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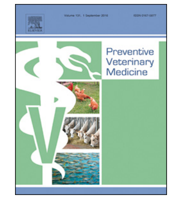

Development and validation of a scoring system to assess the relative vulnerability of swine breeding herds to the introduction of PRRS virus

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ABSTRACT

Biosecurity is defined as the set of practices carried out to prevent the introduction and spread of infectious agents in a herd. These practices are essential in swine production, especially for highly infectious agents such as porcine reproductive and respiratory syndrome virus (PRRSv). Even with years of research and experience over the last three decades, PRRSv is still causing productivity losses and is the major health problem affecting the global swine industry. Despite knowledge of the various ways in which the virus can be transmitted from one herd to another (e.g. animals, semen, truck, air, and people), determining the most frequent ways in which the virus is transmitted in the field is difficult. A systematic approach to assess vulnerabilities at a herd level related to PRRSv transmission could help producers prioritize biosecurity practices to reduce or avoid the occurrence of outbreaks. The aim of this study was to develop a biosecurity vulnerability score that represents the relative vulnerability of swine breeding herds to the introduction of PRRSv. To create the biosecurity vulnerability score (outcome), a multi-criteria decision analysis methodology was used to rank and quantify biosecurity practices based on expert opinion. To validate the biosecurity vulnerability score, a survey of biosecurity practices and PRRS outbreak histories in 125 breed-to-wean herds in the U.S. swine industry was used. Data on the frequency of PRRS outbreaks was used to test the hypothesis that biosecurity vulnerability scores were different between farms that have a low incidence of PRRS outbreaks, compared to farms that have a high incidence. In the two databases used, the scores consistently showed that farms with higher scores have a higher frequency of PRRS outbreaks. In the first validation, farms that had never had an outbreak investigation before had a significant ($p < 0.02$) lower score (0.29; 0.21–0.37) when compared to farms that had 2 or more outbreaks (0.43; 0.39–0.46). In the second, the farms of the control group also had significant ($p < 0.004$) lower scores (0.30; 0.27–0.33) compared to the case group (0.35; 0.33–0.38). Also, the results suggest that events related to swine movements, transmission by air and water, and people movements should be prioritized. The biosecurity vulnerability scores may be useful to assess vulnerabilities on biosecurity protocols in order to reduce the frequency of PRRS outbreaks and may help producers and veterinarians prioritize investments in improving biosecurity practices over time.

1. Introduction

In modern veterinary practice, disease prevention in livestock populations has become increasingly more important (Kimman et al., 2013). This change in focus includes the adoption of biosecurity practices, which are defined as “the implementation of practices that reduce the risk of disease agents being introduced and spread into a population” (Food and Agriculture Organization, 2010).

Previous studies have demonstrated the effect of biosecurity on prevention or reduction of disease incidence (Alonso et al., 2013; Amass, 2004; Hagenaars, 2008). However, evaluation of biosecurity practices on pig farms is extremely complex. Pathogens can be introduced into pig farms in different ways (Pileri and Mateu, 2016) and the effectiveness of specific biosecurity practices depends on the characteristics of the herd, characteristics of the premises, and surrounding areas and connections to other swine premises.

Porcine reproductive and respiratory syndrome (PRRS) continues to be a major health challenge in U.S. herds since it was first reported in 1989 (Keffaber, 1989). While the incidence in the U.S. has declined in recent years (Morrison et al., 2015), the prevalence continues to

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Table 1
Model framework – Categories of risk events, risk events and carrying agents related to PRRSV introduction into a swine breeding herd.

