

1 **Title: An attempt of using public ambient temperature data in swine genetic evaluation**
2 **for litter size traits at birth in Japan**

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14 Running head: USING PUBLIC DATA IN GENETIC EVALUATION

15 **ABSTRACT**

16 To obtain the fundamental information on using ambient temperature information in
17 developing the model for routine swine genetic evaluation in Japan, we analyzed total number
18 born (TNB), number born alive (NBA), and number stillborn (NSB) collected at a Japanese
19 farm, together with off-farm ambient temperature measured at a nearest Automated
20 Meteorological Data Acquisition System station. Five repeatability animal models were
21 exploited, considering the effects of farrowing season (model 1), farrowing month (model 2),
22 quadratic regressions of daily maximum ambient temperature of farrowing day (model 3),
23 season and temperature (model 4), or month and temperature (model 5). Patterns of the effects
24 of daily maximum temperature of farrowing day estimated using model 3 was similar to those
25 of farrowing season by model 1 and those of farrowing month by model 2. Adding the effect
26 of daily maximum temperature of farrowing day (models 4 and 5) could explain phenotypic
27 variability greater than only considering either of farrowing season and month (models 1 and
28 2). Estimated heritability was stable among the models and the rank correlation of predicted
29 breeding values between models was >0.98 for all traits. The results indicate the possibility
30 that using public ambient temperature can capture a large part of the phenotypic variability in
31 litter size traits at birth caused by the seasonality in Japan and do not harm, at least, the
32 performance of genetic evaluation. This study could support the availability of public
33 meteorological data in flexible developing operational models for future swine genetic
34 evaluation in Japan.

35 **KEYWORDS:** genetic parameter estimation, litter size traits at birth, meteorological
36 observation data, pig breeding, temperature

37 1. INTRODUCTION

38 In Japan, pork production traits, including average daily gain, longissimus muscle area, and
39 intramuscular fat content with middle to high heritabilities, have been genetically improved by
40 selection (e.g., Suzuki *et al.* 2005; Kadowaki *et al.* 2012; Ohnishi and Satoh 2018). Now,
41 improving sow lifetime productivity is a pressing challenge to efficient pork production,
42 although the heritabilities of litter size traits at birth have been estimated to be low (e.g.,
43 Tomiyama *et al.* 2011; Ogawa *et al.* 2019a; Ogawa *et al.* 2020). Potentials have been assessed
44 of several approaches, such as choosing a statistical model more appropriate to estimate
45 breeding values for number born alive (NBA) in terms of the parity order of dam (Ogawa *et al.*
46 2019b; Konta *et al.* 2020), exploring a preferable trait to assist in genetically improving NBA
47 (Konta *et al.* 2019; Ogawa *et al.* 2019a; Ogawa *et al.* 2020), and investigating the possibility
48 of genetically improving sow longevity (Ogawa *et al.* 2021a). A possible different approach is
49 to perform a large-scale genetic evaluation across farms because this might predict breeding
50 values that have higher accuracies by using more phenotypic information obtained from
51 relatives reared on different farms and that can be directly compared between individuals on
52 different farms. Therefore, it is important to provide an operational model suitable for a large-
53 scale routine genetic evaluation by simultaneously using data collected from around Japan.

54 Japan is an island country that has four distinct seasons with a climate ranging from
55 subarctic in the north to subtropical in the south, and the conditions are different between the
56 Pacific side and the Sea of Japan side
57 (<https://www.data.jma.go.jp/gmd/cpd/longfcst/en/tourist.html>). Japanese pig farms are widely
58 distributed in Japan (e.g., Koike *et al.* 2018; Ogawa *et al.* 2019c; Fujimoto *et al.* 2021).

59 Previous studies have reported that seasons affect the meat production and reproductive
60 performance of pigs reared in Japan (e.g., Harada *et al.* 1992; Saito and Koketsu 2009; Kakuma
61 2018), and statistical models considering the effects of season at measuring phenotypic
62 information have been widely used in the genetic evaluation of traits that can be recorded
63 throughout the year (e.g., Tomiyama *et al.* 2011; Kadowaki *et al.* 2019; Ogawa *et al.* 2019a;
64 Ogawa *et al.* 2020). The scale of national swine genetic evaluation is getting larger
65 (<http://www.nlbc.go.jp/kachikukairyō/iden/buta/chiikinai.html>), and the current evaluation
66 uses operational models including the fixed cross-classified effects of the combination of
67 region and season at measuring
68 (<http://www.nlbc.go.jp/kachikukairyō/iden/buta/hyokaho.html>). However, these models could
69 not explain the variation by the time of year within each season.

70 Effects of the time of year on pigs' trait expression could be associated with ambient
71 climate conditions, including thermal environment. Using information on thermal environment,
72 such as ambient temperature, might explain not only the variation across seasons but also that
73 within each season. However, full details of thermal environment for farm animals are rarely
74 available. On the other hand, the utility of public meteorological data has been studied
75 worldwide. For instance, by using off-farm temperature data measured at weather stations,
76 Zumbach *et al.* (2008) analyzed carcass weight of pigs raised on 2 farms in North Carolina,
77 USA; Lewis and Bunter (2011) analyzed several production traits of gilts and litter traits of
78 sows on a farm in Australia; Tummaruk (2012) analyzed age at first observed estrus in gilts in
79 4 commercial herds in Thailand; Wegner *et al.* (2014) and Wegner *et al.* (2016) analyzed the
80 numbers of total born, liveborn piglets, stillborn piglets, and weaned piglets of sows on several

81 farms in Germany; and Mellado *et al.* (2018) analyzed the numbers of live pigs, stillborn pigs,
82 and mummified pigs of gilts and sows on a single farm in central west Mexico. Freitas *et al.*
83 (2006) reported that correlations between the temperature humidity index (THI) according to
84 on-farm temperature and humidity records on a Holstein farm in Tifton, Georgia, USA, and
85 THI according to records measured at several weather stations (up to 300 km apart) were >
86 0.92. Following this, Bloemhof *et al.* (2013) showed the utility of daily maximum temperature
87 from weather stations as a heat stress indicator for farrowing rate and total number born on 16
88 farms in Spain and Portugal. Using public meteorological data, other studies reported the
89 results of epidemiological investigations of total number born, weaning-to-first-mating interval,
90 adjusted 21-day litter weight, peripartum pig deaths, and farrowing rates of gilts and sows
91 (mainly crossbred) reared in Japanese commercial farms, in terms of herd management (e.g.,
92 Iida and Koketsu 2013; Iida and Koketsu 2014a; Iida and Koketsu 2014b; Sasaki *et al.* 2018).
93 Previous studies used information on daily maximum temperature to investigate the effect of
94 ambient temperature on reproductive traits of pig (e.g., Lewis and Bunter 2011; Bloemhof *et*
95 *al.* 2013; Iida and Koketsu 2013; Iida and Koketsu 2014a; Iida and Koketsu 2014b; Sasaki *et*
96 *al.* 2018).

97 No study has been investigated in detail about the performance of genetic evaluation
98 of Japanese purebred pig population using public ambient temperature information. This is a
99 challenging task, and as a first step, it seems reasonable to start from assessing the performance
100 of using public meteorological data in swine genetic evaluation by analyzing data from a single
101 farm, owing to secure the interpretability of the results. Total number born (TNB), NBA, and
102 number stillborn (NSB) at birth are the traits having been repeatedly investigated for foreign

103 pig populations (e.g., Lewis and Bunter 2011; Bloemhof *et al.* 2013; Wegner *et al.* 2014;
104 Wegner *et al.* 2016), this could give more opportunities to make a meaningful discussion. This
105 study, aiming at obtaining fundamental information for establishing a more efficient swine
106 breeding scheme in Japan, compared on-farm temperature data measured on a single swine
107 farm and off-farm data acquired at the nearest Automated Meteorological Data Acquisition
108 System (AMeDAS) station (<https://www.jma.go.jp/jma/en/Activities/amedas/amedas.html>),
109 and estimated genetic parameters of TNB, NBA, and NSB and predicted breeding values for
110 these traits using the public temperature data.

111

112 **2. MATERIALS AND METHODS**

113 2.1 Ethics statement

114 All procedures involving animals were performed in accordance with the National Livestock
115 Breeding Center's guidelines for the care and use of laboratory animals.

116 2.2 Phenotypic information and pedigree data

117 We used 1,161 records for TNB, NBA, and NSB of 437 purebred Duroc dams obtained between
118 24 April 2010 and 8 August 2017 at the National Livestock Breeding Center's Miyazaki Station
119 (31°56' N, 130°56' E, 462 m a.s.l.) in Miyazaki Prefecture (Ogawa *et al.* 2020; Yazaki *et al.*
120 2020; Ogawa *et al.* 2021). Miyazaki Prefecture is located along the southeastern coast of the
121 island of Kyusyu in Japan and has a subtropical climate. Artificial insemination was used for
122 all service events. NBA was determined by the next day of the farrowing and included the
123 number of piglets dead when checking to determine NBA but seemed to be alive at farrowing.
124 The number of mummified piglets was not included in NSB. TNB was calculated as the sum

125 of NBA and NSB. The pedigree data included information on 11,631 individuals. Basic
126 statistics from the phenotypic records for the studied traits are listed in Table 1.

127 2.3 On- and off-farm ambient temperature data

128 As on-farm ambient temperature data, temperatures within two sire barns and two growing
129 barns recorded at intervals of 5 or 10 minutes from 4 October 2016 to 24 August 2017 were
130 available. As off-farm ambient temperature data, the daily maximum temperatures acquired by
131 the Kobayashi AMeDAS station (32°00' N, 130°57' E, 276 m a.s.l.), about 6 km from the farm,
132 from 28 December 2009 to 24 August 2017 were obtained from the Japan Meteorological
133 Agency's homepage (<https://www.data.jma.go.jp/gmd/risk/obsdl/>).

