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Feed intake and feeding behavior traits for gestating sows recorded using electronic sow feeders

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Abstract

Electronic sow feeding (**ESF**) systems are used to control feed delivery to individual sows that are group-housed. Feeding levels for gestating sows are typically restricted to prevent excessive body weight gain. Any alteration of intake from the allocated feeding curve or unusual feeding behavior could indicate potential health issues. The objective of this study was to use data recorded by ESF to establish and characterize novel feed intake and feeding behavior traits and to estimate their heritabilities. Raw data were available from two farms with in-house manufactured (**Farm A**) or commercial (**Farm B**) ESF. The traits derived included feed intake, time spent eating, and rate of feed consumption, averaged across or within specific time periods of gestation. Additional phenotypes included average daily number of feeding events (**AFE**), along with the cumulative numbers of days where sows spent longer than 30 min in the ESF (**ABOVE30**), missed their daily intake (**MISSF**), or consumed below 1 kg of feed (**BELOW1**). The appetite of sows was represented by averages of score (**APPETITE**), a binary value for allocation eaten or not (**DA_bin**), or the standard deviation of the difference between feed intake and allocation (**SDA-I**). Gilts took longer to eat than sows (15.5 ± 0.13 vs. 14.1 ± 0.11 min/d) despite a lower feed allocation (2.13 ± 0.00 vs. 2.36 ± 0.01 kg/d). The lowest heritability estimates (below 0.10) occurred for feed intake traits, due to the restriction in feed allocation, although heritabilities were slightly higher for Farm B, with restriction in the eating time. The low heritability for AFE (0.05 ± 0.02) may have reflected the lack of recording of nonfeeding visits, but repeatability was moderate (0.26 ± 0.03, Farm A). Time-related traits were moderately to highly heritable and repeatable, demonstrating genetic variation between individuals in their feeding behaviors. Heritabilities for BELOW1 (Farm A: 0.16 ± 0.04 and Farm B: 0.15 ± 0.09) and SDA-I (Farm A: 0.17 ± 0.04 and Farm B: 0.10 ± 0.08) were similar across farms. In contrast, MISSF was moderately heritable in Farm A (0.19 ± 0.04) but lowly heritable in Farm B (0.05 ± 0.07). Heritabilities for DA_bin were dissimilar between farms (Farm A: 0.02 ± 0.02 and Farm B: 0.23 ± 0.10) despite similar incidence. Individual phenotypes constructed from ESF data could be useful for genetic evaluation purposes, but equivalent capabilities to generate phenotypes were not available for both ESF systems.

Key words: appetite, gestation, group-housing, heritability, sow health

Abbreviations

DFI	daily feed intake
DFR	daily rate of feed consumption
DFT	daily time spent eating
ESF	electronic sow feeding
RFID	radio-frequency identification tags

Introduction

Electronic sow feeding (**ESF**) systems are used during the gestation period to control the delivery of feed to individual sows in loose housing systems. These systems typically identify sows that fail to eat on a daily basis. Depending on the system, ESF may also record data for individual feed intake and the timing of eating events, but these data are currently not used to construct phenotypes for individual sows. Data obtained from ESF create opportunities, both from phenotypic and genetic perspectives, for obtaining new phenotypes and examining the implications of alterations to normal feed intake or feeding behavior patterns during gestation on the health or outcomes for individual sows at farrowing or during lactation.

Feeding levels for sows during gestation are typically based on the requirements of the average sow with assumptions regarding maintenance requirements, desired sow body weight, and litter weight gains (National Research Council, 1998; Spoolder and Vermeer, 2015; Bunter et al., 2018). However, feeding allocations are typically much lower than the amount of feed that sows would voluntarily consume (van Barneveld et al., 2007). Feed intake and feeding behavior are well understood from ESF data recorded on growing pigs (Huisman, 2002; Huisman and Van Arendonk, 2004) but have not yet been widely investigated for gestating sows. A better appreciation of feed intake and feeding behaviors for gestating sows may also assist in improving their management.

The first objective of this study was to quantify feed intake and feeding behavior traits within two ESF systems for large dynamic groups of gestating sows, under restrictive feeding. The second objective was to investigate the genetic background of the traits derived from the ESF data recorded during gestation. The hypotheses were that ESF data could be used to construct meaningful phenotypes for gestating sows that are heritable and relevant to breeding programs, by providing direct information on feed intake or feeding behavior characteristics.

Materials and Methods

This research was funded by the Australian Pork CRC under the project 2A-116 and approved by the University of New England Animal Ethics Committee through CHM Alliance Pty Ltd (CHM PP 103/17) and Rivalea Australia (17R031C) ethics committees.

Data used in the study

Routinely recorded data from ESF systems were obtained from two farms (Farms A and B) using two different ESF systems. Both farms had large dynamic groups of gestating sows (~250 or 300 sows per pen) fed using ESF. **Farm A** used feeders manufactured in-house, while **Farm B** used the Osborne **TEAM** (Total Electronic Animal Management) system (Osborne Industries, INC., KS). The ESFs were able to deliver two diets (Farm A only), and multiple feeding curves could be applied to individual sows (both systems). Both ESF systems delivered feed in increments up to the allocated amount along with water and had a capacity of 60 to 70 sows per feeder. Therefore, each group pen contained multiple ESF located in feeder banks. Sows generally had to traverse a long walk to return to the feeders once an ESF had been exited at the end of a feeding event.

Intake for individual sows was controlled through recognition of individual sows via radio-frequency identification (**RFID**) tags. However, nonfeeding visits to the feeders were not recorded by either system. Reporting systems routinely identified sows that failed to eat their daily allocation, enabling staff to react promptly. Gilts and sows were trained to use the ESF systems prior to their grouping for gestation. In case of repeated failure to eat allocations in early gestation, sows were removed from ESF systems and housed differently. After mating, sows and gilts entered gestation groups within a few days. Sows removed from groups due to re-mating were returned to groups after mating, with updated mating dates and adjusted feeding curves. On both farms, gilts were penned separately to sows, and only a small proportion of sows were allocated different amounts to their contemporaries, based on body condition.

Individual farm details

The data for Farm A were obtained during the period January to December 2015, from an ESF system that recorded event-based data, and every feed delivery event was recorded with a date and times (entry and exit). Mixed parity sows entered the ESF system over 2 d to create a group of approximately 250 sows, distributed across a range of mating weeks. Additional sows entered the system weekly until group sizes (max *N* per pen ~300 sows) were stable. Therefore, some sows were only present in the ESF system for a part of their gestation during the recording period.

