Stochastic model of porcine reproductive and respiratory syndrome virus control strategies on a swine farm in the United States

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Objective—To use mathematical modeling to assess the effectiveness of control strategies for porcine reproductive and respiratory syndrome (PRRS) virus on a swine farm.

Sample—A hypothetical small, medium, or large farrow-to-weaning swine farm in the Midwestern United States.

Procedures—Stochastic models were formulated to simulate an outbreak of PRRS on a farm. Control strategies assessed in those models included none (baseline) and various combinations of mass immunization, herd closure, and gilt acclimatization. Nine different models resulting from the combination of low, moderate, or high PRRS virus virulence and small, medium, or large herd size were simulated. A stabilized status, the outcome of interest, was defined as the absence of positive PCR assay results for PRRS virus in 3-week-old piglets. For each scenario, the percentage of simulations with a stabilized status was used as a proxy for the probability of disease control.

Results—Increasing PRRS virus virulence and herd size were negatively associated with the probability of achieving a stabilized status. Repeated mass immunization with herd closure or gilt acclimatization was a better alternative than was single mass immunization for disease control within a farm.

Conclusions and Clinical Relevance—Repeated mass immunization with a PRRS modified-live virus vaccine with herd closure or gilt acclimatization was the scenario most likely to achieve a stabilized status. Estimation of the cost of various PRRS control strategies is necessary. (Am J Vet Res 2014;75:260–267)

Porcine reproductive and respiratory syndrome was first recognized in the United States in the late 1980s when veterinary practitioners noted the appearance of a previously unrecognized disease in US swine herds. Infection with PRRS virus causes reproductive disorders in sows and pneumonia and growth reduction in growing pigs. Since being identified, PRRS has become endemic in many regions, with occasional outbreaks of more severe forms of the disease. It is estimated that PRRS causes between $560 and $664 million in losses annually for US swine producers.

Abbreviations

MLV  Modified-live virus  
PRRS  Porcine reproductive and respiratory syndrome  
R0  Basic reproduction number

Swine veterinarians have used several strategies to control PRRS, including mass immunization, herd closure, and gilt acclimatization. Inactivated PRRS virus vaccines are considered ineffective or of limited efficacy. Results of multiple studies indicate that administration of MLV vaccines significantly reduces lesions and clinical signs following homologous or heterologous PRRS virus challenge, even though the infection dynamics, rate of transmission, and RNA concentration of the PRRS virus do not differ significantly between unvaccinated and MLV-vaccinated pigs. Despite the fact...
that vaccination of pigs with an MLV vaccine does not prevent infection with PRRS virus, it does decrease the duration of infectivity for PRRS-infected pigs in herds with endemic PRRS virus or at high risk of becoming infected with PRRS virus. Thus, the effectiveness of MLV vaccination for the control of PRRS, specifically as a method for whole herd exposure in herd closure programs, needs to be assessed.

Mathematical models have been used to explain the dynamics of PRRS virus infection and vaccination strategies, with previous models formulated for farrow-to-finish swine farms under European conditions. However, epidemiological aspects of swine production in the United States differ from those in Europe in regard to the type of endemic PRRS virus infection and herd demographics. In the United States, farrow-to-weaning is a typical swine farm structure, which allows breeding pigs to be segregated from weaned pigs; therefore, the study reported here considered only sows and suckling piglets. The purpose of the study reported here was to use stochastic modeling to compare the effectiveness of various combinations of control strategies for PRRS virus at the individual herd level. The results will aid in the determination of the most effective strategy for PRRS virus control.

**Materials and Methods**

**Modeling framework** — The foundation for all modeling in the study was a typical Midwestern US farrow-to-weaning swine farm, on which sows are managed in a 3-stage production cycle (breeding, which lasts for approx 1 week; gestation, which lasts for approx 16 weeks; and farrowing, which lasts for approx 3 weeks). Sows in different stages are segregated from each other. Piglets born within the same week are managed as a cohort and weaned at 3 weeks old, at which time they leave the premises.

A modification of the Reed-Frost equation was used to formulate discrete-time stochastic models by the use of generic software. These models were created to simulate the dynamics of PRRS virus infection on a small (n = 390 sows), medium (1,533), or large (3,876) farm with and without (baseline) the implementation of various control strategies. The small, medium, and large herd size categories represented the 10th percentile, mean, and 90th percentile herd size for US swine farms, respectively. A separate model was created for each combination of herd size (small, medium, or large) with virulence level (low, moderate, or high) of the infecting PRRS virus, resulting in a simulation for each of 9 models at baseline and for each of 4 scenarios that included the implementation of various combinations of control strategies. Monte Carlo simulation was used to fit ad hoc probability distributions that modeled the uncertainty and variability associated with biological processes related to PRRS transmission, and each scenario consisted of 10,000 iterations (ie, simulations); calculations for each simulation were estimated for 200 weeks.

