the BWvar_TNB was fitted and was statistically significant ($P < 0.05$). The predicted probabilities for piglet survival at birth (day 0) for a given BWvar_TNB fitted by farm are presented in Fig. 4. From day 3 of age, the birth weight variation of total piglets born alive was calculated (BWvar_TBA). This variation was not statistically significant ($P < 0.05$) at all subsequent time points (Supplementary Table S2). The predicted probabilities for piglet survival at day 3 and above for a given BWvar_TBA fitted by sex and farm are presented in Fig. 4 and Supplementary Fig. S5.

The predicted probabilities for survival at birth fitted to the individual piglets are presented in Fig. 5. Piglets with a low BW0 had a lower survival probability at birth than their heavier counterparts. The figure also illustrates no increased neonatal mortality for very heavy BW0 piglets. Piglets that had low individual BW0 and came from litters with a high BWvar_TNB had the lowest survival probabilities (see red dots on bottom right in Fig. 5). Another crucial observation from Fig. 5 was that the highly uniform litters (at the far left of the graph) were mostly uniformly heavy (not uniformly light) and had high neonatal survival rates.

The cross-fostering effect was included in the models, and its interaction with parity was statistically significant ($P < 0.05$). The parity of foster sow played a significant role in fostering piglets as indicated by the results in Supplementary Table S3. Our study indicates that the younger the sow, the more effective it was as a foster mother. Cross-fostering increased the probability of survival of low-body-weight piglets, as shown in Supplementary Fig. S6a. Considering the survival probability to day 7 and beyond, cross-fostering had a greater effect on the FBN farm than in Agroscope. For example, cross-fostering a 1 kg piglet increased the probability of survival from 0.64 to 0.85 at FBN. At Agroscope, the heavier piglets were given to the foster sow, and only 2.5% (n = 12) of the cross-fostered piglets were 1 kg and below. The survival probability for a 1 kg piglet increased from 0.50 to 0.73. In the absence of cross-fostering, survival decreased with increasing BWvar_TBA (Supplementary Fig. S6b). Cross-fostering increased and stabilised the probability of survival for litters with high BWvar_TNB at Agroscope; however, this was unexpectedly not observed with the FBN herd as shown in Supplementary Fig. S6b.

Critical birth weight and within-litter birth weight variation cut-off values for piglet survival

The cut-off points for BW0, BWvar and both combined into an index were estimated from the ROC curve analysis and are presented in Table 3. A BW0 cut-off value of 1.18 kg was obtained for the combined dataset from the two farms. The cut-off was also similar for both male and female piglets. At the farm level, Agroscope had a slightly higher cut-off than FBN (1.19 vs. 1.17 kg). This estimated cut-off point aligns closely with the average birth weights of stillborn piglets, which were 1.19 ± 0.40 kg and 1.17 ± 0.39 kg at Agroscope and FBN, respectively. Slightly higher BW0 cut-off values were determined for piglet survival at later time points. A BW0 cut-off value of 1.22 kg (AUC = 0.74) increased the probability of piglets surviving until weaning. Different BWvar cut-off values were determined for the Agroscope and FBN research farms, between males and females and on survival to a given time point as presented in Table 3. There was no consensus regarding a critical BWvar cut-off value that could consistently predict preweaning piglet survival. The proportion of piglets at increased risk of dying before weaning due to low BW0 and high BWvar_TNB are presented in the Venn diagram in Fig. 6. The figure excludes piglets with higher birth weights (48.3%) that are considered safe (i.e. with BW0 > 1.18 and BWvar < 0.277). The results revealed that overall, 13.4% of piglets had a high risk of death due to low BW0 alone (Fig. 6). The percentage of piglets from litters with high BWvar without the additional risk of low BW0 was 36.3%. The percentage of piglets with a high mortality risk due to both low BW0 and high BWvar was 14.9%. The receiver operator characteristics analyses in BWVR and BWVCI yielded cut-off values of 2.06 and 0.30, respectively. These critical cut-off values were used to categorise piglets as at risk of mortality at birth or as otherwise safe. The optimal cut-off values were obtained by maximising the accuracy of the prediction. These cut-off values resulted from various combinations of BW0 and BWvar_TNB, as presented in Supplementary Fig. S7. The BWVR index had a higher specificity (probability of a true negative) in comparison to the BWVCI.