In this ESF system, sows were able to consume feed without being interrupted, as the back gate opened to allow another sow entry to the feeder only when no other sow was present in the feeder. No limitation was imposed on the time sows spent in the feeders. Feed delivery was at a fixed rate of between 240 and 300 g/min depending on the feeder, regardless of the total feed allocation, and was monitored as auger rotations calibrated using a constant 2-min delivery. Daily feed allocations for individual sows were activated at midday every 24 h. Therefore, it was possible for a sow to have two active allocations within one calendar day. Gilts received 2.4 kg/d from days 1 to 34 of gestation, 2.0 kg/d from 35 to 90 d, and 2.2 kg/d from day 91 until the exit to the farrowing house. Comparable feeding levels for sows were 2.7, 2.2, and 2.4 kg/d.

The data for Farm B were obtained during the period December 2017 to May 2018. The Osborne TEAM system allows protection of sows from pen mates only for a fixed time period, to discourage them from long feeding events. In this system, the maximum time sows were allowed to eat was 10 min. Feed delivery was monitored as auger rotations, and the feed allocations were reset at 10:00 a.m. every morning. The Osborne TEAM system software stored a single record per sow per day as allocation vs. balance remaining, by overwriting the balance at each feeding event. The frequency and timing of both feeding and nonfeeding events were, therefore, not recorded. Both sows and gilts were allocated 2.2 kg/d during the first 28 d of gestation, followed by 1.9 kg throughout the rest of gestation.

Data preparation

Data preparation was carried out using R (R Core Team, 2018). Preparation of the event-based ESF data in Farm A included the elimination of within-diet duplicates and combining multiple diet entries along with adjacent events (occurring within 60 s) into one feeding event. Adjacent events within 60 s resulted from the loss of connectivity between the sows tag and the receiving system; moreover, it took longer than 60 s for a sow to traverse the pen to reenter the feeders. The consolidated feeding events were then used to construct a single daily record per sow. Where there was one calendar day without any feeding events flanked by adjacent days of consumption, a zero feed delivery was allocated (N = 21,289). Zero intake within one calendar day resulted from sows consuming their allocation on the previous or subsequent day and did not necessarily reflect poor appetite. Visits to the ESF longer than 250 min were rare (N = 4; 0.0007%), considered as errors (or sleeping) and were substituted with the average value, whereas visits recorded longer than 50 min were restricted to a value of 50 min (N = 3,456; 0.64% of all events).

More than one million individual records (N = 1,005,940) for 4,106 sows were collapsed to one record per day (N = 563,516). Sows with 90 or more days recorded within their gestation were retained for further analyses (414,887 individual daily records). The final data set used for Farm A contained 2,847 sows recorded for 3,939 mating events with outcomes known. Up to 28% of sows were recorded over two gestations in this data set. Sows with unknown outcomes were generally due to the loss of identification tag, which can be a common problem in ESFs with large dynamic groups.

In Farm B, the data set contained 54,627 individual daily records for 540 sows extracted directly from the ESF database. The final data set for Farm B contained observations for 540 focal group sows, recorded throughout one gestation only.

Trait definitions

Common traits were defined for both farms where possible (Table 1). However, traits involving time could only be constructed for the event-based system (Farm A). The complete suite of traits (daily records) included feed intake (**DFI**, kg/d), time spent eating (**DFT**, min/d), and rate of feed consumption (**DFR**, g/min). Daily phenotypes were subsequently used to construct phenotypes averaged within time periods as well as across the complete gestation. Seven time periods were considered to align with specific time points of interest. Time periods were: days: 1 to 7 (entry to ESF), 8 to 14 (maternal pregnancy recognition), 15 to 34 (early pregnancy loss or returns), 35 to 90 (mid-pregnancy), 91 to 100 (late pregnancy), 101 to 105 (pre-transfer), and more than 105 d of gestation length (close to transfer). Averages within each time period and across the complete gestation (e.g., AFI) were calculated for: feed intake (**AFI**, kg/d); time spent eating (**AFT**, min/d), and rate of feed consumption (AFR, g/min), calculated as (AFI/AFT) × 1,000.

Additional traits calculated across the complete gestation included cumulative counts of: the number of feeding events per day, expressed as an average per day (**AFE**); the cumulative number of missed feeding days (**MISSF**) or days with feed intake below 1 kg, including MISSF (**BELOW1**); and the number of days with time spent in the feeder longer than 30 min (**ABOVE30**).

Traits representing sow appetite were also constructed. These included scores: high appetite (score = 3), where sows that ate their daily allocation in one feeding event; moderate appetite (score = 2), where the daily allocation was consumed, but over more than one feeding event; low appetite (score = 1), where the daily allocation was not consumed, but there was more than one feeding event; and poor appetite (score = 0), where sows had only one feeding event and not all allocation was consumed. Zero values for AFI resulted in score 0 (poor appetite) for consecutive low intake days or score 3 (high appetite), if the total allocation was consumed over flanking days. Farm B did not record the number of daily feeding events and thus did not have an appetite score. Subsequently, the daily appetite score was also represented as a binary value, with value = 1 for total allocation consumed vs. value = 0, when some allocation remained (allowing for 0.01 kg differences). This trait was comparable across farms. The appetite scores and corresponding binary values were averaged across the gestation to construct the phenotypes (abbreviated as **APPETITE** and **DA_bin**) used for analyses. The standard deviation of the difference between daily feed intake and daily allocation (**SDA-I**) was also calculated across the gestation period to reflect variability in daily feed consumption relative to allocation.

Models for analyses

Systematic effects

Data from each farm were analyzed separately. Least square means (**LSM**) for day of gestation were constructed using the generalized linear models function (R Core Team, 2018) for all traits recorded daily to illustrate feed allocation and feed intake curves and the changes in the rate of feed consumption or appetite over time (Figures 1 and 2). Significant model terms (all $P < 0.05$) for DFI, DFT, and DFR included mating-year-month (11

Table 1. Feed intake and feeding behavior traits defined for each farm

Trait definition, units	Trait abbreviation for the complete period	Farm A	Farm B
Average daily feed intake, kg/d	AFI[1]	✓	✓
Average time spent eating, min/d	AFT[1]	✓	×
Average rate of feed consumption, g/min	AFR[1]	✓	×
Average number of feeding events per day, N/d	AFE	✓	×
The total missed feeding events, count	MISSF	✓	✓
The total days with feeding intake below 1 kg, count	BELOW1	✓	✓
The total days with feeding events above 30 min, count	ABOVE30	✓	×
Average score for appetite of sows, scored 0 to 3	APPETITE	✓	×
Appetite of sows binary, scored 0/1	DA_bin	✓	✓
Standard deviation of the difference between feed intake and allocation for each sow within each mating cycle, kg	SDA-I	✓	✓

✓, trait constructed; ×, trait not constructed.