**Model assumptions** — The Reed-Frost equation was modified to account for the assumption that there were no completely susceptible sows in the herd. Other assumptions included sows within the same production stage (breeding, gestation, and farrowing) had equal probability of interacting with each other, all newly introduced gilts entered the production cycle at the breeding stage, and piglets were weaned at 3 weeks old and left the farm. Furthermore, it was assumed that infection with PRRS virus did not result in permanent immunity. Also, although administration of an MLV PRRS vaccine did not prevent infection, it reduced the duration of infectivity by approximately 30%. It was also assumed that maternal (passive) immunity waned over time in piglets born to recovered sows. However, waning of vaccinal immunity in piglets was not considered plausible because of the short duration they remained on the premises.

**Model development** — Virulence of the infecting PRRS virus was expressed as $R_0$, which is the number of pigs that would be infected with PRRS virus following the introduction of 1 PRRS-infected pig into a completely susceptible population. The $R_0$ estimate depends on the duration of infectivity and the probability that an infected animal will have sufficient contact with a susceptible animal for viral transmission to occur. Thus, the $R_0$ was calculated as the product of the transmission rate and duration of infectivity. When $R_0$ is $< 1$, infection is unlikely to be transmitted to susceptible animals. Conversely, when $R_0$ is $> 1$, infection will spread within a susceptible population, and when $R_0$ is equal to 1, the infection rate will remain constant. The $R_0$ for sows differs from that for piglets because PRRS virus infection in sows has different characteristics, compared with those of PRRS virus infection in piglets (PRRS-infected piglets develop more severe clinical signs than do sows). To represent low, moderate, and high virulence of type II, or North American, PRRS virus in the model, an $R_0$ of 0.14, 3.00, and 3.22, respectively, was used for sows and an $R_0$ of 7.26, 9.76, and 13.13, respectively, was used for piglets. The $R_0$ for sows was estimated by the model simulated by Nodelijk et al, and the $R_0$ for piglets was estimated by the model simulated by Le. The minimum and maximum values for each variable were estimated by expert opinion.

Separate epidemiological compartmental models were created for sow and piglets, and these models were linked by the birth rate of live piglets. Variable estimates used in these models were drawn from a Pert distribution to account for variability and uncertainty and to reflect a realistic situation in which the variables could change randomly. For each variable, the distribution shape was specified with estimates of the minimum, most likely, and maximum values on the basis of review of the literature, empirical evidence, and expert opinion (Appendix 1). Variables were modified as necessary to account for PRRS-induced production losses (eg, the farrowing rate for PRRS-infected sows was less than the farrowing rate for sows not infected with PRRS virus).

For the sow model, the proportions of sows classified as susceptible, infected, and recovered at the beginning of each simulation were chosen to mimic the distribution of sows within each category given the prevalence of PRRS virus infection in the herd. Differ-
ence equations were then used to calculate the number of susceptible, infected, and recovered sows at the end of each specific 1-week time interval. For the piglet model, age of the piglets was structured so that piglets were clustered and moved in 1-week cohorts. To account for vertical transmission of PRRS virus between sows and piglets, it was assumed that infected piglets were born to infected sows and susceptible piglets were born to susceptible sows. However, piglets from recovered sows were considered maternally immune rather than recovered at birth. Transitions among immunologic states (susceptible, infected, recovered, or maternally immune) for both sows and piglets were summarized (Appendix 2).

Baseline scenario—The baseline scenario was developed to describe the dynamics of PRRS virus infection on a farrow-to-weaning swine farm in the absence of the implementation of PRRS control strategies. As the simulation proceeded and the piglets got older, the number of susceptible and infected piglets increased, whereas the number of maternally immune piglets decreased.

The baseline scenario had a constant number of pigs throughout the simulation. On the basis of expert opinion, the PRRS prevalence for replacement gilts was assumed to be half of that for the residing sows on the farm. Susceptible pigs became infected at a transmission rate that was equal to the R0 divided by the duration of infectivity (Appendix 1). Transmission of PRRS virus was assumed to occur only among sows within the same production stage (breeding, gestation, or farrowing) and piglets within the same 1-week cohort.

