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Sixteen-year longitudinal study assessing the effects of air filtration on the occurrence of porcine reproductive and respiratory syndrome in breeding herds

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Highlights

- Filtration effects on porcine reproductive and respiratory syndrome was assessed.
- Air filtration associates with lower disease incidence rates
- Year-round and seasonal air filtration were linked to lower incidence rates
- Positive and negative-pressure systems showed similar protective effects
- Protective effect of air filtration increased over time

Abstract

Infectious diseases in livestock pose ongoing risks to food security, animal and public health, with swine pathogens capable of spreading over long distances through aerosols. Air filtration has become a key biosecurity intervention to mitigate the risk of airborne transmission, particularly for porcine reproductive and respiratory syndrome

(**PRRS**), a major disease that burdens the swine industry. While the effectiveness of air filtration is well documented, limited research has evaluated its long-term impact while accounting for ventilation pressure and regional pig density. This study estimated the effect of air filtration approach (year-round vs. partial-year) and pressure type (positive vs. negative) on the occurrence of PRRS in U.S. sow herds. This study analyzed 16 years (2009–2024) of longitudinal data from 25 production systems in 12 states, representing about 1.6 million sows, including 245 non-filtered and 178 filtered farms. Generalized additive models with a negative binomial distribution were used to assess the effects of air filtration status on the total number of PRRS outbreaks per farm, incorporating Gaussian process smooths for spatial autocorrelation. Compared to non-filtered farms, those with year-round and partial-year air filtration showed significantly lower PRRS incidence rates, with 0.494 times ($p < 0.001$) and 0.502 times ($p = 0.006$) the incidence rate of non-filtered farm, respectively. Farms with negative-pressure filtration had 0.492 times ($p < 0.001$) the incidence rate, while positive-pressure farms showed 0.416 times ($p < 0.001$) the incidence rate of non-filtered farms. A temporal sub-analysis revealed that the protective effect of air filtration increased over time. This study offers valuable evidence on the effects of different air filtration approaches on PRRS occurrence while accounting for regional disease burden and ventilation pressure. Altogether, the findings provide solid long-term, field-based evidence to inform air filtration decisions and guide tailored biosecurity planning across diverse production systems.

Keywords: Swine disease; Airborne transmission; Filtration system; Disease mitigation, Biosecurity

Implications

Airborne transmission of swine pathogens remains a challenge for the swine industry. This study evaluated the long-term impact of different air filtration approaches on porcine reproductive and respiratory syndrome occurrence using 16 years of field data. Both year-round and partial-year filtration, as well as positive and negative-pressure systems, resulted in a porcine reproductive and respiratory syndrome incidence rate that was 0.5 times lower the rate of non-filtered farms. These findings offer reliable, field-based evidence to guide investment decisions in filtration systems. Swine producers, veterinarians, and policy makers may use these results to support science-based biosecurity planning tailored to farm design, resource availability, and regional risk.

Introduction

Dissemination of infectious viral diseases remain a persistent challenge for the global swine industry, as viruses can be transported through different routes into farms and infect animals (La et al., 2022; Arruda et al., 2019; VanderWaal and Deen, 2018; Desrosiers, 2011). Several studies have reported field evidence of long-distance airborne dissemination of swine viruses, including porcine reproductive and respiratory syndrome virus (**PRRSV**, Otake et al., 2010; Dee et al., 2009a), influenza A virus (Corzo et al., 2013), porcine epidemic diarrhea virus (Alonso et al., 2014), foot and mouth disease virus and pseudorabies (Desrosiers, 2004, 2005). Among these pathogens, PRRSV is one of the most extensively studied due to its substantial impact on production and economic performance (Osemeke et al., 2025). PRRSV is classified into two major genotypes, PRRSV- 1 and PRRSV-2, both of each have a global distribution, with PRRSV-1 predominating in Europe and PRRSV-2 predominating in North America and Asia (Zimmerman et al., 2019). Reported distances of aerosol transmission of PRRSV range from a few meters to 33 kilometers, although longer distances are considered exceptional cases requiring specific circumstances. (Desrosiers, 2023).To mitigate the risk of viruses entering farms through the air, biosecurity interventions have been experimentally verified and/or implemented in the field (Ouyang et al., 2023). For example, filtering incoming air into swine farms captures particles containing viruses (Alonso et al., 2013b; Dee et al., 2006, 2010), using electrostatic precipitators to collect and inactivate airborne pathogens (Wang et al., 2024, 2025), and ultraviolet germicidal irradiation exposure to inactivate pathogens (Li et al., 2021). Among these, air filtration remains the most commonly used bioaerosol control strategy (Ouyang et al., 2023). The percentage of air-filtered sow farms in the United States of America (**U.S.**) increased from 7.4% in 2009 to 20.2% in 2025 (unpublished data, MSHMP, 2025; Vilalta et al., 2018a).