Discussion

The objective of this study was to evaluate how BW0, BWvar and other sow and environmental factors, namely, parity, sex, litter size, year, season and farm and their interactions, affect the probability of piglet survival from birth to weaning. Additionally, the study aimed to investigate the potential of piglet BW0 and BWvar

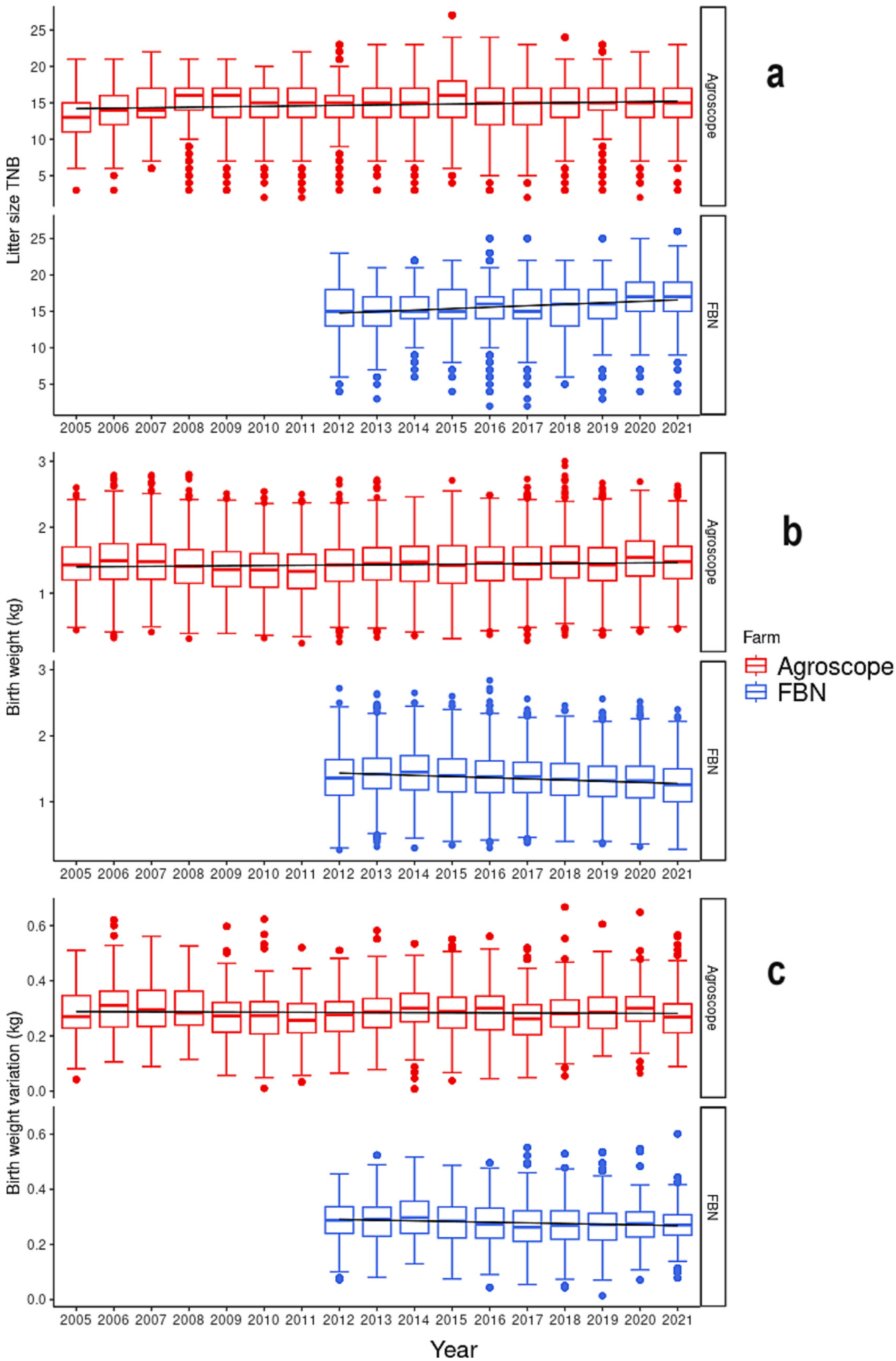

Fig. 1. Trends of total number of piglets born (TNB, a), birth weight (b) and within-litter birth weight variation (c) over time presented as box plots and the mean regression line at Agroscope and FBN research farms. Abbreviation: FBN = Research Institute for Farm Animal Biology. The box plot is an outlier box plot with the center line in the box indicating the median for the data and the points outside the box are the outliers.