Categories of risk events (CRE_k) (*1st level*)	Risk events (RE_j) (*2nd level*)	Carrying agents (CA_j) (*3rd level*)
1. Swine movement	I. Semen delivered to premises	Semen; Semen packaging; Vehicle and driver.
	II. Breeding replacement animals delivered to premises	Replacement animals; Livestock trailer; Driver; Tools.
	III. Cull breeding animals hauled from premises	Livestock trailer; Driver; Tools.
	IV. Weaned pigs hauled from premises	Livestock trailer; Driver; Tools.
2. Pickup/Deliveries	I. Dead animals removed from premises	Rendering truck; Driver.
	II. Feed or feed ingredients delivered to premises	Feed truck; Driver; Feed; Feed mill on the premises.
	III. Propane and fuel delivered to premises	Vehicle and driver.
	IV. Garbage collected from premises	Vehicle and driver.
	V. Electrical meter read on premises	Vehicle and driver.
	VI. New tools and supplies are delivered to premises	Tools and supplies; Vehicle and driver.
	VII. Tools and supplies transferred from other swine premises are delivered to premises	Tools and supplies; Vehicle and driver.
3. People movement	I. On-farm employees enter premises	On-farm employees; Equipment; Vehicles.
	II. Repair, maintenance, electrical and plumbing personnel enter premises	Visitors; Tools supplies and equipment; Vehicles.
	III. Veterinarians, off-site production managers, vendors and other visitors enter premises	Visitors; Tools supplies and equipment; Vehicles.
4. Pork/food product entry	I. Entry of pork and other food	Food.
5. Manure removal	I. Manure removal	Equipment; Visitors; Personnel.
6. Domestic animals, feral swine, other wild animals and insects	I. Entry of animals	Animals.
	II. Entry of rodents	Rodents.
	III. Entry of insects	Insects
7. Air and water	I. Entry of air	Air.
	II. Entry of water	Water.

increase over time (MSHMP, 2018) and PRRS virus (PRRSv) still causes significant economic losses worldwide (Holtkamp et al., 2013; Nathues et al., 2017). PRRSv can be transmitted between farms via different risk events including swine movements, pickup and deliveries of supplies from or to farms, people movement, contact with other animals, air and water (Otake et al., 2002; Perez et al., 2015; Zimmerman et al., 2012).

Herd-specific biosecurity assessments are useful to determine how PRRSv may be introduced in swine herds and research is needed to quantify the relative importance of specific biosecurity practices to reduce the frequency of outbreaks. Biosecurity assessments have been used to identify relevant risk factors of disease spread onto swine farms (Bottoms et al., 2013; Holtkamp et al., 2011; Laanen et al., 2013; Sternberg Lewerin et al., 2015). However, identifying the vulnerabilities to PRRSv introduction specific to a certain production system and developing a generalized score that accounts for all major risk events is an intrinsically complex process.

Given the complexity of evaluating biosecurity practices to prevent the introduction of PRRSv, applying a technique that uses multiple factors to score swine breeding herds based on their relative vulnerability to PRRSv introduction would be beneficial for prioritizing and identifying gaps in biosecurity practices and predicting the frequency of outbreaks. Several methods exist to evaluate these factors, allowing for a ranking of specific factors by relative importance. One method by which to do this is multi-criteria decision analyses (MCDA) (Belton and Stewar, 2002), which has been applied extensively in a variety of fields (Santos et al., 2017; Steele et al., 2009; Thokala et al., 2016), including to assess vulnerability (Cardona, 2003; Joerin et al., 2010). MCDA was chosen for the present study because it provides a systematic way to integrate information from a range of sources, compare scenarios and prioritize decisions (Cox et al., 2013).

The objective of this study was to develop a biosecurity vulnerability score (BVS) that represents the relative vulnerability of swine breeding herds to the introduction of PRRSv. To validate the BVS, a survey of biosecurity practices and PRRS outbreak histories in 125 breed-to-wean herds in two different populations in the U.S. was used. Data on the frequency of PRRS outbreaks was used to test the hypothesis that BVS were different between farms that have a low incidence of PRRS outbreaks, compared to farms that have a high incidence.

2. Material and methods

2.1. Study design

A MCDA-based biosecurity scoring system was developed based on expert opinion and validated. The MCDA structure was used to establish the hierarchical order of the risk events related to PRRSv introduction into breeding herds. Risk events occur when carrying agents enter the site. Carrying agents are defined as anything that may be contaminated or infected with PRRS virus that is brought onto the farm. An expert opinion panel was used to estimate the relative importance between the risk events. The validation was made in two steps using a survey to collect biosecurity data and PRRS outbreak histories from 125 breed-to-wean farms in the U.S. swine industry from two distinct populations. Data on frequency of PRRS outbreaks was compared to the BVS.