[1] Each of these traits is also averaged within specific time periods of gestation.

levels), parity group (2 levels: gilts vs. sows), sow line (5 levels), shed-pen (9 levels), and gestation day (99 levels) for Farm A. For Farm B, sow breed group (2 levels: maternal vs. terminal), parity group (2 levels: gilts vs. sows), and gestation day (99 levels) were fitted regardless of their significance, to accommodate sampling and stratification due to these effects. On both farms, models for traits within each time period also included linear covariates for the number of observations within each period to accommodate missing records, whereas, for AFI, MISSF, and BELOW1, the cumulative number of observations (range 90 to 106) was fitted as a linear covariate. LSM for feed intake and feeding behavior traits reflecting averages within time periods were also constructed using the above models, excluding gestation day. In order to analyze the significance of changes in traits between time periods of gestation, the data were analyzed longitudinally in a linear mixed model by using the R package "lme4" (Bates et al., 2015). For Farm A, the random effect was the sow by gestation event (levels = 3,939), and for Farm B, the random effect was sow (levels = 540). LSM were compared from analyses, which excluded (model 1) or accounted for (model 2) repeated records per sow. Pairwise comparisons were made with the Tukey–Kramer adjustment using the R package "emmeans" (Lenth, 2018) to illustrate significant differences among the levels of class effects.

Genetic parameters

Pedigree was extended for parameter estimation. Sows on Farm A were predominantly (90.5%) pedigreed F1 (Large White × Landrace) females or pedigreed purebred females. These sows were the progeny of 221 sires and 1,835 dams, and the pedigree was extended over four generations to contain 954 sires and 5,697 dams in total. Sows from Farm B represented three maternal and three terminal purebred lines. These sows were the progeny of 136 sires and 377 dams, and their pedigree was extended over the five generations to contain in total 511 sires and 1,337 dams.

Parameter estimates for each trait were obtained by fitting a linear mixed animal model using restricted maximum likelihood procedures in ASReml (Gilmour et al., 2014). Estimates of heritabilities were obtained from univariate analyses using a general formulation pertinent to Farm A:

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Z_1a} + \mathbf{Z_2pe} + \mathbf{e}$$

where $\mathbf{y}$ is the vector of observations, $\mathbf{b}$ is a vector of fixed effects (described above), $\mathbf{a}$ is a vector of additive genetic effects, $\mathbf{pe}$ is a vector of permanent environmental effects, and $\mathbf{e}$ is a vector of residual effects. The matrix $\mathbf{X}$ is the incidence matrix for the fixed effects, whereas $\mathbf{Z}_1$ and $\mathbf{Z}_2$ are the design matrices relating animals to their additive and permanent environmental effects. Repeatability (r) was estimated as the sum of additive and permanent environmental effects, expressed as a proportion of the phenotypic variance. No permanent environmental effects were estimated for Farm B, since each sow had only a single record per trait. Covariances and parameters were estimated by using the same systematic

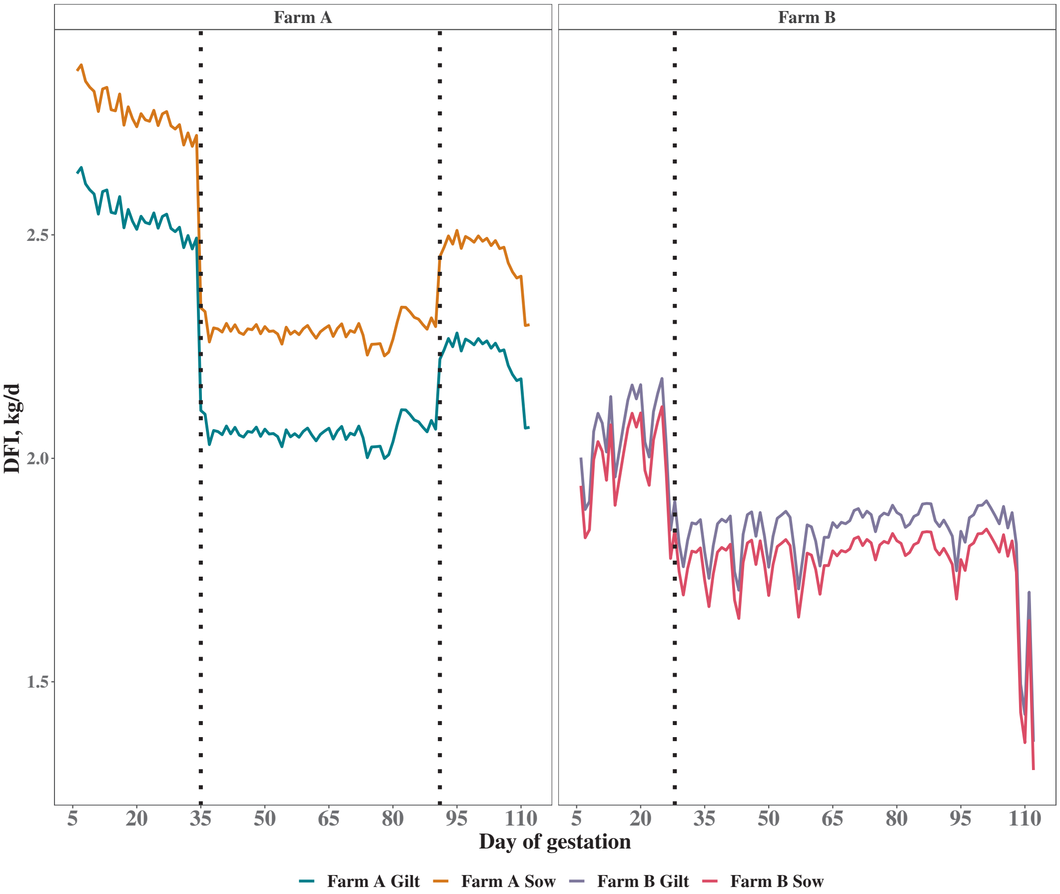

Figure 1. LSM for DFI for farms A and B, with vertical dotted lines representing the timing of changes in feed allocation.

effects from models above, with the exception of line (six levels) replacing breed group (two levels) in Farm B to avoid potentially inflated additive variance.

Results and Discussion

Systematic effects

Feed intake and feeding behavior trends throughout gestation
Trends are shown in Figures 1 and 2, whereas the corresponding details for traits within time intervals are provided in Table 2. Farm-specific differences in feed allocation (not shown) reflected the diet and management goals specific to each population and are not discussed further. The plots were constructed by using the data from the range of 5 to 112 d of gestation, because there was a low incidence of sows outside that range (1.93% Farm A and 0.17% Farm B of total daily records) resulting in poor estimates. Although not shown in plots due to the low record numbers, intakes were generally low in the first 5 d of gestation. Days with partial recording of feed intake were avoided where transfer dates could be confirmed.