134 2.4 Numerical analyses

135 The following single-trait linear animal model was used:

$$136 \quad \mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{Wpe} + \mathbf{e},$$

137 where \mathbf{y} is the vector of phenotypic records; \mathbf{b} is the vector of macro-environment effects (fixed
138 effect); \mathbf{a} is the vector of breeding values (random effect); \mathbf{pe} is the vector of permanent
139 environment effects (random effect); \mathbf{e} is the vector of random errors (random effect); and \mathbf{X} ,
140 \mathbf{W} , and \mathbf{Z} are the design matrices relating \mathbf{y} to \mathbf{b} , \mathbf{a} , and \mathbf{pe} , respectively. Macro-environment
141 effects included farrowing year (2010 to 2017), parity of dam (1st to 8th), mating sire breed
142 (Duroc, Large White), and the time of year as one of farrowing season (spring [March–May],
143 summer [June–August], autumn [September–November], winter [December–February];
144 model 1), farrowing month (January to December; model 2), daily maximum temperature of
145 farrowing day at Kobayashi AMeDAS station (quadratic regression; model 3), farrowing
146 season and daily maximum temperature of farrowing day (model 4), or farrowing month and

147 daily maximum temperature of farrowing day (model 5). The mean and variance–covariance
148 of the random effects were as follows:

$$149 \quad E \begin{bmatrix} \mathbf{a} \\ \mathbf{pe} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \quad \text{and} \quad \text{var} \begin{bmatrix} \mathbf{a} \\ \mathbf{pe} \\ \mathbf{e} \end{bmatrix} = \begin{bmatrix} \mathbf{A}\sigma_a^2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}\sigma_{pe}^2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}\sigma_e^2 \end{bmatrix},$$

150 where σ_a^2 is the additive genetic variance; σ_{pe}^2 is the permanent environmental variance;
151 σ_e^2 is the error variance; \mathbf{A} is the additive genetic relationship matrix; and \mathbf{I} is the identity
152 matrix. Variance components were estimated in AIREMLF90 program (Miszta *et al.* 2002).
153 Standard errors of the estimated heritability and repeatability were calculated using the
154 elements of the inverse of the average-information matrix at convergence (Klei and Tsuruta
155 2008). Default setting was used as convergence criteria in the iteration procedure, that is, an
156 iteration was stopped when at least one of the following conditions was first satisfied:

$$157 \quad \frac{\sum_{i=1}^n (\hat{\theta}_{i,k} - \hat{\theta}_{i,k-1})^2}{\sum_{i=1}^n \hat{\theta}_{i,k}^2} < 10^{-12} \quad \text{and} \quad \frac{\sum_{i=1}^n |\hat{\theta}_{i,k} - \hat{\theta}_{i,k-1}|}{n} < 10^{-6},$$

158 where $\hat{\theta}_{i,k}$ is the estimated value of parameter i in iteration k and n is the number of parameters
159 to be estimated.

160

161 **3. RESULTS AND DISCUSSION**

162 3.1 Comparing on- and off-farm temperature data

163 Fig. 1 illustrates the relationship of on- and off-farm daily maximum temperatures. Values of
164 Pearson's correlation coefficients between the temperatures were very high, ranging from 0.92
165 to 0.96, and therefore it is reasonable to assume that off-farm daily maximum temperatures
166 corresponded 1:1 with on-farm daily maximum temperatures in this study. The reason for such

167 high correlations might be that the distance between the farm and the AMeDAS station is only
168 6 km, with no obvious geographical barrier between the farm and station (Freitas *et al.* 2006).
169 Sasaki *et al.* (2018) used meteorological data measured at weather stations nearest each of 25
170 swine farms and found that the coefficient of determination between on- and off-farm
171 temperatures was high (0.85). Our coefficients of determination ranged from 0.84 to 0.93, equal
172 to or higher than that found by Sasaki *et al.* (2018).

173 Nevertheless, the ranges of the values of on-farm temperatures in all barns were
174 narrower than that of off-farm temperatures, and the distributions were slightly different
175 between boar barns and growing barns (Fig. 1). These differences could be due to factors
176 controlling on-farm environmental conditions. Apparent abnormal values of on-farm
177 temperatures might reflect the effect of installation site or a flaw in the measuring devices.

178 On-farm temperatures were collected from October 2016, whereas most farrowing
179 records were obtained before that date. Therefore, we used off-farm temperature data measured
180 at Kobayashi, supposing that the 1:1 correspondence between on- and off-farm daily maximum
181 temperatures also held before October 2016. Fig. 2 shows the relationships of off-farm daily
182 maximum temperature of farrowing day with farrowing seasons and months. Values of the
183 temperatures varied not only across the seasons and months in average but also within each
184 season and month. This fact reflects the potential for capturing the phenotypic variation of traits
185 within each season and month by using ambient temperature data. Previous study reported that
186 the thermoneutral zone of sow was from 18 to 20°C (e.g., Curtis 1983; Peltoniemi *et al.* 1999;
187 Bloemhof *et al.* 2013). Therefore, it could be expected that seasons and months with average
188 values of temperature deviating from sow' thermoneutral zone, such as summer and winter

189 seasons and months within these seasons, might affect their phenotypic performance in this
190 study.

191 3.2 Effects of farrowing season, farrowing month, and daily maximum ambient temperature of
192 farrowing day

193 Table 2 summarizes the results about the estimated effects of farrowing season,
194 farrowing month, and off-farm daily maximum temperature of farrowing day. Fig. 3 illustrates
195 the changes in the effects of off-farm daily maximum temperature of farrowing day estimated
196 using model 3. Fig. 4 shows the relationships of the effect of off-farm daily maximum
197 temperature of farrowing day estimated using model 3 with corresponding farrowing seasons
198 and months. Proportions of variances of phenotypic records explained by the estimated effects
199 of farrowing season, farrowing month, and off-farm daily maximum temperature of farrowing
200 day, as well as Pearson's correlation coefficients between the values explained by those effects,
201 are listed in Table 3. Fig. 5 shows the relationship between mating and farrowing dates and that
202 between off-farm daily maximum temperatures of mating and farrowing days.

203 Values of the effects of spring and summer at farrowing on TNB estimated using
204 model 1 were similar to each other, that of autumn was slightly lower than those of spring and
205 summer, and that of winter was the lowest (Table 2). TNB would be largely determined by
206 ovulation rate, early embryonic mortality, and early fetal death (e.g., Edwards *et al.* 1968; Wildt
207 *et al.* 1975; Nardone *et al.* 2006). Considering that the average value of gestation length in our
208 population was 115.9 days, nearly 4 months, and that >90% of the farrowing records exhibited
209 the gestation length ranging from 114 to 118 days (Fig. S1), most litters farrowed in winter had
210 been artificially inseminated from August to October, hotter months in this study (Fig. 2). A

211 heat-stressed dam before and after insemination could exhibit lower feed intake, diminished
212 follicle stimulating hormone (FSH) and luteinizing hormone (LH) secretion, and increased
213 body temperature and oxidative stress, these might cause lower ovarian function and higher
214 early embryonic mortality (e.g., Flowers *et al.* 1989; Flowers and Day 1990; Quesnel *et al.*
215 1998; Kim *et al.* 2013). Previous studies have shown that the temperature in the period between
216 several days prior to and after insemination had greater effects on TNB (Omtvedt *et al.* 1971;
217 Bloemhof *et al.* 2013; Wegner *et al.* 2016).

218 Values of the estimated effects of spring and autumn at farrowing on NSB were similar,
219 that of summer was slightly higher than those of spring and autumn, and that of winter was the
220 highest (Table 2). It has been reported that heat stress in later pregnancy increased the number
221 of stillborn piglets (e.g., Edwards *et al.* 1968; Omtvedt *et al.* 1971; Wegner *et al.* 2016).
222 Therefore, the slightly lower value for summer at farrowing might be due to heat stress in dams.
223 On the other hand, the lowest value for winter might be caused by cold stress in not only dam
224 but also piglet. For example, previous studies reported the range of comfortable temperature of
225 18°C to 23°C for lactating sow (Yan and Yamamoto 2000; Brown-Brandl *et al.* 2001) and the
226 minimum comfortable temperature of around 34°C to 35°C for newborn piglet (Mount 1959;
227 Manno *et al.* 2005). Considering the physiological temperature in dam's utero, between 38°C
228 to 40°C, piglets encounter a colder environment immediately, this triggers the reduction of
229 body temperature soon, known as hypothermia (Tuchscherer *et al.* 2000; Pandorfi *et al.* 2005;
230 Malmkvist *et al.* 2006).