Table 2
A summary of test statistics for the fixed effects fitted in the logistic regression model affecting piglet survival at birth (day 0) and day 3 with fostering effect.

Effect	df	Den. df	F Value	Pr > F
Total Number Born (Day 0)				
Parity	4	62 675	66.59	0.001
Sex	1	68 380	33.13	0.001
Farm	1	1 452	182.63	0.001
Parity*Farm	4	66 744	7.66	0.001
Litter size_TNB	1	23 125	9.15	0.003
Birth weight	1	68 380	2 712.99	0.001
BWvar_TNB	1	33 788	11.87	0.001
Total Born Alive (at day 3) with fostering effect				
Sex	1	58 533	79.99	0.001
Farm	1	1 529	6.35	0.012
Parity	4	58 533	9.28	0.001
Parity*Farm	4	58 533	8.89	0.001
Cross-fostering	1	58 533	185.93	0.001
Parity*fostering	4	58 533	2.36	0.051
Litter size_TBA	1	15 454	16.95	0.001
Birth weight	1	58 533	5 745.24	0.001
BWvar_TBA	1	18 831	0.77	0.380

Abbreviations: BWvar_TBA = within-litter birth weight variation based on total number of piglets born alive; BWvar_TNB = within-litter birth weight variation based on total number of piglet born; Den. df = denominator degrees of freedom computed via Kenward-Rodger approximation; Litter size_TBA = total number of piglets within a litter born alive; Litter size_TNB = the total number of piglets born within a litter, dead or alive; Pr = *P*-value associated with an F-statistic.

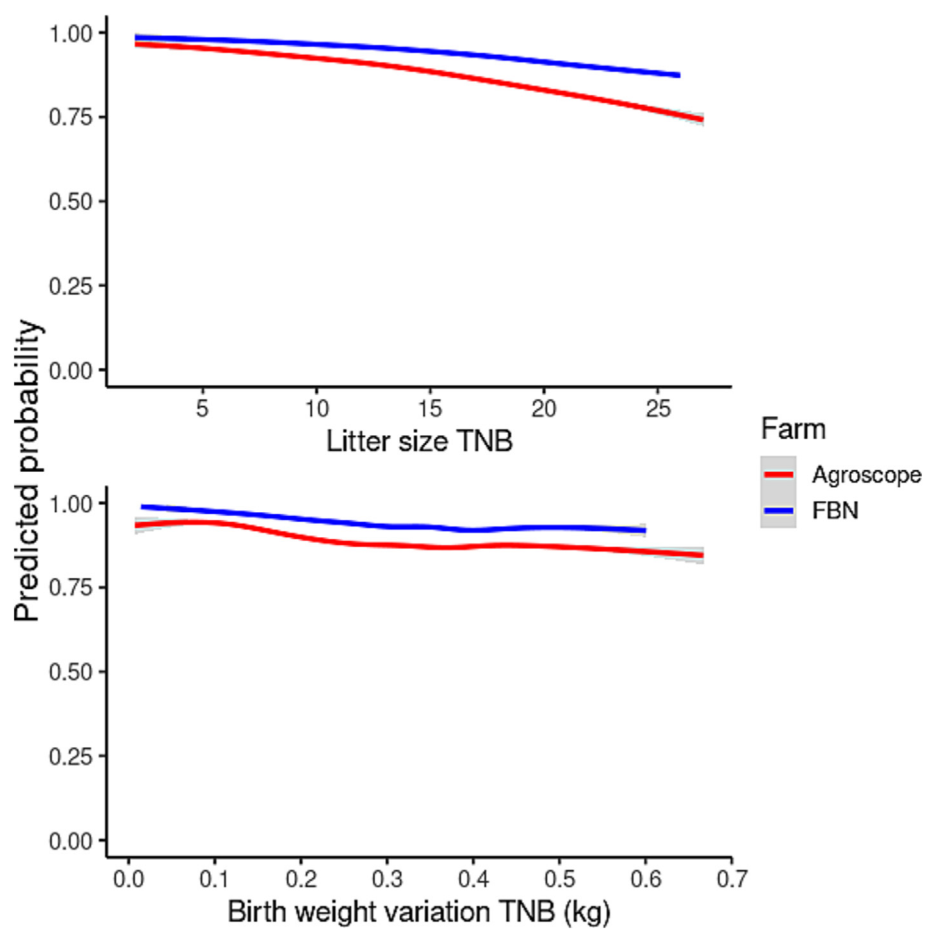

Fig. 2. Predicted probabilities for piglet survival at birth in relation to litter size (a) and birth weight variation (b) at the Agroscope and FBN research farms. The total number of piglets born (TNB) was considered for both litter size and birth weight variation. Abbreviation: FBN = Research Institute for Farm Animal Biology.