Observed daily feed intake closely followed feed allocation, as expected (Figure 1). Sows that do not consume their allocation repeatedly in early gestation, typically indicating a failure to train to this feed delivery system, were removed from ESF systems and are, therefore, not present in these data. Smoother curves were observed for Farm A compared with Farm B (Figure 1) most likely due to the higher number of observations and better cross-classification of gestation day with other model terms, particularly date of observation, for Farm A. For Farm A, both sows and gilts were allocated more feed at day 91 of gestation (2.4 and 2.2 kg/d, respectively), yet full consumption of the higher allocation appeared later for some sows, indicating that all sows did not increase their intake immediately in response to an increase in allocation. In Farm B, the feeding curve was the same for gilts and sows, but throughout gestation, gilts ate more feed than sows (Figure 1 and Table 2). The reason for this is unclear but might reflect greater pressure on sows to exit feeders early in sow-only groups, relative to gilt-only groups, resulting in lower intake.

The feeding pattern in both farms was disrupted at both the beginning and at the end of gestation. In addition, the impact on the intake of weekly introductions of new sows to groups is evident from the weekly cycles for DFI observed in Farm B. A plausible explanation for disruption at the start of gestation includes acclimatization within the time period of group construction, affected by the stress of remixing (Thomas et al., 2018). According to Chapinal et al. (2008), the period of acclimatization encompasses the first 2 wk of adaptation and should be excluded from analyses. Conversely, as sows approach the end of pregnancy, they potentially experience increasing difficulties in locomotion, accessibility of feeders, or increasing physical restriction to intake capacity due to the increasing size of the uterus. This phenomenon has not been reported in other studies but suggests that feed intake may be inadvertently compromised for group-housed sows in late

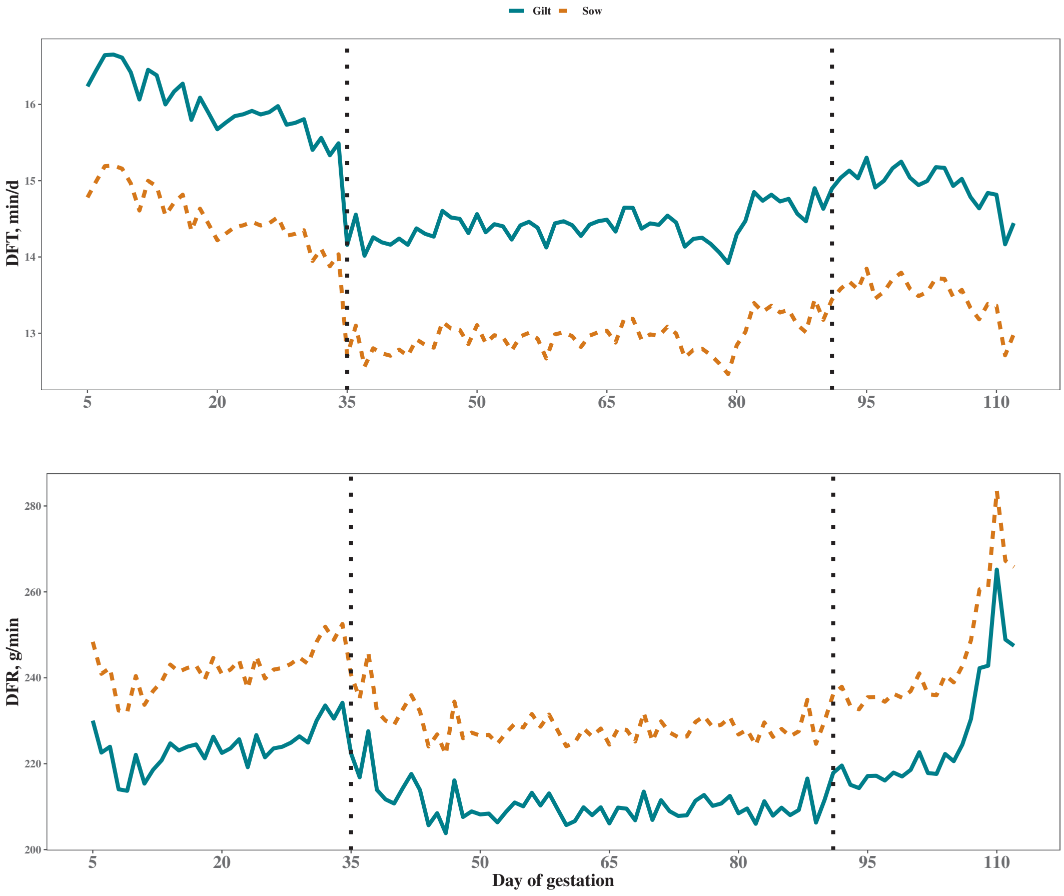

Figure 2. LSM for DFT and DFR for Farm A, with vertical dotted lines representing the timing of changes in feed allocation.

Table 2. LSM with SE in parentheses for feed intake (farms A and B), along with time spent eating and rate of feed consumption (Farm A only) averaged within time periods and across the complete gestation for gilts (G) and sows (S)

	Gestation phase, d							
	1 to 7	8 to 14	15 to 34	35 to 90	91 to 100	101 to 105	>105	Average
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
G	2.22 (0.14)^{d}	2.44 (0.01)^{f}	2.38 (0.00)^{e}	1.97 (0.00)^{a}	2.17 (0.00)^{c}	2.16 (0.01)^{c}	2.13 (0.02)^{b}	2.13 (0.00)
S	2.63 (0.01)^{d}	2.77 (0.01)^{e}	2.66 (0.02)^{d}	2.18 (0.00)^{a}	2.37 (0.00)^{c}	2.36 (0.01)^{c}	2.29 (0.01)^{b}	2.36 (0.01)
Mean	2.46 (0.45)	2.63 (0.26)	2.54 (0.16)	2.09 (0.11)	2.28 (0.16)	2.28 (0.24)	2.22 (0.38)	2.26 (0.12)
CV[1]	18.2	9.87	6.26	5.38	6.79	10.6	17.2	5.47
				Feed intake, kg/d (Farm B)				
N	523	540	540	540	540	540	539	540
G	1.79 (0.06)^{ab}	2.20 (0.03)^{d}	2.08 (0.02)^{c}	1.81 (0.01)^{b}	1.77 (0.02)^{ab}	1.82 (0.02)^{b}	1.68 (0.03)^{a}	1.88 (0.01)
S	1.66 (0.04)^{a}	1.91 (0.02)^{c}	1.90 (0.01)^{c}	1.79 (0.01)^{b}	1.81 (0.01)^{b}	1.84 (0.01)^{bc}	1.70 (0.02)^{a}	1.82 (0.01)
Mean	1.69 (0.68)	1.99 (0.41)	1.95 (0.25)	1.80 (0.15)	1.80 (0.22)	1.83 (0.24)	1.69 (0.33)	1.83 (0.12)
CV	40.3	20.8	12.8	8.11	12.0	13.0	19.3	6.78
				Time spent eating, min/d (Farm A)				
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
G	15.0 (0.17)^{a}	16.9 (0.17)^{d}	16.4 (0.15)^{c}	15.0 (0.14)^{a}	15.6 (0.17)^{b}	15.7 (0.20)^{b}	15.6 (0.25)^{ab}	15.5 (0.13)
S	14.4 (0.14)^{b}	15.3 (0.14)^{c}	14.6 (0.12)^{b}	13.6 (0.12)^{a}	14.5 (0.14)^{b}	14.5 (0.17)^{b}	14.0 (0.20)^{b}	14.1 (0.11)
Mean	14.7 (4.71)	16.0 (4.93)	15.4 (4.29)	14.2 (4.03)	15.0 (4.88)	15.0 (5.53)	14.7 (6.20)	14.7 (3.76)
CV	32.1	30.8	27.8	28.3	32.6	36.9	42.2	25.5
				Rate of feed consumption, g/min (Farm A)				
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
G	173 (2.82)^{c}	159 (2.07)^{b}	156 (1.65)^{b}	140 (1.42)^{a}	151 (1.92)^{b}	157 (2.36)^{b}	164 (4.35)^{c}	145 (1.36)
S	195 (2.26)^{d}	195 (1.68)^{d}	194 (1.34)^{d}	171 (1.15)^{a}	179 (1.56)^{b}	181 (1.94)^{b}	191 (3.55)^{c}	177 (1.10)
Mean	186 (78.4)	180 (62.0)	177 (50.6)	158 (42.3)	167 (55.0)	170 (65.2)	179 (110)	163 (41.4)
CV	42.2	34.5	28.5	26.9	33.0	38.3	61.1	25.4