231 Values of the estimated effects for NBA were like the difference between those for
232 TNB and NSB because TNB was the sum of NBA and NSB in this study. From what has been

233 discussed above, one can add the effects about the time at mating, such as mating year and
234 either of mating season, mating month, or temperature of mating day. However, care must be
235 taken to accurate data collection about the mating and farrowing dates and a characteristic data
236 structure about these factors (Fig. 5), due to seasonal variation in ambient temperature and less
237 variability in gestation length. Ogawa *et al.* (2019c) reported the estimated effects of farrowing
238 season for NBA in Landrace and Large White dams raised on multiple farms in different
239 prefectures of a single Japanese pig breeding company. Ogawa *et al.* (2019c) showed lower
240 estimated values for winter than for spring, although the difference between the values was
241 0.30 in Landrace and 0.21 in Large White, both smaller than this study. This inconsistency
242 might be due to differences in breed, farm location, and rearing condition. Our population was
243 reared in Miyazaki Prefecture, in southern Japan, and analyzing data obtained at different
244 locations, such as northern Japan, might yield different effects of the time of year. Tummaruk
245 *et al.* (2004) estimated the effects of farrowing month on NBA in Landrace and Large White
246 populations in Thailand, showing that NBA was significantly lower in August and September
247 than from November to June. The inconsistency might be due in part to the difference in climate
248 conditions between countries. Bertoldo *et al.* (2012) observed that the estimated effects of
249 season on litter size varied among studies, possibly owing to confounding factors, including
250 parity of dam and semen characteristics. Tummaruk *et al.* (2004) and Tummaruk *et al.* (2010)
251 reported that the effect of season on litter size was more prominent in gilts than in sows,
252 although it is possible that their results were affected by culling for reproductive performance
253 at earlier parities (Sasaki *et al.* 2018).

254 Variations in phenotypic records explained by farrowing season in model 1 and that

255 by farrowing month in model 2 was largely in common, although the proportion on variance
256 explained by farrowing month was greater than that explained by farrowing season for all traits
257 (Table 3). Considering the effect of the time of year as farrowing month could explain
258 additional variations which are not explained by farrowing season, though the statistical model
259 becomes more complicated, that is, the number of levels increases from 4 to 12, and thus the
260 average number of records per level is decreased. Therefore, in terms of data connectedness
261 and reliability of the results, more careful consideration is required to interpret the results
262 obtained using more complicated model, especially when the data structure is severely
263 unbalanced and the data size is small. We assumed no interaction between farrowing year and
264 farrowing season or month, and the average number of records per level decreases further when
265 considering farrowing year-by-season and year-by-month effects.

266 The quadratic curve for the effect of off-farm daily maximum temperature of
267 farrowing day estimated using model 3 was convex upward for TNB and NBA and downward
268 for NSB (Fig. 3), although the value of the effect for TNB became stable when the temperature
269 was $>20^{\circ}\text{C}$. Phenotypic variation explained by the temperature in model 3 was partly in
270 common with those explained by farrowing season in model 1 and farrowing month in model
271 2 (Table 3). The proportions of variances explained by the temperature were the lowest for
272 TNB and NBA, while it was lower than that explained by farrowing month but greater than
273 that explained by farrowing season for NSB.

274 Model 3 assumes that the effect of the time of year is the same when the daily
275 maximum temperatures are the same on different days. However, sows farrowed in spring and
276 sows farrowed in autumn might be differently affected, partly because of different responses

277 to daylight hours, daily temperature range, and relative humidity, even if the daily maximum
278 temperatures are the same. Therefore, we performed the analyses using models 4 and 5. For
279 TNB and NSB, simultaneous considering the effects of the temperature and season or month
280 (models 4 and 5) could explain more proportions of variance than considering only one of the
281 effects of season, month, and temperature (models 1, 2, and 3) (Table 3). This indicates the
282 availability of using temperature data to explain additional variation which could not capture
283 by considering the effects of season and month. On the other hand, interpreting the respective
284 values of effects of farrowing season, farrowing month, and daily maximum temperature of
285 farrowing days estimated using models 4 and 5 were more difficult than those estimated using
286 the other models (Table 2, Fig. S5). This could be due to confounding; that is, there are overlaps
287 among the variations explained by farrowing season, month, and daily maximum temperature
288 of farrowing day. Lewis and Bunter (2011) discussed the possibility of confounding when
289 dissociating the effects of contemporary group and daily maximum temperature.

290 We adopted the quadratic regression of phenotypic values on temperatures, according
291 to the results from the preliminary analysis and aiming to prevent over-fitting (Figs. S1, S2, S3,
292 and S4). Including quadratic regression of daily maximum temperature of farrowing day lost 2
293 degrees of freedom, whereas including discrete effects of farrowing season and farrowing
294 month lost 4 and 12 degrees of freedom, respectively. Furthermore, considering farrowing
295 season and month would reduce both the average number of records per level the
296 connectedness with other effects. On the other hand, considering daily maximum temperature
297 as covariates in the model restricts the expression of the effect of the time of year. Therefore,
298 modeling should be flexible in response to the structure and size of the data analyzed.

299 3.3 Genetic parameter estimation and breeding value prediction

300 Results of estimating genetic parameters are listed in Table 4. Values of Spearman's rank
301 correlation coefficients of predicted breeding values the 437 sows with their own records
302 between the models are shown in Table 5. Values of estimated heritability and repeatability
303 were stable across the models for all traits, mainly due to the small proportions of variance in
304 phenotypic records explained by farrowing month, farrowing year, and daily maximum
305 temperature of farrowing day (Table 3). Values of Spearman's rank correlation coefficients
306 were >0.98 . These results could imply the possibility that including temperature information
307 into the analytical model at least did not harm the performance of breeding value prediction.

308 3.4 General discussion

309 With the aim of increasing the rate of genetic improvement, it is important to develop an
310 operational model suitable for routine large-scale genetic evaluation that can handle integrated
311 data collected around Japan. In this study, we used public meteorological data as a source of
312 climate information to analyze phenotypic records of TNB, NBA, and NSB. This is the first
313 study to assess the performance of using public ambient temperature data in swine genetic
314 evaluation in Japan. We revealed that adding the effect of temperature could explain additional
315 variations that did not explain by considering only the effect of season (Table 3). Possible
316 reasons for our results would be that high one-to-one correspondence of off-farm temperature
317 data with on-farm temperature (Fig. 1) and that the values of temperature varied within each
318 season (Fig. 2). On the other hand, it should be noted that such correspondence might not be
319 guaranteed on other farms, depending on physical and management characteristics. Therefore,
320 it is important to investigate factors affecting the relationship between on- and off-farm ambient

321 temperatures. Exploring a more appropriate use of temperature data, such as daily average and
322 minimum temperatures, daily temperature range, and other factors including relative humidity,
323 as well as choosing a different expression of the effect of ambient temperature, including linear-
324 plateau regression and smoothing spline, might explain more phenotypic variation (Zumbach
325 *et al.* 2008; Lewis and Bunter 2011; Bloemhof *et al.* 2013; Guy *et al.* 2017; Tiezzi *et al.* 2020).
326 Moreover, AMeDAS relative humidity data and mesh climate data are now available as
327 different sources of climate information. Effects of time of year, and even those of year, might
328 vary among regions and farms. If an interaction of region and farm with time could be
329 explained by using public meteorological data, the statistical modelling might become simpler
330 and more objective. To tackle these challenging issues, further analysis should be performed to
331 investigate the performance of the integrated use of different kinds of public meteorological
332 data with a larger data set with a more complex structure.

333 Recently, studies have investigated the methodology for efficient breeding using
334 information obtained from public databases; for example, genomic prediction incorporating
335 biological information (e.g., Melzer *et al.* 2013; Ogawa *et al.* 2015; Okada *et al.* 2018) and
336 prediction of breeding value by exploiting public meteorological data (e.g., Zumbach *et al.*
337 2008; Fragomeni *et al.* 2016a; Tiezzi *et al.* 2020). For the letter, it is likely that a sow's response
338 to high ambient temperature is somewhat heritable and that the genetic correlations of sow
339 reproductive traits among seasons and ambient temperatures are not unity (e.g., Bloemhof *et*
340 *al.* 2008; Lewis and Bunter 2011; Tiezzi *et al.* 2020). Similar results were also reported for
341 production traits (e.g., Lewis and Bunter 2011; Fragomeni *et al.* 2016b; Usala *et al.* 2021). In
342 pig breeding, selection has been performed to improve meat production and number of piglets

343 weaned both in Japan (e.g., Suzuki *et al.* 2005; Tomiyama *et al.* 2011; Ohnishi and Satoh 2018)
344 and overseas (e.g., Merks 2000; Hill 2016; Zak *et al.* 2017). Genetic improvement of
345 productivity has brought about a large increase in total metabolic heat production (e.g.,
346 Cabezón *et al.* 2016; Johnson 2018; Johnson *et al.* 2019), reducing individual animals' ability
347 to cope with high ambient temperatures (e.g., Brown-Brandl *et al.* 2001; Renaudeau *et al.* 2011;
348 Robbins *et al.* 2021). Pork production in Japan is anticipated to be affected by global warming
349 (Takada *et al.* 2008; Sakatani 2014). Therefore, it is an urgent priority to establish new pig
350 breeding schemes to confront global warming (e.g., Bloemhof *et al.* 2012; Schaubberger *et al.*
351 2019; Tiezzi *et al.* 2020). In this regard, public meteorological data might offer a powerful
352 resource, and therefore, it is important to develop a future breeding scheme to genetically
353 improve heat tolerance of pigs in Japan (Carabaño *et al.* 2019; Mayorga *et al.* 2019; Rauw *et*
354 *al.* 2020).

355

356 **DATA AVAILABILITY STATEMENT**

357 Restrictions apply to the availability of these data, which were used under license for this study.

358

359 **CONFLICTS OF INTERESTS**

360 The authors declare that they have no competing interests.

361

362 **ACKNOWLEDGEMENTS**

363 This work was supported by a grant from the Ministry of Agriculture, Forestry, and Fisheries
364 of Japan (Development of Breeding Technology for Animal Life Production).

