Genetic Parameters of Water and Feed Intake and Behavior Traits of Wean-to-Finish Pigs Under a Polymicrobial Natural Disease Challenge

Jian Cheng
Iowa State University of Science and Technology: Iowa State University https://orcid.org/0000-0002-7560-068X

Austin M. Putz
Iowa State University of Science and Technology: Iowa State University

John C. S. Harding
University of Saskatchewan

Michael K. Dyck
University of Alberta

Frederic Fortin
CDPQ

Graham S. Plastow
University of Alberta

Jack Dekkers (jdekkers@iastate.edu)
Iowa State University https://orcid.org/0000-0003-1557-7577

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Genetic parameters of water and feed intake and behavior traits of wean-to-finish pigs under a polymicrobial natural disease challenge

Jian Cheng[*], Austin M. Putz[*,†], John C. S. Harding[‡], Michael K. Dyck[§], Frederic Fortin[#], Graham S. Plastow[§], PigGen Canada[||], and Jack C. M. Dekkers[*]

[*] Department of Animal Science, Iowa State University, Ames, IA, United States, 50011

[†] Hendrix Genetics, Swine Business Unit, Boxmeer, The Netherlands, 5831 CK

[‡] Department of Large Animal Clinical Science, University of Saskatchewan, Saskatoon, SK, Canada, S7N 5A2

[§] Department of Agriculture, Food and Nutritional Science, University of Alberta, Edmonton, AB, Canada, T6G 2R3

[#] Centre de Développement du Porc du Québec Inc., Québec City, Canada, G1V 4M6

[||] PigGen Canada Research Consortium, Guelph, Ontario, Canada, N1H4G8

ABSTRACT

Background: The pork industry faces unprecedented challenges from disease, which increases cost of production and use of antibiotics, and reduces production efficiency, carcass quality, and animal wellbeing. One solution is to improve the overall resilience of pigs to a broad array of common diseases through genetic selection. Behavioral changes in eating and drinking are usually the very first clinical signs when animals are exposed to stressors such as disease. Changes in feed and water intake behaviors in diseased pigs may reflect the way they cope with the challenge and, thus, could be used as indicator traits to selection of disease resilience. The objectives of this study were to estimate genetic parameters of feed and water intake and behavior traits for wean-to-finish pigs in a natural polymicrobial disease challenge model, estimate genetic correlations of feed and water intake and behavior traits with growth rate and clinical disease traits, and to develop indicator traits for selection of disease resilience.

Results: In general, water intake traits had moderate to high estimates of heritability, especially for average daily water dispensed, duration, and number of visits (0.44 to 0.58). Similar estimates were observed for corresponding feed intake traits (0.35 to 0.51). Most genetic correlation estimates among drinking traits were moderate to high (0.30 to 0.92) and higher than among feeding traits (0 to 0.11). Compared to other water intake traits, water intake duration and number of visits had relatively stronger negative genetic correlation estimates with treatment rate and mortality, especially across the challenge nursery and finisher (-0.39 and -0.45 for treatment rate; -0.20 and -0.19 for mortality).

Conclusion: Most water and feed intake traits under severe disease challenge had moderate to high estimates of heritability, especially for feed or water intake duration and number of visits. Phenotypic and genetic correlations among feed intake traits under disease were generally low but

water intake traits showed high correlations with each other. Water intake duration and number of visits are potential indicator traits to select for disease resilience because of their high heritability and had moderate genetic correlations with treatment and mortality rates under severe disease.

Keywords: feeding and drinking behavior, disease resilience, genetic parameters, pigs

INTRODUCTION

Pork is the most consumed animal protein in the world and accounts for about 32% of total meat consumption (UNEP, 2012). The demand for animal protein is growing and is expected to increase by 73% by 2050 (IISD, 2011). However, the pork industry faces unprecedented challenges from diseases such as porcine reproductive and respiratory syndrome, porcine epidemic diarrhea, African swine fever, swine influenza, and others. Exposure to disease reduces production efficiency and carcass quality, increasing cost of production and use of antibiotics, and reducing animal wellbeing. Holtkamp et al. (2013) estimated the cost of porcine reproductive and respiratory syndrome in the U.S. at $664 million per year. Paarlberg (2014) reported that in the U.S., the porcine epidemic diarrhea virus outbreak in 2013 cost between $900 million and $1.8 billion. Antibiotics, vaccines, and biosecurity or management procedures are the main measures used for disease control but they are not always effective and vaccines are disease specific. An alternative is to improve the overall resilience of pigs to a broad array of common diseases through genetic selection (Albers et al., 1987 and Bisset and Morris,1996). Disease resilience is defined as the ability of an animal to maintain performance in the face of pathogen exposure (Berghof et al., 2018). Disease resilience is, however, difficult to incorporate in breeding programs because nucleus breeding stock must be raised in high-health conditions, preventing the collection of disease resilience data. To collect data on disease resilience and study the genetic basis of response of pigs to multiple diseases, a natural polymicrobial disease challenge model was established at a research station in Quebec, Canada (Putz et al. 2019). Estimates of genetic parameters of production and clinical disease data from this model were reported by Putz et al. (2019) and Cheng et al. (2020).

Behavioral changes in eating and drinking are one of the first observable clinical signs when animals are exposed to stress such as disease or extreme temperatures. Berghof et al. (2018) has explored the opportunities to determine new resilience indicators based on longitudinal data. Putz et a1. (2019) and Cheng et al. (2020) showed that a pigs' feeding behavior under a disease challenge is genetically associated with disease resilience. A pig's drinking pattern or behaviors may also change when affected by disease (Fortin et al. 2018; Kruse et al. 2011; Pedersen and Madsen. 2001). The amount of water each pig drinks and drinking behaviors such as the number of visits to the trough or other drinking systems, and duration of drinking on a daily basis or across the test period can vary significantly with disease and stress levels, as well as with temperature, humidity, and diet (Stockill, 1991). Specifically, Dybkjaer et al. (2006) reported that diarrhea in young pigs could be detected about one day before the clinical signs were apparent by monitoring water usage. Ahmed et al. (2015) reported that Salmonella infection in pigs resulted in reduced feeding and drinking activity. Kruse et al. (2011) used the wavelet transform to analyze water intake patterns to differentiate healthy and non-healthy sows. Changes in drinking behaviors in diseased pigs may reflect the way they cope with the pathogen, thereby indicating the health status and the level of motivation energy, which are partly influenced by the genotype of the pig (Ivoš et al. 1981).

The objectives of this study were to: 1) estimate genetic parameters for feed and water intake and behavior traits for wean-to-finish pigs from a natural disease challenge model; 2) estimate the genetic relationship of feed and water intake and behavior traits with growth rate and clinical disease traits; 3) evaluate the usefulness of day-to-day variation and proportion of off days derived from drinking behavior traits as indicators of disease resilience; and 4) develop other water and feed intake behavior indicator traits to select for disease resilience. For this study, the growth, feed intake, and clinical disease data analyzed by Cheng et al. (2020) were used but the focus herein was on drinking behavior traits that were not analyzed previously. Results for some feed intake and behavior traits from Cheng et al. (2020) are reported herein for comparison with results obtained here for water intake and behavior traits.

MATERIALS AND METHODS

This study was carried out in accordance with the Canadian Council on Animal Care guidelines (CCAC; https:((www.ccac.ca(en(certification(about-certification). The protocol was approved by the Protection Committee of the Centre de Recherche en Sciences Animales de Deschambault (CRSAD) and the Animal Care and Use Committee at the University of Alberta (AUP00002227). The project was fully overseen by the Centre de développement du porc du Québec (CDPQ) in Québec, Canada, and its herd veterinarian together with project veterinarians.

Data collection

All data and samples were collected by trained research staff from CDPQ using established natural challenge protocols, as described by Cheng et al. (2020). Data on 3,285 Large White by Landrace barrows from seven breeding companies were available. The natural challenge protocol consisted of three phases: (1) quarantine nursery (19 days on average, beginning at 3 week of age); (2) challenge nursey (27 days on average); and (3) finishing phase (100 days on average). The average group sizes in the three phases were 4.25, 7.16, and 10.72 pigs per pen, respectively. Pigs were re-grouped when moved to the challenge nursery and to the finisher.

Details of the phenotypes recorded and analyzed in the challenge nursery and finisher were described in Cheng et al. (2020). For health scores, treatment rates, and growth rate, data from pigs that died in the finisher were included in the analyses, with imputation and expansion of treatment and growth rates, as described in Cheng et al. (2020). Health scores were assigned by trained personnel based on clinical signs on a 1 to 5 scale: 1 = severe clinical signs with wasting and 5 = in perfect health, as described by Cheng et al. (2020). Treatment rate was adjusted by multiplying the number of treatments a pig received in the corresponding phase by the ratio of the average length of the phase and the number of days the pig spent in the phase. Mortality was recorded as 0 = survived and 1 = died.

Individual feed intake data were recorded in the finishing barn using IVOG feeding stations (Insentec, Marknesse, Netherlands) and edited using the methods of Casey et al. (2005). Individual water intake data were also recorded in the finishing barn using a individual water intake recording system for each pen. Designed and developed by CDPQ staff, the system allowed the recording of water intake and associated data for each pig's visit. A radio frequency identification system (RFID) was used for the identification of the pigs. The water delivery system includes a 3 L bowl that is closed on 3 sides to reduce water waste, a water nipple in the bowl that can be activated by the pigs, a water meter on the line that feeds the nipple, and a water level meter for the bowl. For each visit, the system records the time of day, the duration, and the amount of water dispensed from the nipple (dispensed) and removed from or added to the bowl. Water disappearance for each visit was calculated as water dispensed plus the change in water level in the bowl. For water and feed intake traits, only data on pigs that survived to slaughter were included in analysis. For feed intake, average daily feed intake, duration, and number of visits were analyzed. In total, feed intake data for 2,337 pigs were included in analyses, while water intake data on 2,331 pigs were available before data cleaning.

All animals were genotyped with the 650 k Affymetrix Axiom Porcine Genotyping Array by Delta Genomics (Edmonton AB, Canada). The 435,172 SNPs that passed quality control, as described by Cheng et al. (2020), were utilized for analysis.

Water intake data editing

Only water intake data collected between 70 and 150 days of age were used for each pig. In addition, to eliminate the potential impact of pen density on water intake traits, only data that were collected before the first pigs from a batch were sent to slaughter were used for analysis. Water disappearance data were summed across all visits on a day to compute the water disappearance and duration for each pig for each day. Water disappearance rate was also computed for each day and each pig as the ratio of water disappearance and intake duration. For the number of visits, visits of the same pig separated by less than 10 seconds were combined as one visit and a visit with zero water consumption was not counted as a visit. Because water dispensed was more heritable than water disappearance (0.44 versus 0.34, see later), water dispensed and dispense rate were also computed for each day and each pig, i.e. ignoring data from the bowl.

Representative water and feed intake data for a randomly selected pig are shown in Figures S1 to S4, illustrating the variability in daily water intake data, which was much larger than for feed intake data, in part because of the technical difficulty of measuring water intake. To reduce the effect of measurement erros, very strict editing protocols were implemented for the water intake data. Firstly, for each water intake trait defined above, outliers were identified on a daily basis within each batch if a pig's data for that day was greater than the predicted mean + 2 times the predicted interquartile range (IQRP) for that day and batch. The predicted mean was based on linear-quadratic regression of the water intake trait data on date by batch, as shown in Figure 1 and S5, while the IQRP was based on linear-quadratic regression of the IQR by day for that batch on date, as shown in Figure 1. A pig's data for a given day were removed for all water intake traits if an outlier was detected for one or more traits for that day. This resulted in removal of 9% of water intake days across all pigs. Secondly, because of the importance of having data at the start and end of the test period, data on pigs with more than 10 missing water intake days at the start (around 70 to 90 days age) or at the end (around 130 to 150 days of age) of the finisher period were removed by trait. This removed 32% to 41% of pigs, depending on the trait. Although removal of such a large portion of data can be a concern, these editing steps increased estimates of heritability for all traits by 52 to 100%, suggesting that the edits removed data that contained a lot of noise.

Derivation of water intake phenotypes

After outlier removal, the following phenotypic random regression model was used to predict the water intake trait for each pig for each day:

$$y_{ijk} = Batch_i + b_1 * Age_{ijk} + b_2 * Age_{ijk}^2 + Pen_j + \sum_{l=0}^{2} a_{ijkl} * Age_{ijk}^l + e_{ijk} \quad (1)$$

where y_{ijk} is the water intake phenotype; $Batch_i$ is a fixed batch effect (i= 1, …, 50); Age_{ijk} is the entry age; b_1 and b_2 are fixed regression coefficients; Pen_j is the random effect of finisher pen within batch, with vector $\boldsymbol{Pen} \sim N(\boldsymbol{0}, \boldsymbol{I}\sigma_P^2)$, where σ_P^2 is the pen variance and $\boldsymbol{I}$ is the identity. matrix; $\sum_{l=0}^{2} a_{ijkl} * Age_{ijk}^l$ is the random regression on age for pig k, where a_{ijkl} denotes the random regression coefficients for the k^{th} animal, and l is the order of the polynomial (l = 0,1, and

2), with variance-covariance structure for the random regression coefficients for an individual equal to $Var\begin{bmatrix} a_{ijk0} \\ a_{ijk1} \\ a_{ijk2} \end{bmatrix} = \begin{bmatrix} \sigma_0^2 & \sigma_{0,1} & \sigma_{0,2} \\ \sigma_{0,1} & \sigma_1^2 & \sigma_{1,2} \\ \sigma_{0,2} & \sigma_{1,2} & \sigma_2^2 \end{bmatrix}$, where $\sigma_0^2, \sigma_1^2, and\ \sigma_2^2$ are the variances for the intercept, linear, and quadratic regression coefficient, respectively, and $\sigma_{0,1}$, $\sigma_{0,2}$, and $\sigma_{1,2}$ are the corresponding covariances; e_{ijk} is the residual effect, with vector $\boldsymbol{e} \sim N(\boldsymbol{0}, \boldsymbol{I}\sigma_e^2)$, where σ_e^2 is the residual variance, allowing for heterogeneous residual variances by age class: 53 to 82 , 83 to 112, 113 to 142, 143 to 172, and greater than 172 days.

Average daily water intake phenotypes were computed based on the predicted values from the random regression model and included average daily water dispensed (ADWD), average daily water disappearance (ADWI), average daily water intake duration (WIDUR), average daily number of water intake visits (WInVisits), average daily water dispensed rate (WDRT), and average daily water disappearance rate (WIRT). Day-to-day variation in phenotypes was computed for each pig as the mean square root of deviations of observed from predicted values from the random regression model (Figure 2) and included day-to-day variation in water dispensed (VAR_{WD}), water disappearance (VAR_{WI}), water intake duration (VAR_{WIDUR}), number of water intake visits ($VAR_{WInVisits}$), water dispense rate (VAR_{WDRT}), and water disappearance rate (VAR_{WIRT}). The coefficient of variation for day-to-day variation phenotypes were calculated as the square root of the mean of the day-to-day variation of the water intake trait divided by the mean of corresponding average daily water intake trait across pigs, e.g. $\sqrt{\mathrm{VAR}_{WI}}/\mathrm{ADWI}$. The proportion of off-water days for each water intake trait was computed as the number of off-water days divided by total number of water intake days and included the proportion of off-water days based on water dispensed (OFF_{WD}), water disappearance (OFF_{WI}), water intake duration (OFF_{WIDUR}), number of water intake visits ($OFF_{WInVisits}$), water dispense rate (OFF_{WDRT}), and water disappearance rate

(OFF_{WIRT}). A day for a pig was considered an off-water day if the residual for that day from the random regression model was less than the IQRP of residuals (Figure 2), where the IQRP was obtained for each water intake day and each batch using linear quadratic regression of the observed IQR of residuals on water intake date. Pigs with more than 30% off-water days for a given trait were removed because their data likely reflects a malfunction of the water drinking system rather than poor resilience. This resulted in removal of 0.2, 5, 18, 18, 5, and 7% of pigs for $OFF_{WInVisits}$, OFF_{WIDUR}, OFF_{WI}, OFF_{WD}, OFF_{WIRT}, and OFF_{WDRT}, respectively.

To determine whether off-water days coincided with off-feed days, a pig's off-water days were compared with that pig's off-feed days throughout the finishing period for days for which a pig had both feed and water intake. In contrast to off-water intake days, off-feed intake days were identified based on quantile regression, as described by Putz et al. (2019). To explore the relationship between off days and health treatments, overlaps of off-water or off-feed days with days in which the pig received treatment were also investigated. To allow for some difference in the timing of off-water, off-feed, and treatment days, a 7-day rolling window was also used to identify the coincident off-feed, off-water, and treatment days. For example, off-water and off-feed events were considered to overlap for a 7-day window if that window included at least one off-water and one off-feed day. A similar strategy was used for overlaps with treatments. Chi-square tests were used to determine whether off-water, off-feed, and treatment events coincided significantly more than expected. The expected number of overlapping off-feed and off-water days was computed as the products of the proportion of off-feed days, the proportion of off-water days, and the total number of days with feed or water intake data (92,682). The expected coincident off-feed or off-water days with treatment were computed as the products of the proportion of off-feed or off-water days, the proportion of treatment days, and the total number days with feed or water intake data. When using 7-day windows, proportions and numbers of days were replaced by proportions and numbers of windows with at least one off-water or off-feed or treatment day.