[1] CV, coefficient of variation.

$^{a–f}$Values in rows with different superscripts were significantly different from pairwise comparison ($P < 0.05$).

gestation and requires further attention. Toward the end of gestation, the number of records reduced, mostly due to the timing of transfer to the farrowing shed, but within the sows that remain, reductions of 3% (Farm A) and 8% (Farm B) in feed intake were observed after day 105 in comparison with the period from 101 to 105 d of gestation (Table 2). A reduction in voluntary intake at this stage of pregnancy could also explain why some researchers do not observe improved outcomes from increasing feed allocation in late pregnancy.

LSM for feed intake and feeding behavior traits of gilts and sows by farm provide detail within specific time periods (Tables 2 and 3). Averages across gestation do not identify if there are critical time periods where differences in intake or behavior are more informative. The time sows spent eating and their rate of feed consumption changed over the gestation period (Farm A). Sows spent more time eating both at the start and the end of gestation relative to mid-gestation (Figure 2 and Table 2). Over the complete gestation, gilts took a longer time to eat their lower feed allocation than sows (sows: 14.1 ± 0.11 and gilts: 15.5 ± 0.13 min/d). The average rates of feed consumption in Farm A were 177 ± 1.10 and 145 ± 1.36 g/min for sows and gilts, respectively, which are significantly lower than the calibrated rate of feed delivery (Table 2). In comparison, for sows in Farm B, the rates of feed consumption calculated from average intake (assuming 10 min of consumption) were 188 and 182 g/min at a minimum. However, to consume the complete allocation in 10 min, the rates required were 220 and 190 g/min. Therefore, a much higher rate of feed intake was required on Farm B for sows to achieve their intake in a single session, or repeated sessions would be required. Setting a time limit on access to feed favors sows that can eat quickly. However, high rates of intake have been shown to have detrimental associations with outcomes, such as low number of born alive piglets or high number of stillborn piglets, shortened lactation length, low number of weaned piglets, and removals of sows due to health issues (Bunter et al., 2018; Vargovic et al., 2019).

Because the amount of feed supplied to gestating sows is restricted, feed allocation is typically consumed in a short time period (Meunier-Salaün et al., 2001). The time needed to consume daily allocations varies between animals, breeds (Labroue et al., 1997; Iida et al., 2017), diets (D´Eath et al., 2018), and experience, including the learnt response as sows adapt (Canario et al., 2013). In the study conducted by Olsson et al. (2011), the time spent eating was 14.2 min/d, which is similar to the current study, for a higher allocation (2.60 kg/d); thus, the rate of feed consumption was higher as well. Iida et al. (2017) reported less time spent eating (9.3 min/d) for a feed allocation of 2.4 kg/d, equivalent to approximately 258 g/min for the rate of feed consumption. A higher speed of eating is possible (Brouns and Edwards, 1994; Greenwood et al., 2019), but in all studies the speed of eating is inherently limited by the feed delivery rate, palatability, and availability of water in feeders. Creating a situation where sows need to eat their meals faster than their natural behavior determined on an individual level is not considered welfare friendly. Previous literature also suggested that limiting time allowed in the feeders is associated with more sows queuing, thus more aggression and vulva bites (Olsson et al., 2011). This was also supported in our previous study (Bunter et al., 2018).

Therefore, understanding the speed of eating is important for both assigning the time allowance per sow (e.g., Osborne TEAM system) in protected systems and has implications for unprotected feeding systems, where sows are not protected from pen mates at feeding (Bench et al., 2013). In unprotected systems, sows that eat the fastest are basically fed ad libitum (Spoolder and Vermeer, 2015), whereas slower eaters or lower-ranking animals might continuously be underfed. In protected systems, time limits are imposed following the recommendations by manufacturers, in order to reduce the number of feeders required and increase the number of sows per feeder. However, since allocations were not consumed by all sows, our results suggest that the time allowed may be inadequate for some sows in Farm B to consume the target allocation. Data analyzed in this project also showed that when a time limit was not imposed, sows tended to eat significantly slower. This clearly demonstrates that sows adapt their feeding behavior to the environment provided in order to achieve intake. It seems that for sows it is relatively easy to slow down intake, but it may not be as easy to eat faster as an adaptation. When more feed was offered, such as at the beginning of gestation, the rate of feed consumption was the highest. For most of the sows, this early gestation intake may also be influenced by previous conditions, as it also follows a period of ad libitum access to feed, which occurred during

Table 3. LSM with SE in parentheses for feeding behavior traits recorded for gilts (G) and sows (S), by farm