2.2. Development of the biosecurity vulnerability score (BVS)

2.2.1. Definitions and hierarchical order of risk events

For the purpose of this study, vulnerability was defined as a measure of the weaknesses in biosecurity practices that can result in PRRSv introduction into a pig population (Cardona, 2003). For this study, biosecurity practices are those applied to prevent or reduce the risk of disease introduction, also known as bioexclusion practices or external biosecurity.

Risk events were defined as events that engender PRRSv introduction in a population of pigs, where one or more carrying agents can be involved (Table 1). For example, risk events include: delivery of semen to farms, delivery of breeding replacement animals, and entry of on-farm employees. Carrying agent was defined as anything that may carry PRRSv into a farm (e.g. semen, livestock trailer, driver, feed and employees) (Table 1) by being infected or contaminated with the virus. The risk events were first grouped, based on their similarity, to represent each category of risk events related to PRRSv' introduction: 1) swine movements; 2) pickup/deliveries; 3) people movement; 4) pork/food product entry; 5) manure removal; 6) contact with wild animals, domestic animals and insects; and 7) air and water (Table 1).

In order to organize the model, a MCDA-based structure was used to order the category of risk events, risk events and carrying agents. Each category of risk events (CRE_k), designated in this study as first-level, was composed of one or more risk events (RE_j). First-level categories were influenced by second-level risk events and the second by the third level comprised of the carrying agents (CA_i) for each risk events. The risk events and their carrying agents were established based on the common events that occur on swine breeding herds and data from literature (Table A in Supplement File).

2.2.2. Experts weighting

The opinions of four experts from the Department of Veterinary Diagnostic and Production Animal Medicine at Iowa State University were used and the weights were derived from their opinion. The experts had documented knowledge on PRRSv transmission; experience with swine production and some of them are co-authors of the study (DL, KB, DH). Each expert received 16 comparison matrices (Microsoft Excel 2010), which were grouped in the 3 hierarchical definitions: 1) categories of risk events (n = 1 matrix); 2) risk events (n = 5 matrices), and 3) carrying agents (n = 10 matrices). Each comparison matrix was formed by factors, defined as the variables that were evaluated relative to each other. For example, the level 1 (category of risk events) has seven factors that are compared to each other (Table 2).

The comparisons followed the analytical hierarchy process (AHP) algorithm (Saaty, 1990, 1977), where a series of pairwise comparisons to set the relative importance between the factors is performed. The experts were requested to perform the comparisons between the factors in each comparison matrix using a qualitative scale. Table 2 is an example of the comparison matrix used to establish the relative importance between the category of risk events (first level) made by one expert. The relative importance of each factor was assigned a numerical value, from 1/9 to 9, reflecting the strength of preference scale for each factor. A numerical value of 1indicates that both factors were of equal importance. In Table 2, for example, the expert judged that the category of events related to people movements were moderately less important (1/3) relative to the category of events related to swine movements for the introduction of PRRSv into a herd.

Once the comparisons were established, matrix operations were performed according to Saaty's methodology (Saaty, 1977) to produce a set of weights that added to 1.0. The weight of each factor is obtained after weighing the relative importance of each factor judged by the expert. An example of how expert opinion (Table 2) produced the weights used in the model is described in table B in Supplement File (AHP weight matrix). In summary, the qualitative scale used by the experts (Table 2) were converted into numbers defined by the method and the sum of each column (factor) is performed (step 1) (Saaty, 1980). The second step included the calculation of the weights using normalized geometric average of lines of the comparison matrix. Lastly, the principal eigenvector of the comparison matrix was then calculated which served to represent the priorities of the factors that comprised the comparison matrix (step 3) which after standardized summed one. The weights for the risk events and carrying agents were also obtained through the same process and are described in the Table D and E in the

Table 2
Comparison matrix to establish the pairwise relative importance of each factor using a qualitative scale. Example of an expert's judgement of the relative importance between the level 1 factors, categories of risk events (CRE_k). The expert's set the relative importance of the factor in the column in relation to the factor in the row.