and their combination into an index, as easy-to-measure diagnostic proxies for preweaning survival and to determine functional cut-off values using an receiver operator characteristics curve analysis. The results indicate that BW0 is a reliable indicator of piglet survival and that piglets below the critical cut-off BW0 of 1.18 kg can be considered low birth weight. These piglets have a higher

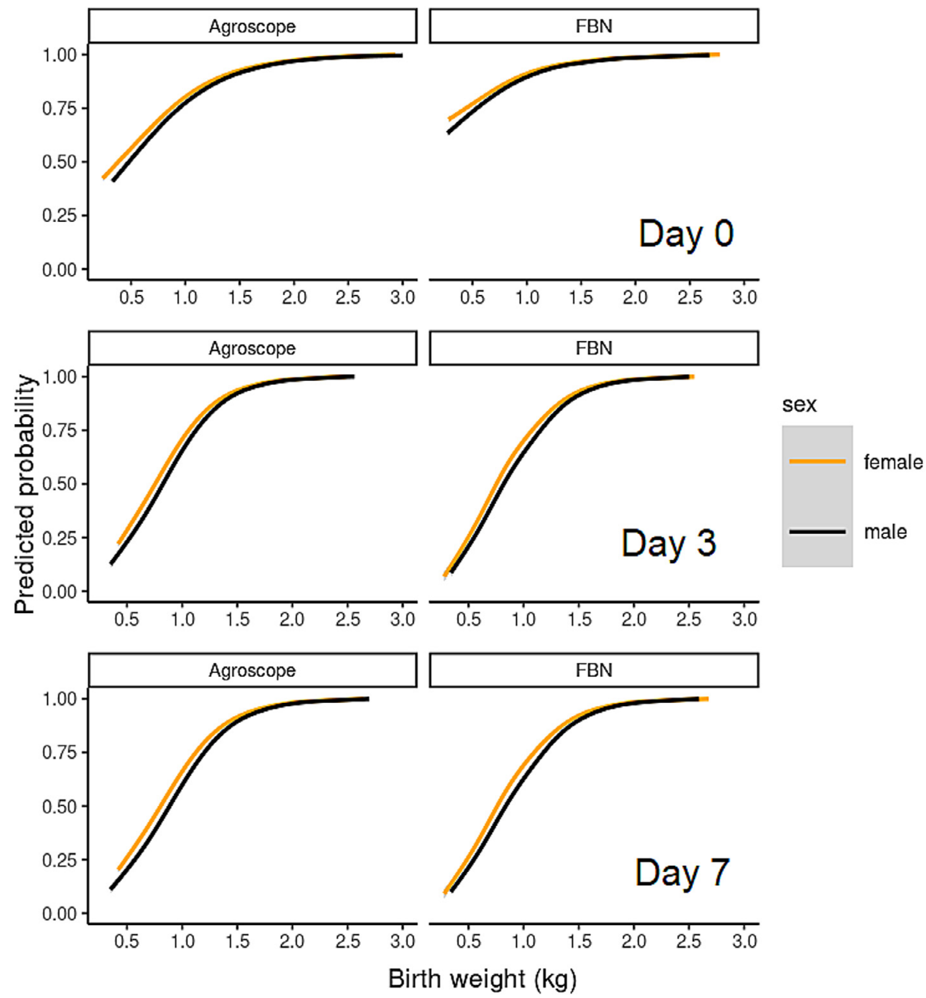

Fig. 3. Predicted probability for piglet survival at days 0, 3 and 7 for a given birth weight fitted by sex and farm. Abbreviation: FBN = Research Institute for Farm Animal Biology. Survival was a binary classification; each piglet was born either alive or dead. The total number of piglets born (TNB) was considered for both litter size and birth weight variation at birth (day 0). The total number of piglets born alive (TBA) was considered for the subsequent days. Days 14, 21 and 28 followed similar patterns and are presented in Supplementary Fig. S4.