Gilts were introduced into the herd only during the breeding stage at a number equal to the number of sows removed from the herd by culling or death during the previous 1-week interval. Sows transitioned from the breeding stage into the gestation stage at a rate equal to the breeding rate, from the gestation stage into the farrowing stage at a rate equal to the farrowing rate, and from the farrowing stage into the breeding stage at a rate equal to the weaning rate. Sows that aborted were returned to the breeding stage at the abortion rate. Culling occurred only in the breeding stage.

PRRS control strategies—Following development of the baseline scenario, 4 additional scenarios were developed to describe the dynamics of PRRS virus infection on a farrow-to-weaning swine farm with implementation of various combinations of PRRS control strategies. The control strategies considered were herd closure, gilt acclimatization, and mass immunization.

The introduction of new pigs with an unknown PRRS status into a herd can affect the number of PRRS-negative pigs in the herd. For example, if replacement gilts become viremic during the breeding stage, they become a source of infection for the other sows in the breeding stage, which in turn can result in vertical transmission of PRRS virus to piglets. Herd closure is described as a method for eliminating PRRS virus from a herd and, for this study, was defined as not introducing any replacement gilts into the breeding stage for a period of 30 weeks; however, breeding of the remaining sows in the herd continued.

The purpose of gilt acclimatization is to expose gilts to PRRS virus at a young age so that they will be recovered from the infection prior to entering the breeding herd. Gilt acclimatization can be achieved by exposure of gilts to viremic nursery pigs, infection of the live resident virus, or MLV vaccination. For this study, administration of a PRRS MLV vaccine was used for gilt acclimatization because the effect of MLV vaccination for control of PRRS within a herd was an outcome of interest. The duration of infectivity for acclimatized gilts was assumed to be 70% that of unacclimatized gilts.

Results of another study suggest that mass vaccination of pigs against PRRS can reduce economic losses associated with PRRS virus infection. For this study, mass immunization was modeled as single or repeated administration of an MLV vaccine. For single mass immunization, all sows were vaccinated once during week 1. For repeated mass immunization, all sows were vaccinated every 15 weeks beginning at week 1. On the basis of expert opinion, the efficacy of PRRS MLV vaccines ranged from 90% to 95% (mean, 92.5%), and similar to gilt acclimatization, the duration of infectivity for vaccinated sows was assumed to be 70% that of unvaccinated sows. For example, for every 100 sows vaccinated, the vaccine would be ineffective in 7.5 sows, which means that those sows would essentially be unvaccinated, whereas the 92.5 sows in which the vaccine was effective would have a duration of infectivity equal to 0.70 × duration of infectivity.

Control scenarios—In the United States, most farrow-to-weaning swine farms that have pigs infected with PRRS virus use either single or repeated mass immunization with an MLV vaccine in combination with herd closure or gilt acclimatization to mitigate the effects of the disease. Therefore, the 4 scenarios assessed in this study included herd closure with single mass immunization (scenario 1), herd closure and gilt acclimatization with repeated mass immunization (scenario 2), gilt acclimatization with single mass immunization (scenario 3), and gilt acclimatization with repeated mass immunization (scenario 4).

For scenario 1, all sows were vaccinated with a PRRS MLV vaccine during week 1 and gilts were not introduced into the herd during the first 30 weeks of the simulation. At week 31, a number of gilts equal to the number of sows that died or were culled during the first 30 weeks of the simulation was introduced into the breeding stage. During the subsequent weeks, the rate of gilt introduction was the same as that in the baseline scenario. All gilts that were introduced into the herd after the 30-week herd closure period were assumed to be seronegative for antibodies against PRRS virus as determined by an ELISA. The recovery rate for vaccinated sows was assumed to be approximately 1.4 times that for unvaccinated sows. Because lifetime immunity against PRRS virus is not achieved by vaccination with an MLV vaccine, all pigs were assumed to have vaccine-induced immunity against PRRS that waned exponentially as described.

For scenario 2, all sows were vaccinated with a PRRS MLV vaccine during week 1 and then once every 15 weeks thereafter throughout the 200-week simula-
tion. Herd closure and the reintroduction of replacement gilts after week 30 were modeled as described for scenario 1. The gilts introduced after the herd closure period had ended were assumed to be acclimatized to PRRS (ie, were seropositive for antibodies against PRRS virus as determined by an ELISA).