The air filtration system in swine facilities was first implemented in France in 1979, and by the late 1990s, positive pressure ventilation filtration systems were adopted in boar studs and nucleus farms in France and Canada (Desrosiers and Cousin, 2023). Currently, air filtration systems are implemented in mainly boar studs and breeding swine farms using negative- and positive-pressure ventilation systems (Smith et al., 2019). Negative pressure barns use exhaust fans to pull air from inside the barn towards the outside, creating lower pressure that pulls filtered outside air into the barn. Typically, filters are placed either above ceiling inlets in the attic (Figure 1A) or in panels or sidewalls for tunnel ventilation (Alonso et al., 2013b). Positive pressure barns use fans to push clean, filtered air into the barn, creating higher internal pressure that forces air out through exhaust shutters (Figure 1B). Positive- and negative-pressure filtration differ in airflow direction, building tightness, and management, each of which can independently affect PRRS risk and confound filtration approach effects. The adoption of both negative- and positive-pressure filtration systems in breeding farms in the U.S. has increased in recent years, negative-pressure systems is often preferred for their ease of retrofit, while positive-pressure filtration ensures only filtered air enters the barn and prevent infiltration risk through unsealed cracks (Desrosiers and Cousin, 2023; Smith et al., 2019; Ramirez et al., 2016). Both ventilation pressure types of air filtration systems are designed to create an air filtered airspace, and the selection of ventilation type is guided by facility design and operational objectives. Air filtration scheduling approach vary, with most farms operating under air filtration year-round, while others implement partial-year filtration during cooler months, typically from October to April, and suspend filtration during summer when higher ventilation rates are required (Reicks, 2009).

The effectiveness of air filtration on PRRS prevention has been evaluated under both experimental and field studies. Dee et al. (2005, 2006, 2010) demonstrated the efficacy of air filtration in reducing aerosol transmission of PRRSV through positive pressure filter chamber experiments and a production region model using the negative pressure filtration system. Using field data, Dee et al. (2012) analyzed data from 38 herds over four years and found a 7.97-fold higher risk of PRRSV infection when breeding herds were unfiltered. Based on seven years of data, Alonso et al. (2013) reported an 80% lower risk of novel PRRSV introduction in 20 year-round negative filtered herds compared to 17 non-filtered controls. Furthermore, Desrosiers and Cousin (2023) reviewed studies on air filtration for PRRSV prevention published between 2012 and 2021, with 10 out of 11 reporting the associations of air filtration on lower incidence of PRRSV outbreaks. However, previous field studies have largely focused on negative-pressure filtered farms with year-round or unspecified filtration approaches (Wenke et al., 2018; Dee et al., 2012; Spronk et al., 2010; Pitkin et al., 2009). This highlights the need to evaluate the effects of different ventilation pressure and filtration approaches on PRRS occurrence. Furthermore, most of these studies were conducted more than a decade ago, their findings may not fully capture current industry conditions, such as increased regional farm density from newly established farms, herd size, and enhanced biosecurity protocols (VanderWaal et al., 2025; Harlow et al., 2024; USDA NASS, 2024; Alarcón et al., 2021). In addition, some prior studies focused on a single production system, broader evaluation across systems is needed to capture management variability and assess air filtration effectiveness industry-wide. These gaps make updated evidence essential both for herds that have been air filtered for years and for those considering the adoption of air filtration systems.

While air filtration is widely used, its long-term effectiveness across different ventilation pressures and filtration approach while controlling for pig density has not been well quantified under evolving industry conditions. Therefore, the objectives of this study were to estimate the effects of (1) air filtration approach (year-round vs. partial-year) and, (2) air filtration ventilation pressure type (positive vs. negative) on the occurrence of PRRS in the U.S. sow herds over a 16-year period.