Variance component estimation

Variance components were estimated by genomic best linear unbiased prediction (GBLUP) using ASReml 4.0 (Gilmour et al, 2015). The following general model was used in single-trait and bivariate analyses to estimate variance components and genetic correlations:

$$y_{ijk} = Batch_i + Age_{ijk} + Pen_j + u_{ijk} + litter_{ijk} + e_{ijk} \quad (2)$$

where y_{ijk} is the trait; $Batch_i$ is a fixed batch effect (i= 1, …, 50); Age_{ijk} is the covariate of age when the pig entered the quarantine nursery; Pen_j is the random effect of pen by batch corresponding the different phases, with vector $\boldsymbol{Pen} \sim \mathrm{N}(\mathbf{0}, \boldsymbol{I}\sigma_P^2)$, where σ_P^2 is the pen variance; u_{ijk} is the random additive genetic effect, with the vector $\boldsymbol{u} \sim \mathrm{N}(\mathbf{0}, \boldsymbol{G}\sigma_A^2)$, where $\boldsymbol{G}$ is the genomic relationship matrix and σ_A^2 is the additive genetic variance; $litter_{ijk}$ is the litter environmental effect, with vector $\boldsymbol{litter} \sim \mathrm{N}(\mathbf{0}, \boldsymbol{I}\sigma_l^2)$, where σ_l^2 is the litter environmental variance; e_{ijk} is the residual effect, with vector $\boldsymbol{e} \sim \mathrm{N}(\mathbf{0}, \boldsymbol{I}\sigma_e^2)$, where σ_e^2 is the residual variance. The genomic relationship matrix, ***G***, was created separately for each company using the software preGSf90 (Misztal et al., 2002) based on method one of VanRaden (2008). Then, the seven ***G*** matrices were combined into one ***G*** matrix, with genetic relationships between companies set to zero, such that the analyses focused on pooled within-company variances. Water-to-feed and feed-to-water ratio traits were also analyzed as conditional traits by fitting the corresponding feed or water intake phenotype of that animal as a covariate. For example, for analysis of ADFI conditional on ADWI, ADWI was fitted as a covariate in the model for analysis of ADFI.

RESULTS

Phenotypic data

Table 1 shows phenotypic means (SD) for all water intake, feed intake, and behavior traits, and the numbers of records retained for analysis. Comparing feed with water intake behaviors, pigs spent more than three times as much time eating than drinking on a daily basis but pigs made nearly twice as many visits to the drinker than to the feeder per day. As a result, pigs spent six times more time eating than drinking per visit. Day-to-day variation in feed intake duration was nearly three times greater than day-to-day variation in water intake duration, while day-to-day variation for the number of feed intake visits was less than for the number of water intake visits. Day-to-day variation in daily feed intake and in feed intake rate was lower than for water disappearance and water disappearance rate. However, the coefficients of day-to-day variation were greater for feed intake, number of visits, and feed intake rate than for the corresponding water intake traits. The proportions of off-water or off-feed intake days were small but twice as large for water intake traits than for feed intake traits, noting that different methods were used to identify off-water versus off-feed intake days.

Using only data on days for which a pig had both feed and water intake data, 54% of pigs had at least one off-feed day, 96% of pigs had at least one off-water day, and 41% of pigs received at least one treatment. On a daily basis, 2% of days were classified as off-feed, 12% as off-water, and 1% as treatment. Results for the overlap between off-days and treatment rate are in Table 2. Co-incidences of off-feed and off-water days and treatment days were all significantly ($P<0.0001$) greater than expected based on a Chi-square test, by a factor that ranged from 1.4 to 12.2 (Table 2), both on a daily basis and on a 7-day rolling window basis. On the basis of the 7-day rolling window, 10, 41, and 6% of windows had at least one off-feed, off-water, or treatment day, respectively.

Heritabilities of feed and water intak and behavior traits

Table 1 shows estimates of heritability and litter effects for the water intake, feed intake, and behavior traits. Water intake traits in general had moderate to high estimates of heritability, especially average daily water dispensed, duration, and number of visits (0.44 to 0.58). Similar estimates were observed for corresponding feed intake traits (0.35 to 0.51). Note that water dispensed (ADWD) and dispensed rate (WDRT) had higher estimates of heritability than water disappearance (ADWI) and disappearance rate (WIRT), respectively. Interestingly, estimates of heritability increased for all water intake traits (to 0.42 to 0.60) when the corresponding feed intake trait was fitted as a covariate. Similar increases were observed for feed intake and duration (to 0.42 and 0.55, respectively) when fitting the corresponding water intake trait as a covariate. Day-to-day variation in water intake traits had moderate estimates of heritability (0.22 to 0.38), while corresponding feed intake traits had a wider range of estimates (0 to 0.47). Day-to-day variation in the number of feed intake visits had the highest estimate of heritability (0.47), while day-to-day variation in feed intake and intake rate had low estimates of heritability (0.08 and 0, respectively). The proportion of off-days had low to moderate estimates of heritability for both water intake and feed intake traits (0.15 to 0.31 and 0.10 to 0.26, respectively). Litter effects were low for all traits, ranging from 0 to 0.13.

Correlations among water and feed intake and behavior traits

Table 3 shows estimates of genetic and phenotypic correlations among water and feed intake and behavior traits. Most of the genetic correlation estimates among water intake traits were moderate to high (0.30 to 0.92), except for water disappearance rate with water intake duration and number of visits (0.10 and -0.07). Note that water dispensed was highly correlated with water disappearance, both genetically and phenotypically (0.84 and 0.79). In contrast, most genetic correlations among feed intake traits were estimated to be low (0 to 0.11), except for feed intake rate with average daily feed intake (0.44). The majority of phenotypic correlations among water intake traits were also moderate to high (0.31 to 0.90), except for water intake duration with intake rate (0.09) and number of water intake visits with dispense rate and intake rate (0.09 and -0.08, respectively). Phenotypic correlations among feeding traits were low, except for feed intake rate with average daily feed intake and duration (0.51 and -0.70, respectively).

Table 4 shows estimates of phenotypic and genetic correlations between corresponding water and feed intake and behavior traits. Surprisingly, the water intake traits were not highly correlated with feed intake traits, either genetically (0.08 to 0.36) or phenotypically (0.13 to 0.39). The same was true for day-to-day variation and off-days traits.

Correlations of water and feed intake and behavior traits with growth traits

Estimates of genetic and phenotypic correlations of water and feed intake and behavior traits with growth rate in the three phases (quarantine nursery, challenge nursery, and finisher) are shown in Table 5. Water intake traits in general had low positive genetic correlation estimates with growth rate in the quarantine nursery but moderate positive genetic correlation estimates with growth rate in the challenge nursey and finisher. This means that, genetically, pigs that had higher growth rate under challenge, drank more water in the finisher, spent more time drinking, paid more visits to the drinker, and drank faster. Average daily feed intake and feed intake rate had moderate-to-high positive genetic correlation estimates with growth rate in the challenge nursey and finisher but lower genetic correlations with growth rate in quarantine nursery. Feed intake duration and number of visits, however, had very low and even negative genetic correlation estimates with growth rate in the different phases. This indicates that, genetically, pigs that had higher growth rate under challenge, ate more feed and ate faster in the finisher. Fitting feed or water intake traits as covariates for water and feed intake traits had minimal effects on the correlation estimates for growth rate, except for genetic correlations of ADWI and ADWD with finisher ADG, which decreased to near zero.

Most day-to-day variation traits for water intake traits had low positive genetic correlation estimates with growth rate in the quarantine and challenge nursery. Estimates of correlations with growth rate in finisher were stronger for day-to-day variation in water disappearance, dispensed, and duration (0.21, 0.20, and 0.27, respectively) than for day-to-day variation in number of visits, disappearance rate, and dispensed rate. Day-to-day variation in feed intake traits had stronger genetic correlation estimates with growth rate than day-to-day variation in the corresponding water intake traits. Day-to-day variation in daily feed intake had high positive genetic correlation estimates with growth rate in the quarantine and challenge nursery (0.55 and 0.65) and a moderate genetic correlation estimate with growth rate in the finisher (0.30). Day-to-day variation in feed intake duration and number of visits, however, had moderate negative genetic correlation estimates with growth rate in the challenge nursery and finisher. Day-to-day varitation in feed intake rate had very low estimates of heritability and, thus, had genetic correlation estimates with high standard errors. For the proportion of off-water or -feed days, off-water traits generally had lower genetic correlation estimates with growth rate than off-feed traits. Off-days for feed intake and intake rate had moderate-to-high negative genetic correlation estimates with growth rate in the challenge nursery and finisher (-0.35 to -0.80). Off-days for feed intake duration also had a high negative genetic correlation estimate with growth rate in the finisher. Estimates of phenotypic correlations in general were of a similar magnitude as genetic correlation estimates for off-days for all water and feed intake traits.

Correlations of water and feed intake and behavior traits with clinical disease traits

Table 6 shows estimates of phenotypic correlations of water and feed intake and behaviors with health scores and with treatment and mortality rates in the different phases. Phenotypic correlations with mortality rates were not computed because only pigs that survived were included for the water and feed intake trait analyses. Water intake traits generally had low phenotypic correlation estimates with health scores and treatment rates. Average daily feed intake and intake rate, however, had moderately high phenotypic correlation estimates with health score in the finisher (0.39 and 0.24) and with treatment rates (-0.18 to -0.30 for feed intake and -0.09 to -0.17 for intake rate). Fitting feed or water intake traits as covariates for water and feed intake traits did not substantially change their correlation estimates with health scores and treatment rates, except for ADWI and ADWD, for which phenotypic correlations decreased. Similar trends were found for day-to-day variation and off-days for water intake traits, which generally had low phenotypic correlation estimates with health scores and treatment rates. By contrast, day-to-day variation and off-days for feed intake and duration traits tended to have stronger phenotypic correlation estimates with health score in the finisher and with treatment rates. The proportion of off-feed days for intake rate also had strong phenotypic correlation estimates with health scores and treatment rates.

Estimates of genetic correlations of water and feed intake behavior traits with clinical disease traits are shown in Table 7. Treatment rate in the finisher had a zero estimate of heritability and was, thus, excluded from these analyses. Interestingly, water intake duration and number of visits had relatively stronger negative genetic correlation estimates with treatment and mortality rates than other traits, especially across the challenge nursery and finisher (-0.39 and -0.45 for treatment rate; -0.20 and -0.19 for mortality). This implies that, genetically, pigs that were more likely to die or that received more treatments spent less time drinking and paid fewer visits to drinker. Average daily water disappearance and dispensed were genetically positively correlated with health scores and negatively correlated with treatment and mortality rates, but these correlation estimates were not strong in general. Interestingly, water disappearance rate had moderate genetic correlation estimates with health scores in the challenge nursery and finisher (0.41 and 0.36), which means that pigs with higher health scores, genetically had a higher water disappearance rate. For feeding traits, feed intake duration and number of visits had moderately negative genetic correlation estimates with mortality in the finisher and across the challenge nursery and finisher (-0.23 to -0.43), which means that, genetically, pigs that were more likely to die spent less time eating and paid fewer visits to feeder. Average daily feed intake had moderate genetic correlation estimates with treatment rate (-0.25 to -0.33) and health score in the finisher (0.31). Fitting feed or water intake traits as covariates for water and feed intake traits in general had minimal effect on estimates of genetic correlations with clinical traits, except for ADWI and ADWD with health score in the finisher and with treatment rate across the challenge nursery and finisher, for which adding the covariate decreased the genetic correlation estimates.

Day-to-day variation in water intake traits in general had low to moderate genetic correlations with health scores and with treatment and mortality rates (Table 7). However, these correlation estimates, e.g., of day-to-day variation in water intake duration with treatment rate (-0.23 to -0.43) had unexpected directions because pigs that are less resilient were expected to have higher day-to-day variation in water intake traits. Day-to-day variation in feed intake traits generally had moderate to high genetic correlation estimates with resilience traits and in the expected direction.

Most off-days traits for water intake traits had low genetic correlation estimates with health scores and with treatment and mortality rates, except for off-days for water dispensed with mortality in the finisher and across the nursery and finisher (-0.46 and -0.37) and for off-days for water intake duration with treatment rate across the nursery and finisher (-0.46), but again in the unexpected direction. On the other hand, the proportion of off-days for for feed intake had strong genetic correlation estimates with health score in the finisher (-0.45), with treatment rate in the finisher and across the nursery and finisher (0.38 and 0.51), and with mortality across the nursery and finisher (0.48), all in the expected direction. Off-days for number of feed intake visits had moderate positive genetic correlation estimates with mortality in the finisher and across the nursery and finisher (0.32 and 0.34). Off-feed days for feed intake rate had moderate to high genetic correlation estimates with health score in the finisher (-0.36), with treatment rate in the finisher and across the nursery and finisher (0.28 and 0.48), and with mortality in the challenge nursery (0.60), all in the expected direction.

DISCUSSION

Although several studies have explored the impact of water intake on pig production performance and health (Fortin et al. 2018; Kruse et al. 2011; Pedersen and Madsen, 2001), very few studies have addressed the effect of health status on individual water intake and drinking behaviors (Ahmed at el. 2015). To our knowledge, this is the first study to report genetic parameters of individual water intake and drinking behaviors, especially under a disease challenge. In this study, we were also able to combine feed intake and water intake data and explore the relationship between feeding and drinking behaviors under a severe disease challenge and the relationship of these traits with disease resilience. Water intake is difficult to measure because pigs like to play with water, especially in hot weather, which makes individual water intake data noisier than individual feed intake data. To address this, we developed stringent methods for quality control and editing of the water intake data prior to analysis. Although this removed a large proportion of the data (9% of water intake days and 32 to 41% of pigs, depending on the trait), we believe these data processing steps were critical. In fact, estimates of heritability for the water intake traits increased by 50 to 100% following quality control editing. The resulting data and analyses provide novel insights into the phenotypic and genetic relationships among feed and water intake behavior traits under disease, as well as their relationships with disease resilience.

Genetic parameters of water and feed intake and behavior traits under a severe disease challenge

1. Heritability

Many estimates of genetic parameters of feeding behaviors in generally healthy pigs have been reported (Labroue et al,1997; Hall et al, 1999; Schulze et al, 2003; McSweeny et al, 2003; Ding et al, 2018). Reported estimates of heritability for feed intake duration per day, number of visits per day, and feed intake rate range from 0.31 to 0.46, from 0.29 to 0.43, and from 0.41 to 0.50, respectively. These estimates were in general slightly lower than the estimates reported in this study (Table 1), where pigs were under a severe disease challenge. However, to our knowledge, no studies have reported genetic parameters of water intake and drinking behaviors. Nevertheless, the water intake traits had estimates of heritability that were of a similar magnitude as those for feed intake traits. Water intake duration and number of visits per day were the most heritable among the water intake traits and were more heritable than the corresponding feed intake traits. Additionally, both feed and water intake duration and number of visits per day were more heritable than daily feed intake and daily water disappearance or dispensed. It should be noted that daily water dispensed was more heritable than water disappearance. The coefficient of variation was much higher for water dispensed than water disappearance (Table 1), which shows that water dispensed had higher variability. The same holds true for rates of water dispensed and disappearance. However, water dispensed and disappearance were strongly correlated with each other both phenotypically (0.79) and genetically (0.84), which was as expected, as both traits are a combination of water consumption, wastage, and playing behavior.

Putz et al. (2019) and Cheng et al. (2020) reported low to moderate estimates of heritability for day-to-day variation and the proportion of off-days derived from feed intake and duration. Similar results were also reported here because they were based on mostly the same feed intake data (Table 1). Day-to-day variation in the number of feed intake visits, which was not investigated in these previous studies, was found to be highly heritable. In general, both day-to-day variation and the proportion of off-days for water intake traits were low to moderately heritable.