			Model 1[2]		Model 2	
Trait, unit	Mean (SD)	CV[1]	Gilts	Sows	Gilts	Sows
Farm A, N = 3,939						
AFE, N/d	1.17 (0.11)	9.09	1.17 (0.00)^{a}	1.17 (0.00)^{a}	1.17 (0.004)^{a}	1.16 (0.003)^{a}
MISSF, count	4.09 (3.35)	81.9	4.89 (0.12)^{a}	3.48 (0.10)^{b}	4.83 (0.11)^{a}	3.55 (0.10)^{b}
BELOW1, count	6.11 (3.92)	64.2	7.10 (0.14)^{a}	5.35 (0.11)^{b}	7.04 (0.13)^{a}	5.43 (0.11)^{a}
ABOVE30, count	5.40 (8.46)	157	6.80 (0.30)^{a}	4.34 (0.24)^{b}	6.49 (0.27)^{a}	4.69 (0.23)^{b}
APPETITE, scored 0 to 3	2.69 (0.15)	5.63	2.65 (0.01)^{a}	2.71 (0.00)^{b}	2.65 (0.005)^{a}	2.71 (0.004)^{b}
DA_bin, scored 0/1	0.94 (0.05)	4.84	0.94 (0.00)^{a}	0.95 (0.00)^{b}	0.94 (0.002)^{a}	0.95 (0.001)^{b}
SDA-I, kg	0.70 (0.23)	32.8	0.73 (0.01)^{a}	0.68 (0.01)^{b}	0.73 (0.008)^{a}	0.68 (0.007)^{b}
Farm B, N = 540						
MISSF, count	4.79 (5.19)	108	4.45 (0.44)^{a}	4.91 (0.26)^{a}		
BELOW1, count	7.14 (6.06)	84.9	5.75 (0.51)^{a}	7.63 (0.30)^{b}		
DA_bin, scored 0/1	0.90 (0.07)	8.17	0.94 (0.01)^{a}	0.89 (0.00)^{b}		
SDA-I, kg	0.45 (0.15)	32.3	0.42 (0.01)^{a}	0.47 (0.01)^{b}		

[1] CV, coefficient of variation.

[2] Model 1 does not account for repeated records; model 2: gilt (sow) was added as a random effect to model 1.

[a,b] Values in rows with different superscripts were significantly different from a pairwise comparison ($P < 0.05$).

lactation and/or pre-mating. Due to the longer duration of feeding and slower rates of intake, separation of gilts from sows seems important to ensure gilts will obtain their requirements and not have to compete with sows.

Appetite and low intake events

The average number of feeding events per day was 1.17 ± 0.11 (Table 3), reflecting that most (~80%) of the sows and gilts ate their allocation in a single meal event per day, consistent with results observed by Cornou et al. (2008). This may be because sows have some distance (and obstacles) to traverse in order to return to the ESF and choose not to do so, or it may simply reflect that the only feed events recorded were those involving feed delivery. Failure to record nonfeeding visits will result in an underestimate of the value recorded for the total number of visits per day. The data of nonfeeding visits are not required when the aim is to measure intake, whereas this information is relevant if the aim is to observe feeding patterns or behavior. De Haer and Merks (1992) suggested that in growing pigs, nonfeeding visits should not be included in the estimation of parameters related to feeding patterns. This applies to unprotected feeding systems where growing pigs are frequently interrupted by other pigs. However, in gestating sows, if the goal is to assess behavior, nonfeeding visits should be recorded.

In contrast to a desirable feeding pattern (i.e., eating the complete allocation every day), alternatives include irregular eating patterns or low intake, represented by MISSF and BELOW1, respectively (Table 3). The number of days with missed or low intake meals varied between 4.09 ± 3.35 and 7.14 ± 6.06 d across farms, demonstrating several days where feed intake was not achieved. Despite a higher feed allocation and zero intake events for some calendar days, Farm A had a lower average MISSF or BELOW1, and sows exhibited a higher appetite (DA_bin) than Farm B. On average, approximately 5% to 6% of sows did not consume their daily feed allocation, as shown by the mean for trait DA_bin. Since sows were restricted in the amount of feed delivered, yet sow appetite is high (van Barneveld et al., 2007), it was expected that the entire allocation would be consumed daily on both farms. The cause of the difference between farms is not known specifically but potentially relates to population (genetics and parity distribution) and management differences, combined with characteristics of the ESF systems used. Other studies have demonstrated that a reduction in appetite during gestation can arise from compromised health (Matthews et al., 2016) or returning to estrus (Cornou et al., 2008), but the latter was not pertinent to the sows used in this study (all sows were pregnant). An inability to consume total feed allocation within 10 min, which is the maximum time allowed in Farm B, is also reflected by lower appetite (DA_bin). Moreover, sows requiring a longer time period to eat their ration can be forced out of the ESF by other sows, creating reluctance to remain in the feeder later on. In the ESF system where time was not constrained (Farm A), gilts and sows averaged 6.80 ± 0.30 and 4.34 ± 0.24 d, respectively, when the time spent in the feeder was longer than 30 min (ABOVE30).

SDA-I reflects how consistently a sow ate relative to the given allocation each day. Thus, a desirable value should be as close as possible to zero, indicating the sows' intake deviated very little from her allocation over time. Farm A had higher SDA-I than Farm B, indicating higher variation in feed consumption relative to allocation over time. The allocation was also generally higher in Farm A, thus allowing for a bigger deviation (i.e., scale effects), although the coefficient of variation was not different between farms (32.8% vs. 32.3%). In addition, Farm A changed the feed allocation over time more often than Farm B, and it was previously observed (Figure 1) that the adjustment of intake to allocation was not instantaneous for a proportion of sows, also contributing to larger SDA-I. In both farms, significant differences between gilts and sows were observed in SDA-I but not in the same direction. In Farm A, sows had lower SDA-I than gilts, whereas the reverse was observed in Farm B (Table 3).

Genetic parameters

Feed intake and feeding behavior traits

Sow line or breed group was not used to alter feed allocation curves. However, sow line was still fitted in models to avoid potential inflation of additive variances due to the presence of multiple lines. Parameters for AFI traits were negligible (heritability) to low (repeatability) in all time periods and over the complete gestation in Farm A but marginally higher (heritability) in Farm B (Table 4). Since Farm A had no limitation on time spent eating, individual feed intake was predominantly defined by allocation, which was a constant across most sows. Therefore, feed intake in this system reflects a management decision, limiting individual variation in intake. In contrast, where a time limit to feeding events was imposed (Farm B), the resulting feed intake was also potentially a component of individual variation in the speed of eating, which, based on the results from Farm A, is a more heritable trait.

In contrast to this study, the heritability of feed intake is more typically around 0.30 for growing animals fed ad libitum (Labroue et al., 1997; Do et al., 2013) but declined to 0.16 when the feed was restricted to 89% of ad libitum (Hermesch et al., 1999). In growing gilts (Bunter et al., 2007) or lactating sows (Bergsma et al., 2008), where there is also no restriction in allocated feed imposed, moderate to high heritability estimates are also reported for feed intake (Bergsma et al., 2008; Bunter et al., 2009, 2010; Gilbert et al., 2012). Since correlations between feed intake for growers and during lactation are positive (Bunter et al., 2007; Bergsma et al., 2013) and restriction is observed to reduce heritability (Hermesch et al., 1999), the restriction in the amount of feed delivered during gestation clearly alters genetic variation observed for feed intake. These results demonstrate that, in contrast to growing animals fed ad libitum, feed intake per se is not a consistently heritable trait in restrictively fed gestating sows managed under fixed feed allocations with ESFs. Therefore, phenotypes for the trait feed intake derived from ESF data for gestating sows may not be very informative for breeding programs.