Factors	1- Swine Movements	2- Pickup/ Deliveries	3- People movement	4- Pork/food product entry	5- Manure handle	6- Contact with other animals[1]	7- Air and water
1- Swine Movements	1						
2- Pickup/ Deliveries	Very strongly less important (1/7)[2]	1					
3- People movement	Moderately less important (1/3)	Strongly more import (5)	1				
4- Pork/food product entry	Moderately less important (1/3)	Strongly less important (1/5)	Moderately less important (1/3)	1			
5- Manure handle	Strongly less important (1/5)	Moderately less important (1/3)	Moderately less important (1/3)	Moderately more import (3)	1		
6- Contact with other animals	Moderately less important (1/3)	Equally import (1)	Moderately less important (1/3)	Equally import (1)	Equally import (1)	1	
7- Air and water	Moderately less important (1/3)	Equally import (1)	Equally import (1)	Moderately more import (3)	Moderately more import (3)	Moderately more import (3)	1

[1]Domestic animals, feral swine, other wild animals and insects.
[2]Qualitative scale used to set the relative importance of the factor on the vertical axis relative to the factor on the horizontal axis: Extremely less important = 1/9; Very strongly less important = 1/7; Strongly less important = 1/5; Moderately less important = 1/3; Equally important = 1; Moderately more important = 3; Strongly more important = 5; Very strongly more important = 7; Extremely more important = 9.

Supplement File.

A consistency ratio (CR) (Saaty, 1990) was calculated to determine the degree of consistency between experts. The consistency ratio compares the consistency index (CI) of the matrix in question (the one with expert's judgments) versus the consistency index of a random matrix (RM). A random matrix is one where the judgments have been entered randomly and therefore it is expected to be highly inconsistent. The consistency ratio, indicates the probability that the matrix ratings were randomly generated and can be obtained by dividing the consistency index of the matrix in question by the consistency index of a random matrix (CR = CI/RM). Saaty (Saaty, 1990) demonstrated that matrices with consistency ratio ratings greater than 0.10 should be reevaluated. In our study, only matrices with consistency ratios equal to or lower than 0.10 were considered. The average of the weights from each matrix (number of matrices = 16) deemed to be consistent was used as an input for the model.

2.2.3. Biosecurity survey

The survey used to assess biosecurity practices was developed through the PRRS Outbreak Investigation Program, funded by the Iowa Pork Producers Association (Canon et al., 2015). The survey is described in table C in Supplement File. The survey included questions about biosecurity practices for each carrying agent.

2.2.4. Biosecurity vulnerability score (BVS) framework

The MCDA-based model was composed of three hierarchical levels: CRE_k, RE_j, and CA_i, with weights established by expert opinion (Table D and E in Supplement File). The weights and frequencies with which the biosecurity practices were applied were used to calculate the BVS via the following method:

The first equation (Eq. 1) was used to calculate the score for a given risk event by multiplying the biosecurity practices (BP_i) by the assigned weight for the carrying agent (W_CA_i) (Table E in Supplement File) and the risk event weight (W_RE_j) (Table D in Supplement File). For the cases in which risk events had only a single carrying agent (Table 1), the carrying agent weight (W_CA_i) was 1 and the biosecurity practices were weighted directly by W_RE_j.

For the BP_i value, the absence of the practice was classified as 1 and the presence as 0. Because more than one biosecurity practice can be applied for a given carrying agent or risk event, these variables were considered of equal importance and were therefore additive. Thus, the BP_i had a value between 0 (presence of all practices) and 1 (absence).

$$Score\ RE_j = \sum_{i=1}^{n} \left(\frac{1}{n}\sum_{i=1}^{n} BP_{ij} * W\_CA_i\right) * W\_RE_j \tag{1}$$

where $Score\ RE_j$ represents the risk event score for the j -th risk event; BP_{ij} represents the ***ij-th*** biosecurity practices value, and W_CA_i and W_RE_j are the ***i-th*** and ***j-th*** relative importance weighing within CA_i and RE_j. The W_CA_i is equal to 1 when the risk event has only a single carrying agent.