2. Relationships between water and feed intake traits

In general, estimates of phenotypic and genetic correlations among feed intake traits were very low (Table 3). Estimates of the phenotypic (0.15) and genetic (0.10) correlation between daily feed intake and duration were much lower than the range of estimates reported in the literature

(0.17 to 0.88 and 0.14 to 0.97, respectively) (Labroue et al,1997; Schulze et al, 2003; McSweeny et al, 2003; Ding et al, 2018). Cheng et al. (2020) suggested that the low correlations in these data were probably because feed intake and duration were differently affected by the disease challenge. The average number of daily feed intake visits also had low phenotypic (-0.01) and genetic (0.11) correlations with daily feed intake and were also quite different than estimates reported in the literature (-0.4 to -0.09 and -0.35 to 0.02, respectively) (Labroue et al,1997; Schulze et al, 2003; McSweeny et al, 2003; Ding et al, 2018). The average number of daily feed intake visits also had low phenotypic and genetic correlations with daily feed intake duration (0.11 and 0.08, respectively) but these estimates were in the range of estimates reported in the literature (-0.12 to 0.15 and -0.21 to 0.38, respectively, Labroue et al,1997; Schulze et al, 2003; McSweeny et al, 2003; Ding et al, 2018). It is noteworthy that the range of correlation estimates in the literary is large, which could result from differences in feeding systems, breeds, environments, analytical models, health status, etc. The low correlations in our data may also be because the different feed intake traits were differentially affected by disease challenge, as is evident from the large coefficients of day-to-day variation in feed intake, duration, number of visits, and intake rate (0.67, 0.06, 0.14, and 2.5, respectively, Table 1). Feed intake rate had moderate positive phenotypic (0.51) and genetic (0.44) correlation estimates with daily feed intake in our data (Table 3), as well as strong negative phenotypic (-0.70) but very low genetic (0) correlations with duration, and very low phenotypic (0.10) and genetic (0) correlations with number of feed intake visits. Except for the low genetic correlation of feed intake rate with feed intake duration, these estimates were in general consistent with literature estimates (0.41 to 0.42 for phenotypic correlations and 0.20 to 0.49 for genetic correlations with daily feed intake; -0.76 to -0.70 for phenotypic correlations and -0.86 to -0.78 for genetic correlations with feed intake duration; -0.15 to -0.10 for phenotypic correlations and -0.22 to -0.12 for genetic correlations with number of feed intake visits) (Labroue et al,1997; Schulze et al, 2003). Most estimates of phenotypic and genetic correlations among water intake traits were much higher than corresponding estimates among feed intake traits (Table 3). Coefficients of day-to-day variation (Table 1) were more consistent across water intake than across feed intake traits (0.09 to 1.08 versus 0.06 to 2.50, respectively, Table 1).

To our knowledge, no studies have reported on genetic parameters of water intake traits but some studies have explored phenotypic relationships among water intake traits. Using data from cameras, Kashiha et al. (2013) found that water usage was highly related with the duration of drink nipple visits ($R^2 = 0.92$). Maselyne et al. (2015), using an RFID drinking system, found similar magnitudes of the relationships of water usage with the number of water intake visits ($R^2 = 0.69$ to 0.75) and duration ($R^2 =0.65$ to 0.71). All these studies were, however, conducting using generally healthy pigs.

Phenotypic and genetic correlations between corresponding feed and water intake traits were generally low (Table 4). This contradicts previous studies that suggest a high phenotypic relationship between feed and water intake traits (Huynh et al. 2005; Ahmed et al. 2015). However, these studies were conducted under conditions that were very different from our study, where pigs were under severe disease challenge, which may disproportionately affect feed and water intake, resulting in a reduction in the relationships between feed and water intake traits. In the present study, pigs were severely challenged with multiple viral and bacterial pathogens and resulted in chronic disease, particularly of the respiratory tract. Additionally, other factors, such as social stress and vaccination, could affect the pattern of water intake and feed intake.

Relationship of water and feed intake traits with growth rate

Average daily feed intake was strongly correlated with average daily gain (ADG) in the finisher, both phenotypically (0.86) and genetically (0.84), which is consistent with the literature (0.67 to 0.73 for phenotypic correlations and 0.77 to 0.87 for for genetic correlations) (Labroue et al,1997; McSweeny et al, 2003; Young et al. 2012), although pigs were under a severe disease challenge in this study. Feed intake rate was also moderately correlated with ADG in the finisher, both phenotypically (0.34) and genetically (0.42) and consistent with estimates in the same literature (0.25 to 0.28 for phenotypic correlations and 0.17 to 0.48 for genetic correlations) (Labroue et al,1997; McSweeny et al, 2003; Young et al. 2012). Interestingly, daily feed intake and intake rate (recorded in the finisher) were also moderately correlated with ADG in the challenge nursery, both phenotypically (0.40 to 0.42) and genetically (0.34 to 0.49), although ADG in the challenge nursey was weakly correlated with ADG in the finisher, both phenotypically (0.20) and genetically (0.15) (Cheng et al. 2020). This means pigs that grew faster in the challenge nursery ate more feed and ate faster in the finisher. Feed intake duration and number of visits, however, had very low phenotypic (0.16 and -0.03, respectively) and genetic (0.09 and -0.01, respectively) correlations with ADG in the finisher but in the range of estimates reported in the literature (0.13 to 0.64 for phenotypic correlations and 0.02 to 0.69 for genetic correlations with duration; -0.09 to 0.01 for phenotypic correlations and -0.22 to -0.03 for genetic correlations with number of visits) (Labroue et al,1997; McSweeny et al, 2003; Young et al. 2012). Water intake traits in general had low correlations with ADG in the nursery and the finisher, both phenotypically (-0.02 to 0.34) and genetically (-0.02 to 0.39). Very few studies have reported relationships of water intake with growth rate in pigs but Brew et al. (2011) reported a very low phenotypic relationship (R^2 = 0.005) of water intake with ADG in generally healthy growing beef cattle.

Day-to-day variation and the proportion of off-days for water intake traits had low phenotypic and genetic correlations with ADG in the nursery and the finisher (Table 5). In contrast, the proportion of off-days for feed intake, duration, and intake rate had moderate to strong negative phenotypic and genetic correlations with ADG in the finisher (-0.42 to -0.80), as was already established based on these data by Cheng et al. (2020).

Relationship of water and feed intake traits with clinical disease traits

There was clear evidence that off-feed, off-water, and treatment events coincided more often than expected by a factor of 1.42 to 12.22 (Table 2). This suggests that the feeding and drinking behaviors are related to the health status of pigs. However, feed and water intake traits in general had low phenotypic correlations with clinical disease traits (Table 6), except for the proportion of off-feed intake days with health score in the finisher (-0.35) and with treatment rate across the nursery and finisher (0.25 to 0.38). This could be because in the entire finishing period, only 41% of pigs received treatment and there were not many days pigs received medical treatments. Putz et al. (2019) and Cheng et al. (2020) demonstrated that day-to-day variation and the proportion of off-days for feed intake and duration were highly associated with disease resilience, using the same feed intake data as used herein. Water intake traits, however, consistently had low phenotypic correlations with clinical traits.

Estimates of genetic correlations of feed and water intake traits with clinical traits were in general much stronger than the corresponding phenotypic correlations (Table 6 and 7). Specifically, as already established by Cheng et al. (2020) for these data, average daily feed intake had moderately high genetic correlation estimates with health score in the finisher and with treatment rates but a low estimate with mortality. In contrast, feed intake duration and number of visits had moderately high genetic correlation estimates with mortality but low estimates with health scores and treatment rates. This indicates that genetically, mortality was more associated with feed intake duration and number of visits, while treatment rates and health scores were more related with feed intake. Water dispensed, duration, and number of visits generally had moderately high genetic correlation estimates with treatment rates and mortality. It is noteworthy that water dispensed had stronger genetic correlation estimates with treatment rates and mortality than water disappearance did, which means that, genetically, water dispensed was more affected by disease than water disappearance.

Day-to-day variation in feed intake had moderate to high genetic correlation estimates with mortality across the nursery and finisher (Table 6), which was already reported for these data in Putz et al. (2019) and Cheng et al. (2020). Day-to-day variation for feed intake duration and number of visits, on the other hand, had moderately high genetic correlation estimates with health scores, which were not reported previously. These moderate to high genetic correlation estimates were in the expected direction (negative with health score and positive with mortality), which suggests that these traits are potential indicator traits to select for disease resilience. Unfortunately, although day-to-day variation for water intake duration and number of visits had moderately high genetic correlation estimates with treatment rates, the negative sign of these estimates was opposite to expections. This maybe because healthy pigs are more active, developing thirst, or play with the drinker more than sick pigs. The proportion of off-days for feed intake had moderately high genetic correlation estimates with health score in the finisher, treatment rates, and mortality, and in these estimates were in the expected directions. Proportions of off-days for feed intake duration and number of visits, however, only had moderately genetic correlation estimates with mortality. Interestingly, the proportion of off-days for feed intake rate was estimated to be moderately genetically correlated with health score in the finisher and with treatment rates. The proportion of off-days for some drinking traits was also estimated to be moderately genetically correlated with clinical traits but, again, the signs of these estimates were opposite to expectations. Generally speaking, there were very few feed or water intake traits that showed consistent moderate or strong genetic correlations with all clinical traits. This is somewhat unexpected because strong genetic correlations were reported among these three clinical traits (Cheng et al. 2020).

Resilience indicator traits based on feed and water intake traits

Clinical disease traits such as treatment and mortality rates have been shown to have low heritability, both in the data used here (Cheng et al. 2020) and in the literature (Dufrasne et al. 2014; Guy et al. 2018) and are thus, difficult to improve by direct selection. Therefore, an important aim of this study was to find indicator traits of disease resilience that can be selected on instead. To be a useful indicator trait for indirect selection for disease resilience, it must be moderately to highly heritable and have a high genetic correlation with disease resilience. Based on the same data as used here, Putz et al. (2019) and Cheng et al. (2020) suggested that day-to-day variation and the proportion of off-days for feed intake and duration had great potential as indicators because of their moderately high heritabilities and strong genetic correlations with treatment and mortality rates. In the present study, additional feed and water intake traits were investiged and some showed great potential as well. The number of feed intake visits was highly heritable (0.51) and moderately genetically correlated with mortality in the finisher and, thus, could be used as an indicator trait to select against mortality under disease. Water intake duration and number of visits also had high estimates of heritability (0.54 and 0.58, respectively) and moderate genetic correlations with treatment and mortality rates, especially for treatment rate across the nursery and finisher (-0.39 to -0.45). Hence, these two water intake traits also have great potential as indicator traits to select for disease resilience. The water-to-feed ratio traits, obtained by fitting the corresponding feed intake traits as covariates when analyzing water intake, are also promising because of their even higher estimates of heritability (0.56 to 0.60) and similar magnitudes of genetic correlations with clinical traits as the non-ratio water intake traits.

Electronic feeders have been implemented in most nucleus breeding programs and Harlizius et al. (2020) has proved that the variation of individual feed intake collected form the nucleus farm could be used to improve finisher survival rate. Electronic feeders could also be used in commercial farms to provide the data needed to implement these indicator traits. With the availability of new technologies such as 3D cameras, thermal imaging, and sensors, recording feeding and drinking behavior traits on commercial farms can be implemented. Incorporation of these indicator traits into breeding programs could result in genetic improvement of resilience to disease. To achieve this goal, a specialized disease challenge facility or one or more commercial farms with severe disease issues could be used for collection of these resilience indicator traits and connected to selection candidates in the nucleus using genomic prediction.

CONCLUSIONS

Water and feed intake traits under a severe polymicrobial disease challenge in general had high estimates of heritability, especially for duration and number of visits for both feed and water intake. Phenotypic and genetic correlations among feed intake traits were generally low under the disease challenge but water intake traits showed high correlations amongst each other. Corresponding feed and water intake traits were not strongly correlated with each other under the disease challenge conditions. Water intake traits generally had low genetic correlations with growth rate under challenge but some feed intake traits such as daily feed intake and intake rate had moderate to strong genetic correlations with growth rate in the finisher. Day-to-day variation and the proportion of off-days for water intake traits were not highly genetically correlated with treatment and mortality rates, in contrast to the corresponding feed intake traits. However, water intake duration and number of visits were highly heritable and had moderately high genetic correlations with treatment and mortality rates and, thus, are potential indicator traits to select for disease resilience. Especially promising is the number of water intake visits, which had a high heritability of 0.58 and moderately high genetic correlations of -0.45 with treatment rate and -0.19 with mortality.

List of Abbreviations

ADFI, average daily feed intake

ADG, average daily gain

ADWI, average daily water disappearance

ADWD, average daily water dispensed

ADWI|ADFI, ratio trait by fitting ADFI as covariate for ADWI

ADWD|ADFI, ratio trait by fitting ADFI as covariate for ADWD

ADFI|ADWI, ratio trait by fitting ADWI as covariate for ADFI

ADFI|ADWD, ratio trait by fitting ADWD as covariate for ADFI

CV, coefficient of variation

FIDUR, average daily feed intake duration

FInVisits, average number of daily feed intake visits

FIRT: average daily feed intake rate

FIDUR|WIDUR, ratio trait by fitting WIDUR as covariate for FIDUR

FInVisits|WInVisits, ratio trait by fitting WInVisits as covariate for FInVisits

FinADG, average daily gain in finisher

FinMOR, mortality rate for pigs in finisher

FinTRT, number of health treatments per pig in finisher

GBLUP, genomic best linear unbiased prediction

IQR, interquartile range

IQRP, predicted IQR

OFF$_{\mathrm{FIDUR}}$, proportion of off-feed days for feed intake duration

OFF$_{\mathrm{FI}}$, proportion of off-feed days for feed intake

OFF$_{\mathrm{FInVisits}}$, proportion of off-feed days for number of feed intake visits

OFF$_{\mathrm{FIRT}}$, proportion of off-feed days for feed intake rate

OFF$_{\mathrm{WI}}$, proportion of off-water days for water disappearance

OFF$_{\mathrm{WD}}$, proportion of off-water days for water dispensed

OFF$_{\mathrm{WIDUR}}$, proportion of off-water days for water intake duration

OFF$_{\mathrm{WInVisits}}$, proportion of off-water days for water intake visits

OFF$_{\mathrm{WIRT}}$, proportion of off-water days for water disappearance rate

OFF$_{\mathrm{WDRT}}$, proportion of off-water days for water dispense rate

RFID, radio frequency identification system

SNP, single nucleotide polymorphism

VAR$_{\mathrm{FIDUR}}$, day-to-day variation in feed intake duration

VAR$_{\mathrm{FI}}$, day-to-day variation in feed intake

VAR$_{\mathrm{FInVisits}}$, day-to-day variation in number of feed intake visits

VAR_{FIRT}, day-to-day variation in feed intake rate

VAR_{WI}, day-to-day variation in water disappearance

VAR_{WD}, day-to-day variation in water dispensed

VAR_{WIDUR}, day-to-day variation in water intake duration

$VAR_{WInVisits}$, day-to-day variation in number of water intake visits

VAR_{WIRT}, day-to-day variation in water disappearance rate

VAR_{WDRT}, day-to-day variation in water dispense rate

WIDUR, average daily water intake duration

WInVisits, average number of daily water intake visits

WIRT, average daily water disappearance rate

WDRT, average daily water dispensed rate

WIDUR|FIDUR, ratio trait by fitting FIDUR as covariate for WIDUR

WInVisits|FInVisits, ratio trait by fitting FInVisits as covariate for WInVisits

Declarations

Ethics approval and consent to participate

Data used herein were obtained in the study described by Cheng et al. (2020), with the appropriate approvals.

Consent for publication

Not applicable

Availability of data and materials

Data used are on commercially owned animals and are, therefore, not publicly available. Data are, however, available from the authors upon reasonable request.

Competing interests

None

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Authors' contributions

JC analyzed the data and wrote the manuscript with help from JD. AP helped with data analysis. GP, MD, PC, JH, FF, and JD designed the project and developed protocols for animal sourcing, management, and phenotype recording in collaboration with members of PigGen Canada. JH was in charge of veterinary oversight on the project. GP was in charge of the database and genotyping for the project. FF was the lead on day-to-day data collection and scheduling. All authors helped with interpretation of the results and reviewed and approved the final manuscript.

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LITERATURE CITED

Albers G.A.A., Gray G.D., Piper L.R., Barker J.S.F., Lejambre L.F. & Barger I.A. The genetics of resistance and resilience to Haemonchus contortus infection in young merino sheep. Int. J. Parasitol. 1987. 17, 1355-1363.

Bisset S.A. and Morris C.A. 1996. Feasibility and implications of breeding sheep for resilience to nematode challenge. Int. J. Parasitol. 1996. 26, 857-868.

Ahmed, S.T., Mun, H.-S., Yoe, H., Yang, C. J. Monitoring of behavior using a video-recording system for recognition of Salmonella infection in experimentally infected growing pigs. Animal. 2015; 9, 115-121.

Brew, M.N. Myer R.O. Hersom M.J. Carter J.N. Elzo M.A. Hansen G.R. Riley D.G. Water intake and factors affecting water intake of growing beef cattle. Livest. Sci.2011; 140:297-300.

Berghof, T. V. L., M. Poppe, and H. A. Mulder. Opportunities to Improve Resilience in Animal Breeding Programs. Front. Genet. 2018. 14.

Casey, D. S., H. S. Stern, and J. C. M. Dekkers. Identification of errors and factors associated with errors in data from electronic swine feeders. J. Anim. Sci. 2005; 83, 969-982. doi:10.2527/2005.835969x.

Cheng, J., A. M. Putz, J. C. S. Harding, M. K. Dyck, F. Fortin, G. S. Plastow, PigGen Canada, and J. C. M. Dekkers. Genetic analysis of disease resilience in wean-to-finish pigs from a natural disease challenge model. J. Anim. Sci. 2020; skaa244, https://doi.org/10.1093/jas/skaa244.

