**Modeling PRRSV-2 prevalence within a farrowing room**

Onyekachukwu H. Osemeke1, Eduardo de Freitas Costa2, Vinicius Weide, Swaminathan Jayaraman1, Gustavo S. Silva1 Daniel C. L. Linhares1

**ABSTRACT**

**……..**

**Introduction**

Porcine respiratory and reproductive syndrome virus (PRRSV) poses a significant challenge to the global swine industry (Calderón Díaz et al., 2020; Holtkamp et al., 2013). Ascertaining the PRRSV status of pig populations around the time of weaning is crucial to guide decisions on health interventions and pig flow (Holtkamp et al., 2011).

Efficient PRRSV surveillance/monitoring programs allow for the early detection of infection

and helps evaluate changes in PRRSV prevalence over time; aiding swine producers and veterinarians alike to forestall the spread of a PRRSV (Mccaw, 2000; Silva et al., 2017), and evaluate progress made with instituted PRRSV management programs (Holtkamp et al., 2021; Linhares et al., 2014).

Different sample types are routinely submitted to Veterinary Diagnostic Laboratories in the US for PRRSV investigation by RT-rtPCR; these would include samples taken from individual pigs such as serum, swabs, semen, and post-mortem tissues; or aggregate samples taken from multiple pigs such as processing fluids and oral fluids (Trevisan et al., 2019). These samples are either submitted and tested individually or in pools.

The number of samples submitted for disease pathogen investigation is crucial to the success of a surveillance/monitoring exercise. Guided by some epidemiological assumptions, the sample size should have enough power to detect at least one positive unit if the herd is truly positive for the pathogen of interest (Cameron et al., 2020; Stevenson, 2021).

Estimated prevalence at the individual pig level is one of the key variables used in calculating sample size to demonstrate disease freedom (Fosgate, 2009; Stevenson, 2021).

The reference sample for PRRSV surveillance in sow herds is serum from weaning-age pigs (Holtkamp et al., 2011). Although the serum sample is the sample of choice for PRRSV surveillance, it requires more skill, more manpower, is less animal welfare friendly, and is often impractical for frequent PRRSV surveillance in large herds (Turlewicz-Podbielska et al., 2020) compared to other (alternative) sampling options. For this reason, since 2018, aggregate alternative samples have been the most frequently submitted samples for PRRSV surveillance in the US (Trevisan et al., 2019).

Almeida (Nunes de Almeida, 2020) demonstrated that, especially in low prevalence, Family oral fluids (FOFs) are a more convenient and cost-efficient alternative to serum sampling for PRRSV surveillance in weaning-age pigs. A FOF sample is an aggregate sample obtained when oral fluids are wrung off a rope chewed by a sow and her piglets (Almeida et al., 2020). A challenge with interpreting a positive result from testing aggregate sample types is that one only knows that at least one animal that contributed to the sample matrix is pathogen-positive (shedding) but cannot ascertain how many animals exactly are shedding.

Consequently, little to nothing is known about the number of positive pigs in a sampled room given the proportion of test-positive aggregate samples, such as FOF, obtained from that room.

The individual pig is the unit for which sample size is calculated when non-aggregate samples are collected, while the litter is the unit for which sample size is calculated when an aggregate sample such as FOF is to be collected (Rotolo et al., 2017)(Osemeke et al., 2022, *unpublished*); it will be helpful to swine practitioners in making sampling decisions if they understood how the proportion of PRRSV-positive piglets related with the proportion of PRRSV-positive litters, as both parameters are needed assumptions in estimating sample sizes.

To the best of our knowledge, the relationship between the mentioned proportions in a swine farrowing room has not been previously characterized.

This study builds upon a previous study that characterized the probability of a positive FOF sample given the number of viremic (PRRSV-positive) pigs within a litter (Almeida, Zhang, Lopez, et al., 2021), to model a relationship between the True litter-level PRRSV prevalence (TLP or proportion of litters with at least one viremic pig), Apparent litter-level PRRSV prevalence (ALP or proportion of litters that are expected to test positive for FOF), and the Piglet level prevalence (PP or proportion of PRRSV-positive/viremic pigs) in a farrowing room.