Once the scores for each RE_j were calculated, a score for each category of risk event (k) (Score CRE_k) was calculated as the sum of the $Score\ RE_j$ multiplied by the CRE weight (W_CRE_k) of each k risk category (Table D in Supplement File), to reflect the relative importance of each category of risk event (Eq. 2).

$$Score\ CRE_k = \left(\sum_{j=1}^{n} ScoreRE_j\right) * W\_CRE_k \tag{2}$$

where $Score\ CRE_k$ represents the score for PRRSv introduction for each category of risk event (k); RE_j is the result of Eq. 1 and W_CRE_j is its weight within CRE_k.

The BVS was obtained as the sum of the CRE scores for each of the seven categories of risk events.

$$BVS = \sum_{k=1}^{7} (ScoreCRE_k) \tag{3}$$

where BVS represent the biosecurity vulnerability score for PRRSv introduction; CRE_k is the result of Eq. 2 for each category of risk events (first level).

The result was a BVS between 0 and 1, which was obtained in the same way for each category of risk event; the closer the score to one meaning the greater the vulnerability of the herd to PRRSv introduction. In addition, the method allows to identify the $ScoreCRE_k$ that most influenced the value of the BVS, that is, the CRE_k that presented the highest value of the BVS. In Table F in Supplement File, the BVS and CRE_k scores for each farm are described. The Table F describes the values as a scale varying from 0 to 1 on which farms are ranked based on their BVS and CRE_k scores. The BVS values are ranked by farm, within column, and CRE_k scores are ranked by risk event category, within row, both from the highest to lowest.

2.3. Validation

2.3.1. First step validation – outbreak investigation data

The sample population for this step included herds that had a PRRS outbreak during 2015 and 2016 which were part of the PRRS Outbreak Investigation Program at Iowa State University (Canon et al., 2015). The biosecurity survey described above was used to collect data on biosecurity practices from 41 breeding herds located in the state of Iowa. The herds in this sample population included herds that had been voluntarily enrolled in the PRRS Outbreak Investigation and not randomly selected from the population of all breeding herds in Iowa. The information on biosecurity practices collected with the survey was used to calculate the BVS for each herd. Herds were grouped by the number of PRRS outbreaks in the past 5 years reported before the outbreak investigation for the purpose of comparing the frequency of outbreaks to the BVS scores.

2.3.2. Second step validation – case-control study

A case-control study was performed with the objective to test the hypothesis that biosecurity scores differs between farms that had a relatively low incidence of PRRS outbreaks (control), compared to farms that had a relatively high incidence (case).

The target population of the study were the breeding herds that were part of Morrison's Swine Health Monitoring Project (MSHMP). MSHMP is a network of U.S.A. swine producers and represents a convenience sample of 930 sow herds from 25 production systems including approximately 2.7 million sows (MSHMP, 2018). Swine production system was defined as the set of farms owned, managed or both by the same company. These farms are characterized to be high-specialized sites with high animal density and had similar herd characteristics. The source population of this study were farms from the production systems (n = 14) that were contacted and agreed to participate. The study population (n = 84) were the farms from the production systems that we assessed and had the characteristics to fulfill the following eligibility criteria: (1) PRRS status of the breeding herd since 2013 was available; (2) the breeding herd was willing to complete a biosecurity survey; and (3) the breeding herd was a farrow-to-wean farm.

Given the eligibility criteria, each production system was asked to order the eligible breeding herds according to the number of PRRS outbreaks in the last three years. The farms were ordered based on the number of PRRS outbreaks in each system; farms below the 25th percentile were classified as relatively low PRRS incidence (control) and farms beyond the 75th percentile were classified as relatively high PRRS incidence (case). Information from the first validation was used to calculate the sample size needed to detect a statistically significant difference in biosecurity scores. It was assumed that the control group would have at least a 0.05 mean difference in herd vulnerability scores compared to the case group and therefore the sample size required to detect this mean difference with a power of 80% at a significance level of 0.05 was 41 herds per group. The R program (v. 3.3.3) and the package *stats* were used to compute the sample size.