365

366 **REFERENCES**

367 Bertoldo MJ, Holyoake PK, Evans G, Grupen CG. (2012) Seasonal variation in the ovarian
368 function of sows. *Reproduction, Fertility and Development* **24**, 822–834. doi:
369 10.1071/RD11249

370 Bloemhof S, Mathur PK, Knol EF, van der Waaij EH. (2013) Effect of daily environmental
371 temperature on farrowing rate and total born in dam line sows. *Journal of Animal*
372 *Science* **91**, 2667–2679. doi: 10.2527/jas.2012-5902

373 Bloemhof S, Mathur PK, van der Waaij EH, Leenhouders JI, Knol EF. (2012) Genetic aspects
374 of heat stress in pigs expressed in fertility traits. *Paper at: 14 Seminar of the FAO-*
375 *CIHEAM Subnetwork on Sheep and Goat Nutrition and 2nd Lowinputbreeds*
376 *Symposium, Hammamet, Tunisia, 15-18 May 2012.*

377 Bloemhof S, van der Waaij EH, Merks JWM, Knol EF. (2008) Sow line differences in heat
378 stress tolerance expressed in reproductive performance traits. *Journal of Animal*
379 *Science* **86**, 3330–3337. doi: 10.2527/jas.2008-0862

380 Brown-Brandl TM, Eigenberg RA, Nienaber JA, Kachman SD. (2001) Thermoregulatory
381 profile of a newer genetic line of pigs. *Livestock Production Science* **71**, 253–260. doi:
382 10.1016/S0301-6226(01)00184-1

383 Cabezón FA, Schinckel AP, Richert BT, Stewart KR, Gandarillas M, Peralta WA. (2016)
384 Analysis of lactation feed intakes for sows including data on environmental
385 temperatures and humidity. *The Professional Animal Scientist* **32**, 333–345. doi:
386 10.15232/pas.2015-01495

- 387 Carabaño MJ, Ramón M, Menéndez-Buxadera A, Molina A, Díaz C. (2019) Selecting for heat
388 tolerance. *Animal Frontiers* **9**, 62–68. doi: 10.1093/af/vfy033
- 389 Curtis SE. (1983) Environmental management in animal agriculture. *Ames, Iowa: Iowa State*
390 *University Press. pp. 6–96.*
- 391 Edwards RL, Omtvedt IT, Tuesman EJ, Stephens DF, Mahoney GWA. (1968) Reproductive
392 performance of gilts following heat stress prior to breeding and in early gestation.
393 *Journal of Animal Science* **27**, 1634–1637. doi: 10.2527/jas1968.2761634x
- 394 Flowers B, Day BN. (1990) Alterations in gonadotropin secretion and ovarian function in
395 prepubertal gilts by elevated environmental temperature. *Biology of Reproduction* **42**,
396 465–471. doi: 10.1095/biolreprod42.3.465
- 397 Flowers B, Cantley TC, Martin MJ, Day BN. (1989) Effect of elevated ambient temperatures
398 on puberty in gilts. *Journal of Animal Science* **67**, 779–784. doi:
399 10.2527/jas1989.673779x
- 400 Fragomeni BO, Lourenco DAL, Tsuruta S, Andonov S, Gray KA, Huang Y, Misztal I. (2016a)
401 Modeling response to heat stress in pigs from nucleus and commercial farms in different
402 locations in the United States. *Journal of Animal Science* **94**, 4789–4798. doi:
403 10.2527/jas.2016-0536
- 404 Fragomeni BO, Lourenco DAL, Tsuruta S, Bradford HL, Gray KA, Huang Y, Misztal I.
405 (2016b) Using single-step genomic best linear unbiased predictor to enhance the
406 mitigation of seasonal losses due to heat stress in pigs. *Journal of Animal Science* **94**,
407 5004–5013. doi: 10.2527/jas.2016-0820
- 408 Freitas MS, Misztal I, Bohmanova J, West J. (2006) Utility of on- and off-farm weather records

- 409 for studies in genetics of heat tolerance. *Livestock Science* **105**, 223–228. doi:
410 10.1016/j.livsci.2006.06.011
- 411 Fujimoto K, Kawasaki M, Endo Y, Yokoyama T, Yamane I, Yamazaki H, Kure K, Haga T,
412 Sugiura K. (2021) Antimicrobial use on 74 Japanese pig farms in 2019: A comparison
413 of Japanese and European defined daily doses in the field. *PLoS One* **16**, e0255632.
414 doi: 10.1371/journal.pone.0255632
- 415 Guy SZY, Li L, Thomson PC, Hermes S. (2017) Contemporary group estimates adjusted for
416 climatic effects provide a finer definition of the unknown environmental challenges
417 experienced by growing pigs. *Journal of Animal Breeding and Genetics* **134**, 520–530.
418 doi: 10.1111/jbg.12282
- 419 Harada K, Komura H, Duran PG, Ochiai I, Fukuhara R. (1992) Effects of fattening season on
420 the growth pattern and estimated mature size of ultrasonic estimates of carcass traits in
421 live pigs. *Animal Science and Technology* **63**, 1042–1050. (in Japanese) doi:
422 10.2508/chikusan.63.1042
- 423 Hill WG. (2016) Is continued genetic improvement of livestock sustainable? *Genetics* **202**,
424 877–881. doi: 10.1534/genetics.115.186650
- 425 Iida R, Koketsu Y. (2013) Quantitative associations between outdoor climate data and weaning-
426 to-first-mating interval or adjusted 21-day litter weights during summer in Japanese
427 swine breeding herds. *Livestock Science* **152**, 253–260. doi:
428 10.1016/j.livsci.2012.12.014
- 429 Iida R, Koketsu Y. (2014a) Climatic factors associated with peripartum pig deaths during hot
430 and humid or cold seasons. *Preventive Veterinary Medicine* **115**, 166–172. doi:

- 431 10.1016/j.prevetmed.2014.03.019
- 432 Iida R, Koketsu Y. (2014b) Interactions between pre- or postservice climatic factors, parity, and
433 weaning-to-first-mating interval for total number of pigs born of female pigs serviced
434 during hot and humid or cold seasons. *Journal of Animal Science* **92**, 4180–4188. doi:
435 10.2527/jas.2014-7636
- 436 Johnson JS. (2018) Heat stress: impact on livestock well-being and productivity and mitigation
437 strategies to alleviate the negative effects. *Animal Production Science* **58**, 1404–1413.
438 doi: 10.1071/AN17725
- 439 Johnson JS, Zhang S, Morello GM, Maskal JM, Trottier NL. (2019) Technical note:
440 development of an indirect calorimetry system to determine heat production in
441 individual lactating sows. *Journal of Animal Science* **97**, 1609–1618. doi:
442 10.1093/jas/skz049
- 443 Kadowaki H, Suzuki E, Kojima-Shibata C, Suzuki K, Okamura T, Onodera W, Shibata T, Kano
444 H. (2012) Selection for resistance to swine mycoplasmal pneumonia over 5 generations
445 in Landrace pigs. *Livestock Science* **147**, 20–26. doi: 10.1016/j.livsci.2012.03.014
- 446 Kadowaki K, Osawa T, Ishii K, Inoue K. (2019) Estimates of genetic parameters for number
447 born alive using a random regression model with considered parities. *Japanese Journal*
448 *of Swine Science* **56**, 139–148. (in Japanese) doi: 10.5938/youton.56.4_139
- 449 Kakuma T. (2018) Seasonal effects on the pig farm management. *Japanese Journal of Swine*
450 *Science* **55**, 48–55. (in Japanese) doi: 10.5938/youton.55.2_48
- 451 Kim SW, Weaver AC, Shen YB, Zhao Y. (2013) Improving efficiency of sow productivity:
452 nutrition and health. *Journal of Animal Science and Biotechnology* **4**, 26. doi:

- 453 10.1186/2049-1891-4-26
- 454 Klei B, Tsuruta S. (2008) Approximate variance for heritability estimates. Accessed May. 21,
455 2020. http://nce.ads.uga.edu/~shogo/html/research/AI_SE.pdf
- 456 Koike N, Mai TN, Shirai M, Kubo M, Hata K, Marumoto N, Watanabe S, Sasaki Y, Mitoma S,
457 Notsu K, Okabayashi T, Wiratsudakul A, Kabali E, Norimine J, Sekiguchi S. (2018)
458 Detection of neutralizing antibody against porcine epidemic diarrhea virus in
459 subclinically infected finishing pigs. *The Journal of Veterinary Medical Science* **80**,
460 1782–1786. doi: 10.1292/jvms.18-0132
- 461 Konta A, Ogawa S, Kimata M, Ishii K, Uemoto Y, Satoh M. (2019) A study on the potential
462 for improving number born alive using teat number in pig female breeds. *Nihon*
463 *Chikusan Gakkaiho* **90**, 207–212. (in Japanese) doi: 10.2508/chikusan.90.207
- 464 Konta A, Ogawa S, Kimata M, Ishii K, Uemoto Y, Satoh M. (2020) Comparison of two models
465 to estimate genetic parameters for number of born alive in pigs. *Animal Science Journal*
466 **91**, e13417. doi: 10.1111/asj.13417
- 467 Lewis CRG, Bunter KL. (2011) Effects of seasonality and ambient temperature on genetic
468 parameters for production and reproductive traits in pigs. *Animal Production Science*
469 **51**, 615–626. doi: 10.1071/AN10265
- 470 Manno MC, Oliveira RFM, Donzele JL, Ferreira AS, Oliveira WP, Lima KRS, Vaz RGM.
471 (2005) Effect of thermal environment on performance of growing pigs from 15 to 30
472 kg. *Revisita Brasileira de Zootecnia* **34**, 1963–1970. doi: 10.1590/S1516-
473 35982005000600021
- 474 Mayorga EJ, Renaudeau D, Ramirez BC, Ross JW, Baumgard LH. (2019) Heat stress