It is expected that the results from this study will not only provide insights to swine practitioners as to the likely relationship between PP, TLP, and ALP, but also provide a template/framework for determining piglet-level prevalence of PRRSV (and potentially other swine pathogens) that are being monitored using aggregate samples.

**2. Methodology**

**2.1 PRRSV detection in pig litters using FOF**

Based on a dataset from Almeida et al. (Almeida, Zhang, Zimmerman, et al., 2021) 199 litters had all piglets sampled for PRRSV RNA detection by RT-rtPCR (reverse transcription, real time polymerase chain reaction); also, each *i* litter was sampled using FOF. The litters were sampled from 11 farrowing rooms across 6 different swine breeding farms.

The effect of the proportion of positive piglets () on the detection of a positive litter using FOF () was assessed with a generalized linear mixed model employing a logit link function and a 'residual' Bernoulli distribution. In addition, the linear predictor comprised random effects for farms (*j*) according to:

, (1)

where is the intercept of the model. is the random error assumed , and is the random effect accounting for the farm-effect in the model, assumed , where . Approximate maximum likelihood inference was based upon Laplacian integration, as implemented in R (R Core Team, 2018) in routine glmer from library lme4 (Bates et al., 2015).

**2.2 Stochastic model**

Let's consider a random variable: number of positive piglets in the *i-*thlitter ), assuming that each piglet's status (positive/negative) is a Bernoulli trial, with a fixed *p* probability, thus arises from a binomial process. Consider a room with *n* litters with different sizes () drawn from a discrete empirical distribution, and total number of piglets in the room . In a simplistic scenario, the allocation of positive piglets in each litter ) would follow the relative size of the litter in the room. However, given that we are modeling an infectious disease, there might be a situation where the total number of positive animals (*N*) may be "clustered" in a few litters.

Accounting for this, the number of positive animals in each *i* litter () is calculated as a special case of the multinomial distribution, sampling recursively from binomial distributions using a clustering factor:

, (2)

where *j* stands for the successive allocation of positive animals within each litter. is the probability of success in this binomial process. Finally, *pl* is defined as:

. (3)

The reader should be aware that *c* is a clustering factor. Thus when , and the positive piglets will be totally clustered in the smallest number of litters as possible. On the other hand, when , piglets will be spread according to the relative size (number of piglets) of each litter regarding the room size.

To obtain the clustering factor *c* we used the observed distribution of the within litter prevalence reported in Almeida et al. (Almeida, Zhang, Zimmerman, et al., 2021) across *n*=7 rooms. The lost function was the minimization of the mean squared errors of the predicted *vs* observed distribution of the within litter prevalence . The objective function can be used to calculate a parameter estimate . Each room was randomly chosen, 5000 times obtaining the parameters ,, and . For each sampled room, 300 values of *c* were sampled from a uniform distribution , obtaining a distribution to optimize *.*

2.2.2 *Apparent prevalence at the litter level*

The simulated proportion of positive piglets per litter obtained from 2.2 were used as input for the logistic model fit in 2.1, calculating the marginal probability of detection of each simulated litter using FOF sampling. Now we are interested in modeling a random variable (*S*) describing the number of positive litters detected in a routine FOF sampling in a farrowing room. Assuming the probability of each litter being detected by FOF ( see eq. 1) are independent of each other, and the positive/negative status of a litter , *S* equals . The parameters and distributions used in the simulations are described in table 1. In this simulation, 5000 stochastic iterations were performed, each one representing a different room, propagating the between litter variability observable in different farrowing rooms.