Material and methods

Data collection

Breeding herd data from the Morrison Swine Health Monitoring Project (**MSHMP**) were collected from July 1st, 2009 to December 31st, 2024. The MSHMP covers approximately 65% of the breeding herds in the U.S. swine industry and represents over 3.9 million sows from more than 35 production systems (i.e., swine company) across 26 states, making it a highly representative dataset (MSHMP, 2025). The collected longitudinal herd-level dataset includes farm ID, geospatial coordinates, herd size, air filtration status (indicating whether the farm is filtered or not, date on which air filtration was implemented), the air filtration approach (categorized as year-round filtration for continuous use throughout the year, seasonal filtration for use only during high-risk months without specifying the months), and air filtration type (categorized as positive or negative filtration ventilation pressure). The dataset also includes weekly herd PRRS status, with MSHMP collection data from participants weekly to track any status change. The PRRS status is classified according to the American Association of Swine Veterinarians breeding herd classification guidelines (**AASV**; Holtkamp, 2021) definition, categorizing herds as positive unstable, positive stable, provisionally negative or negative for PRRSV. The participation duration of each farm in MSHMP varied over time. Some farms have been involved since the project's inception, while others joined later. Additionally, some farms exited the project due to being sold to non-participating systems or ceasing operations. The original dataset included 1 152 825 farm-weeks from 1 425 herds from 2009 to 2024.

Data curation

The original dataset containing 1 425 herds was reduced to 688 herds for several reasons, including incomplete PRRS health status, herd types other than sow herds, herds that have left the project or ceased operations, absence of geographical coordinates, herd size less than 500 sows which are considered atypical for a U.S. commercial sow farm and some did not have air filtration information available (Supplementary Figure S1).

The curated dataset was further prepared to address the two study objectives. In the curated dataset, most filtered farms operated with year-round negative pressure. Therefore, for the analysis of filtration approach effects, 90 herds were excluded because they either did not report their air filtration ventilation pressure type or used positive pressure air filtration systems. Positive-pressure farms were analyzed separately in the filtration ventilation pressure type analysis. For the air filtration type effects analysis, 68 herds were excluded because they either had an unknown air filtration type or were partially filtered. In partially filtered farms, the filtration period can vary by farm, and the dataset did not include specific duration information; therefore, to avoid confounding, these herds were excluded from the filtration type analysis. As a result, all farms included in the filtration approach analysis used negative pressure air filtration, while all farms in the filtration type analysis were filtered year-round. Furthermore, to enable regional comparison, non-filtered farms located within a specific radius of filtered farms were included in both analyses. The radius was selected after evaluating multiple distance thresholds (e.g., 50 km, 100 km, 150 km. 200 km, 300 km) and visually inspecting farm distributions on the map to ensure that non-filtered farms were somewhat close to filtered farms. The data was also reviewed to ensure a balanced dataset, where the number of non-filtered farms matched or exceeded that of filtered farms. For instance, the 50 km threshold included fewer non-filtered herds than filtered herds (138 vs 175), and thus was not considered appropriate. After testing multiple candidate distances between filtered and non-filtered farms, a final radius of 150 km was selected for both analyses. The spatial distributions and the number of farms for representative tested distances (50 km, 100 km, 150 km, and 300 km) used in the filtration type analysis are shown in Supplementary Figure S2.

New variables were generated in both datasets for the analyses. *Herd size* was categorized as small (< 2 500 sows), medium (2 500 to 5 000 sows), and large (≥ 5 000 sows) based on typical U.S. sow farm size distributions during the study period (Knox, 2025; MetaFarms, 2024; Sloter et al., 2013). *Farm-weeks-at-risk* was calculated as the total number of weeks each farm was at risk under a specific air filtration status, determined by counting the weekly observations for each farm ID and its air filtration status (i.e., non-filtered, positive, or negative pressure). The analyzed dataset was therefore aggregated by farm-weeks-at-risk for each farm. Subsequently, the number of outbreaks for each farm during each farm-weeks-at-risk was calculated (i.e., *outbreak*). An outbreak was defined as a change in PRRS health status on a farm from negative, provisionally negative, positive stable, or positive unstable to positive unstable. Farms in positive unstable status remained "at risk" as they are still susceptible to new PRRSV strain introductions, and these "re-breaks" were recorded by MSHMP. Outbreaks that occurred before a farm entered the MSHMP database were not counted in the outbreak variable, as prior status information was unavailable; however, the weeks of these ongoing outbreaks were included in the farm-weeks-at-risk calculation.