- 475 adaptations in pigs. *Animal Frontiers* **9**, 54–61. doi: 10.1093/af/vfy035
- 476 Melzer N, Wittenburg D, Repsilber D. (2013) Integrating milk metabolite profile information
477 for the prediction of traditional milk traits based on SNP information for Holstein cows.
478 *PLoS One* **8**, e70256. doi: 10.1371/journal.pone.0070256
- 479 Merks JWM. (2000) One century of genetic changes in pigs and the future needs. *BSAS*
480 *Occasional Publication* **27**, 8–19. doi: 10.1017/S1463981500040498
- 481 Mellado M, Gaytán L, Macías-Cruz U, Avendaño L, Meza-Herrera C, Lozano EA, Rodríguez
482 Á, Mellado J. (2018) Effect of climate and insemination technique on reproductive
483 performance of gilts and sows in a subtropical zone of Mexico. *Austral Journal of*
484 *Veterinary Sciences* **50**, 27–34. doi: 10.4067/S0719-81322018000100106
- 485 Misztal I, Tsuruta S, Strabel T, Auvray B, Druet T, Lee DH. (2002) BLUPF90 and related
486 programs. *Proceedings of the 7th World Congress of Genetics Applied to Livestock*
487 *Production, Montpellier, France.*
- 488 Mount LE. (1959) The metabolic rate of the new-born pig in relation to environmental
489 temperature and to age. *The Journal of Physiology* **147**, 333–345. doi:
490 10.1113/jphysiol.1959.sp006247
- 491 Nardone A, Ronchi B, Lacetera N, Bernabucci U. (2006) Climatic effects on productive traits
492 in livestock. *Veterinary Research Communications* **30(Suppl. 1)**, 75–81. doi:
493 10.1007/s11259-006-0016-x
- 494 Ogawa S, Kimata M, Ishii K, Uemoto Y, Satoh M. (2021a) Genetic analysis for sow stayability
495 at different parities in purebred Landrace and Large White pigs. *Animal Science Journal*
496 **92**, e13599. doi: 10.1111/asj.13599

- 497 Ogawa S, Konta A, Kimata M, Ishii K, Uemoto Y, Satoh M. (2019a) Estimation of genetic
498 parameters for farrowing traits in purebred Landrace and Large White pigs. *Animal*
499 *Science Journal* **90**, 23–28. doi: 10.1111/asj.13120
- 500 Ogawa S, Konta A, Kimata M, Ishii K, Uemoto Y, Satoh M. (2019b) Genetic parameter
501 estimation for number born alive at different parities in Landrace and Large White pigs.
502 *Animal Science Journal* **90**, 1111–1119. doi: 10.1111/asj.13252
- 503 Ogawa S, Konta A, Kimata M, Ishii K, Uemoto Y, Satoh M. (2019c) Genetic relationship of
504 litter traits between farrowing and weaning in Landrace and Large White pigs. *Animal*
505 *Science Journal* **90**, 1510–1516. doi: 10.1111/asj.13304
- 506 Ogawa S, Matsuda H, Taniguchi Y, Watanabe T, Takasuga A, Sugimoto Y, Iwaisaki H. (2015)
507 Estimated genetic variances due to QTL candidate regions for carcass traits in Japanese
508 Black cattle. *Book of Abstracts of the 66th Annual Meeting of the European Association*
509 *for Animal Production, Warsaw, Poland*.
- 510 Ogawa S, Ohnishi C, Ishii K, Uemoto Y, Satoh M. (2020) Genetic relationship between litter
511 size traits at birth and body measurement and production traits in purebred Duroc pigs.
512 *Animal Science Journal* **91**, e13497. doi: 10.1111/asj.13497
- 513 Ogawa S, Yazaki N, Ohnishi C, Ishi K, Uemoto Y, Satoh M. (2021b) Maternal effect on body
514 measurement and meat production traits in purebred Duroc pigs. *Journal of Animal*
515 *Breeding and Genetics* **138**, 237–245. doi: 10.1111/jbg.12505
- 516 Ohnishi C, Satoh M. (2018) Estimation of genetic parameters for performance and body
517 measurement traits in Duroc pigs selected for average daily gain, loin muscle area, and
518 backfat thickness. *Livestock Science* **214**, 161–166. doi: 10.1016/j.livsci.2018.05.022

- 519 Okada D, Endo S, Matsuda H, Ogawa S, Taniguchi Y, Katsuta T, Watanabe T, Iwaisaki H.
520 (2018) An intersection network based on combining SNP coassociation and RNA
521 coexpression networks for feed utilization traits in Japanese Black cattle. *Journal of*
522 *Animal Science* **96**, 2553–2566. doi: 10.1093/jas/sky170
- 523 Omtvedt IT, Nelson RE, Edwards RL, Stephens DF, Turman EJ. (1971) Influence of heat stress
524 during early, mid and late pregnancy of gilts. *Journal of Animal Science* **32**, 312–317.
525 doi: 10.2527/jas1971.322312x
- 526 Peltoniemi OAT, Love RJ, Heinonen M, Tuovinen V, Saloniemi H. (1999) Seasonal and
527 management effects on fertility of the sow: a descriptive study. *Animal Reproduction*
528 *Science* **55**, 47–61. doi: 10.1016/S0378-4320(98)00159-6
- 529 Quesnel H, Pasquier A, Mounier AM, Prunier A. (1998) Influence of feed restriction during
530 lactation on gonadotropic hormones and ovarian development in primiparous sows.
531 *Journal of Animal Science*, **76**, 856–863. doi: 10.2527/1998.763856x
- 532 Rauw WM, de la Peña EM, Gomez-Raya L, Cortés LAG, Ciruelos JJ, Izquierdo EG. (2020)
533 Impact of environmental temperature on production traits in pigs. *Scientific Reports* **10**,
534 2106. doi: 10.1038/s41598-020-58981-w
- 535 Renaudeau D, Gourdine JL, St-Pierre NR. (2011) A meta-analysis of the effects of high ambient
536 temperature on growth performance of growing-finishing pigs. *Journal of Animal*
537 *Science* **89**, 2220–2230. doi: 10.2527/jas.2010-3329
- 538 Robbins LA, Green-Miller AR, Lay Jr. DC, Schinckel AP, Johnson JS, Gaskill BN. (2021)
539 Evaluation of sow thermal preference across three stages of reproduction. *Journal of*
540 *Animal Science* **99**, 1–10. doi: 10.1093/jas/skab202

- 541 Saito H, Koketsu Y. (2009) Factors associated with an occurrence of decreased pigs born alive
542 in parity 2 in commercial herds. *Journal of Veterinary Epidemiology* **13**, 40–45. doi:
543 10.2743/jve.13.40
- 544 Sakatani M. (2014) Effects of summer heat stress on domestic animals. *Japanese Journal of*
545 *Large Animal Clinics* **5 (supplement)**, 238–246. (in Japanese) doi: 10.4190/jjlac.5.238
- 546 Sasaki Y, Fujie M, Nakatake S, Kawabata T. (2018) Quantitative assessment of the effects of
547 outside temperature on farrowing rate in gilts and sows by using a multivariate logistic
548 regression model. *Animal Science Journal* **89**, 1187–1193. doi: 10.1111/asj.13048
- 549 Schauburger G, Mikovits C, Zollitsch W, Hörtenhuber SJ, Baumgartner J, Niebuhr K, Piringer
550 M, Knauder W, Anders I, Andre K, Hennig-Pauka I, Schönhart M. (2019) Global
551 warming impact on confined livestock in buildings: efficacy of adaptation measures to
552 reduce heat stress for growing-fattening pigs. *Climatic Change* **156**, 567–587. doi:
553 10.1007/s10584-019-02525-3
- 554 Suzuki K, Kadowaki H, Shibata T, Uchida H, Nishida A. (2005) Selection for daily gain, loin-
555 eye area, backfat thickness and intramuscular fat based on desired gains over seven
556 generations of Duroc pigs. *Livestock Production Science* **97**, 193–202. doi:
557 10.1016/j.livprodsci.2005.04.007
- 558 Takada R, Yamazaki M, Sugiura T, Yokozawa M, Otsuka M, Murakami H. (2008) Future
559 prediction of the effect of global warming on a pig growth performance estimated from
560 changes of the mean ambient temperature. *Nihon Chikusan Gakkaiho* **79**, 59–65. (in
561 Japanese) doi: 10.2508/chikusan.79.59
- 562 Tiezzi F, Brito LF, Howard J, Huang YJ, Gray K, Schwab C, Fix J, Maltecca C. (2020)

- 563 Genomics of heat tolerance in reproductive performance investigated in four
564 independent maternal lines of pigs. *Frontiers in Genetics* **11**, 629. doi:
565 10.3389/fgene.2020.00629
- 566 Tomiyama M, Kubo S, Takagi T, Suzuki K. (2011) Evaluation of genetic trends and
567 determination of the optimal number of cumulative records of parity required in
568 reproductive traits in a Large White pig population. *Animal Science Journal* **82**, 621–
569 626. doi: 10.1111/j.1740-0929.2011.00889.x
- 570 Tummaruk P. (2012) Effects of season, outdoor climate and photo period on age at first
571 observed estrus in Landrace×Yorkshire crossbred gilts in Thailand. *Livestock Science*
572 **144**, 163–172. doi: 10.1016/j.livsci.2011.11.010
- 573 Tummaruk P, Tantasuparuk W, Techakumphu M, Kunavongkrit A. (2004) Effect of season and
574 outdoor climate on litter size at birth in purebred Landrace and Yorkshire sows in
575 Thailand. *Journal of Veterinary Medical Science* **66**, 477–482. doi:
576 10.1292/jvms.66.477
- 577 Tummaruk P, Tantasuparuk W, Techakumphu M, Kunavongkrit A. (2010) Seasonal influences
578 on the litter size at birth of pigs are more pronounced in the gilt than sow litters. *The*
579 *Journal of Agricultural Science* **148**, 421–432. doi: 10.1017/S0021859610000110
- 580 Usala M, Macciotta NOP, Bergamaschi M, Maltecca C, Fix J, Schwab C, Shull C, Tiezzi F.
581 (2021) Genetic parameters for tolerance to heat stress in crossbred swine carcass traits.
582 *Frontiers in Genetics* **11**, 612815. doi: 10.3389/fgene.2020.612815
- 583 Wegner K, Lambertz C, Das G, Reiner G, Gauly M. (2014) Climatic effects on sow fertility
584 and piglet survival under influence of a moderate climate. *Animal* **8**, 1525–1533. doi:

585 10.1017/S1751731114001219

586 Wegner K, Lambertz C, Das G, Reiner G, Gauly M. (2016) Effects of temperature and
587 temperature-humidity index on the reproductive performance of sows during summer
588 months under a temperate climate. *Animal Science Journal* **87**, 1334–1339. doi:
589 10.1111/asj.12569

590 Wildt DE, Riegler GD, Dukelow WR. (1975) Physiological temperature response and
591 embryonic mortality in stressed swine. *American Journal of Physiology* **229**, 1471–
592 1475. doi: 10.1152/ajplegacy.1975.229.6.1471

593 Yan PS, Yamamoto S. (2000) Relationship between thermoregulatory responses and heat loss
594 in piglets. *Nihon Chikusan Gakkaiho*, **71**, 505–509. (in Japanese) doi:
595 10.2508/chikusan.71.10_505

596 Yazaki N, Ogawa S, Ohnishi C, Ishii K, Uemoto Y, Satoh M. (2020) Effectiveness of body
597 measurement traits for improving production traits in Duroc pigs. *Nihon Chikusan*
598 *Gakkaiho* **91**, 9–16. (in Japanese) doi: 10.2508/chikusan.91.9

599 Zak LJ, Gaustad AH, Bolarin A, Broekhuijse MLWJ, Walling GA, Knol EF. (2017) Genetic
600 control of complex traits, with a focus on reproduction in pigs. *Molecular Reproduction*
601 *and Development* **84**, 1004–1011. doi: 10.1002/mrd.22875

602 Zumbach B, Misztal I, Tsuruta S, Sanchez JP, Azain M, Herring W, Holl J, Long T, Culbertson
603 M. (2008) Genetic components of heat stress in finishing pigs: Development of a heat
604 load function. *Journal of Animal Science* **86**, 2082–2088. doi: 10.2527/jas.2007-0523

605 **TABLE 1** Descriptive statistics of phenotypic measurements of the studied traits

Trait	Abbreviation	Mean	SD	Min	Max
Total number born	TNB	8.8	2.8	1	17
Number born alive	NBA	7.7	2.8	1	15
Number stillborn	NSB	1.1	1.5	0	10

606 Abbreviations: Max, maximum value; Min, minimum value; SD, standard deviation.

607 **TABLE 2** Estimated values of effects of farrowing season, farrowing month, and off-farm daily maximum temperature of farrowing day

Factor	Level	Total number born					Number born alive					Number stillborn				
		Model					Model					Model				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Season	Spring	0.91	-	-	0.97	-	1.37	-	-	1.20	-	-0.45	-	-	-0.22	-
	Summer	0.87	-	-	0.97	-	1.12	-	-	0.95	-	-0.23	-	-	0.05	-
	Autumn	0.62	-	-	0.69	-	1.03	-	-	0.84	-	-0.43	-	-	-0.16	-
	Winter	0.00	-	-	0.00	-	0.00	-	-	0.00	-	0.00	-	-	0.00	-
Month	January	-	0.00	-	-	0.00	-	0.00	-	-	0.00	-	0.00	-	-	0.00
	February	-	0.58	-	-	0.69	-	0.24	-	-	0.20	-	0.34	-	-	0.48
	March	-	1.07	-	-	1.26	-	1.52	-	-	1.45	-	-0.43	-	-	-0.17
	April	-	1.14	-	-	1.47	-	1.60	-	-	1.49	-	-0.49	-	-	-0.05
	May	-	1.32	-	-	1.72	-	1.72	-	-	1.58	-	-0.39	-	-	0.14
	June	-	1.40	-	-	1.80	-	1.71	-	-	1.57	-	-0.29	-	-	0.24

	July	-	1.34	-	-	1.71	-	1.63	-	-	1.49	-	-0.26	-	-	0.24
	August	-	0.76	-	-	1.14	-	0.82	-	-	0.68	-	-0.05	-	-	0.46
	September	-	1.21	-	-	1.61	-	1.75	-	-	1.61	-	-0.53	-	-	0.01
	October	-	0.62	-	-	1.00	-	1.09	-	-	0.96	-	-0.50	-	-	0.01
	November	-	1.03	-	-	1.34	-	1.28	-	-	1.18	-	-0.28	-	-	0.13
	December	-	0.46	-	-	0.58	-	0.62	-	-	0.58	-	-0.17	-	-	-0.02
<hr/>																
Temperature	Linear	-	-	0.08	-0.02	-0.08	-	-	0.19	0.06	0.02	-	-	-0.12	-0.08	-0.10
	Quadratic ($\times 10^2$)	-	-	-0.13	0.03	0.14	-	-	0.37	0.13	0.04	-	-	0.25	0.16	0.18
<hr/>																

608 *Note:* Values were adjusted so that the estimated values of winter were 0 for Models 1 and 4 and those of January were 0 for Models 2 and 5.

609 **TABLE 3** Proportions of variances of phenotypic records explained by the estimated effects of farrowing season, farrowing month, and off-farm
 610 maximum temperature of farrowing day (diagonal) and Pearson's correlation coefficients between the values explained by those effects (below
 611 diagonal)

Model	Total number born					Number born alive					Number stillborn				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	<u>1.40%</u>					<u>2.87%</u>					<u>1.33%</u>				
2	0.827	<u>2.06%</u>				0.880	<u>3.66%</u>				0.842	<u>1.94%</u>			
3	0.642	0.574	<u>0.53%</u>			0.619	0.601	<u>1.62%</u>			0.579	0.524	<u>1.41%</u>		
4	0.977	0.821	0.769	<u>2.31%</u>		0.987	0.883	0.723	<u>2.91%</u>		0.854	0.743	0.885	<u>1.82%</u>	
5	0.863	0.972	0.727	0.889	<u>3.71%</u>	0.879	0.999	0.631	0.889	<u>3.66%</u>	0.730	0.873	0.760	0.857	<u>2.55%</u>

612

613 **TABLE 4** Estimated values of genetic parameters (standard errors in parentheses)