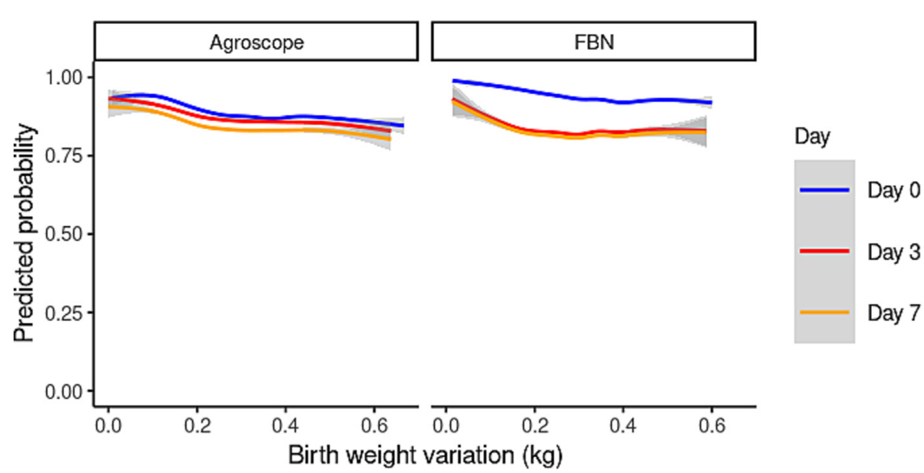

Fig. 4. Predicted probability for piglet survival at days 0, 3 and 7 with a given birth weight variation fitted by farm. Abbreviation: FBN = Research Institute for Farm Animal Biology. Survival was a binary classification; each piglet was born either alive or dead. The birth weight variation of total piglets born (BWvar_TNB) was considered for both litter size at birth (day 0), and total piglets born alive (BWvar_TBA) were considered for the subsequent days. Days 14, 21 and 28 followed similar patterns and are shown in Supplementary Fig. S5.

risk of not surviving to weaning and should receive timely and targeted interventions to improve their chances of survival. On the other hand, BWvar provided a less accurate survival prediction despite its clear influence on piglet survival. The variation in birth weight also becomes less significant with increasing age and cross-fostering effects. To quantitatively assess and monitor the relation-

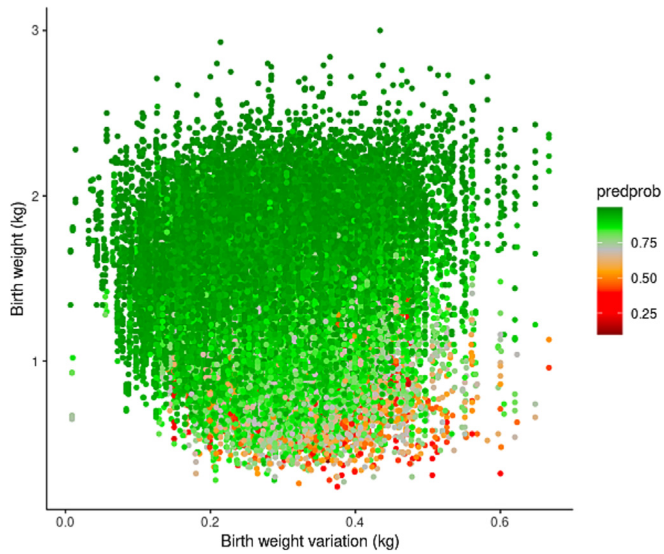

Fig. 5. Predicted probabilities for piglet survival at birth for a given birth weight and birth weight variation of total piglets born (BWvar_TNB) obtained from the mixed model presenting the probabilities for individual piglets. The color key represents the predicted probability (predprob) of survival (0 – 1) for a given piglet birth weight and within-litter birth weight variation.

ship between BW0 and its variation, we developed two novel indexes: BWVR and BWVCI. These indexes increased the accuracy of correctly classifying piglets at increased risk of mortality due to low BW0 and high BWvar within litter. Based on the BW0, which is a single and easy-to-measure phenotype, its variation within the litter was calculated i.e. BWvar, and novel concepts of BWVR and BWVCI were introduced. Thus, BW0 is a fundamental phenotype with vital information, and its use provided a robust framework to evaluate preweaning survival outcomes.