Table 1 – Descriptions of model parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter/variable** | **Distribution/function** | **Description** | **Source** |
| *p* | Fixed= (range of values from 1% to 100%) | Probability of a piglet being positive in a room (prevalence) | Almeida |
|  | p\*T | Total number of positive animals in the room | Calculation |
|  |  | Total number of piglets in the room | Calculation |
|  | empirical {(), ()} \* | Number of piglets in the *i-*thlitter | Almeida |
| *n* | Fixed=56 | Number of crates in a room | Almeida |
|  |  | Number of positive piglets in *i-*thlitter | Calculation |
|  |  | Probability of success in this binomial process (i.e., allocation of positive piglets in a litter) for the in *i-*thlitter | Calculation |
| *c* | Fixed=0.63 | Clustering factor | Optimized based on Almeida |

\* empirical {(3, 4, 5, 6, 7, 8, 9, 10 ,11, 12, 13, 14, 15, 25), (0.0092, 0.0092, 0.0046, 0.0046, 0.0553, 0.0691, 0.0922, 0.1014 0.1982, 0.2074, 0.1244, 0.0783, 0.0415, 0.0046)}

**2.3 Sensitivity analysis**

To assess the effect of the clustering factor (*c*) and the room size (*n*) on the estimated relationship between pig-level-prevalence and litter-level prevalence we selected five values for *c* (0.05, 0.34, 0.63, 0.83, 1) and five values for *n* (10, 33, 56, 79, 102) combining then as a factorial design for the sensitivity analysis, totaling 25 different scenarios.

we set minimum (m−) and maximum (m+) values for the mentioned parameters (Table 2). The baseline used for simulation is now named *m* and is a range of values in increments of 0.5 from -1 to +1, when equals zero, the model runs the baseline values (eq 4). The parameters were not varied at the same time to observe the effect of each one on the output in a univariate fashion.

(4)

**2.4 Scenario analysis**

The relationship between the litter prevalence and the piglet level prevalence were assessed for a 56-crate room, assuming a clustering level of 0.63.

**3. Results**

**3.1 PRRSV detection in pig litters using FOF**

Chart, line chart

Description automatically generated

*Figure 1: A jitter plot of the Probability of PRRSV detection in FOF by the proportion of positive pigs within litters (within litter prevalence). 95% prediction intervals are represented by the grey region around the regression line.*

**3.2 Stochastic model**

**3.2.1 Observed distribution of clustering in sampled farms**

The clustering distribution across all sampled rooms had a minimum value of 0, a median of 0.629, a mean of 0.580, and a maximum value of 1. The distributions of the clustering parameter across all sampled rooms are represented in figure 2

**Chart, histogram

Description automatically generated**

*Figure 2: A histogram showing the distribution of the clustering parameter c across all sampled rooms from Almeida’s study.*

**3.2.2 The relationship between piglet-level prevalence and litter-level prevalence**

*Table 2: Showing the relationship between the proportion of positive piglets in a 56-crate farrowing room and the True and Apparent (by FOF) proportion of positive litters assuming a clustering level of 0.63.*

|  |  |  |
| --- | --- | --- |
| **Proportion of PRRSV-positive piglets**  **(%)** | **True proportion of PRRSV-positive litters (Upper and lower 95% quantiles)**  **(%)** | **Apparent proportion of PRRSV-positive litters by FOF (Upper and lower 95% quantiles)**  **(%)** |
| 1 | 3.57(1.79,7.14) | 1.79(0.00,3.57) |
| 5 | 8.93(5.36,10.71) | 7.14(5.36,8.93) |
| 10 | 14.29(10.71,16.07) | 10.71(8.93,14.29) |
| 15 | 17.86(16.07,21.43) | 16.07(14.29,19.64) |
| 20 | 23.21(19.64,26.79) | 21.43(17.86,25.00) |
| 25 | 28.57(25.00,32.14) | 26.79(23.21,30.36) |
| 30 | 33.93(30.36,37.50) | 32.14(28.57,33.93) |
| 35 | 39.29(35.71,42.86) | 35.71(33.93,39.29) |
| 40 | 42.86(39.29,48.21) | 41.07(37.50,44.64) |
| 45 | 48.21(44.64,51.79) | 46.43(42.86,50.00) |
| 50 | 53.57(50.00,57.14) | 51.79(48.21,55.36) |