Despite the lack of genetic variation for feed intake under restricted allocation, time spent eating and, therefore, the rate of feed consumption traits were both moderately heritable and also repeatable across gestations (Table 4), demonstrating strong consistency in eating behavior, on average, for individual sows across adjacent parities. Data for individual feed intake recorded for the focal sows as growing pigs or lactating sows were not available. Therefore, it can only be speculated that the time sows spend eating would be correlated with feed intake traits under ad libitum circumstances. If this association was present, data on time spent eating during gestation might also be useful for identifying variation in sow appetite, which may also have important implications for feed intake during lactation.

The lowest heritability estimates for time spent eating and rate of feed consumption occurred at both the start (first 7 d) and end (>105 d) of gestation (AFT: 0.08 ± 0.03 and 0.13 ± 0.04; AFR: 0.06 ± 0.02 and 0.08 ± 0.03). The highest estimates occurred for data recorded in the middle (35 to 90 d) of gestation (AFT: 0.27 ± 0.05 and AFR: 0.30 ± 0.05). Generally, all heritability

Table 4. Heritability estimates, h^2 (SE), permanent environmental effect, pe^2 (SE), repeatability, *r* (SE), and phenotypic variance, σ_p^2, for AFI, AFT, and AFR, along with the number of observations (*N*)

	Gestation phase, d							
	1 to 7	8 to 14	15 to 34	35 to 90	91 to 100	101 to 105	>105	Average
Feed intake, AFI (kg/d) Farm A								
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
h^2 (SE)	0.01 (0.01)	0.02 (0.02)	0.00 (0.00)	0.00 (0.01)	0.00 (0.01)	0.00 (0.00)	0.01 (0.02)	0.03 (0.02)
pe^2 (SE)	0.00 (0.03)	0.00 (0.00)	0.03 (0.03)	0.06 (0.03)	0.00 (0.00)	0.00 (0.00)	0.03 (0.04)	0.05 (0.04)
r (SE)	0.01 (0.01)	0.02 (0.01)	0.03 (0.03)	0.07 (0.03)	0.00 (0.00)	0.00 (0.00)	0.04 (0.04)	0.08 (0.03)
σ_p^2	0.138	0.044	0.006	0.002	0.013	0.047	0.137	0.001
Feed intake, AFI (kg/d) Farm B								
N	523	540	540	540	540	540	539	540
h^2 (SE)	0.11 (0.08)	0.00 (0.00)	0.09 (0.08)	0.13 (0.08)	0.00 (0.00)	0.10 (0.08)	0.00 (0.00)	0.17 (0.10)
σ_p^2	0.454	0.152	0.055	0.021	0.046	0.057	0.107	0.015
Daily time, AFT (min/d) Farm A								
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
h^2 (SE)	0.08 (0.03)	0.16 (0.04)	0.21 (0.04)	0.27 (0.05)	0.23 (0.04)	0.18 (0.04)	0.13 (0.04)	0.31 (0.05)
pe^2 (SE)	0.17 (0.04)	0.19 (0.04)	0.28 (0.04)	0.34 (0.05)	0.31 (0.04)	0.29 (0.04)	0.28 (0.05)	0.37 (0.05)
r (SE)	0.25 (0.03)	0.35 (0.03)	0.49 (0.02)	0.61 (0.02)	0.54 (0.02)	0.47 (0.03)	0.41 (0.03)	0.67 (0.02)
σ_p^2	21.4	21.9	16.9	15.5	23.0	29.4	37.2	13.4
Rate of feed consumption, AFR (g/min) Farm A								
N	3,836	3,914	3,939	3,939	3,936	3,772	3,220	3,939
h^2 (SE)	0.06 (0.02)	0.09 (0.03)	0.22 (0.05)	0.30 (0.05)	0.16 (0.04)	0.13 (0.03)	0.08 (0.03)	0.38 (0.06)
pe^2 (SE)	0.10 (0.04)	0.22 (0.04)	0.24 (0.05)	0.28 (0.05)	0.25 (0.04)	0.26 (0.04)	0.05 (0.04)	0.28 (0.05)
r (SE)	0.15 (0.03)	0.31 (0.03)	0.47 (0.02)	0.58 (0.02)	0.41 (0.03)	0.39 (0.03)	0.12 (0.04)	0.66 (0.02)
σ_p^2	5,784	3,207	2,079	1,522	2,799	4,043	11,644	1,427

estimates within time periods were lower than for the trait values derived from the complete gestation (AFT: 0.31 ± 0.05 and AFR: 0.38 ± 0.06). Estimates for averages across gestation were consistent with comparable traits (time spent eating and rate of feed consumption) from previous studies in growing pigs (Labroue et al., 1997; Do et al., 2013; Reyer et al., 2017; Shirali et al., 2017). In many species, including humans, speed of eating is established as a moderately to highly heritable behavioral phenotype (Llewellyn et al., 2008), and the data for these sows and gilts support this consensus.

Canario et al. (2013) previously pointed out that animals can achieve the same feed intake with different feeding strategies, and this behavioral flexibility can be used for selective breeding in different environments, complementary to strategies based on feed intake. The data from ESFs may provide some opportunities generally to obtain phenotypes on feeding behavior and appetite, which potentially have wider application than just sow performance for breeding programs.

Appetite and low intake events

Heritability estimates for traits available for both farms (MISSF, BELOW1, DA_bin, and SDA-I) differed in magnitude (Table 5). Traits MISSF and SDA-I were moderately heritable and repeatable in Farm A, but lowly heritable in Farm B, while DA_bin was moderately heritable in Farm B, but only lowly heritable in Farm A.

The low estimates of heritability for AFE (Table 5) could reflect the lack of information for nonfeeding visits and the relatively low incidence of sows with more than one feeding visit (Table 3). However, the repeatability for AFE was moderate (0.26 ± 0.03), demonstrating a consistent pattern across gestations. When the number of feeding visits was previously investigated for growing pigs, heritability estimates were much higher, above 0.40 (Labroue et al., 1997; Do et al., 2013; Lu et al., 2017; Shirali et al., 2017), more similar to the repeatability in these data, implying that heritability may have been underestimated. Further investigation of visits to the ESFs for gestating sows is warranted since nonfeeding visits might indicate lack of satiation or high appetite, and, in addition, the extent of nonfeeding visits might affect the outcomes for sows or their health (Bunter et al., 2018; Vargovic et al., 2019). Olsson et al. (2011) reported that more than 50% of visits to the feeders are nonfeeding visits, and when entering the feeder, every third sow is attacked by pen mates that are near the feeders. Therefore, sows visiting feeders frequently may suffer more injuries from pen mates and, in the case of these data, will also exercise significantly more than sows that do not traverse pens to revisit feeders.