Birth weight and birth weight variation effects on survival

The declining trend in BW0, which was confirmed in both farms, could be associated with the unfavourable genetic correlation with litter size. Litter size has been genetically improved since the 1990s, when it was included in the breeding objectives for pigs (Knap et al., 2023). In terms of genetic variability, BW0 is favourably correlated to preweaning survival and has a higher heritability than the latter (Roehe and Kalm, 2000). The individual BW0 and litter BWvar can be measured at birth and could, therefore, be used as proxies for survival at a given time point, which could otherwise only be determined retrospectively. Low birth weight impairs not only survival but also postnatal growth and carcass and meat quality (Bee, 2007; Fix et al., 2010; Romero et al., 2022). The low-birth-weight piglets are not only more prone to neonatal deaths and

Table 3
A summary of receiver operating characteristic curve analysis for piglet birth weight (BW0) or birth weight variation within-litter (BWvar) either as single or combined predictors of survival.

Predictor	Farm/Sex	Data set	Cut-off	Accuracy	Sensitivity	Specificity
BW0	Agroscope	Day 0	1.19	0.74	0.78	0.50
	FBN		1.17	0.70	0.71	0.50
	Males		1.18	0.74	0.77	0.47
	Females		1.18	0.71	0.73	0.53
	Overall		1.18	0.73	0.75	0.50
		Day 3	1.20	0.75	0.78	0.62
		Day 7	1.22	0.75	0.78	0.60
		Day 14	1.22	0.74	0.78	0.59
		Day 21	1.30	0.70	0.70	0.65
		Day 28	1.22	0.74	0.78	0.57
BWvar	Agroscope	Day 0	0.233	0.35	0.29	0.77
	FBN		0.265	0.45	0.44	0.64
	Males		0.257	0.42	0.39	0.68
	Females		0.277	0.50	0.49	0.57
	Overall		0.277	0.50	0.49	0.58
		Day 3	0.275	0.55	0.56	0.49
		Day 7	0.275	0.55	0.56	0.48
		Day 14	0.275	0.54	0.56	0.48
		Day 21	0.275	0.54	0.56	0.48
		Day 28	0.275	0.54	0.56	0.48
BWVR	Agroscope	Day 0	4.02	0.73	0.77	0.48
	FBN		3.73	0.76	0.78	0.41
	Males		4.25	0.69	0.71	0.51
	Females		3.74	0.76	0.79	0.45
	Overall		3.81	0.75	0.79	0.43
	Optimal*		2.06	0.89	0.97	0.11
BWVCI	Agroscope	Day 0	0.46	0.68	0.69	0.54
	FBN		0.47	0.64	0.65	0.55
	Males		0.46	0.69	0.71	0.52
	Females		0.47	0.65	0.66	0.58
	Overall		0.46	0.67	0.69	0.53
	Optimal*		0.30	0.89	0.98	0.08

Abbreviations: BWVCI = birth weight-to-variation composite index; BWVR = birth weight-to-variation ratio; FBN = Research Institute for Farm Animal Biology.
In the receiver operator characteristics analysis, the variation of total piglets born (BWvar_TNB) was used for piglets' survival at birth, and the variation of total piglets born alive (BWvar_TBA) was used for subsequent days to weaning.
* The optimal cut-off values were obtained by maximising the Youden Index and manually selecting the values that had the maximum accuracy.

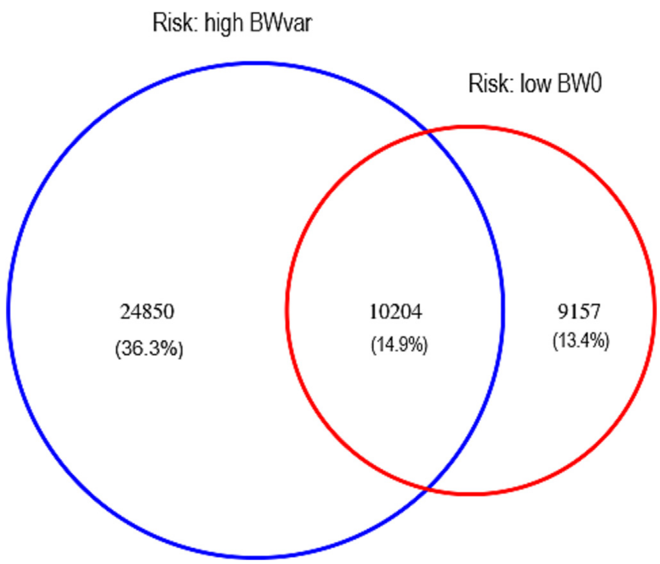

Fig. 6. Venn diagram presenting the proportion of piglets at risk of preweaning mortality due to low birth weight (≤ 1.18 kg), high birth weight variation (≥ 0.277 kg) and their intersection. Abbreviations: BW0 = birth weight; BWvar = within-litter birth weight variation. The figure excludes piglets with BW0 > 1.18 (n = 47 581, i.e. 71.6%) and BWvar < 0.277 (n = 32 128, i.e. 48.3%). The values in brackets are the percentages of the total number of respective BW0 or BWvar records.