Dybkjaer, L., Jacobsen A.P., Togersen F.A., Poulsen H.D. Eating and drinking activity of newly weaned piglets: effects of individual characteristics, social mixing, and addition of extra zinc to the feed. J. Anim. Sci. 2006; 84(3):702-11.

Dufrasne, M., Misztal, I., Tsuruta, S., Gengler, N., and Gray, K. A. Genetic analysis of pig survival up to commercial weight in a crossbred population. Livest. Sci. 2014; 167, 19-24. doi: 10.1016/j.livsci.2014.05.001.

Ding R, Yang M, Wang X, Quan J, Zhuang Z, Zhou S, Li S, Xu Z, Zheng E, Cai G, Liu D., Huang W, Yang J. and Wu Z. Genetic architecture of feeding behavior and feed efficiency in a duroc pig population. Front. Genet. 2018; 9:220. doi: 10.3389/fgene.2018.00220.

Fortin, F., Turgeon J., Gagnon P., Caron-Simard V. Results and perspectives about automated water intake recording, infrared thermography and visual systems. 2018; BANFF Pork Seminar, Banff, Alberta, Canada, 10-11 January.

Gilmour. A. R., Gogel, B.J., Cullis, B.R., Welham, S.J., Thompson, R. ASReml user guide release 4.1 structural specification. 2015; Hemel Hempstead: VSN International.

Guy, S. Z. Y., Li, L., Thomson, P. C., and Hermesch, S. “Genetic parameters for health of the growing pig using medication records,” in Proceeding 11th World Congress of Genetics Applied to Livestock Production, (Auckland). 2018.

Hall, A. D., Hill, W. G., Bampton, P. R., and Webb, A. J. Genetic and phenotypic parameter estimates for feeding pattern and performance tests traits in pigs. Europe PubMed Central, 1999; 68, 43-48.

Huynh, T.T.T., Aarnonk A.J.A., Verstegen M.W.A., Gerrits W.J.J., Heetkamp M.J.W., Kemp B., Canh T.T. Effects of increasing temperatures on physiological changes in pigs at different relative humidities. J. Anim. Sci. 2005; 83, 1385-1396.

Holtkamp, D.J., Kliebenstein, J.B., Neumann, E.J., Zimmerman, J.J., Rotto, H.F., Yoder, T.K., Wang, C., Yeske, P.E., Mowrer, C.L., Haley, C.A. Assessment of the economic impact of porcine reproductive and respiratory syndrome virus on United States pork producers. J. Swine Health Prod. 2013; 21:72-84.

IISD. International Institute for Sustainable Development. 2011; http://sdg.iisd.org/news/fao-world-livestock-report-projects-drastic-increase-in-meat-consumption/ .

Ivoš, J., Krsnik B. and Kovacˇević S. Ecology and production in pig-breeding. Stocˇarstvo. 1981; 35, 379-416.

Kruse, S., Traulsen I., Salau J., Krieter J. A note on using wavelet analysis for disease detection in lactating sows. Comput. Electron. Agric. 2011; 77(1):105-9.

Kashiha, M., Bahr, C., Haredasht, S. A., Ott, S., Moons, C., Niewold, T. A., Odberg, F., et al. The automatic monitoring of pigs water use by cameras. Comput. Electron. Agric. 2013; 90, 164-169.

Labroue, F., Gueblez, R., and Sellier, P. Genetic parameters of feeding behaviour and performance traits in group-housed Large White and French Landrace growing pigs. Genet. Sel. Evol. 1997; 29(4), 451-468.

Morgan, C. A., Emmans G.C., Tolkamp B.J., Kyriazakis I. Analysis of the feeding behavior of pigs using different models. Physiol. Behav. 2000; 68, 395-403.

Misztal, I., Tsuruta, S., Strabel, T., Auvray, B., Druet, T., and Lee, D. H. "BLUPF90 and related programs (BGF90)," in Procceding 7th World Congress of Genetics Applied to Livestock Production, (Montpellier). 2002.

McSweeny, J. M., Hermesch, S., and Crump, R. Genetic analysis of feeding pattern traits in pigs. Animal Genetics and Breeding Unit, a Joint Venture of the University of New England and NSW Agriculture, University of New England, Armidale, NSW, 2003; 2351.

Maselyne, J., I. Adriaens, T. Huybrechts, B. De Ketelaere, S. Millet, J. Vangeyte, A. Van Nuffel, W. Saeys. Measuring the drinking behaviour of individual pigs housed in group using radio frequency identification (RFID). Animal. 2015; pp. 1-10.

Pedersen, B. K., Madsen T.N. Monitoring water intake in pigs: prediction of disease and stressors. In Stowell RR, Bucklin R, Bottcher RW, editors. Proceedings of the Sixth International Livestock Environment Symposium. Amer. Soc. Ag. Eng., St. Joseph, MI, p. 173-9. 2001.

Paarlberg. Updated estimated economic welfare impacts of Porcine Epidemic Diarrhea virus (PEDV) Department of Agricultural Economics, Purdue University, 2014; Working Paper #14-4

Putz, A. M., Harding J.C.S., Dyck M.K., Fortin F., Plastow G.S., Dekkers J.C.M. and PigGen Canada. Novel resilience phenotypes using feed intake data from a natural disease challenge model in wean-to-finish pigs. Front. Genet. 2019; 9:660. doi: 10.3389/fgene.2018.00660.

Stockill, P. Water: The neglected nutrient. Large Animal Veterinarian July/August. 1991.

Schulze, V., Roehe, R., Bermejo, J. L., Looft, H., & Kalm, E. The influence of feeding behaviour on feed intake curve parameters and performance traits of stationtested boars. Livest. Prod. Sci., 2003; 82, 105-116.

UNEP. The critical role of global food consumption patterns in achieving sustainable food systems and food for all. 2012; http://www.humanmedia.org/dcc/pdf/unep_food_report_2012.pdf

VanRaden, P. Efficient methods to compute genomic prediction. J. Dairy Sci.2008; 91, 4414-4423. doi: 10.3168/jds.2007-0980

Young, J. M., Dekkers, J., Gabler, N., Johnson, A., Nettleton, D., Rothschild, M. , and Tuggle, C. The effect of selection for residual feed intake during the grow/finish phase of production on feeding behavior traits and sow reproduction and lactation efficiency in yorkshire pigs. PhD Dissertation. 2012; Iowa State University, Ames.

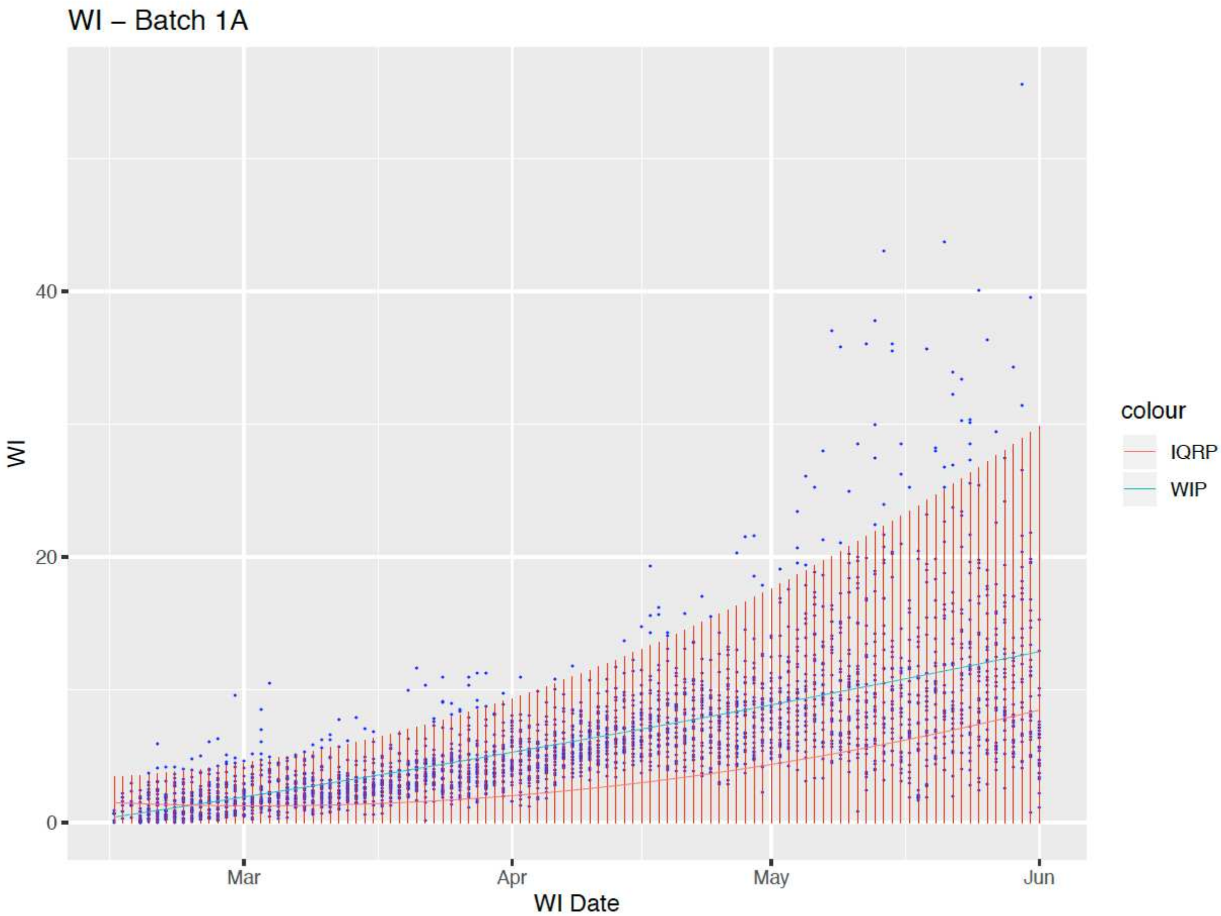

Figure 1. Outlier detection for water disappearance (WI) for a random batch of pigs based on predicted mean (WIP) + 2 times the predicted interquartile range (IQRP).

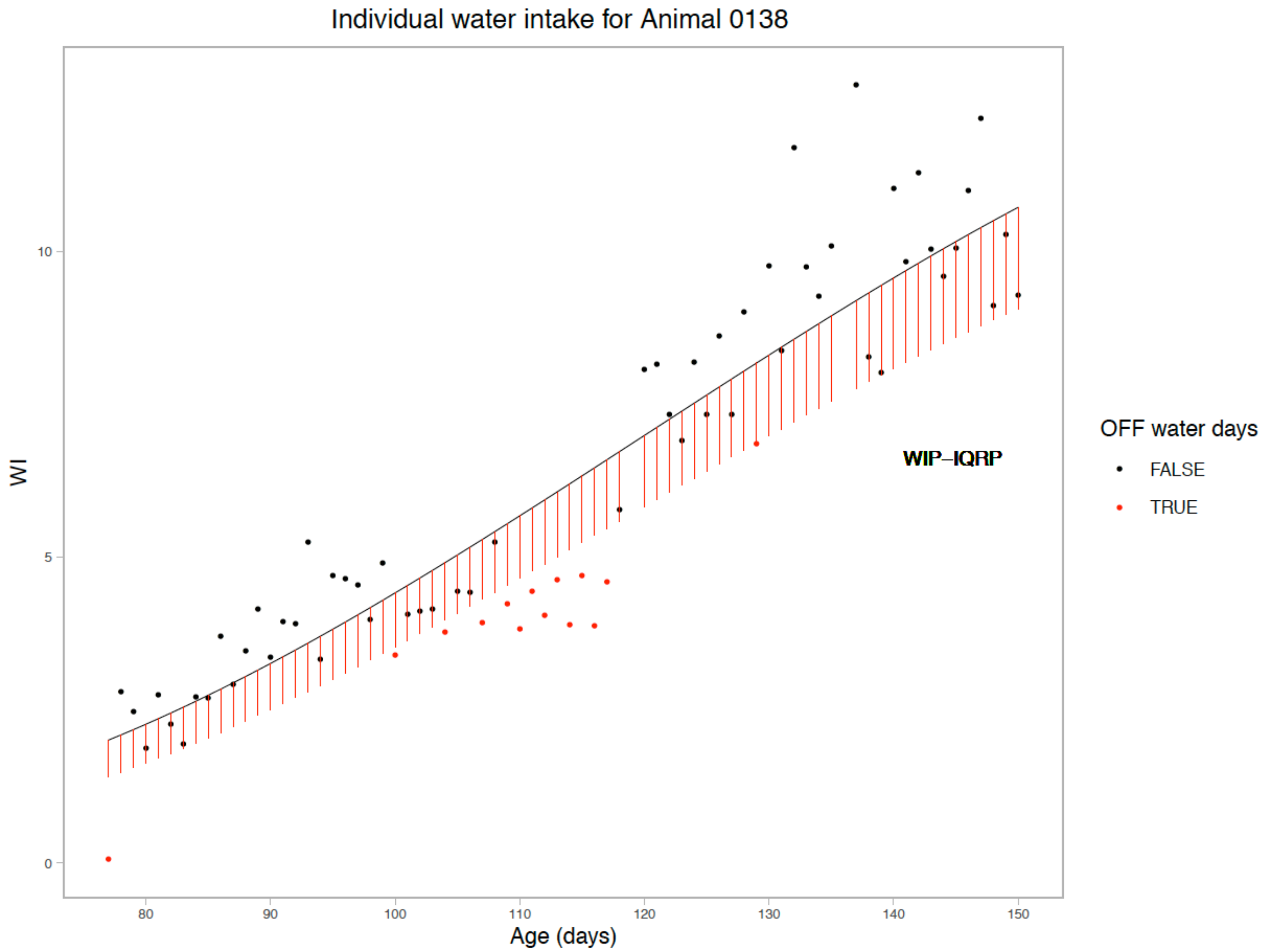

Figure 2. Derivation of day-to-day variation and proportion of off-water days for the water disappearance (WI) data of an randomly selected pig. TRUE: off-water days; FALSE: non off-water days. Solid line represents the predicted WI based on a quadratic random regression model; day-to-day variation in WI was computed as the square root of the sum of squared residuals. Red lines represent the predicted interquartile range of random regression residuals within the batch based on a quadratic regression model; daily water intake data that had residuals less than the predicted interquartile range were considered off-water days.

Table 1. Summary statistics and estimates (SE in parentheses) of heritability (h^2) and litter effects (c^2) for water and feed intake and behavior traits

Trait	No. records	Mean	SD	CV	h^2 (SE)	c^2 (SE)
Water intake						
ADWI (L/d)	1,379	5.06	2.42	0.48	0.34 (0.08)	0.05 (0.04)
ADWD (L/d)	1,426	4.84	3.30	0.68	0.44 (0.07)	0.04 (0.04)
WIDUR (min/d)	1,525	14.73	4.37	0.30	0.54 (0.07)	0.06 (0.03)
WInVisits	1,598	31.32	7.49	0.24	0.58 (0.06)	0.01 (0.03)
WIRT (L/min)	1,529	0.36	0.13	0.36	0.25 (0.06)	0.00 (0.00)
WDRT (L/min)	1,533	0.32	0.18	0.56	0.30 (0.07)	0.02 (0.03)
ADWI|ADFI	1,379	-	-	-	0.42 (0.08)	0.02 (0.04)
ADWD|ADFI	1,426	-	-	-	0.50 (0.07)	0.02 (0.03)
WIDUR|FIDUR	1,525	-	-	-	0.56 (0.07)	0.05 (0.03)
WInVisits|FInVisits	1,598	-	-	-	0.60 (0.06)	0.02 (0.03)
Feed intake						
ADFI (kg/d)	2,337	2.20	0.32	0.15	0.35 (0.05)	0.03 (0.03)
FIDUR (min/d)	2,337	59.51	11.49	0.19	0.49 (0.06)	0.04 (0.03)
FInVisits	2,337	17.71	6.79	0.38	0.51 (0.05)	0.08 (0.03)
FIRT (kg/min)	2,337	0.038	0.009	0.25	0.45 (0.05)	0.03 (0.03)
ADFI|ADWI	2,337	-	-	-	0.42 (0.06)	0.00 (0.00)
ADFI|ADWD	2,337	-	-	-	0.42 (0.06)	0.00 (0.00)
FIDUR|WIDUR	2,337	-	-	-	0.55 (0.07)	0.02 (0.03)
FInVisits|WInVisits	2,337	-	-	-	0.46 (0.07)	0.12 (0.04)
Water intake						
VAR_{WI}	1,379	2.08	1.41	0.29[1]	0.35 (0.07)	0.00 (0.00)
VAR_{WD}	1,426	2.51	1.66	0.33[1]	0.38 (0.08)	0.01 (0.04)
VAR_{WIDUR}	1,525	4.84	2.06	0.15[1]	0.25 (0.07)	0.13 (0.04)
$VAR_{WInVisits}$	1,598	8.83	2.74	0.09[1]	0.33 (0.07)	0.06 (0.04)
VAR_{WIRT}	1,529	0.11	0.04	0.92[1]	0.22 (0.06)	0.00 (0.00)
VAR_{WDRT}	1,533	0.12	0.05	1.08[1]	0.22 (0.07)	0.00 (0.00)
Feed intake						
VAR_{FI}	2,337	0.50	0.10	0.67[1]	0.08 (0.04)	0.02 (0.03)
VAR_{FIDUR}	2,337	13.35	3.79	0.06[1]	0.23 (0.05)	0.02 (0.03)
$VAR_{FInVisits}$	2,292	6.12	2.46	0.14[1]	0.47 (0.06)	0.08 (0.03)
VAR_{FIRT}	2,292	0.058	0.006	2.50[1]	0.00 (0.00)	0.04 (0.03)
Water intake						
OFF_{WI}	1,308	0.12	0.08	0.67	0.27 (0.07)	0.05 (0.04)
OFF_{WD}	1,315	0.11	0.09	0.81	0.21 (0.07)	0.01 (0.04)
OFF_{WIDUR}	1,517	0.11	0.06	0.55	0.15 (0.06)	0.10 (0.04)
$OFF_{WInVisits}$	1,595	0.12	0.06	0.50	0.31 (0.07)	0.01 (0.03)
OFF_{WIRT}	1,515	0.11	0.07	0.64	0.17 (0.06)	0.00 (0.00)
OFF_{WDRT}	1,483	0.11	0.08	0.73	0.16 (0.06)	0.00 (0.00)
Feed intake						
OFF_{FI}	2,337	0.04	0.05	1.25	0.10 (0.04)	0.05 (0.03)