*Figure 3: A plot of litter prevalence against piglet level prevalence for a 56-crate farrowing room, assuming a clustering level of 0.63.*

Chart, box and whisker chart

Description automatically generated

*Figure 3: A boxplot representation of the distribution of True- and Apparent litter prevalence in a 56-crate room given different piglet-level prevalence scenarios and a clustering factor of 0.63.*

**3.3 Sensitivity analysis**

The sensitivity analysis was done to evaluate the effect of variations in clustering level and room size on the proposed relationship between piglet level prevalence and litter prevalence. As can be seen from the plots, ALP was relatively more stable to changes in clustering and number of crates compared to TLP. Generally, TLP and ALP increasingly converged to similar values with increasing clustering and increasing room size. Clustering changes appeared to have a more significant effect on ALP and TLP than changes in the number of crates in the room.

**Diagram, line chart

Description automatically generated**

*Figure 4: A graphical representation of changes in the relationship between the proportion of PRRSV-positive pigs and the proportion of PRRSV-positive litters (True and Apparent) with changes in clustering of PRRSV within room, and number of litters within rooms.*

**4. Discussion**

The use of mathematical models to describe disease dynamics in swine populations is not new. Mathematical models have been used to characterize and describe PRRSV transmission dynamics (Amirpour Haredasht et al., 2017; Evans et al., 2010; Nodelijk et al., 2000; Phoo-ngurn et al., 2019; Rotolo et al., 2017; Suksamran et al., 2017) and to also evaluate PRRSV control strategies (Arruda et al., 2016; Jeong et al., 2014).

Perhaps explained by the theory of PRRSV being highly infectious but not highly contagious (Pileri & Mateu, 2016), or by the mere fact that pigs in conventional US barns do not interact randomly with each other (ref) and are more likely to transmit PRRSV to pigs within the same crate or with their closest neighbors (Murato et al., 2020), some studies have described the non-homogenous distribution of PRRSV in pig barns (M. N. Almeida et al., 2021; Rotolo et al., 2017)

Clustering estimates the degree of homogeneity (or more aptly put; heterogeneity) of PRRSV between litters in a farrowing room; it may be overreaching to deterministically model a one-size-fits-all clustering for PRRSV. This is because the spread of PRRSV between litters within a farrowing room would depend on 1) Management practices such as cross-fostering, and vaccination (Mccaw, 2000; Pileri & Mateu, 2016) 2) PRRSV strain (there is evidence of differences in characteristics such as virulence and spread between PRRSV strains) (Cho et al., 2007; Ogno et al., 2019; Pileri & Mateu, 2016) 3) Barn structure (for example, presence or type of ventilation systems in use) (ref) 4)Time since outbreak 5) Secondary infections which may increase pig susceptibility to PRRSV, encourage huddling or increase production of infectious respiratory fluids(ref). This uncertainty however does not undermine the importance of these results, on the contrary, it adds some precision to the list of conventional epidemiological assumptions guiding sample size calculations for disease pathogen surveillance viz a viz making an informed guestimate of the clustering level in addition to disease prevalence.

*Paper on R0 of PRRSV and role of vac and biosec* (Pileri & Mateu, 2016)

A critical goal of this study is to estimate the most likely relationship between the pig level prevalence and apparent litter prevalence by FOF, considering the pen-level sensitivity and specificity of this sample type. As observed from Figure 3, ALP is not as sensitive as TLP to variations in clustering parameter; we are therefore confident of the estimates on Table 2.

One can also decide the number of crates to randomly sample for FOF to detect a disease given an assumed pig level prevalence. For example, assuming an at least 10% pig-level prevalence, serum sampling requires you sample about 30 pigs to be 95% confident of detecting at least one positive animal (Cannon & Roe, 1982; Holtkamp et al., 2011). From the table, 10% pig-level prevalence corresponds to about 11% ALP or about 7 litters in a 56-crate room likely to give a positive FOF test. This number can be used to calculate an appropriate sample size for FOF to detect at least 1 positive litter; Table 2 is therefore useful to the practitioner in tying back what an assumed litter prevalence would mean at the individual pig level.