For scenario 3, it was assumed gilt acclimatization had been performed at a separate facility and sufficient time had passed such that all gilts had developed complete immunity to PRRS and were no longer shedding the virus. Gilts were introduced into the herd as described for the baseline scenario, and all sows were vaccinated with a PRRS MLV vaccine during week 1.

For scenario 4, gilt acclimatization and introduction were modeled as described for scenario 3. Repeat-ed mass immunization was modeled as described for scenario 2.

Sensitivity analysis—For sensitivity analyses, the model that combined a medium-sized herd with a PRRS virus with moderate virulence was used as the refer-ent. The probability of achieving a stabilized status (ie, the absence of positive PCR results for PRRS virus in 3-week-old piglets) was the outcome of interest, and the effects of varying the values for the respective vari-ables on that probability were assessed with t tests. The null hypothesis was that the probability of achieving a stabilized status was not affected by varying the value of a given variable. For all analyses, values of P ≤ 0.05 were considered significant. Independent variables for which changing the value resulted in a significant change in the probability of achieving a stabilized state were considered key determinants for the control of PRRS virus infection at the herd level.

Results

For each of the 9 models (combination of herd size [small, medium, or large] and PRRS virus virulence [low, moderate, or high]), the percentage of simulations that resulted in a stabilized status (absence of positive PCR assay results for PRRS virus in 3-week-old piglets) was summarized (Table 1). In general, the probability of the farm achieving a stabilized status decreased as herd size and PRRS virulence increased. Virulence level appeared to have a greater influence on the probability of the farm achieving a stabilized status than did herd size. For the baseline scenario (no PRRS control strategies implemented), a stabilized status was achieved only in the model for small herd size and low PRRS virus virulence, and when the PRRS virus virulence was moderate or high, the percentage of simulations that achieved a stabilized status was < 6% for all models, even those with a small herd size. For the scenarios (1 through 4) in which various combinations of PRRS control strategies were implemented, the percentage of simulations that achieved a stabilized status was higher than that for the corresponding baseline scenario for all models except the model for small herd size and low PRRS virus virulence, in which all simulations in all scenarios achieved a stabilized status.

For the models in which PRRS virus virulence was low, all simulations achieved a stabilized status for each of the 4 scenarios that included implementation of PRRS control strategies. For the models in which PRRS virus virulence was moderate or high, the scenarios that included repeated mass immunization (scenarios 2 and 4) resulted in a higher percentage of simulations that achieved a stabilized status than did the corresponding scenarios that included single mass immunization (scenarios 1 and 3). Among all 4 scenarios, scenario 2 (herd closure and gilt acclimatization with repeated mass immunization) consistently resulted in the highest percentage of simulations that achieved a stabilized status, followed by scenarios 4 (gilt acclimatization with repeated mass immunization) and 3 (gilt acclimatization with single mass immunization). Of the scenarios that included implementation of some form of PRRS control strategy, scenario 1 (herd closure with single mass immunization) always resulted in the lowest percentage of simulations that achieved a stabilized status.

The mean percentage of 3-week-old piglets infected with PRRS at 200 weeks (end of the simulation period) was not affected by herd size (Table 2). Implementation of PRRS control strategies effectively eliminated the infection from 3-week-old piglets by the end of the simulation period when the virulence of the infecting virus was low. When the PRRS virus virulence was moderate or high, scenario 2 consistently resulted in the lowest mean percentage of PRRS-infected 3-week-old piglets.

Table 1—Percentage of simulations that achieved a stabilized status (absence of positive PCR assay results for PRRS virus in 3-week-old piglets) for a Midwestern US farrow-to-weaning swine farm for each combination of herd size (small [n = 390 sows], medium [1,533], or large [3,876]) and virulence level (low, moderate, or high) of infecting PRRS virus as determined by stochastic modeling with Monte Carlo simulation for scenarios that did and did not include various PRRS control strategies.

<table>
<thead>
<tr>
<th>Virulence level</th>
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<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
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<td>4</td>
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<td>100</td>
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<td>Moderate</td>
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<td>23.32</td>
<td>22.56</td>
<td>32.64</td>
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<td>26.23</td>
<td>24.79</td>
<td>24.15</td>
<td>26.23</td>
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</table>

Each simulation consisted of 10,000 iterations, and calculations were estimated for 200 weeks.