OFF_{FIDUR}	2,337	0.04	0.04	1.00	0.26 (0.05)	0.01 (0.02)
$OFF_{FInVisits}$	2,292	0.05	0.07	1.40	0.13 (0.04)	0.04 (0.03)
OFF_{FIRT}	2,292	0.05	0.13	2.60	0.13 (0.05)	0.01 (0.03)

CV: coefficient of variation; ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average daily feed intake visits; FIRT: feed intake rate; VAR_{WI}, VAR_{WD}, VAR_{WIDUR}, $VAR_{WInVisits}$, VAR_{WIRT}, VAR_{WDRT}, VAR_{FI}, VAR_{FIDUR}, $VAR_{FInVisits}$, and VAR_{FIRT} are the day-to-day variation for corresponding drinking and feeding traits; OFF_{WI}, OFF_{WD}, OFF_{WIDUR}, $OFF_{WInVisits}$, OFF_{WIRT}, OFF_{WDRT}, OFF_{FI}, OFF_{FIDUR}, $OFF_{FInVisits}$, and OFF_{FIRT} are the proportion of off days for corresponding drinking and feeding traits

[1] Coefficients of day-to-day variation, calculated as the SD of VAR of the trait divided by the mean of the corresponding trait, e.g. $\sqrt{\mathrm{VAR}_{FI}}/\mathrm{ADFI}$;

Table 2. Percentages of observations with off-feed, off-water, and treatment events (on diagonal) and of observed (upper diagonal) and expected (with independence, below diagonal) concurrent off-feed and off-water days and days pigs received treatment on a daily and a 7-day window basis.

On a daily basis	Off-feed	Off-water	Treatment
Off-feed	**2.48**	0.96	0.24
Off-water	0.24	**12.50**	0.29
Treatment	0.02	0.12	**0.88**
On a 7-day window basis			
Off-feed	**9.72**	5.82	2.67
Off-water	4.09	**41.10**	3.71
Treatment	0.60	2.45	**5.93**

All observed percentages of concurrent events (above diagonal) were greater than expected (below diagonal) based on a Chi-square test at $p < 0.0001$.

Table 3. Estimates of genetic (upper triangle) and phenotypic (lower triangle) correlations (SE in parentheses) among drinking behavior and among feeding behavior traits

Drinking traits						
	ADWI	ADWD	WIDUR	WInVisits	WIRT	WDRT
ADWI		0.84 (0.05)	0.68 (0.08)	0.47 (0.11)	0.69 (0.09)	0.82 (0.07)
ADWD	0.79 (0.01)		0.82 (0.06)	0.57 (0.09)	0.33 (0.14)	0.92 (0.03)
WIDUR	0.60 (0.02)	0.61 (0.02)		0.82 (0.04)	0.10 (0.15)	0.59 (0.09)
WInVisits	0.36 (0.03)	0.34 (0.03)	0.80 (0.01)		-0.07 (0.13)	0.30 (0.13)
WIRT	0.78 (0.01)	0.53 (0.02)	0.09 (0.03)	-0.08 (0.03)		0.44 (0.12)
WDRT	0.66 (0.02)	0.90 (0.01)	0.31 (0.03)	0.09 (0.03)	0.66 (0.02)	

Feeding traits				
	ADFI	FIDUR	FInVisits	FIRT
ADFI		0.10 (0.10)	0.11 (0.10)	0.44 (0.08)
FIDUR	0.15 (0.03)		0.08 (0.09)	0.00 (0.00)
FInVisits	-0.01 (0.03)	0.11 (0.03)		0.00 (0.00)
FIRT	0.51 (0.02)	-0.70 (0.01)	-0.10 (0.02)	

ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average number of daily feed intake visits; FIRT: feed intake rate.

Table 4. Estimates of phenotypic and genetic correlations (SE in parentheses) between corresponding drinking and feeding behavior traits

Drinking trait	Feeding trait	Genetic	Phenotypic
ADWI	ADFI	0.36 (0.10)	0.39 (0.03)
ADWD	ADFI	0.23 (0.10)	0.29 (0.03)
WIDUR	FIDUR	0.10 (0.09)	0.16 (0.03)
WInVisits	FInVisits	0.24 (0.08)	0.29 (0.03)
WIRT	FIRT	0.24 (0.12)	0.27 (0.03)
WDRT	FIRT	0.08 (0.11)	0.13 (0.03)
VAR_{WI}	VAR_{FI}	0.10 (0.23)	0.05 (0.03)
VAR_{WD}	VAR_{FI}	-0.08 (0.23)	0.03 (0.03)
VAR_{WIDUR}	VAR_{FIDUR}	-0.14 (0.14)	0.08 (0.03)
$VAR_{WInVisits}$	$VAR_{FInVisits}$	0.18 (0.10)	0.13 (0.03)
VAR_{WIRT}	VAR_{FIRT}	-0.06 (1.58)	0.16 (0.05)
VAR_{WDRT}	VAR_{FIRT}	0.64 (2.08)	-0.02 (0.03)
OFF_{WI}	OFF_{FI}	-0.25 (0.20)	-0.10 (0.03)
OFF_{WD}	OFF_{FI}	0.04 (0.24)	-0.14 (0.03)
OFF_{WIDUR}	OFF_{FIDUR}	-0.29 (0.16)	-0.05 (0.03)
$OFF_{WInVisits}$	$OFF_{FInVisits}$	0.08 (0.16)	-0.01 (0.03)
OFF_{WIRT}	OFF_{FIRT}	-0.23 (0.25)	-0.12 (0.03)
OFF_{WDRT}	OFF_{FIRT}	-0.07 (0.28)	-0.09 (0.03)

ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average number of daily feed intake visits; FIRT: feed intake rate; VAR_{WI}, VAR_{WD}, VAR_{WIDUR}, $VAR_{WInVisits}$, VAR_{WIRT}, VAR_{WDRT}, VAR_{FI}, VAR_{FIDUR}, $VAR_{FInVisits}$, and VAR_{FIRT} are the day-to-day variation for corresponding drinking and feeding traits; OFF_{WI}, OFF_{WD}, OFF_{WIDUR}, $OFF_{WInVisits}$, OFF_{WIRT}, OFF_{WDRT}, OFF_{FI}, OFF_{FIDUR}, $OFF_{FInVisits}$, and OFF_{FIRT} are the proportion of off days for corresponding drinking and feeding traits.

Table 5. Estimates of phenotypic and genetic correlations (SE in parentheses) of drinking and feeding behavior traits with growth rate (ADG) in three phases

Trait	Quarantine nursery		Challenge nursery		Finisher	
	Genetic	Phenotypic	Genetic	Phenotypic	Genetic	Phenotypic
Water intake						
ADWI	0.10 (0.13)	0.06 (0.03)	0.39 (0.13)	0.27 (0.03)	0.29 (0.12)	0.34 (0.03)
ADWD	0.13 (0.11)	0.06 (0.03)	0.22 (0.12)	0.19 (0.03)	0.22 (0.11)	0.25 (0.03)
WIDUR	0.15 (0.10)	0.02 (0.03)	0.17 (0.11)	0.10 (0.03)	0.23 (0.10)	0.27 (0.03)
WInVisits	0.04 (0.10)	-0.03 (0.03)	0.07 (0.11)	-0.02 (0.03)	0.17 (0.10)	0.18 (0.03)
WIRT	0.14 (0.14)	0.10 (0.03)	0.34 (0.14)	0.31 (0.03)	0.19 (0.14)	0.27 (0.03)
WDRT	0.13 (0.13)	0.08 (0.03)	0.15 (0.14)	0.22 (0.03)	0.13 (0.13)	0.21 (0.03)
ADWI|ADFI	-0.04 (0.12)	-0.02 (0.03)	0.24 (0.14)	0.15 (0.03)	-0.02 (0.13)	0.01 (0.04)
ADWD|ADFI	0.04 (0.11)	-0.01 (0.03)	0.04 (0.13)	0.10 (0.03)	0.00 (0.12)	-0.01 (0.04)
WIDUR|FIDUR	0.12 (0.10)	0.02 (0.03)	0.15 (0.11)	0.13 (0.11)	0.23 (0.10)	0.25 (0.03)
WInVisits|FInVisits	0.06 (0.10)	-0.02 (0.03)	0.10 (0.11)	0.01 (0.03)	0.13 (0.10)	0.19 (0.03)
Feed intake						
ADFI	0.27 (0.10)	0.23 (0.02)	0.49 (0.09)	0.42 (0.02)	0.84 (0.03)	0.86 (0.01)
FIDUR	0.10 (0.09)	0.01 (0.03)	-0.09 (0.11)	-0.08 (0.03)	0.09 (0.10)	0.16 (0.03)
FInVisits	-0.14 (0.08)	-0.10 (0.03)	-0.03 (0.10)	-0.08 (0.03)	-0.01 (0.09)	-0.03 (0.03)
FIRT	0.08 (0.09)	0.15 (0.03)	0.34 (0.09)	0.40 (0.02)	0.35 (0.09)	0.42 (0.02)
ADFI|ADWI	0.27(0.12)	0.21 (0.03)	0.49 (0.11)	0.46 (0.03)	0.82 (0.04)	0.86 (0.01)
ADFI|ADWD	0.27 (0.11)	0.22 (0.03)	0.54 (0.10)	0.48 (0.02)	0.80 (0.04)	0.86 (0.01)
FIDUR|WIDUR	0.12 (0.10)	0.01 (0.03)	-0.12 (0.12)	-0.16 (0.03)	-0.01 (0.11)	0.11 (0.03)
FInVisits|WInVisits	-0.22 (0.10)	-0.09 (0.03)	-0.13 (0.12)	-0.10 (0.03)	0.03 (0.11)	-0.06 (0.03)
Water intake						
VAR_{WI}	0.10 (0.13)	-0.01 (0.03)	0.23 (0.15)	0.15 (0.03)	0.21 (0.13)	0.17 (0.03)
VAR_{WD}	0.05 (0.13)	0.00 (0.03)	0.10 (0.14)	0.12 (0.03)	0.20 (0.13)	0.15 (0.03)
VAR_{WIDUR}	0.09 (0.12)	0.01 (0.03)	0.03 (0.14)	0.08 (0.03)	0.27 (0.12)	0.12 (0.03)
$VAR_{WInVisits}$	0.01 (0.12)	-0.02 (0.03)	-0.07 (0.14)	0.03 (0.03)	0.08 (0.13)	-0.01 (0.03)
VAR_{WIRT}	0.10 (0.15)	0.04 (0.03)	0.13 (0.16)	0.14 (0.03)	0.09 (0.16)	0.14 (0.03)
VAR_{WDRT}	0.13 (0.15)	0.04 (0.03)	0.14 (0.17)	0.13 (0.03)	0.13 (0.15)	0.13 (0.03)
Feed intake						
VAR_{FI}	0.55 (0.20)	0.15 (0.02)	0.65 (0.27)	0.17 (0.02)	0.30 (0.22)	-0.04 (0.02)
VAR_{FIDUR}	0.11 (0.12)	0.03 (0.03)	-0.31 (0.13)	-0.18 (0.02)	-0.23 (0.12)	-0.31 (0.02)
$VAR_{FInVisits}$	-0.11 (0.09)	-0.06 (0.03)	-0.20 (0.11)	-0.09 (0.02)	0.01 (0.10)	-0.12 (0.02)
VAR_{FIRT}	0.40 (0.87)	0.00 (0.02)	-0.37 (1.25)	-0.03 (0.02)	0.16 (0.86)	-0.08 (0.02)
Water intake						
OFF_{WI}	0.03 (0.14)	0.05 (0.03)	0.38 (0.15)	0.19 (0.03)	0.19 (0.14)	0.16 (0.03)
OFF_{WD}	0.11 (0.15)	0.03 (0.03)	0.01 (0.18)	0.15 (0.03)	-0.05 (0.17)	0.16 (0.03)
OFF_{WIDUR}	0.18 (0.14)	0.03 (0.03)	0.12 (0.16)	0.06 (0.03)	0.11 (0.15)	0.04 (0.03)
$OFF_{WInVisits}$	0.10 (0.13)	0.00 (0.03)	-0.03 (0.14)	0.01 (0.03)	-0.04 (0.13)	-0.06 (0.03)
OFF_{WIRT}	-0.02 (0.18)	0.04 (0.03)	0.31 (0.19)	0.19 (0.03)	0.00 (0.19)	0.10 (0.03)
OFF_{WDRT}	0.24 (0.18)	0.07 (0.03)	0.24 (0.21)	0.16 (0.03)	0.18 (0.18)	0.14 (0.03)
Feed intake						
OFF_{FI}	-0.15 (0.17)	-0.07 (0.02)	-0.35 (0.17)	-0.21 (0.02)	-0.80 (0.08)	-0.71 (0.01)

OFF_{FIDUR}	0.02 (0.13)	0.03 (0.03)	0.03 (0.14)	-0.02 (0.03)	-0.51 (0.10)	-0.46 (0.02)
$OFF_{FInVisits}$	0.36 (0.13)	0.12 (0.02)	0.08 (0.16)	0.10 (0.03)	-0.01 (0.15)	-0.07 (0.02)
OFF_{FIRT}	0.03 (0.15)	-0.03 (0.02)	-0.39 (0.16)	-0.24 (0.02)	-0.42 (0.13)	-0.47 (0.02)

ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average number of daily feed intake visits; FIRT: feed intake rate; ADWI|ADFI, ADWD|ADFI, WIDUR|FIDUR, WInVisits|FInVisits, ADFI|ADWI, ADFI|ADWD, FIDUR|WIDUR, FInVisits|WInVisits are the fitting the second trait as covariate for the first trait; VAR_{WI}, VAR_{WD}, VAR_{WIDUR}, $VAR_{WInVisits}$, VAR_{WIRT}, VAR_{WDRT}, VAR_{FI}, VAR_{FIDUR}, $VAR_{FInVisits}$, and VAR_{FIRT} are the day-to-day variation for corresponding drinking and feeding traits; OFF_{WI}, OFF_{WD}, OFF_{WIDUR}, $OFF_{WInVisits}$, OFF_{WIRT}, OFF_{WDRT}, OFF_{FI}, OFF_{FIDUR}, $OFF_{FInVisits}$, and OFF_{FIRT} are the proportion of off days for corresponding drinking and feeding traits.