Another key application of the proposed tables is to help the practitioner estimate his piglet-level prevalence given the results of FOF-testing. Given that a representative number of litters were sampled (sample size to estimate prevalence), the proportion of positive FOF results on RT-qPCR tests (apparent litter prevalence by FOF) can be used to deduce the likely proportion of total pigs that are PRRSV-positive pigs (piglet-level prevalence).

**5. Conclusion**

This study explored the use of mathematical models to characterize the relationship between PP, TLP, and ALP in a farrowing room. A key takeaway from this study is the demonstration of the effect of a clustering parameter on the characterized relationship between the mentioned proportions; like other sampling assumptions, clustering could be considered when estimating probable sample size…..

**REFERENCES**

Almeida, M. N., Rotto, H., Schneider, P., Robb, C., Zimmerman, J. J., Holtkamp, D. J., Rademacher, C. J., & Linhares, D. C. L. (2020). Collecting oral fluid samples from due-to-wean litters. *Preventive Veterinary Medicine*, *174*. https://doi.org/10.1016/j.prevetmed.2019.104810

Almeida, M. N., Zhang, M., Lopez, W. A. L., Vilalta, C., Sanhueza, J., Corzo, C. A., Zimmerman, J. J., & Linhares, D. C. L. (2021). A comparison of three sampling approaches for detecting PRRSV in suckling piglets. *Preventive Veterinary Medicine*, *194*. https://doi.org/10.1016/j.prevetmed.2021.105427

Almeida, M. N., Zhang, M., Zimmerman, J. J., Holtkamp, D. J., & Linhares, D. C. L. (2021). Finding PRRSV in sow herds: Family oral fluids vs. serum samples from due-to-wean pigs. *Preventive Veterinary Medicine*, *193*, 105397. https://doi.org/10.1016/j.prevetmed.2021.105397

Amirpour Haredasht, S., Polson, D., Main, R., Lee, K., Holtkamp, D., & Martínez-López, B. (2017). Modeling the spatio-temporal dynamics of porcine reproductive and respiratory syndrome cases at farm level using geographical distance and pig trade network matrices. *BMC Veterinary Research*, *13*(1). https://doi.org/10.1186/s12917-017-1076-6

Arruda, A. G., Friendship, R., Carpenter, J., Greer, A., & Poljak, Z. (2016). Evaluation of control strategies for porcine reproductive and respiratory syndrome (PRRS) in swine breeding herds using a discrete event agent-based model. *PLoS ONE*, *11*(11), 166596. https://doi.org/10.1371/journal.pone.0166596

Calderón Díaz, J. A., Fitzgerald, R. M., Shalloo, L., Rodrigues da Costa, M., Niemi, J., Leonard, F. C., Kyriazakis, I., & García Manzanilla, E. (2020). Financial Analysis of Herd Status and Vaccination Practices for Porcine Reproductive and Respiratory Syndrome Virus, Swine Influenza Virus, and Mycoplasma hyopneumoniae in Farrow-to-Finish Pig Farms Using a Bio-Economic Simulation Model. *Frontiers in Veterinary Science*, *7*, 922. https://doi.org/10.3389/FVETS.2020.556674/BIBTEX

Cameron, A. R., Meyer, A., Faverjon, C., & Mackenzie, C. (2020). Quantification of the sensitivity of early detection surveillance. *Transboundary and Emerging Diseases*, *67*(6), 2532–2543. https://doi.org/10.1111/TBED.13598

Cannon, R. M., & Roe, R. T. (1982). *Livestock disease surveys . A field manual for veterinarians. Bureau of Rural Science, Department of Primary Industry*. Australian Government Pub. Service. https://books.google.fr/books?id=2P6sOSdHmx0C

Cho, J. G., Deen, J., & Dee, S. A. (2007). Influence of isolate pathogenicity on the aerosol transmission of Porcine reproductive and respiratory syndrome virus. *Canadian Journal of Veterinary Research*, *71*(1), 23–27.