higher preweaning mortality rate, but they are also at an increased risk of disease and impaired organ development, which is important for animal welfare. Although studies have suggested that high-birth-weight piglets are associated with various risks during parturition, including dystocia suffocation and prolonged expulsion (Nam and Sukon, 2022), our study suggests that high-birth-weight piglets have high neonatal survival probabilities. The trends for BWvar_TNB over time were generally constant (Agroscope) or slightly declining (FBN), which is desirable. The literature findings indicate that increased litter size has resulted in poor litter uniformity, with an increased proportion of small piglets (Peltoniemi et al., 2021). Litters with high BWvar have more deaths, especially if the litter's mean birth weight is low, in which case, low-birth-weight piglets are more likely to die than their normal birth weight littermates (Milligan et al., 2001). In our study, the litter variation was calculated separately by sex and then pooled to account for the significant difference between male and female piglets on BW0 and BWvar (Wittenburg et al., 2011). In addition, BWvar_TNB (including stillborns) was applied to analyse survival at birth. Subsequently, the stillborns were excluded, and BWvar_TBA was used for the analysis of survival at different time points up to weaning. This way, the stillborns and those that died at birth did not influence the statistics of the surviving piglets on which management decisions are based. Stillborn piglets have to undergo intrapartum development and contribute to the sow's reproductive traits (Wittenburg et al., 2011). However, the surviving piglets should be the crucial proportion influencing the herd dynamics and management decisions. Indeed, TNB and TBA are two different traits with a genetic correlation of about 0.9 and a heritability estimate of about 0.11 (Putz et al., 2015).

Notably, BWvar was statistically significant for survival at birth but not at later time points. This is because the stillborns, which are mainly low birth weight, have been eliminated and in some cases, the litter variation has been evened out by cross-fostering the piglets. As a result, the influence of BWvar on survival diminishes.

The exact thresholds for what constitute low variation for a uniform litter size can differ depending on production systems and breeding programmes. By considering the lower quartile of the BWvar_TNB (< 0.224 kg), as being a uniform litter, then a litter size of 14 (mean and median) with an average BW0 of 1.63 kg (upper quartile) or a litter of 16 (upper quartile) with BW0 of 1.4 kg (mean and median) would realise piglet survival probability of > 92%. Although this would result in lower litter size than modern commercial breeding, positive survival trends would be realised and with knowledge of genetic correlations for BW0 and BWvar would make it possible to build an index that will allow a more balanced genetic progress (Knap et al., 2023).

Influence of the fixed effects on piglet survival

The fixed effects fitted in the mixed model equations were mainly effects reported to influence survival traits in preweaning piglets. They significantly influenced the piglets' survival at birth, but their effects became inconsistent with advanced age and changes in management (such as cross-fostering). The seasonal effects on survival rates could be due to management and environmental changes in individual years and seasons. These include, for example, differences in feed quality and feeding according to season and year, potential effects of cold or heat stress due to seasonal changes and breeding management. There was a significant sow parity by farm interaction. These variations could arise from farm-specific differences around farrowing in terms of management practices, environmental factors and nutrition. This is cognizant to the fact that contemporary farrowing groups in each farm comprise sows of different parities and have different prefarrowing nutritional provisions. Of the variables fitted, BW0 had the highest F-value in all models making it the most important factor influencing preweaning survival.

From the logistic regression models, the probability of survival followed a curvilinear relationship with BW0 whereby the threshold could not be directly determined. Only at a BW0 ≥ 1.5 kg was the probability of survival close to 1. By applying an receiver operator characteristics analysis, the cut-off threshold was estimated with moderate accuracy. Similar curvilinear relationships between BW0 and survival have been reported for piglets weighing < 0.7 kg having < 25% survival probability and above 0.9 kg having > 70% survival probability (Knol et al., 2022). Similarly, the linear negative relationship between BWvar and survival has been reported, indicating that selection against high BWvar_TNB could be an indirect means to improve piglet survival at birth (Knol et al., 2022). The influence of BWvar_TNB was not significant after day 3 of age, most likely because at this time point, cross-fostering had already been carried out, and the litter size had evened out. Significant cross-fostering by sow parity interaction was observed. Cross-fostering to primiparous sows may be necessitated when the older sows have more piglets than functional teats they have, and the available foster sows within the farrowing group are typically gilts which tend to have smaller litter sizes. Research on hyperprolific sows in Denmark also reports that first parity sows are best suited, as nurse sows during cross-fostering exhibiting higher preweaning survival than multiparous sows (Bruun et al., 2023). However, the piglets have a lower average daily gain.