*Virulence level was determined on the basis of the R0 (ie, number of pigs that would become infected with PRRS virus following the introduction of 1 PRRS-infected pig into a completely susceptible population) for both sows and piglets. Low virulence was defined as an R0 of 0.14 for sows and 7.26 for piglets, moderate virulence was defined as an R0 of 3.00 for sows and 9.76 for piglets, and high virulence was defined as an R0 of 3.22 for sows and 13.13 for piglets. The baseline scenario did not include the implementation of any PRRS control strategies. Scenario 1 included herd closure with single mass immunization with an MLV vaccine. Scenario 2 included herd closure and gilt acclimatization with repeated mass immunization with an MLV vaccine. Scenario 3 included gilt acclimatization with single mass immunization with an MLV vaccine. Scenario 4 included gilt acclimatization with repeated mass immunization with an MLV vaccine.
Results of sensitivity analyses indicated that the recovery rate for sows had a significant effect on the probability that a herd would achieve a stabilized status across all scenarios. In the baseline scenario and scenarios 1 and 3, the recovery rate for nonvaccinated sows had the most substantial effect on the outcome, whereas in scenarios 2 and 4, the recovery rate for vaccinated sows had the most substantial effect on the outcome. For the baseline scenario, the recovery rate for unvaccinated sows, recovery rate for piglets, rate of loss of maternal immunity, farrowing rate for noninfected sows, and mortality rate in pigs had a significant negative correlation with the probability that a herd would achieve a stabilized status, whereas the rate of loss of active immunity, number of piglets born alive from infected sows, and breeding rate had a significant positive correlation with the probability that a herd would achieve a stabilized status.

Discussion

In the present study, a simulation model was used to evaluate the within-herd dynamics of PRRS virus transmission following implementation of various combinations of control strategies and the probability that those strategies would eradicate PRRS from weaned piglets. Results suggested that herd closure was a more effective strategy than was gilt acclimatization for PRRS control on a typical Midwestern US farrow-to-weaning swine farm. Further, mass immunization of all pigs on the farm with a PRRS MLV vaccine every 15 weeks in combination with herd closure or gilt acclimatization increased the likelihood that the herd would achieve a stabilized status (i.e., absence of positive PCR assay results for PRRS virus in 3-week-old piglets), compared with mass immunization of all pigs with a PRRS MLV vaccine only once.

Stochastic modeling was used to elucidate the within-herd transmission of PRRS virus on a farrow-to-weaning swine farm with and without (baseline) implementation of various combinations of PRRS control strategies. Control strategies investigated included herd closure, gilt acclimatization, and single or repeated mass immunizations. Stabilization of pig farms is the first step toward PRRS eradication. Results indicated that both herd size and PRRS virus virulence had an effect on the likelihood that a herd would achieve a stabilized status; however, PRRS virus virulence had a greater effect on the likelihood that a herd would achieve a stabilized status than did herd size.

Of the 4 scenarios evaluated for the control of PRRS virus at the herd level, scenario 2 (herd closure and gilt acclimatization with repeated mass immunization) resulted in the highest percentage of simulations in which a stabilized status was achieved, whereas scenario 1 (herd closure with single mass immunization) resulted in the lowest percentage of simulations in which a stabilized status was achieved when PRRS virus virulence was moderate or high, regardless of herd size. Furthermore, the percentage of simulations that resulted in a stabilized status was higher for scenario 2, compared with that for scenario 4 (gilt acclimatization with repeated mass immunization), which suggested that herd closure was a more effective PRRS control strategy than was gilt acclimatization. However, comparisons among the 4 scenarios were difficult because the probability of the farm achieving a stabilized status was dependent on the virulence of the infecting PRRS virus. In the present study, the model for large herd size and highly virulent PRRS virus resulted in the lowest percentage of simulations that achieved a stabilized status, regardless of the scenario. Unfortunately, a large herd infected with a highly virulent PRRS virus is the situation most frequently encountered by US swine practitioners; therefore, herd size, PRRS virus virulence, and multiple PRRS control strategies should be considered when herd-level PRRS control programs are developed.

The duration of maternal immunity to PRRS virus in piglets varies, but estimates range from 3 to 10 weeks. Investigators of 2 other studies have used an R₀ of 3.91,92 Therefore, it is reasonable to assume that the R₀ for piglets will be higher than the R₀ for sows. Given the age dependency for PRRS virus infection, 9.76 was assumed to be more appropriate for the present study. Estimates of the duration of active immunity to PRRS virus range from 36,37 to 80 weeks. On the basis of expert opinion, a 36-week duration of active immunity to PRRS virus was used for the models of the present study.