Evans, C. M., Medley, G. F., Creasey, S. J., & Green, L. E. (2010). A stochastic mathematical model of the within-herd transmission dynamics of porcine reproductive and respiratory syndrome virus (PRRSV): Fade-out and persistence. *Preventive Veterinary Medicine*, *93*(4), 248–257. https://doi.org/10.1016/J.PREVETMED.2009.11.001

Fosgate, G. T. (2009). Practical sample size calculations for surveillance and diagnostic investigations. In *Journal of Veterinary Diagnostic Investigation* (Vol. 21, Issue 1, pp. 3–14). Journal of Veterinary Diagnostic Investigation. https://doi.org/10.1177/104063870902100102

Holtkamp, D. J., Kliebenstein, J. B., Neumann, E., Zimmerman, J. J., Rotto, H., Yoder, T. K., Wang, C., Yeske, P., Mowrer, C. L., Haley, C. A., Neumann, E. J., Rotto, H. F., & Yeske, P. E. (2013). Assessment of the economic impact of porcine reproductive and respiratory syndrome virus on United States pork producers . In *Journal of Swine Health and Production* (Vol. 21). http://lib.dr.iastate.edu/econ\_las\_pubs/50

Holtkamp, D. J., Polson, D. D., Torremorell, M., Morrison, B., Classen, D. M., Becton, L., Henry, S., Rodibaugh, M. T., Rowland, R. R., Snelson, H., Straw, B., Yeske, P., & Zimmerman, J. (2011). Terminology for classifying swine herds by porcine reproductive and respiratory syndrome virus status. In *Journal of Swine Health and Production* (Vol. 19, Issue 1, pp. 44–56). http://www.aasv.org/shap.html.

Holtkamp, D. J., Torremorell, M., Corzo, C. A., L Linhares, D. C., Almeida, M. N., Yeske, P., Polson, D. D., Becton, L., Snel-son, H., Donovan, T., Pittman, J., Johnson, C., Vilalta, C., Silva, G. S., & Sanhueza, J. (2021). Proposed modifications to porcine reproductive and respiratory syndrome virus herd classification. *J Swine Health Prod*, *29*(5), 261–270. http://www.aasv.org/shap.html.

Jeong, J., Aly, S. S., Cano, J. P., Polson, D., Kass, P. H., & Perez, A. M. (2014). Stochastic model of porcine reproductive and respiratory syndrome virus control strategies on a swine farm in the United States. *American Journal of Veterinary Research*, *75*(3), 260–267. https://doi.org/10.2460/AJVR.75.3.260

Linhares, D. C. L., Cano, J. P., Torremorell, M., & Morrison, R. B. (2014). Comparison of time to PRRSv-stability and production losses between two exposure programs to control PRRSv in sow herds. *Preventive Veterinary Medicine*, *116*(1–2), 111–119. https://doi.org/10.1016/J.PREVETMED.2014.05.010

Mccaw, M. B. (2000). Case report Effect of reducing crossfostering at birth on piglet mortality and performance during an acute outbreak of porcine reproductive and respiratory syndrome. *Number 1 Swine Health Prod*, *8*(1), 15–21. http://www.aasp.org/shap.html.