Each production system enrolled 3 herds in the case group and 3 herds in the control group (6 herds per production system). The proportion of case to control groups was 1:1 and herd selection was done using random sampling within each group after classifying the herds based on the history of past PRRS outbreaks (low or high PRRS incidence). The same biosecurity survey previously described was used to collect information about herd demographics, biosecurity practices, history of PRRS outbreaks and frequency of risk events.

2.4. Statistical analysis

The BVS were calculated using Microsoft Excel. The difference between the BVS and the groups at first step validation (frequency of PRRS outbreaks) was tested using a linear model. At second step validation (case-control study) a linear mixed model with production system as a random effect was used to correct for the presence of farms within production system. All analyses were done in R program (v. 3.3.3) using the packages *stats*, *nlme*, *lsmeans* and *varComp*.

3. Results

3.1. Expert opinion - weights

The results of the weighting procedure for the categories of risk events and for each risk event can be found in Table D in Supplement File. The most important categories of risk events judged by the experts were those relating to swine movements (weight = 0.33), pickup/deliveries from/to premises (0.26) and people movement (0.15). The weights for the carrying agents (3rd level) are described separately in Table E in Supplement File.

Given the hierarchical structure of the method, all risk events were ranked in order of importance with the weight of the risk events multiplied by its category weight. This order is included in the last column of Table D in Supplement File (Rank). The five most important events that occur in breeding herds related to PRRSv introduction, as judged by the experts, were breeding replacement animals, semen delivery, air transmission, weaned pigs transported from premises and dead animal's removal, respectively.

3.2. 1st step validation: outbreak investigation data

The mean BVS of all (n = 41) herds was 0.43, herds that had never had an outbreak before (category 0) had the lowest score of 0.29 (se = 0.03), while herds that had 4 or more outbreaks in the past 5 years had the highest score of 0.48 (se = 0.02) (Table 3). Additionally, the BVS for farms that did not had an outbreak before the outbreak investigation differed significantly from farms that had 2 or more outbreaks of PRRS in previous years. Also, a moderately positive correlation (*Spearman r* = 0.52, p-value < 0.01) was observed between the number of past outbreaks and the BVS (Fig. 1).

Table 3
Statistical results for comparison of BVS between the PRRS outbreaks categories.

Number of PRRS outbreaks before the outbreak investigation	N	Mean BVS[1]	SE[2]	CI 95%[3]
0	4	0.29[a]	0.03	[0.21, 0.37]
1	3	0.40[ab]	0.04	[0.30, 0.49]
2	17	0.43[b]	0.01	[0.39, 0.46]
3	9	0.44[b]	0.02	[0.39, 0.49]
4	8	0.48[b]	0.02	[0.42, 0.53]

[1] Comparison between groups: different letters mean difference between groups at 0.05 significance level.
[2] SE – Standard error.
[3] CI 95% - Lower and upper confidence interval at 95%.

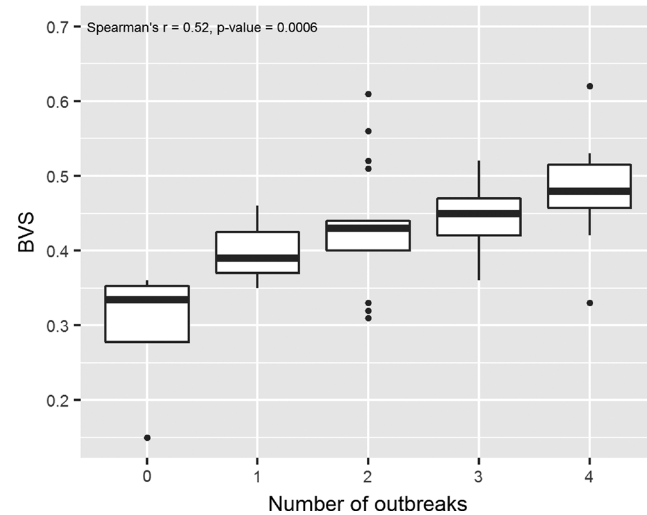

Fig. 1. Biosecurity vulnerability score (BVS) and the difference between categories based on the number of PRRS outbreaks in the past 5 years before the outbreak investigation.