In the present study, the results varied slightly when the outcome was modeled as the percentage of simulations that achieved a stabilized status versus when the outcome was modeled as the mean percentage of PRRS-infected 3-week-old piglets at the end of the simulation period (i.e., 200 weeks). The mean percentage of PRRS-infected piglets at the end of the simu-

### Table 2—Mean percentage of PRRS-infected 3-week-old piglets at week 200 for stochastic Monte Carlo simulations of PRRS virus transmission on a Midwestern US farrow-to-weaning swine farm.

<table>
<thead>
<tr>
<th>Virulence level*</th>
<th>Scenariot</th>
<th>Herd size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
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<tr>
<td></td>
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</tr>
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</tr>
<tr>
<td></td>
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<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>Baseline</td>
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<td></td>
<td>4</td>
<td>4.638</td>
</tr>
</tbody>
</table>

See Table 1 for key.
lution period was not affected by herd size, which sug-
ggested that the probability of a large herd achieving a
stabilized status was attributable only to its large size.
Also, the baseline scenario (no PRRS control strate-
gies implemented) resulted in the lowest percentage of
simulation that achieved a stabilized status (ie, worst
outcome) regardless of herd size or PRRS virus viru-
lence. However, the mean percentage of PRRS-infected
3-week-old piglets at the end of the simulation period
was not always highest (ie, worst outcome) for the
baseline scenario. In fact, when PRRS virus virulence
was moderate or high, the baseline scenario resulted in
a lower mean percentage of PRRS-infected piglets than
did scenario 1. This suggested that the introduction of
PRRS-infected gilts onto a farm did not make the num-
ber of PRRS-infected piglets increase substantially but
rather resulted in the maintenance of a constant num-
ber of PRRS-infected piglets such that it was unlikely
that the farm would ever achieve a stabilized status.

Sensitivity analysis is a useful method to identify
the most influential variable in a model and compare
the relative importance of each variable within a group
of variables for a specific outcome.41,42 For the models
of the present study, sensitivity analysis suggested that
the recovery rate of sows from PRRS virus infection was
an important determinant for the control of PRRS at the
herd level. In the baseline scenario and scenarios 1 and
3 (gilt acclimatization with single mass immunization),
the recovery rate of unvaccinated sows was the most
important determinant in a herd achieving a stabilized
status, whereas in scenarios 2 and 4, the recovery rate
of vaccinated sows was the most important determinant
in a herd achieving a stabilized status. Administration
of a PRRS MLV vaccine to pigs does not prevent those
pigs from becoming infected; however, it does reduce
the duration of infectivity and increase the recovery
rate of vaccinated pigs, compared with those in unvac-
cinated pigs.43 Results of this study indicated that
repeated mass immunization of all sows in a herd with a
PRRS MLV vaccine was more effective for controlling
the disease (ie, minimized the percentage of PRRS-
infected 3-week-old piglets at 200 weeks) than was
mass immunization of all sows in a herd with a PRRS
MLV vaccine once during week 1. Therefore, single
mass immunization of all sows with a PRRS MLV vac-
cine is not recommended for the control of PRRS virus
at the herd level.

Previous stochastic models and mathematical anal-
yses44,51 have proven useful for obtaining quanti-
tative information regarding the transmission of
PRRS virus and studying the efficacy of various con-
trol measures at the herd level. However, none of those
studies16,17,44,45 were modeled on the basis of swine pro-
duction in the United States as was the present study;
therefore, the results of the present study should be
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particularly farrow-to-weaning farms.

The results of the present study were sensitive to the
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Contrasting the results of the present study to those of
other that achieved a stabilized status (ie, worst
outcome) regardless of herd size or PRRS virus viru-
lence. However, the mean percentage of PRRS-infected
3-week-old piglets at the end of the simulation period
was not always highest (ie, worst outcome) for the
baseline scenario. In fact, when PRRS virus virulence
was moderate or high, the baseline scenario resulted in
a lower mean percentage of PRRS-infected piglets than
did scenario 1. This suggested that the introduction of
PRRS-infected gilts onto a farm did not make the num-
ber of PRRS-infected piglets increase substantially but
rather resulted in the maintenance of a constant num-
ber of PRRS-infected piglets such that it was unlikely
that the farm would ever achieve a stabilized status.