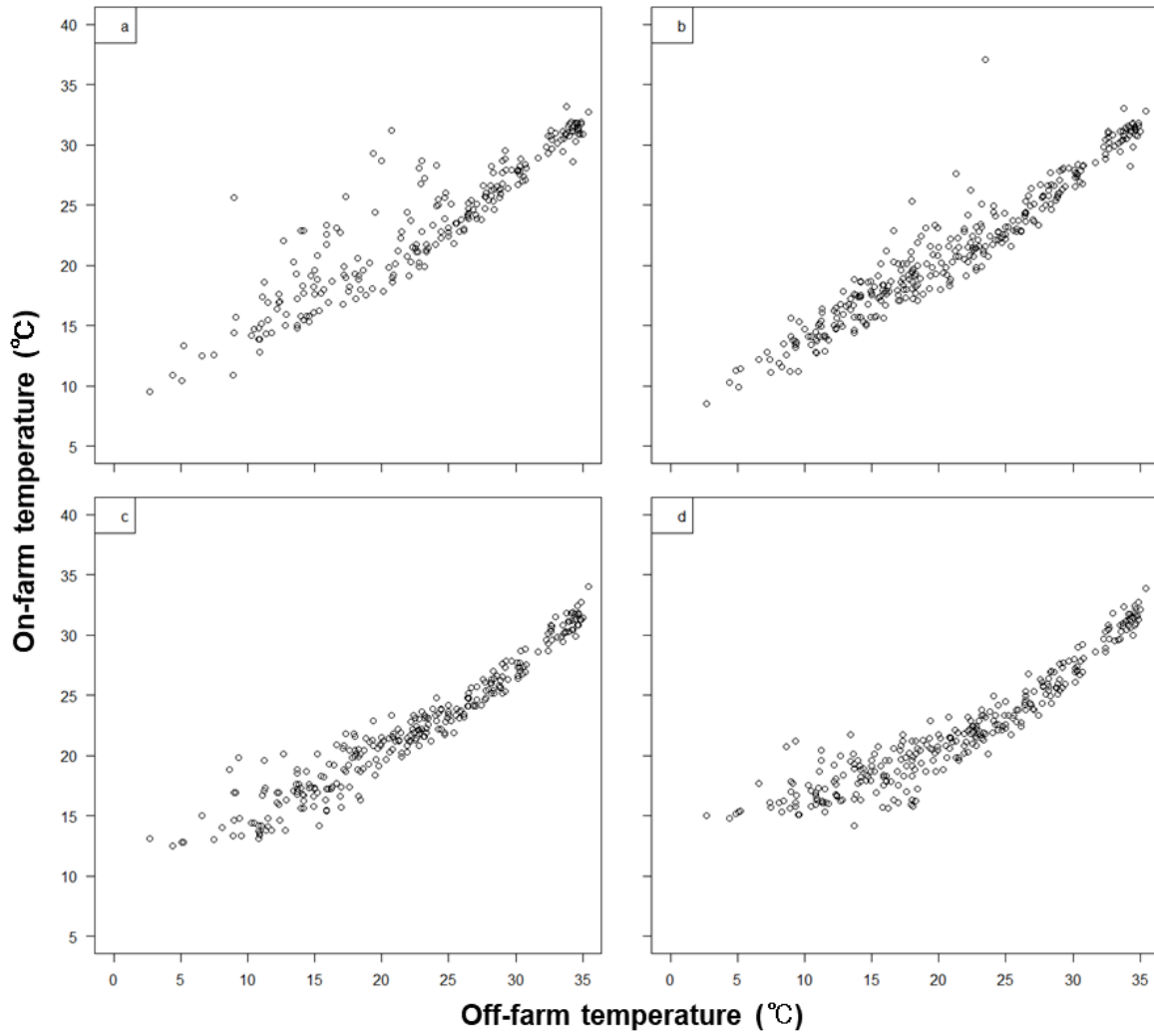
Model	σ_a^2	σ_{pe}^2	σ_e^2	h^2	rep^2
<i>Total number born</i>					
1	0.76 (0.43)	0.62 (0.38)	6.31 (0.31)	0.10 (0.05)	0.18 (0.03)
2	0.88 (0.45)	0.56 (0.39)	6.29 (0.32)	0.11 (0.06)	0.19 (0.03)
3	0.69 (0.43)	0.67 (0.39)	6.38 (0.32)	0.09 (0.05)	0.18 (0.03)
4	0.77 (0.43)	0.62 (0.38)	6.32 (0.32)	0.10 (0.05)	0.18 (0.03)
5	0.88 (0.45)	0.57 (0.39)	6.29 (0.32)	0.11 (0.06)	0.19 (0.04)
<i>Number born alive</i>					
1	1.20 (0.52)	0.42 (0.40)	6.27 (0.32)	0.15 (0.06)	0.20 (0.04)
2	1.32 (0.50)	0.30 (0.40)	6.27 (0.31)	0.17 (0.06)	0.21 (0.04)
3	1.16 (0.50)	0.38 (0.40)	6.40 (0.32)	0.15 (0.06)	0.19 (0.04)
4	1.19 (0.50)	0.41 (0.40)	6.28 (0.32)	0.15 (0.06)	0.20 (0.04)
5	1.33 (0.52)	0.29 (0.40)	6.29 (0.32)	0.15 (0.06)	0.20 (0.04)
<i>Number stillborn</i>					
1	0.17 (0.10)	0.12 (0.10)	1.90 (0.09)	0.08 (0.05)	0.13 (0.03)
2	0.18 (0.10)	0.12 (0.10)	1.90 (0.09)	0.08 (0.05)	0.13 (0.03)
3	0.17 (0.10)	0.11 (0.10)	1.90 (0.09)	0.08 (0.05)	0.13 (0.03)
4	0.18 (0.10)	0.11 (0.10)	1.90 (0.09)	0.08 (0.05)	0.13 (0.03)
5	0.18 (0.10)	0.11 (0.10)	1.89 (0.09)	0.08 (0.05)	0.13 (0.03)

614 *Note:* σ_a^2 , additive genetic variance; σ_{pe}^2 , permanent environmental variance; σ_e^2 , error
615 variance; h^2 , heritability; rep^2 , repeatability.

616 **TABLE 5** Spearman's rank correlations of predicted breeding values of 437 sows with their own records between different models

Model	Total number born				Number born alive				Number stillborn			
	1	2	3	4	1	2	3	4	1	2	3	4
2	0.997				0.997				0.993			
3	0.996	0.991			0.991	0.990			0.994	0.990		
4	>0.999	0.997	0.996		>0.999	0.997	0.993		0.995	0.996	0.997	
5	0.996	>0.999	0.990	0.996	0.997	>0.999	0.990	0.997	0.987	0.997	0.991	0.996

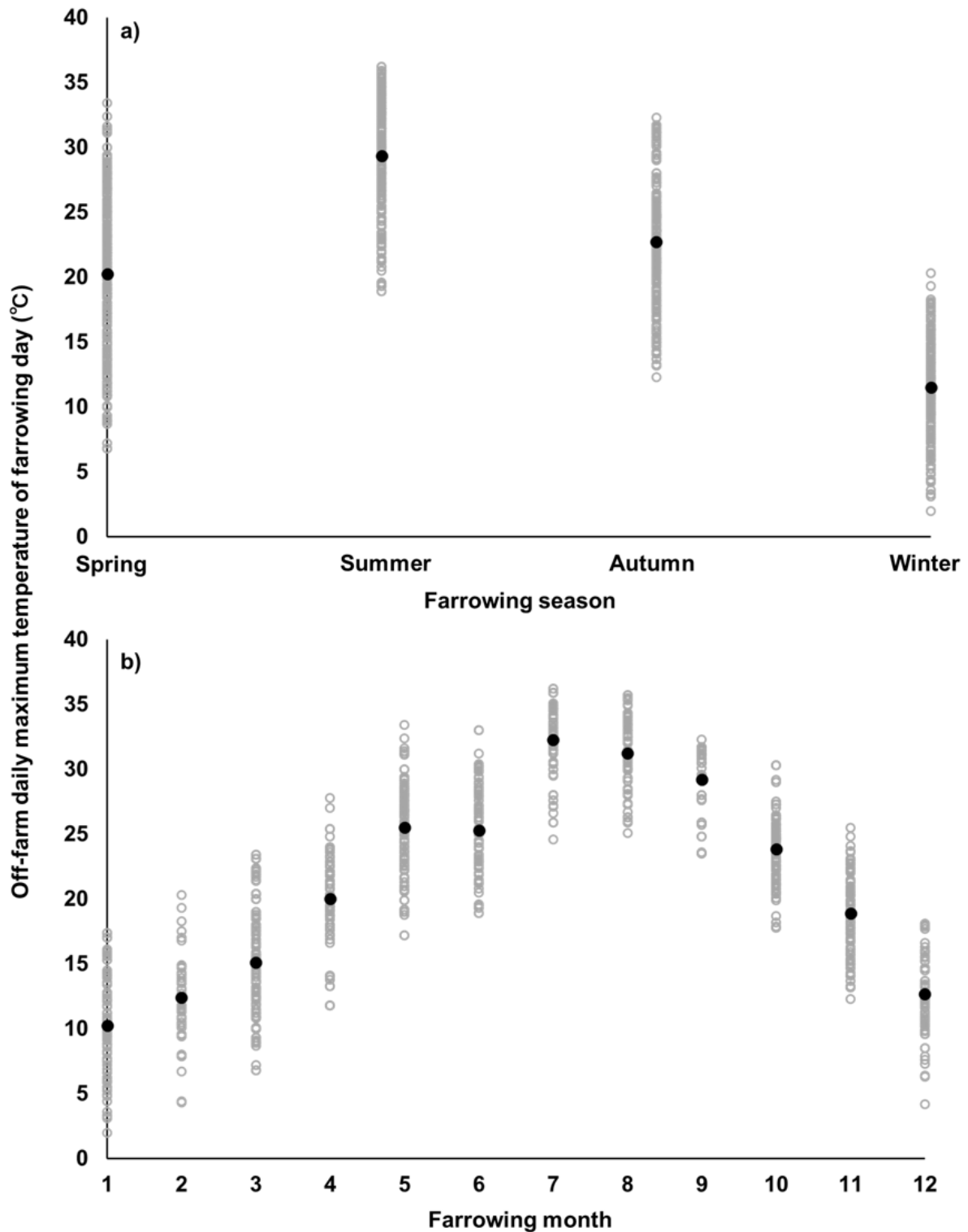
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618

619 **FIGURE 1** Scatter plots for on- and off-farm daily maximum temperatures. (a, b) Boar barns;

620 (c, d) growing barns.