3.3. 2nd step validation: case-control study

A total of 84 herds were enrolled from 14 production systems to investigate differences in biosecurity practices between groups. As described above, the criteria used to classify the herds was based on the number of PRRS outbreaks in the last three years and Table 4 describes the farms within groups.

The BVS for each group is described in Table 5. The biosecurity score was statistically different between groups (p < 0.003). BVS for herds with a low incidence of PRRS outbreaks ranged from 0.12 to 0.46, with a mean of 0.30 and a standard error of 0.02. BVS from the case group varied between 0.20 (lower vulnerability) and 0.52 (higher vulnerability), with a mean of 0.35 and a standard error of 0.02. The intraclass correlation coefficient (ICC) was 0.61, evidencing that the observations within production system are more similar to each other compared to the others.

The BVS and the score for each category of risk event for individual herds is reported in Table F (Supplemental File). Table F also shows the rank of vulnerability scores for the herds from the least vulnerable (1) to the most vulnerable (29) based on the scores distribution and for each category of risk event. For each herd studied, the last column of Table F presents the category of risk event that most influenced the BVS. The results suggest that most farms in the control group had relatively higher scores or vulnerability (23 of 42 herds) to PRRSv transmission through air and water. In contrast, most of the farms in the case group demonstrated higher vulnerability to transmission by swine movements (28 of 42 herds).

Table 4
Table describing the frequency of PRRS outbreaks in the last 3 years in case and control groups.

Group	N	Mean	Min.[1]	Median	Max.[1]	% of naïve herds
Low (control)	42	0.2	0	0	1	81.0%
High (case)	42	3.0	2	3	6	0%

[1] Min. – Minimum value; Max – Maximum value.

Table 5
Statistical results between case and control groups in the herd vulnerability scores.

Group	N	Score distribution[1]					Model estimates			
		Min.	Q1	Median	Q3	Max.	Mean[2]	SE[3]	CI 95%[4]	p-value
Low (control)	42	0.12	0.26	0.29	0.37	0.46	0.30[a]	0.02	[0.26, 0.35]	0.005
High (case)	42	0.20	0.30	0.36	0.40	0.52	0.35[b]	0.02	[0.31, 0.40]	

1 Min. – Minimum value; Q1 – Lower quartile; Q3 – Upper quartile; Max – Maximum value.
2 Comparison between groups: different letters mean difference between groups at 0.05 significance level.
3 SE – Standard error.
4 CI 95% - Lower and upper confidence interval at 95%.

4. Discussion

The model described in this study provides a structured and consistent method to evaluate and rank the relative vulnerability of swine breeding herds to the introduction of PRRS virus. This allows for the assessment of the relative importance of selected biosecurity practices and aids in the decision-making process to improve biosecurity.

Multi-criteria decision analysis has previously been used in veterinary medicine for different purposes ranging from design methods to prioritize infectious diseases (Brookes et al., 2014; Cox et al., 2013), development of surveillance programs (East et al., 2013; Santos et al., 2017) and to evaluate control strategies of contagious animal diseases (Mourits et al., 2010). However, this was the first time that MCDA analysis was applied to rank the relative vulnerability of swine breeding herds to the introduction of pathogens. A similar approach was described using the AHP, where an index system to evaluate swine farms in China were created (Zang et al., 2012), but the index didn't have a specific pathogen nor any validation of the index were demonstrated.

Other studies have described generic biosecurity scoring systems (Laanen et al., 2011; Pinto and Urcelay, 2003; Postma et al., 2015), however, the method demonstrated here can be used to identify critical points in biosecurity protocols, which can help to establish practices to mitigate PRRSv introduction. The results suggest that expert opinion can be used to rank vulnerabilities to the introduction of pathogens at the herd level, mainly because obtaining the relative importance of biosecurity practices are not available in the literature and due to the absence of this type of information the use of expert opinion is necessary (van der Fels-Klerx et al., 2000).