Murato, Y., Hayama, Y., Shimizu, Y., Sawai, K., & Yamamoto, T. (2020). *Evaluation of sampling methods for effective detection of infected pig farms during a disease outbreak*. https://doi.org/10.1371/journal.pone.0241177

Nodelijk, G., De Jong, M. C. M., Van Nes, A., Vernooy, J. C. M., Van Leengoed, L. A. M. G., Pol, J. M. A., & Verheijden, J. H. M. (2000). Introduction, persistence and fade-out of porcine reproductive and respiratory syndrome virus in a Dutch breeding herd: A mathematical analysis. *Epidemiology and Infection*, *124*(1), 173–182. https://doi.org/10.1017/S0950268899003246

Nunes de Almeida, M. (2020). Improved Porcine Reproductive and Respiratory Syndrome Virus Surveillance in Swine Breeding Herds [Iowa State University]. In *ProQuest Dissertations and Theses*. https://doi.org/10.31274/etd-20210114-104

Ogno, G., Rodríguez-Gómez, I. M., Canelli, E., Ruedas-Torres, I., Álvarez, B., Domínguez, J., Borghetti, P., Martelli, P., & Gómez-Laguna, J. (2019). Impact of PRRSV strains of different in vivo virulence on the macrophage population of the thymus. *Veterinary Microbiology*, *232*, 137–145. https://doi.org/10.1016/j.vetmic.2019.04.016

Phoo-ngurn, P., Kiataramkul, C., & Chamchod, F. (2019). Modeling the spread of porcine reproductive and respiratory syndrome virus (PRRSV) in a swine population: transmission dynamics, immunity information, and optimal control strategies. *Advances in Difference Equations*, *2019*(1), 1–12. https://doi.org/10.1186/S13662-019-2351-6/FIGURES/5

Pileri, E., & Mateu, E. (2016). Review on the transmission porcine reproductive and respiratory syndrome virus between pigs and farms and impact on vaccination. In *Veterinary Research* (Vol. 47, Issue 1, pp. 1–13). BioMed Central. https://doi.org/10.1186/s13567-016-0391-4

Rotolo, M. L., Sun, Y., Wang, C., Giménez-Lirola, L., Baum, D. H., Gauger, P. C., Harmon, K. M., Hoogland, M., Main, R., & Zimmerman, J. J. (2017). Sampling guidelines for oral fluid-based surveys of group-housed animals. *Veterinary Microbiology*, *209*, 20–29. https://doi.org/10.1016/j.vetmic.2017.02.004

Silva, G. S., Schwartz, M., Morrison, R. B., & Linhares, D. C. L. (2017). Monitoring breeding herd production data to detect PRRSV outbreaks. *Preventive Veterinary Medicine*, *148*, 89–93. https://doi.org/10.1016/J.PREVETMED.2017.10.012

Stevenson, M. A. (2021). Sample Size Estimation in Veterinary Epidemiologic Research. In *Frontiers in Veterinary Science* (Vol. 7, p. 539573). Frontiers Media S.A. https://doi.org/10.3389/fvets.2020.539573

Suksamran, J., Lenbury, Y., Satiracoo, P., & Rattanakul, C. (2017). A model for porcine reproductive and respiratory syndrome with time-dependent infection rate: traveling wave solution. *Adv Differ Equ*, *2017*, 215. https://doi.org/10.1186/s13662-017-1282-3

Trevisan, G., Linhares, L. C. M., Crim, B., Dubey, P., Schwartz, K. J., Burrough, E. R., Main, R. G., Sundberg, P., Thurn, M., Lages, P. T. F., Corzo, C. A., Torrison, J., Henningson, J., Herrman, E., Hanzlicek, G. A., Raghavan, R., Marthaler, D., Greseth, J., Clement, T., … Linhares, D. C. L. (2019). Macroepidemiological aspects of porcine reproductive and respiratory syndrome virus detection by major United States veterinary diagnostic laboratories over time, age group, and specimen. *PLoS ONE*, *14*(10), e0223544. https://doi.org/10.1371/journal.pone.0223544

Turlewicz-Podbielska, H., Włodarek, J., & Pomorska-Mól, M. (2020). Noninvasive strategies for surveillance of swine viral diseases: a review. *Journal of Veterinary Diagnostic Investigation : Official Publication of the American Association of Veterinary Laboratory Diagnosticians, Inc*, *32*(4), 503. https://doi.org/10.1177/1040638720936616

|  |
| --- |
|  |