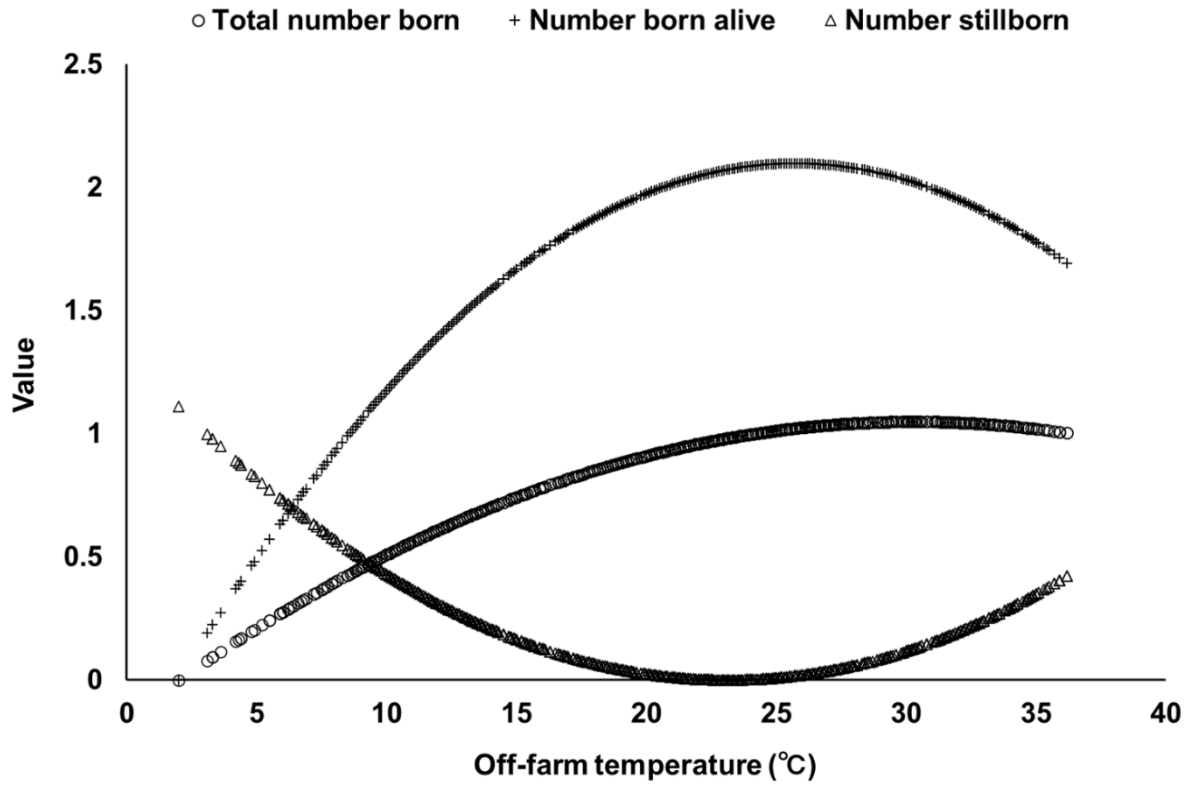


621

622 **FIGURE 2** Relationships between off-farm daily maximum temperature of farrowing day and

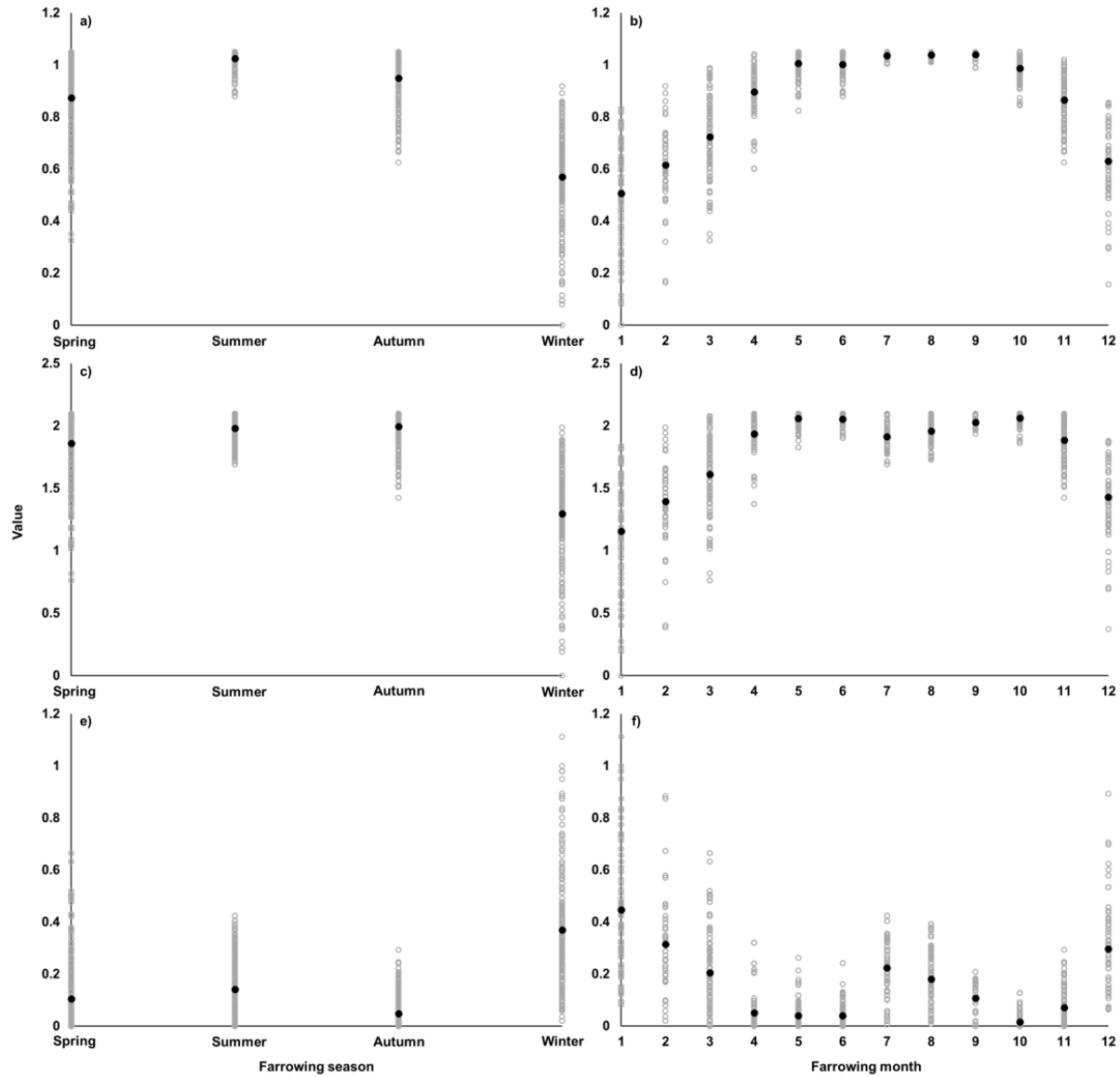
623 farrowing seasons and months. Black dots show the average values within each level of seasons

624 and months.



625

626 **FIGURE 3** Changes in the effects of off-farm maximum temperature of farrowing day
627 estimated using model 3. Values were adjusted so that their minimum value was equal to zero.



628

629

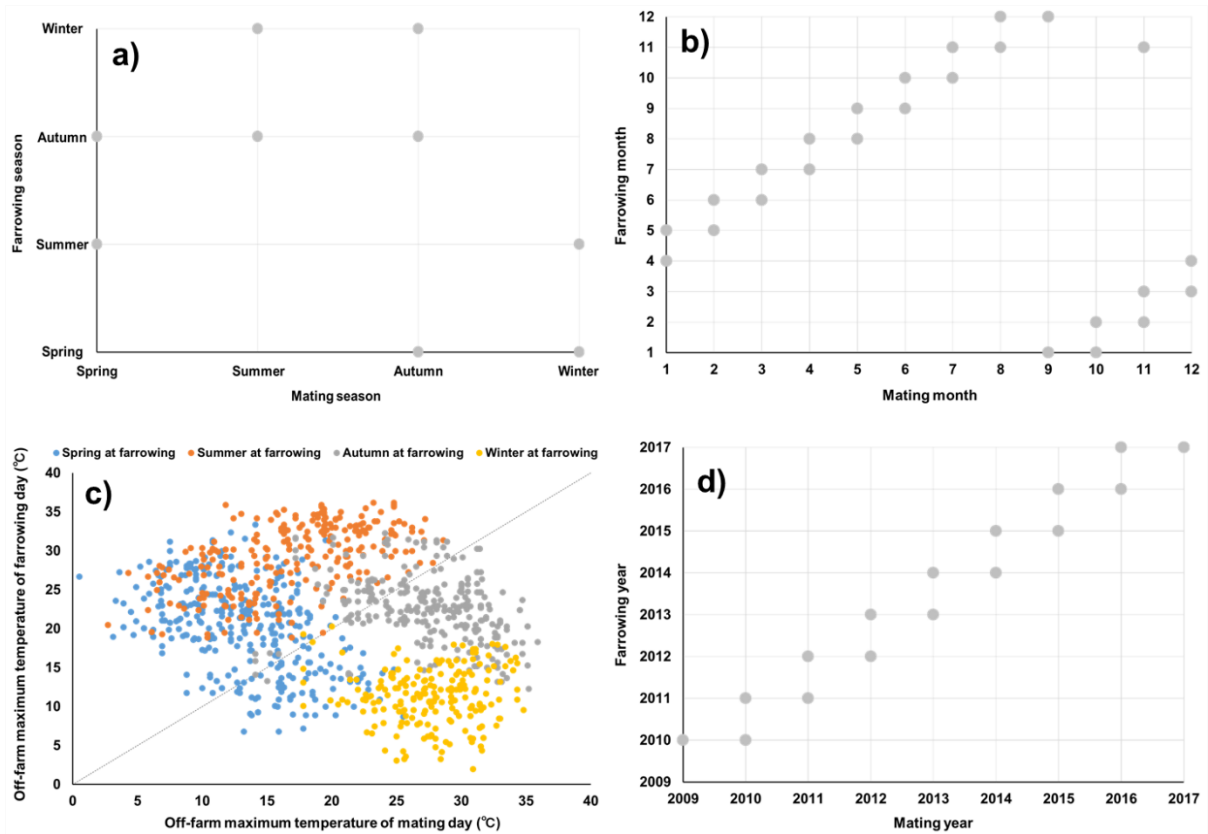
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633

FIGURE 4 Relationships between the effect of off-farm maximum temperature of farrowing day estimated using model 3 and corresponding farrowing seasons and months for total number born (a and b), number born alive (c and d), and number stillborn (e and f). Black dots show the average values within each level of seasons and months. Values were adjusted so that their minimum value was equal to zero.



634

635 **FIGURE 5** Relationship between mating and farrowing seasons (a), mating and farrowing

636 months (b), off-farm maximum temperatures of mating and farrowing days (c), and mating and

637 farrowing years (d) for each of farrowing records. Some records showed same month

638 (November in autumn) as mating and farrowing months, possibly due to errors in mating dates.