Table 6. Estimates of phenotypic correlations (SE in parentheses) of drinking and feeding behaviors with health scores, treatment rates, and mortality in different phases

Trait	Health score		Treatment rate		
	cNursery	Finisher	cNursery	Finisher	Combined
Water intake					
ADWI	0.11 (0.03)	0.19 (0.03)	-0.13 (0.03)	-0.03 (0.03)	-0.12 (0.03)
ADWD	0.03 (0.03)	0.13 (0.03)	-0.11 (0.03)	-0.02 (0.03)	-0.09 (0.03)
WIDUR	0.00 (0.03)	0.03 (0.03)	-0.11 (0.03)	-0.02 (0.03)	-0.09 (0.03)
WInVisits	-0.04 (0.03)	-0.04 (0.03)	-0.10 (0.03)	-0.04 (0.03)	-0.10 (0.03)
WIRT	0.16 (0.03)	0.26 (0.03)	-0.13 (0.03)	-0.07 (0.03)	-0.13 (0.03)
WDRT	0.06 (0.03)	0.18 (0.03)	-0.12 (0.03)	-0.04 (0.03)	-0.11 (0.03)
ADWI|ADFI	0.05 (0.03)	0.03 (0.03)	-0.06 (0.03)	0.04 (0.03)	-0.01 (0.03)
ADWD|ADFI	-0.01 (0.03)	0.02 (0.03)	-0.06 (0.03)	0.03 (0.03)	-0.02 (0.03)
WIDUR|FIDUR	0.01 (0.03)	0.03 (0.03)	-0.12 (0.03)	-0.02 (0.03)	-0.09 (0.03)
WInVisits|FInVisits	-0.05 (0.03)	-0.03 (0.03)	-0.10 (0.03)	-0.04 (0.03)	-0.09 (0.03)
Feed intake					
ADFI	0.14 (0.02)	0.39 (0.02)	-0.27 (0.02)	-0.18 (0.02)	-0.30 (0.02)
FIDUR	-0.03 (0.02)	0.02 (0.02)	0.00 (0.02)	-0.03 (0.02)	-0.01 (0.02)
FInVisits	-0.03 (0.02)	-0.05 (0.02)	-0.02 (0.02)	-0.01 (0.02)	-0.03 (0.02)
FIRT	0.12 (0.02)	0.24 (0.02)	-0.17 (0.02)	-0.09 (0.02)	-0.17 (0.02)
ADFI|ADWI	0.15 (0.03)	0.37 (0.03)	-0.22 (0.03)	-0.17 (0.13)	-0.25 (0.03)
ADFI|ADWD	0.17 (0.03)	0.38 (0.03)	-0.24 (0.03)	-0.16 (0.03)	-0.25 (0.03)
FIDUR|WIDUR	-0.06 (0.03)	0.00 (0.03)	0.03 (0.03)	-0.01 (0.03)	0.01 (0.03)
FInVisits|WInVisits	0.01 (0.03)	-0.03 (0.03)	0.01 (0.03)	-0.01 (0.03)	-0.01 (0.03)
Water intake					
VAR_{WI}	0.04 (0.03)	0.12 (0.03)	-0.06 (0.03)	0.00 (0.03)	-0.04 (0.03)
VAR_{WD}	0.01 (0.03)	0.09 (0.03)	-0.07 (0.03)	0.02 (0.03)	-0.04 (0.03)
VAR_{WIDUR}	0.03 (0.03)	0.04 (0.03)	-0.06 (0.03)	0.03 (0.03)	-0.02 (0.03)
$VAR_{WInVisits}$	-0.01 (0.03)	-0.04 (0.03)	0.03 (0.03)	0.06 (0.03)	0.05 (0.03)
VAR_{WIRT}	0.06 (0.03)	0.19 (0.03)	-0.08 (0.03)	-0.04 (0.03)	-0.09 (0.03)
VAR_{WDRT}	0.04 (0.03)	0.15 (0.03)	-0.07 (0.03)	-0.04 (0.03)	-0.08 (0.03)
Feed intake					
VAR_{FI}	0.10 (0.02)	0.09 (0.02)	0.18 (0.02)	0.03 (0.02)	0.15 (0.02)
VAR_{FIDUR}	-0.03 (0.02)	-0.21 (0.02)	0.23 (0.02)	0.19 (0.02)	0.27 (0.02)
$VAR_{FInVisits}$	-0.03 (0.03)	-0.11 (0.02)	0.06 (0.02)	0.09 (0.02)	0.07 (0.02)
VAR_{FIRT}	-0.01 (0.02)	-0.06 (0.02)	0.01 (0.02)	0.05 (0.02)	0.04 (0.02)
Water intake					
OFF_{WI}	0.05 (0.03)	0.14 (0.03)	0.00 (0.03)	0.03 (0.03)	0.01 (0.03)
OFF_{WD}	0.05 (0.03)	0.10 (0.03)	-0.07 (0.03)	-0.04 (0.03)	-0.06 (0.03)
OFF_{WIDUR}	0.00 (0.03)	-0.03 (0.03)	-0.04 (0.03)	0.06 (0.03)	0.01 (0.03)
$OFF_{WInVisits}$	0.00 (0.03)	-0.06 (0.03)	0.07 (0.03)	0.07 (0.03)	0.08 (0.03)
OFF_{WIRT}	0.08 (0.03)	0.20 (0.03)	-0.05 (0.03)	-0.01 (0.03)	-0.05 (0.03)

OFF_{WDRT}	0.06 (0.03)	0.15 (0.03)	-0.08 (0.03)	-0.03 (0.03)	-0.08 (0.03)
Feed intake					
OFF_{FI}	-0.07 (0.02)	-0.35 (0.02)	0.31 (0.02)	0.25 (0.02)	0.38 (0.02)
OFF_{FIDUR}	0.03 (0.02)	-0.16 (0.02)	0.21 (0.02)	0.17 (0.02)	0.24 (0.02)
$OFF_{FInVisits}$	0.03 (0.02)	-0.03 (0.02)	0.10 (0.02)	0.10 (0.02)	0.12 (0.02)
OFF_{FIRT}	-0.10 (0.02)	-0.36 (0.02)	0.24 (0.02)	0.16 (0.02)	0.24 (0.02)

cNursery: challenge nursery; Combined: challenge nursery and finisher combined; ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average number of daily feed intake visits; FIRT: feed intake rate; ADWI|ADFI, ADWD|ADFI, WIDUR|FIDUR, WInVisits|FInVisits, ADFI|ADWI, ADFI|ADWD, FIDUR|WIDUR, FInVisits|WInVisits are the fitting the second trait as covariate for the first trait; VAR_{WI}, VAR_{WD}, VAR_{WIDUR}, $VAR_{WInVisits}$, VAR_{WIRT}, VAR_{WDRT}, VAR_{FI}, VAR_{FIDUR}, $VAR_{FInVisits}$, and VAR_{FIRT} are the day-to-day variation for corresponding drinking and feeding traits; OFF_{WI}, OFF_{WD}, OFF_{WIDUR}, $OFF_{WInVisits}$, OFF_{WIRT}, OFF_{WDRT}, OFF_{FI}, OFF_{FIDUR}, $OFF_{FInVisits}$, and OFF_{FIRT} are the proportion of off days for corresponding drinking and feeding traits.

Table 7. Estimates of genetic correlations (SE in parentheses) of drinking and feeding behaviors with health scores, treatment rates, and mortality in different phases

Trait	Health score		Treatment rate		Mortality		
	cNursery	Finisher	cNursery	Combined	cNursery	Finisher	Combined
Water intake							
ADWI	0.09 (0.21)	0.30 (0.20)	-0.13 (0.18)	-0.18 (0.24)	-0.18 (0.19)	-0.10 (0.23)	-0.15 (0.17)
ADWD	-0.01 (0.19)	0.22 (0.19)	-0.20 (0.16)	-0.24 (0.21)	-0.06 (0.17)	-0.29 (0.20)	-0.20 (0.14)
WIDUR	-0.21 (0.18)	0.10 (0.17)	-0.27 (0.14)	-0.39 (0.19)	-0.10 (0.15)	-0.18 (0.18)	-0.20 (0.13)
WInVisits	-0.14 (0.17)	-0.18 (0.17)	-0.33 (0.14)	-0.45 (0.19)	-0.24 (0.16)	-0.02 (0.17)	-0.19 (0.13)
WIRT	0.41 (0.20)	0.36 (0.20)	-0.05 (0.20)	0.04 (0.25)	0.02 (0.22)	-0.01 (0.23)	0.12 (0.18)
WDRT	0.15 (0.19)	0.24 (0.20)	-0.03 (0.18)	-0.08 (0.23)	0.07 (0.20)	-0.20 (0.21)	-0.04 (0.16)
ADWI|ADFI	-0.01 (0.14)	0.11 (0.21)	-0.19 (0.16)	-0.01 (0.23)	-0.23 (0.18)	-0.10 (0.20)	-0.16 (0.14)
ADWD|ADFI	-0.08 (0.13)	0.08 (0.19)	-0.16 (0.15)	-0.13 (0.21)	-0.10 (0.16)	-0.25 (0.19)	-0.11 (0.15)
WIDUR|FIDUR	-0.13 (0.12)	0.10 (0.17)	-0.26 (0.13)	-0.37 (0.19)	-0.26 (0.15)	-0.17 (0.18)	-0.20 (0.13)
WInVisits|FInVisits	-0.13 (0.11)	-0.17 (0.17)	-0.34 (0.13)	-0.48 (0.18)	-0.31 (0.15)	0.02 (0.17)	-0.16 (0.12)
Feed intake							
ADFI	0.02 (0.16)	0.31 (0.15)	-0.25 (0.14)	-0.33 (0.17)	0.02 (0.15)	-0.12 (0.18)	-0.13 (0.20)
FIDUR	-0.11 (0.16)	0.05 (0.16)	-0.03 (0.14)	0.00 (0.20)	0.40 (0.15)	-0.32 (0.16)	-0.43 (0.18)
FInVisits	-0.01 (0.15)	-0.13 (0.15)	-0.05 (0.13)	0.06 (0.19)	-0.10 (0.14)	-0.27 (0.16)	-0.23 (0.11)
FIRT	0.00 (0.14)	0.10 (0.15)	-0.06 (0.14)	-0.12 (0.17)	-0.32 (0.15)	-0.02 (0.15)	0.10 (0.17)
ADFI|ADWI	0.20 (0.13)	0.36 (0.17)	-0.16 (0.15)	-0.35 (0.19)	0.08 (0.18)	0.03 (0.20)	-0.03 (0.15)
ADFI|ADWD	0.23 (0.13)	0.37 (0.16)	-0.18 (0.15)	-0.32 (0.19)	0.03 (0.17)	-0.02 (0.19)	-0.06 (0.15)
FIDUR|WIDUR	0.10 (0.12)	0.01 (0.18)	0.02 (0.14)	-0.01 (0.20)	0.40 (0.16)	-0.08 (0.18)	0.07 (0.13)
FInVisits|WInVisits	-0.13 (0.13)	-0.01 (0.19)	0.20 (0.14)	0.28 (0.21)	0.00 (0.16)	-0.21 (0.19)	-0.15 (0.14)
Water intake							
VAR_{WI}	0.09 (0.22)	0.16 (0.22)	-0.10 (0.19)	-0.15 (0.27)	0.00 (0.20)	-0.10 (0.22)	-0.06 (0.17)
VAR_{WD}	-0.16 (0.21)	0.04 (0.21)	-0.19 (0.18)	-0.14 (0.23)	0.10 (0.19)	-0.33 (0.21)	-0.17 (0.16)
VAR_{WIDUR}	-0.22 (0.22)	0.28 (0.20)	-0.23 (0.17)	-0.43 (0.26)	0.26 (0.19)	-0.16 (0.25)	0.01 (0.15)
$VAR_{WInVisits}$	-0.16 (0.21)	-0.14 (0.21)	-0.15 (0.18)	-0.28 (0.24)	0.17 (0.18)	0.18 (0.22)	0.13 (0.15)
VAR_{WIRT}	0.21 (0.23)	0.27 (0.23)	-0.11 (0.21)	-0.05 (0.30)	-0.01 (0.23)	0.09 (0.24)	0.10 (0.20)

VAR_{WDRT}	0.12 (0.23)	0.07 (0.24)	0.00 (0.21)	-0.01 (0.27)	0.21 (0.23)	-0.02 (0.24)	0.14 (0.20)
Feed intake							
VAR_{FI}	0.22 (0.29)	-0.23 (0.31)	0.14 (0.25)	-0.30 (0.38)	0.71 (0.29)	0.45 (0.36)	0.56 (0.35)
VAR_{FIDUR}	-0.21 (0.20)	-0.32 (0.19)	0.11 (0.17)	0.03 (0.25)	0.65 (0.19)	-0.17 (0.20)	-0.24 (0.23)
$VAR_{FInVisits}$	-0.19 (0.12)	-0.30 (0.15)	0.07 (0.12)	0.09 (0.19)	-0.01 (0.15)	0.04 (0.17)	0.05 (0.11)
VAR_{FIRT}	-0.73 (1.74)	-0.20 (0.87)	0.35 (1.15)	0.85 (2.85)	-0.82 (1.48)	NA	NA
Water intake							
OFF_{WI}	-0.11 (0.22)	0.20 (0.22)	-0.04 (0.20)	-0.18 (0.25)	-0.29 (0.21)	-0.04 (0.24)	-0.16 (0.18)
OFF_{WD}	-0.34 (0.23)	-0.14 (0.24)	-0.25 (0.20)	-0.10 (0.29)	-0.21 (0.23)	-0.46 (0.26)	-0.37 (0.18)
OFF_{WIDUR}	-0.18 (0.19)	0.06 (0.23)	-0.19 (0.20)	-0.46 (0.32)	0.27 (0.22)	-0.18 (0.27)	0.04 (0.18)
$OFF_{WInVisits}$	-0.07 (0.17)	-0.27 (0.19)	-0.02 (0.18)	-0.12 (0.23)	0.31 (0.19)	0.10 (0.20)	0.22 (0.16)
OFF_{WIRT}	0.38 (0.27)	0.23 (0.26)	-0.16 (0.24)	-0.08 (0.34)	-0.08 (0.27)	0.18 (0.28)	0.10 (0.23)
OFF_{WDRT}	0.31 (0.28)	0.18 (0.29)	-0.24 (0.25)	-0.30 (0.30)	-0.10 (0.29)	-0.13 (0.30)	-0.12 (0.24)
Feed intake							
OFF_{FI}	-0.06 (0.24)	-0.45 (0.21)	0.38 (0.19)	0.51 (0.23)	0.27 (0.24)	0.28 (0.30)	0.48 (0.25)
OFF_{FIDUR}	0.18 (0.19)	-0.16 (0.19)	0.26 (0.17)	0.08 (0.21)	-0.15 (0.19)	0.26 (0.20)	0.24 (0.20)
$OFF_{FInVisits}$	-0.02 (0.18)	-0.03 (0.22)	0.20 (0.18)	0.14 (0.25)	0.23 (0.24)	0.32 (0.23)	0.34 (0.17)
OFF_{FIRT}	0.01 (0.20)	-0.36 (0.23)	0.28 (0.19)	0.48 (0.24)	0.60 (0.27)	-0.09 (0.27)	NA

cNursery: challenge nursery; Combined: challenge nursery and finisher combined; ADWI: average daily water disappearance; ADWD: average daily water dispensed; WIDUR: average daily water intake duration; WInVisits: average number of daily water intake visits; WIRT: water disappearance rate; WDRT: water dispensed rate; ADFI: average daily feed intake; FIDUR: average daily feed intake duration; FInVisits: average number of daily feed intake visits; FIRT: feed intake rate; ADWI|ADFI, ADWD|ADFI, WIDUR|FIDUR, WInVisits|FInVisits, ADFI|ADWI, ADFI|ADWD, FIDUR|WIDUR, FInVisits|WInVisits are the fitting the second trait as covariate for the first trait; VAR_{WI}, VAR_{WD}, VAR_{WIDUR}, $VAR_{WInVisits}$, VAR_{WIRT}, VAR_{WDRT}, VAR_{FI}, VAR_{FIDUR}, $VAR_{FInVisits}$, and VAR_{FIRT} are the day-to-day variation for corresponding drinking and feeding traits; OFF_{WI}, OFF_{WD}, OFF_{WIDUR}, $OFF_{WInVisits}$, OFF_{WIRT}, OFF_{WDRT}, OFF_{FI}, OFF_{FIDUR}, $OFF_{FInVisits}$, and OFF_{FIRT} are the proportion of off days for corresponding drinking and feeding traits.