Sensitivity analysis is a useful method to identify
the most influential variable in a model and compare
the relative importance of each variable within a group
of variables for a specific outcome.41,42 For the models
of the present study, sensitivity analysis suggested that
the recovery rate of sows from PRRS virus infection was
an important determinant for the control of PRRS at the
herd level. In the baseline scenario and scenarios 1 and
3 (gilt acclimatization with single mass immunization),
the recovery rate of unvaccinated sows was the most
important determinant in a herd achieving a stabilized
status, whereas in scenarios 2 and 4, the recovery rate
of vaccinated sows was the most important determinant
in a herd achieving a stabilized status. Administration
of a PRRS MLV vaccine to pigs does not prevent those
pigs from becoming infected; however, it does reduce
the duration of infectivity and increase the recovery
rate of vaccinated pigs, compared with those in unvac-
cinated pigs.43 Results of this study indicated that
repeated mass immunization of all sows in a herd with a
PRRS MLV vaccine was more effective for controlling
the disease (ie, minimized the percentage of PRRS-
infected 3-week-old piglets at 200 weeks) than was
mass immunization of all sows in a herd with a PRRS
MLV vaccine once during week 1. Therefore, single
mass immunization of all sows with a PRRS MLV vac-
cine is not recommended for the control of PRRS virus
at the herd level.

Previous stochastic models and mathematical anal-
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Appendices appear on the next page
Appendix 1
Variable definitions and minimum, mean, and maximum values used for stochastic mathematical modeling of the dynamics of PRRS virus transmission and infection on a typical Midwestern US farrow-to-weaning swine farm.

<table>
<thead>
<tr>
<th>Parameter (symbol)</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd size</td>
<td>390</td>
<td>1,533</td>
<td>3,876</td>
<td>Sows</td>
<td>Reference 19</td>
</tr>
<tr>
<td>Basic reproduction number for sows (R_s)*</td>
<td>0.14</td>
<td>3.00</td>
<td>3.22</td>
<td>—</td>
<td>Reference 16</td>
</tr>
<tr>
<td>Basic reproduction number for piglets (R_p)*</td>
<td>7.26</td>
<td>8.76</td>
<td>13.13</td>
<td>—</td>
<td>Footnote a</td>
</tr>
<tr>
<td>Duration of infectivity for unvaccinated sows (D_n)</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>Weeks</td>
<td>Reference 25</td>
</tr>
<tr>
<td>Duration of infectivity for piglets (D_p)</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>Weeks</td>
<td>Reference 16</td>
</tr>
<tr>
<td>Duration of infectivity for vaccinated sows (D_v)</td>
<td>0.77</td>
<td>2.78</td>
<td>4.17</td>
<td>Weeks</td>
<td>Reference 26</td>
</tr>
<tr>
<td>Recovery rate for unvaccinated sows (α_n)</td>
<td>0.17</td>
<td>0.25</td>
<td>1.00</td>
<td>Sows/wk</td>
<td>1/D_n</td>
</tr>
<tr>
<td>Recovery rate for piglets (α_p)</td>
<td>0.08</td>
<td>0.13</td>
<td>0.25</td>
<td>Piglets/wk</td>
<td>1/D_p</td>
</tr>
<tr>
<td>Recovery rate for vaccinated sows (α_v)</td>
<td>0.24</td>
<td>0.36</td>
<td>1.3</td>
<td>Sows/wk</td>
<td>1/D_v</td>
</tr>
<tr>
<td>Duration of active immunity (A)</td>
<td>26</td>
<td>36</td>
<td>52</td>
<td>Weeks</td>
<td>Reference 17</td>
</tr>
<tr>
<td>Rate of loss of active immunity (δ)</td>
<td>0.019</td>
<td>0.028</td>
<td>0.038</td>
<td>Animals/wk</td>
<td>1/A</td>
</tr>
<tr>
<td>Duration of maternal immunity (M)</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>Weeks</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>Rate of loss of maternal immunity (ψ)</td>
<td>0.20</td>
<td>0.25</td>
<td>0.33</td>
<td>Piglets/wk</td>
<td>1/M</td>
</tr>
<tr>
<td>Transmission rate in sows (τ)</td>
<td>0.034</td>
<td>0.750</td>
<td>0.805</td>
<td>Sows/wk</td>
<td>R/mean D_s</td>
</tr>
<tr>
<td>Transmission rate in piglets (β)</td>
<td>0.908</td>
<td>1.220</td>
<td>1.641</td>
<td>Piglets/wk</td>
<td>R/mean D_p</td>
</tr>
<tr>
<td>Death rate in sows (δ)</td>
<td>0.102</td>
<td>0.173</td>
<td>0.262</td>
<td>Sows/wk</td>
<td>Reference 19</td>
</tr>
<tr>
<td>Mortality rate in piglets (ε)</td>
<td>3.117</td>
<td>4.490</td>
<td>5.933</td>
<td>Pigs/wk</td>
<td>Reference 19</td>
</tr>
<tr>
<td>Mortality rate in infected piglets (ε`)</td>
<td>0.067</td>
<td>0.100</td>
<td>0.133</td>
<td>Piglets/wk</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>No. of piglets born alive from noninfected sows (η)</td>
<td>0.06</td>
<td>0.83</td>
<td>1.25</td>
<td>Piglets/litter</td>
<td>Reference 17; expert opinion</td>
</tr>
<tr>
<td>No. of piglets born alive from infected sows (η`)</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>Piglets/litter</td>
<td>Reference 17; expert opinion</td>
</tr>
<tr>
<td>Breeding rate (π)</td>
<td>0.85</td>
<td>0.90</td>
<td>0.95</td>
<td>Sows/wk</td>
<td>Reference 27</td>
</tr>
<tr>
<td>Farrowing rate for noninfected sows (ρ)</td>
<td>0.047</td>
<td>0.052</td>
<td>0.056</td>
<td>Week</td>
<td>Reference 19</td>
</tr>
<tr>
<td>Farrowing rate for infected sows (ρ`)</td>
<td>0.038</td>
<td>0.044</td>
<td>0.050</td>
<td>Week</td>
<td>Reference 28</td>
</tr>
<tr>
<td>Abortion rate for noninfected sows (σ)</td>
<td>0.007</td>
<td>0.011</td>
<td>0.016</td>
<td>Week</td>
<td>1/16 – ρ_T</td>
</tr>
<tr>
<td>Abortion rate for infected sows (σ`)</td>
<td>0.013</td>
<td>0.019</td>
<td>0.025</td>
<td>Week</td>
<td>1/16 – ρ`_T</td>
</tr>
<tr>
<td>Farrowing-to-weaning rate (ξ)</td>
<td>—</td>
<td>0.03</td>
<td>—</td>
<td>Animals/wk</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>Culling rate</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
<td>%/wk</td>
<td>Reference 19</td>
</tr>
<tr>
<td>Vaccine efficacy for mass immunization</td>
<td>90.0</td>
<td>92.5</td>
<td>95.0</td>
<td>%</td>
<td>Expert opinion</td>
</tr>
<tr>
<td>Prevalence of sows ELISA-positive for antibodies against PRRS virus</td>
<td>28.2</td>
<td>39.4</td>
<td>50.5</td>
<td>%</td>
<td>Footnote a</td>
</tr>
</tbody>
</table>