When evaluating biosecurity protocols to mitigate the risk of disease introduction, it is important to keep in mind the other herd-level risk factors (i.e. swine density and environmental factors) that may have an impact on biosecurity failures that were not incorporated in our scores. Our aim was to assess the gaps at external biosecurity and the practices that producers can control or change to mitigate the risk of PRRSV introduction, those risk factors cannot be controlled directly and didn't fit in the hierarchical framework used here (CRE, RE and CA). The BVS did not incorporate the frequency of events, in contrast to another scoring system reported in the literature (Laanen et al., 2010). However, it can be used to identify the most important risk factors that increase vulnerability and can also be used to predict relative vulnerability of different farms within a production system and/or region based on frequencies of risk events since the probability of introduction of pathogens increases as the frequency of risk events increases (Romagosa, 2017; Sternberg Lewerin et al., 2015).

This study provides methods to develop a pathogen-specific vulnerability score and compare aspects of biosecurity between groups of farms with relatively low or high frequency PRRS outbreaks. The results provide information on possible categories of risk events that may need attention in addition to suggesting opportunities for biosecurity enhancement. The comparison between the group scores suggests that herds that had lower incidences of PRRS outbreaks in recent years had lower BVS, reinforcing the importance of biosecurity practices to prevent disease introduction (Amass, 2005; Postma et al., 2015; Visschers et al., 2015).

The BVS and the scores for each category of risk events ($ScoreCRE_k$) allow for the relative comparison (ranking) of farms' vulnerabilities based on expert opinion and their biosecurity practices but does not represent absolute values of risk (probability). The last column of Table F in Supplement File presents the category of risk events that most influenced the scores for each farm in the study. These differences may be used as a way of prioritizing biosecurity practices among different herds to aid in identifying gaps in biosecurity protocols. This ranking was already described to assess the vulnerability to microbiological contamination in drinking water systems (Joerin et al., 2010). Our results suggest that events related to swine movements, transmission by air and water, and people movements should be prioritized, reinforcing the important role of these transmission routes in PRRSv introduction. These results corroborate literature that cited the aforementioned events as the most important risk factors to PRRSv introduction and spread (Alonso et al., 2013; Dee et al., 2004; Ramirez and Zaabel, 2012; Zimmerman et al., 2012).

Certain limitations to our study exist. Some bias about the importance of the biosecurity practices may have been introduced because all of the experts were from the same department and University. However, to minimize the effects of possible bias three strategies were used: 1) the method to weight the opinion of each expert was based on what the experts chose from the matrices, not asking directly for the weights, 2) only the matrices with an acceptable consistency ratio were used, and 3) the average of the weights were used to eliminate extreme opinions. Furthermore, the ranking of risk events showed are consistent with the main factors associated with PRRS outbreaks found in the literature (Perez et al., 2015; Pileri and Mateu, 2016) and the variability of the weights (sd) among the experts was small (Table D and E in Supplement File). The use of a more representative expert panel would increase the legitimacy of the indicator.

In addition, the information collected using a survey may be subject to information bias and did not consider temporal variations among the biosecurity practices performed or modified after an outbreak, affecting the internal validity. For example, some herds classified as "high" may have improved biosecurity after another PRRS outbreak, resulting in subsequent lower scores. Our convenience sample may have influenced the external validity of the study, therefore the BVS estimated may not be generalized to herds across US because the breeding herds assessed here do not necessarily represent the sow farms found in most common production system in U.S. where PRRSV is endemic and which the biosecurity practices described in the survey are usually applied.

In conclusion, a tool that consistently evaluate biosecurity practices and its relationship with PRRSv introduction on swine breeding herds was developed. The BVS of the farms with the highest frequency of PRRSV outbreak always had the highest scores. Also, the results suggest that events related to swine movements, transmission by air and water, and people movements should be prioritized. This tool can help producers or decision makers to set priorities for improving and monitoring biosecurity practices over time. The results demonstrated a link between the BVS and the frequency of PRRSv outbreaks and suggests which categories of risk events that may need more attention at a herd level.

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Competing interests

The authors have declared no competing interests.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.prevetmed.2018.10.004.

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