Supplementary figures:

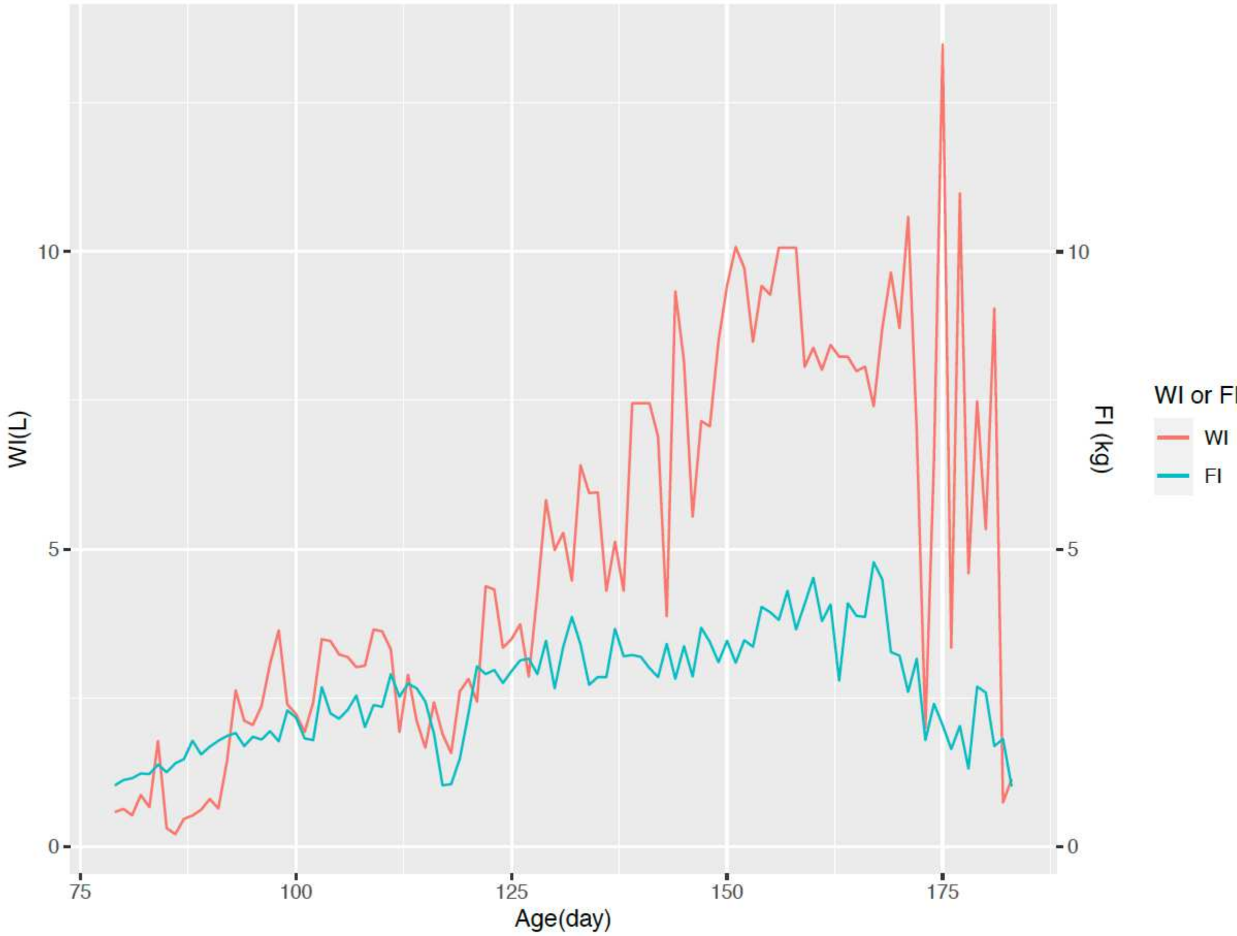

Figure S1. Raw daily feed intake (FI) and water disappearance (WI) for a randomly selected animal (0132). Both WI and FI had large day-to-day variation and had concurrent drops at around 120 and 160 days.

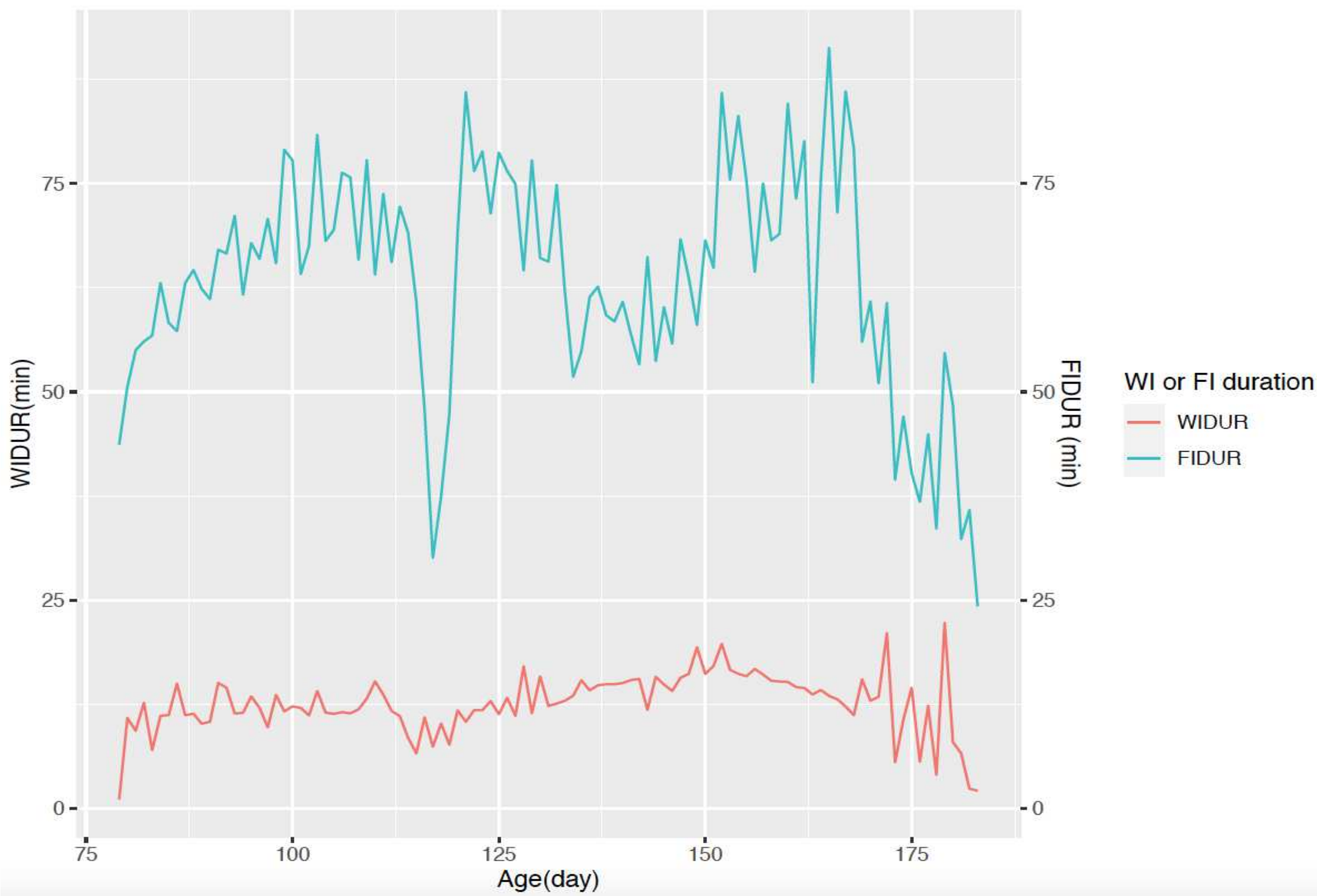

Figure S2. Raw daily feed intake duration (FIDUR) and water intake duration (WIDUR) for a randomly selected animal (0132).

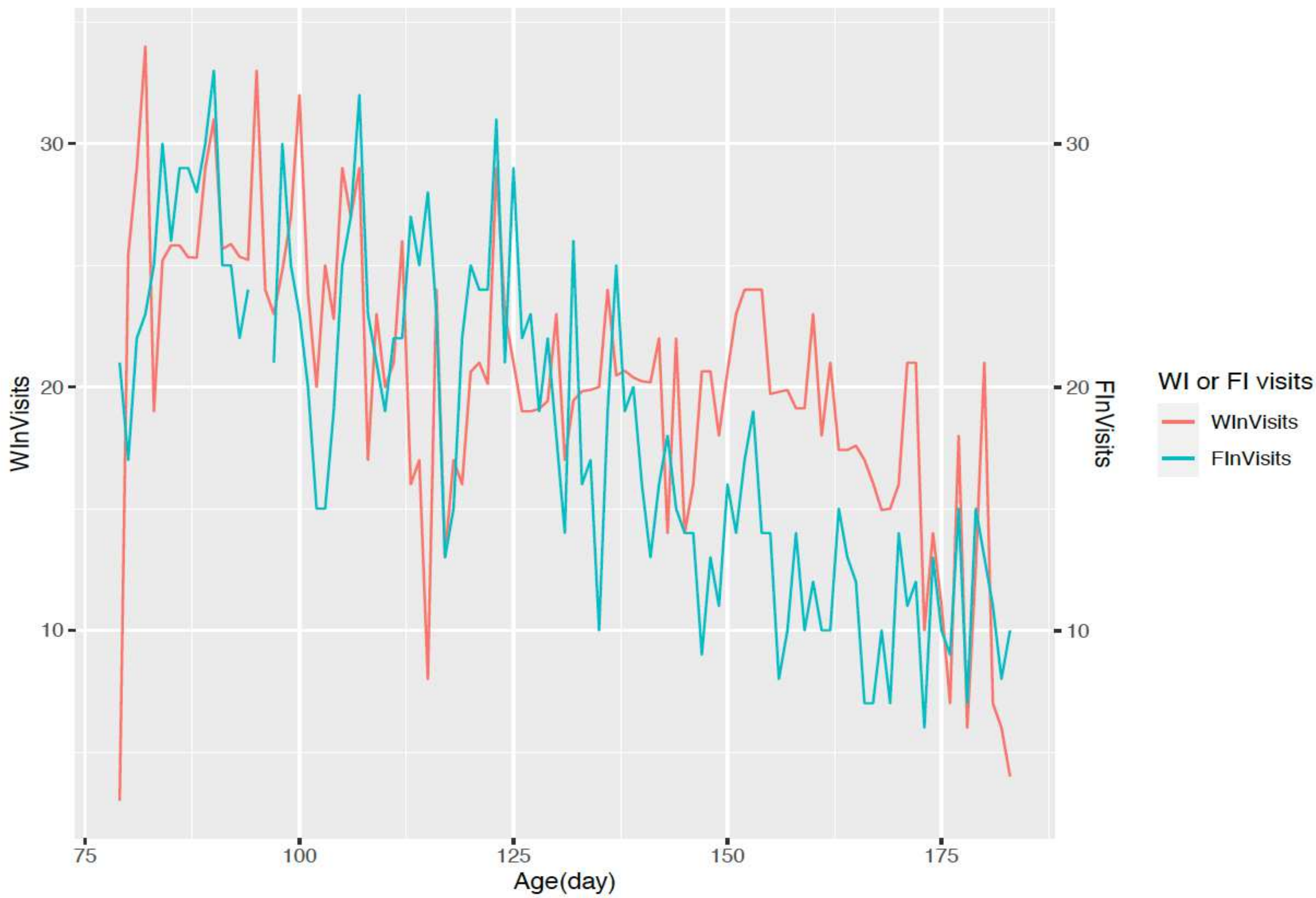

Figure S3. Raw daily feed intake visits (FInVisits) and water intake visits (WInVisits) for a randomly selected animal (0132).

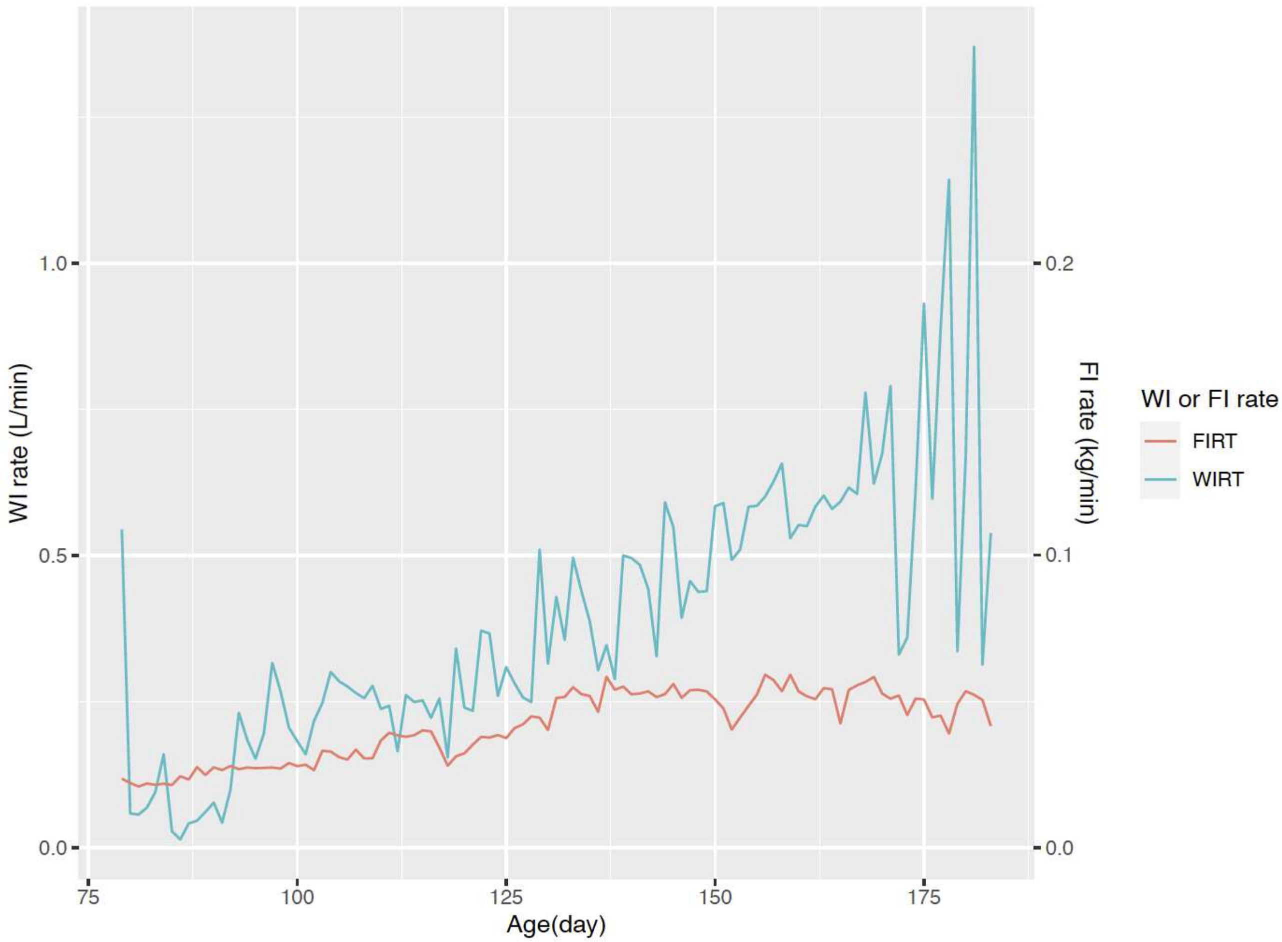

Figure S4. Raw daily feed intake rate (FIRT) and water disappearance rate (WIRT) for a randomly selected animal (0132).

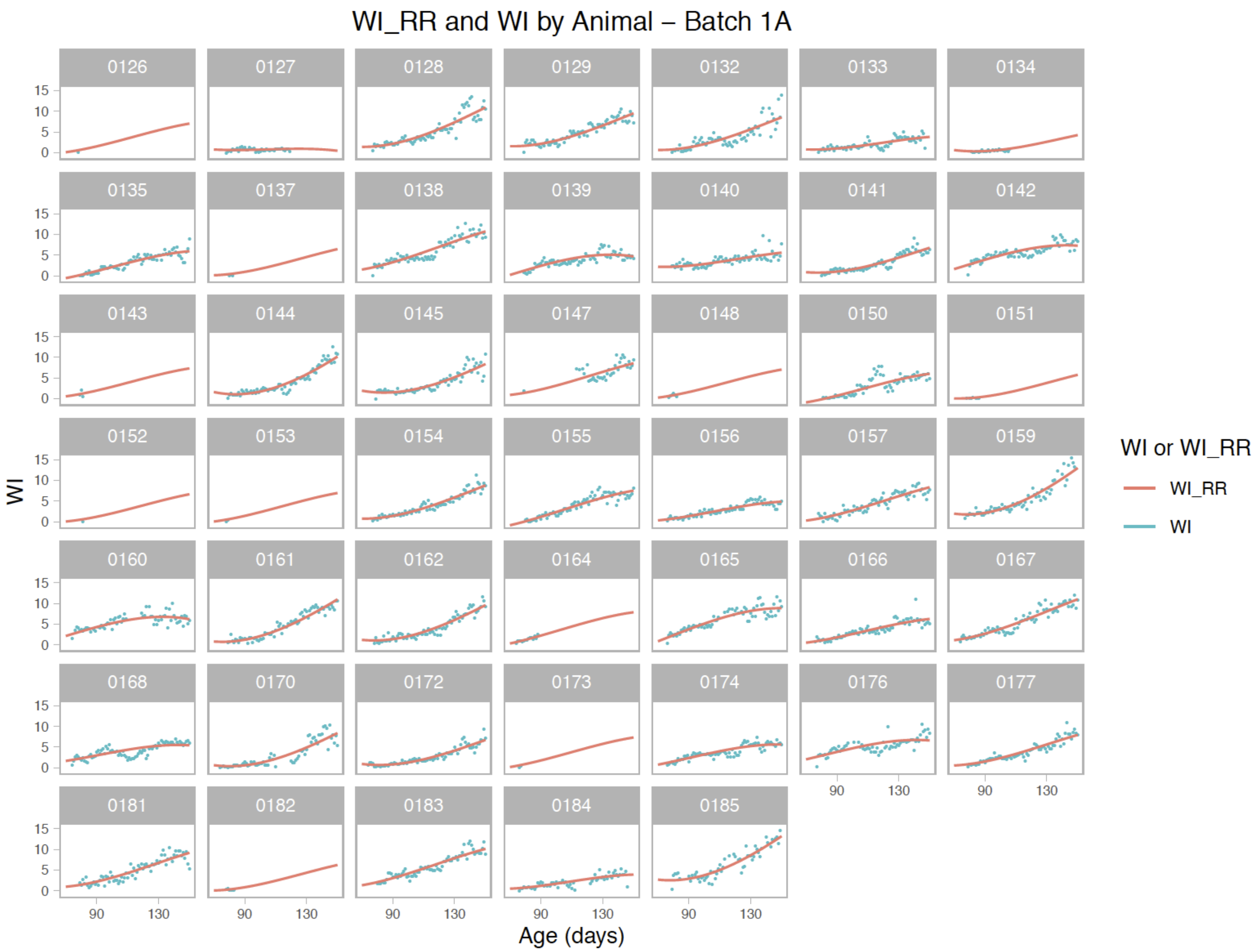

Figure S5. Raw water disappearance (WI) and predicted water disappearance (WI_RR) patterns defined using quadratic random regression model for for individual pigs in batch 1A.