For variables not calculated directly from other variables in the model, minimum and maximum values were determined by expert opinion or empirical evidence.
*Basic reproduction number is a unitless variable. †A 16-week gestation for sows was assumed.
— = Not determined.

Appendix 2
Possible events leading to the transition of pigs among 3 immunologic states (susceptible [S], infected [I], and recovered [R]) for PRRS virus on a Midwestern US farrow-to-weaning swine farm.

<table>
<thead>
<tr>
<th>Event</th>
<th>Effect on distribution of pigs in each immunologic state</th>
<th>Difference equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infection of a sow</td>
<td>S; I → R → S – 1; I + 1; R</td>
<td>tS(I)/(N)</td>
</tr>
<tr>
<td>Infection of a piglet</td>
<td>S; I → R → S – 1; I + 1; R</td>
<td>tI(R)/(N)</td>
</tr>
<tr>
<td>Recovery of an infected pig</td>
<td>S; I → R → S – 1; I + 1; R</td>
<td>tR(I)/(N)</td>
</tr>
<tr>
<td>Recovered pig becomes susceptible again</td>
<td>S; I → R → S + 1; I + 1; R</td>
<td>tR(I)/(N)</td>
</tr>
<tr>
<td>Maternally immune piglet becomes susceptible</td>
<td>S; I → R → S + 1; I + 1; R</td>
<td>tR(I)/(N)</td>
</tr>
</tbody>
</table>

I = Number of infected pigs during the interval immediately before the event. M = Number of maternally immune piglets during the interval immediately before the event. N = Number of pigs in the population during the interval immediately before the event. R = Number of recovered pigs during the interval immediately before the event. S = Number of susceptible pigs during the interval immediately before the event. See Appendix 1 for remainder of key.