Moderate heritability estimates were obtained for all feeding behavior traits relating to missed or low intake meals (MISSF, BELOW1, SDA-I, APPETITE, and DA_bin) for one or both farms, showing that there is a detectable genetic variation in these traits. However, very different phenotypic variances were observed between farms for MISSF and BELOW1. Therefore, the genetic variance was more similar than heritabilities for these traits across farms but generally higher in Farm B. When traits reflecting the appetite of sows (APPETITE, DA_bin, and SDA-I) are compared, the most consistent heritability is estimated for SDA-I for both farms (0.17 ± 0.04 and 0.10 ± 0.08), and this trait could be calculated from the data using both types of feeding systems.

When growing pigs miss a meal, they do not fully compensate that meal in the following day, even if additional feed is available (Brumm et al., 2005). Brumm et al. (2005) also stated that lacking obvious signs of compromised health from missing one meal does not mean that there are no other long-term consequences. According to Canario et al. (2013), feeding behavior is an indicator of animal welfare and it is correlated with an inner state of the animal. In this study, sows that missed more meals or had more low intake meals also had significantly lower average feed intake, demonstrating that they also failed to compensate for missed meals. This was largely a result of a fixed allocation. A similar observation was made by Matthews et al. (2016).

The highest repeatability occurred for the trait ABOVE30, which represents the number of days when sows spent more than 30 min within the ESF in a single feeding event. Information on time spent in feeders is important since prolonged visits reduce the time available for other sows to consume their allocations. Occupancy should be accounted for when the number of feeders required per pen or sow group is calculated. In these data, it seems that prolonged visits to the feeders were not a one-time event, and sows were fairly consistent in this behavior. The reason for sows staying in the ESF for a long time period is not known. If this phenotype was related to issues with event timing (i.e., the system fails to read a sows RFID tag on exit), then the trait would be repeatable but not heritable, and this was not the case. High ABOVE30 could potentially be related to fear and, therefore, avoidance (hiding) behavior or represent

Table 5. Heritability estimates, h^2 (SE), permanent environmental effect, pe^2 (SE), repeatability, r (SE), and phenotypic variance, σ_p^2, for feeding behavior traits (Farm A: N = 3,939; Farm B: N = 540)

		Model 1				Model 2[1]	
Trait	Farm	h^2 (SE)	pe^2 (SE)	r (SE)	σ_p^2	h^2 (SE)	σ_p^2
AFE, count	A	0.05 (0.02)	0.21 (0.04)	0.26 (0.03)	0.01	0.06 (0.03)	0.01
MISSF, count	A	0.19 (0.04)	0.15 (0.04)	0.33 (0.03)	10.4	0.19 (0.04)	10.7
	B	0.05 (0.07)			26.7		
BELOW1, count	A	0.16 (0.04)	0.16 (0.04)	0.32 (0.03)	13.8	0.16 (0.04)	13.9
	B	0.15 (0.09)			35.9		
ABOVE30, count	A	0.18 (0.04)	0.40 (0.04)	0.58 (0.02)	66.7	0.19 (0.04)	67.3
APPETITE, score	A	0.01 (0.01)	0.09 (0.03)	0.10 (0.03)	0.02	0.00 (0.02)	0.02
DA_bin, score	A	0.02 (0.02)	0.06 (0.04)	0.08 (0.03)	0.002	0.01 (0.02)	0.00
	B	0.23 (0.10)			0.005		
SDA-I, kg	A	0.17 (0.04)	0.16 (0.04)	0.33 (0.03)	0.05	0.18 (0.04)	0.05
	B	0.10 (0.08)			0.02		

[1] Exclusion of repeated records.

a preference for solitude, but this is only speculation. When time per feeder is limited, sows that prefer to eat more slowly need to alter their behavior, which could potentially reduce feed intake, increase stress, and compromise welfare. There is some uncertainty as to how much of the 30 (or more) min was needed for eating. Presumably, sows were not spending 30 min eating since their entire allocation can be consumed within approximately 14 min (Table 2).

Differences in parameters (traits) between farms could be related to farm or population differences, differences in the effects of the ESF systems, diet composition, sampling effects, or other unidentified environmental factors. Because only 28% of animals had repeated records on Farm A, the partitioning of permanent environmental from additive effects was potentially affected by sampling correlations between these effects. However, simplifying the data in Farm A to one record per sow and excluding the permanent environmental effect from the models did not significantly alter the heritability estimates for any trait (Table 5).

Implications for breeding programs

Despite the relative lack of information supplied by average feed intake itself, given that the ability to express feed intake under restricted feeding is fairly limited, other behavioral traits (e.g., time spent eating, the frequency of missed meals, or variation in eating patterns) provide opportunities to improve outcomes for sows. However, not all ESF systems are currently capable of recording all of the traits presented here, demonstrating that some attention to the software development of ESF systems is required to enable this capacity. In addition, currently, ESF systems generate reports if a sow missed a meal but not if the feed intake was below allocation or for cumulative low feed intakes or other individual sow phenotypes (i.e., traits derived for this study).

This study demonstrated that heritabilities for gestation feed intake differed slightly between two populations with different ESF systems, in a manner consistent with expectation based on restricted feed allocation and/or the time sows were allowed to consume their allocation. Variation in ESF phenotypes among individual sows reflected significant genetic variation for some of these traits. Traits related to time spent eating (AFT and ABOVE30) and feeding behaviors (MISSF, BELOW1, SDA-I, and DA_bin) were moderately heritable, whereas the heritability for feed intake itself was low to negligible. As pointed out previously, feed intake becomes more heritable when the time spent eating was limited, partially reflecting genetic variation in the eating speed. The time spent eating might be related to intakes during other periods of an animal's life (e.g., lactation), which warrants further investigation. In addition, feed intake and feeding behavior traits might be related to the outcomes for sows.

In conclusion, the results in this study demonstrated that data from electronic sow feeders could be used to construct useful phenotypes for feed intake or feeding behavior traits for individual sows in group housing, some of which were heritable. The data demonstrated that "normal healthy" sows exhibited variation in appetite and feeding behaviors, which has implications both for better management and for breeding programs. Further investigation of these traits in other farms and environments is warranted. Traits that appear to have some potential for breeding programs include traits reflecting the time spent eating or the prevalence of missed or low intake meals. In particular, gilts eat slower than sows, which in the unprotected systems without separation by parity could result in reduced intake and stress for gilts generally. Slower eating sows are similarly affected. Late gestation reductions in the voluntary intake and a slow response to increased allocations may also be important issues to address for the management of sows in ESF systems during gestation.

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Conflict of interest statement

The authors disclose no actual or potential conflicts of interest that may affect the ability to objectively present or review research or data.

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