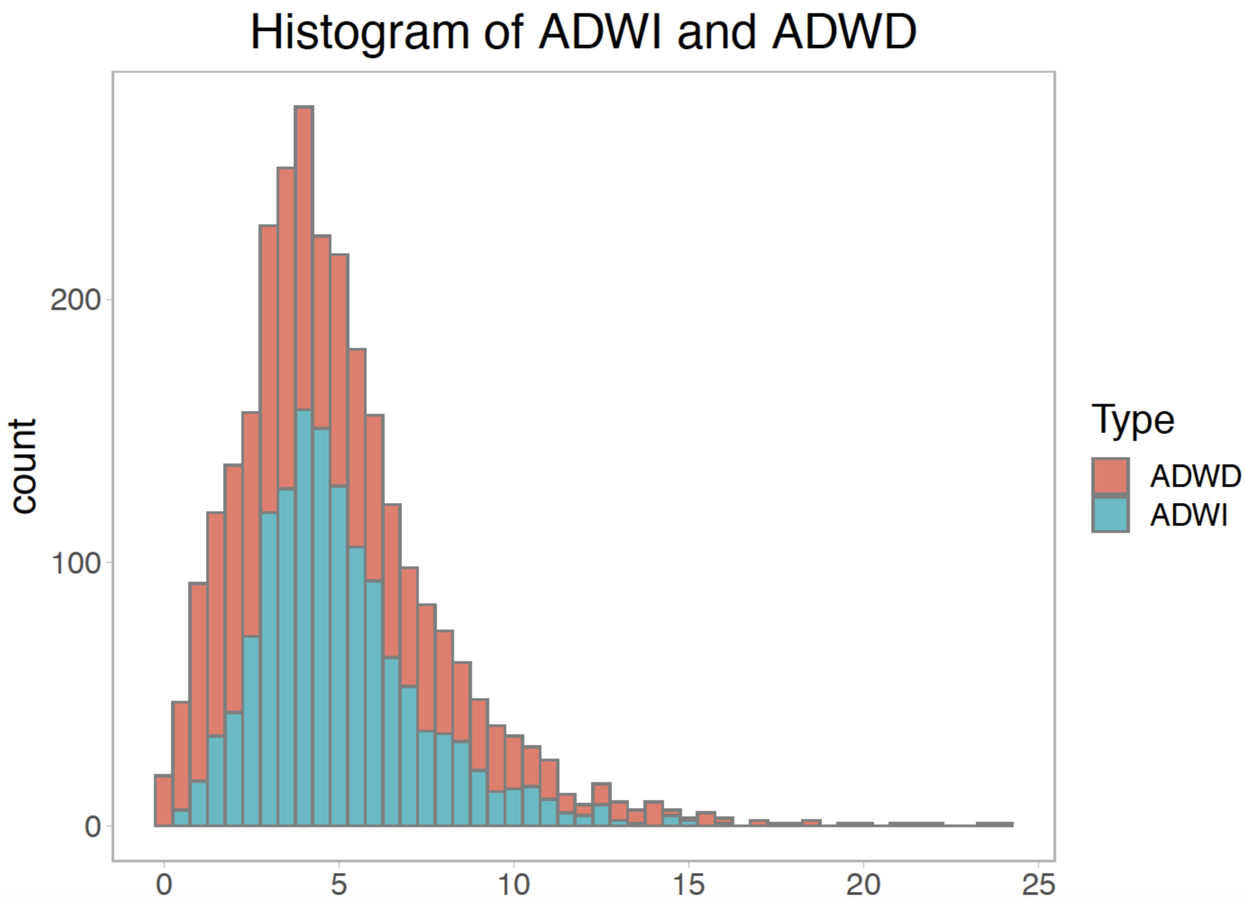

Figure S6. Histogram for average daily water disappearance (ADWI) and water dispensed (ADWD).

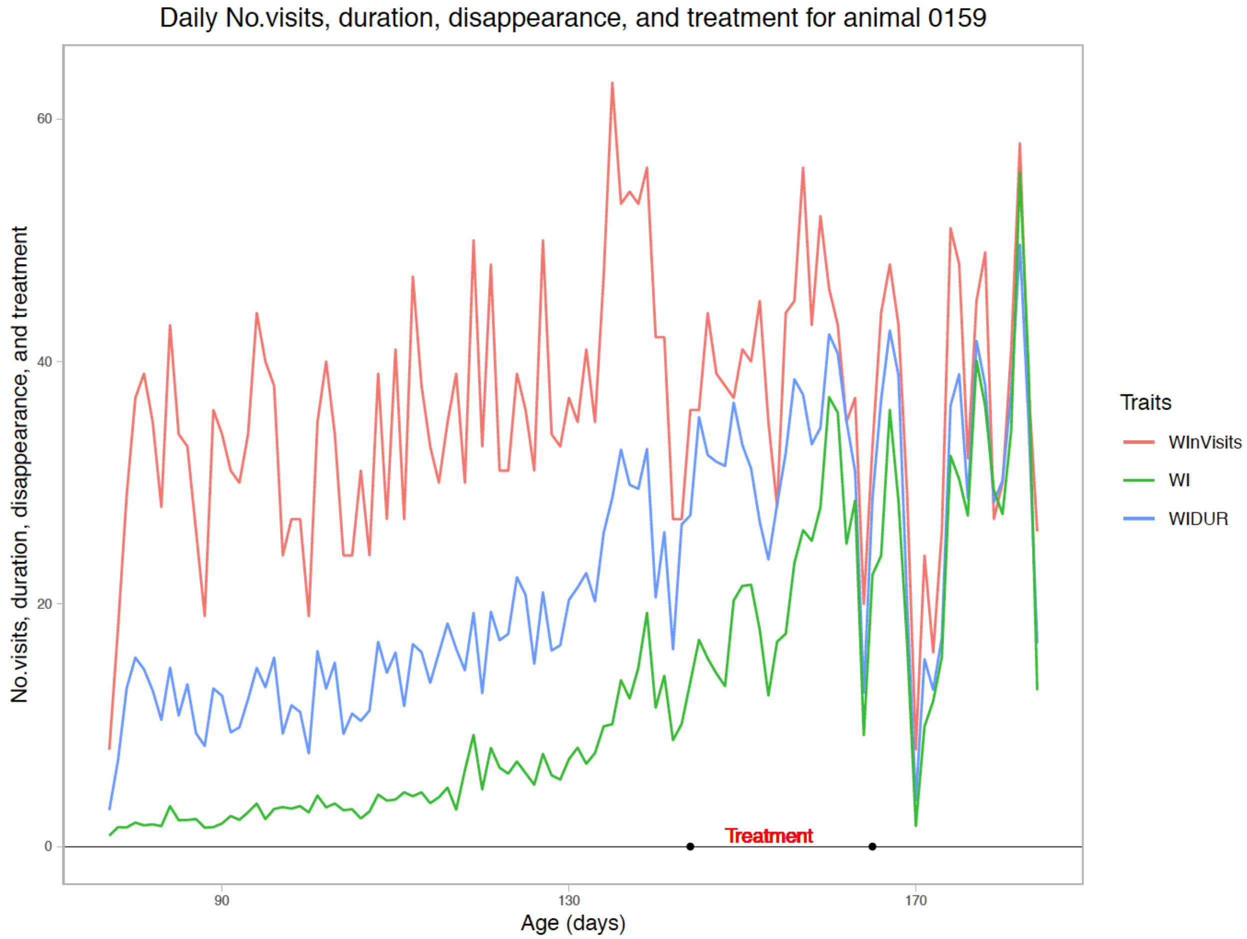

Figure S7. Raw daily water disappearance (WI), number of visits (WInVisits), and duration (WIDUR) for a randomly selected animal (0159).

Figures

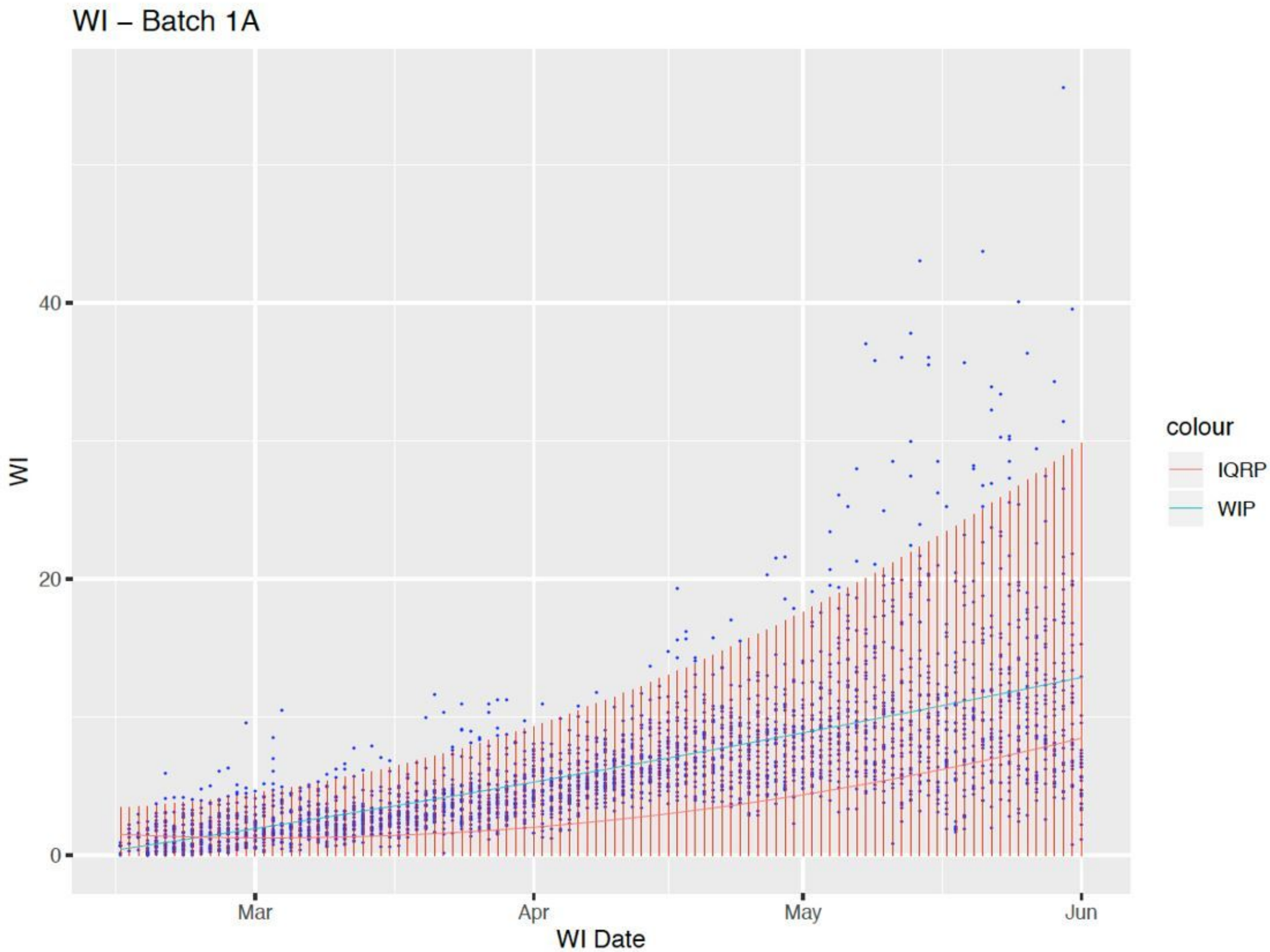

Figure 1

Outlier detection for water disappearance (WI) for a random batch of pigs based on predicted mean (WIP) + 2 times the predicted interquartile range (IQRP).

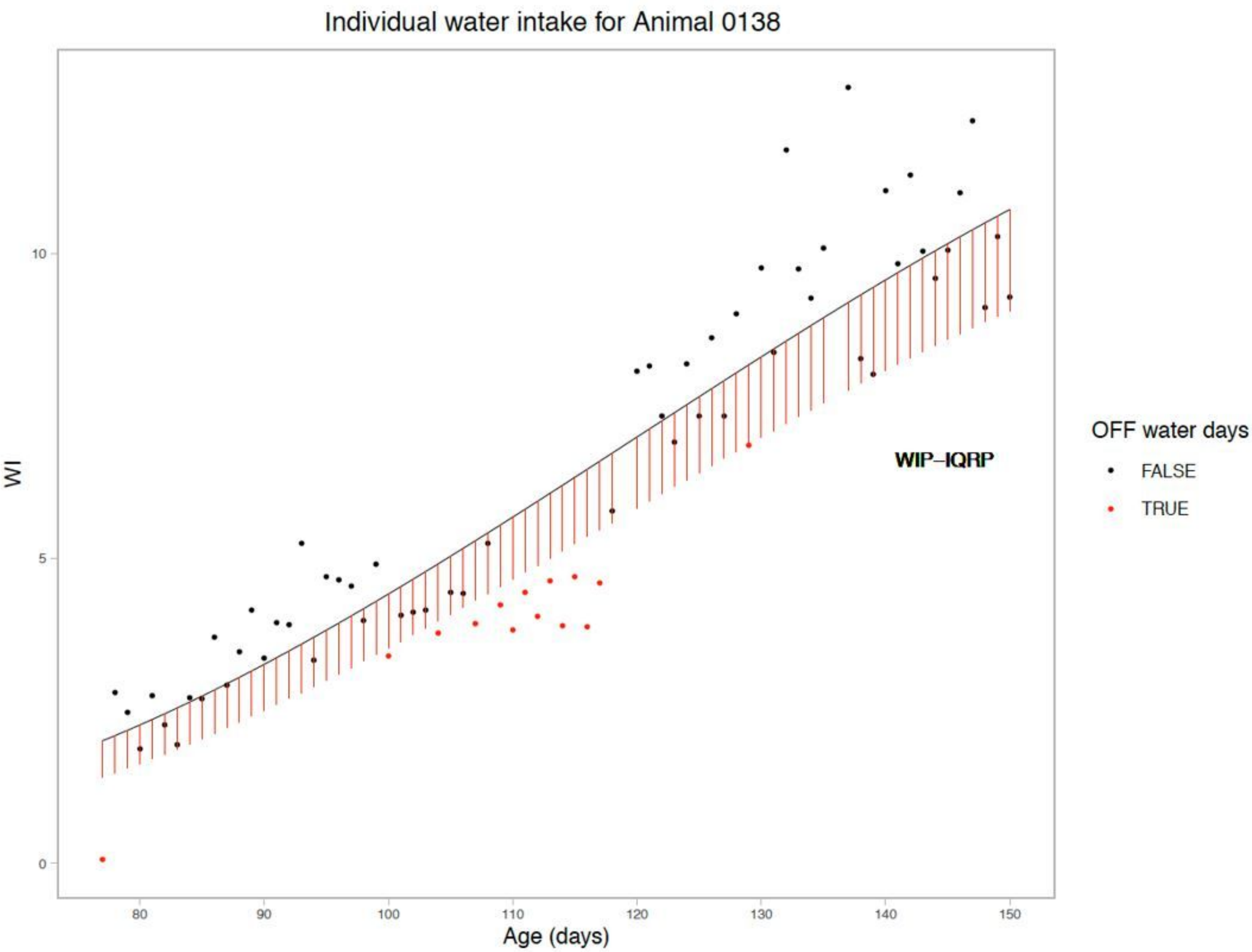

Figure 2

Derivation of day-to-day variation and proportion of off-water days for the water disappearance (WI) data of an randomly selected pig. TRUE: off-water days; FALSE: non off-water days. Solid line represents the predicted WI based on a quadratic random regression model; day-to-day variation in WI was computed as the square root of the sum of squared residuals. Red lines represent the predicted interquartile range of random regression residuals within the batch based on a quadratic regression model; daily water intake data that had residuals less than the predicted interquartile range were considered off-water days.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- sfig1.jpg
- sfig2.jpg

- sfig3.jpg
- sfig4.jpg
- sfig5.jpg
- sfig6.jpg
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