Receiver operating characteristic curve analysis and cut-off values

In the present study, the cut-off value determined with receiver operator characteristics for low-birth-weight piglets of 1.18 kg is in alignment with that reported by Patterson et al. (2020) in a large commercial pig operation in the USA. The latter study predicted the probabilities of mortality until day 4 using logistic regression models and reported an AUC of 0.76, which is consistent with our study. In another study using USA and EU data and applying a mixed-effects logistic regression model, a BW0 threshold of

1.11 kg was identified, with piglets below this BW0 having a preweaning mortality rate of 34.4% (Feldpausch et al., 2019). In terms of growth, Beaulieu et al. (2010) reported that pigs with a BW0 of 1.20 kg or less required an additional 10 days on average to reach slaughter weight compared to the heavier counterparts weighing above 1.75 kg. This might be due to a suggested lack of compensatory growth of low-birth-weight pigs in the grower–finisher period (Rehfeldt and Kuhn, 2006).

When considering the BWvar cut-off value for predicting preweaning piglet survival, there were different critical cut-off points when segregated by farm, sex and time point. Unlike BW0, a reliable BWvar cut-off value as a proxy for determining preweaning survival could not be determined. Given that piglets with low birth weight from litters with high BWvar are at increased risk of mortality, it was expected that combining BW0 and BWvar into an index would increase the accuracy of survival prediction. This is because, the index would serve as a more inclusive indicator allowing the assessment of the birth weight of newborns in the context of the whole litter. The BWVR is a simple yet effective metric that compares the birth weight of each piglet to the SD of birth weights within the same litter. A higher BWVR indicates that a piglet's birth weight is proportionally larger relative to its littermates, suggesting potentially better survival prospects. Conversely, a lower BWVR is an indication of low BW0 and greater BWvar, which may indicate an increased risk for the smaller piglets. The BWVCI utilises PCA statistical models to weigh and integrate the BW0 and BWvar variables, thereby enhancing the predictive accuracy beyond the variables independently. By giving more weight to BW0 than BWvar, the index provides a more balanced and accurate assessment of piglet viability.

Observations from our study revealed that BWvar_TNB was more important than litter size in determining piglet survival at birth. In addition, piglets from litters with less variation in BW0 tended to have higher neonatal survival rates. These findings underscore the significance of uniformity of birth weight within a litter. Interventions could, therefore, potentially focus on breeding piglets with more balanced birth weights. In conclusion, individual piglet BW0 was the most important single predictor for preweaning survival from both the logistic regression and receiver operator characteristics analyses and can be used effectively as an easy-to-measure proxy for preweaning survival. Integrating BW0 and BWvar into composite indexes such as the BWVR and BWVCI represents a promising advancement in predicting preweaning survival in piglets. This approach not only emphasises the significance of BW0 as a predictive indicator of piglet vitality and survival but also underscores its versatility as a fundamental phenotype that encapsulates vital information necessary for advancing pig production practices and research methodologies. Further research could focus on phenotyping strategies for such indirect proxy traits and improving prediction models to increase the accuracy of predicting preweaning survival.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101479) can be found at the foot of the online page, in the Appendix section.

Ethics approval

The experimental procedure for Agroscope was approved by the Office for Food Safety and Veterinary Affairs of the Canton of Fribourg (animal experimentation licence 2018_30_FR), and all procedures were conducted in accordance with the Swiss Ordinance on Animal Protection and the Ordinance on Animal Experimentation and the ARRIVE guidelines. At FBN, no ethical approval was necessary for the purposes of this study, as all information required was obtained from existing databases.

Data and model availability statement

The data that support the study findings are publicly available and are deposited on the Zenodo repository under a CC BY-NC-SA 4.0 licence at https://doi.org/10.5281/zenodo.14012129. The SAS and R codes used for the models are provided in the Supplementary File: statistical models. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

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