The year when air filtration was first recorded on each farm was converted into a categorical variable *filtration start year*. To account for the regional farm density, the number of MSHMP-monitored breeding farms within a 35 km radius of each studied farm was calculated (i.e., *number of neighboring farms*). This radius was chosen based on the maximum range of local transmission used by Galvis et al. (2022). Since the MSHMP database covers approximately 65% of U.S. breeding herds, to further control for regional pig density, county-level hog inventory data (i.e., *number of pigs in the county*) were calculated from the 2022 Census of Agriculture, conducted by the United States Department of Agriculture's National Agricultural Statistics Service (Paploski et al., 2024; USDA NASS, 2022). Variables in both datasets were summarized and described using the *table1* function of the package *table1* (Rich, 2023). Breeding herd cumulative incidence of PRRS between different filter approach and filtration type was visualized by PRRS season which for our study has been defined to begin in (July 1 and ending on June 30th of the following year). Incidence rate of PRRS by 100 farm-weeks was summarized by filter approach and filtration type.

Statistical analysis

The spatial autocorrelation refers to the tendency for disease outcomes at nearby locations to be more similar than those farther apart. We assessed the spatial autocorrelation in both the filtration approach and ventilation pressure datasets using Moran's I with the *moran.test* function (Bivand et al., 2017; Moran, 1950).

Generalized additive models (**GAM**) were used to assess the association between PRRS outbreaks and the air filtration approach and ventilation pressure. GAM were chosen for their ability to deal with spatial autocorrelation while evaluating the effects of covariates on the outcome (Wood, 2017). The GAM was fitted using the *gam* function in the *mgcv* package in R (R Core Team, 2025; Wood, 2023). The response variable, PRRSV *outbreak*, refers to the number of outbreaks for each farm-weeks-at-risk period of each farm. A spatial smoother was included in the GAM as a Gaussian process spline (Comber et al., 2024; Donnelly et al., 2022; Wood, 2017). The GAMs were fitted using a negative binomial distribution to account for the count data *outbreak* (Wood, 2017; Dohoo et al., 2014a). Covariates in the model included the *breeding herd size*, *number of neighboring farms, number of pigs in the county*, *filtration start year* and the variable of interest: *air filtration approach* or *air filtration type*. In addition, *log*(*farm-weeks-at-risk*) was included in the GAM as an offset term. To account for repeated and nested observations (herds within production systems), random effects were introduced, and generalized additive mixed models were tested with the herd as random effect (Dohoo et al., 2014b). Final models were selected by comparing Akaike Information Criterion values and applying backward selection, guided by model diagnostics and expert opinion to ensure validity and confounding control. Random effects were excluded from the final model, as Akaike Information

Criterion indicated a better fit without random components and the estimates remained nearly identical. Model results of the fitted generalized additive mixed models are included in the Supplementary Table S1.

Model diagnostics, including residual and basis dimension checks, were conducted using the *gam.check* function (Wood, 2023). Concurvity in the GAM, analogous to multicollinearity in linear models, was tested using the *concurvity* function, examining both overall and pairwise values (Wood, 2023). Multicollinearity among the parametric terms was evaluated by refitting the parametric components of the GAM using a negative binomial generalized linear model (*glm.nb*). Variance inflation factors were calculated using the *vif* function from the *car* package, with a variance inflation factor greater than 10 indicating high multicollinearity (Ripley et al., 2013; Fox et al., 2012; O'brien, 2007). Model results were summarized using function *as_flextable* (Gohel and Skintzos, 2022)*,*with decimal places following the guidelines outlined by Cole (2015)

Sub analyses

To specifically assess differences among filtered farms, two sub-analyses were conducted. Sub-analysis (1) compared only year-round and partially filtered herds using the Objective 1 (air filtration approach) dataset, after excluding non-filtered herds. Sub-analysis (2) compared only positive versus negative pressure herds using the Objective 2 (filtration type analysis) dataset, after excluding non-filtered herds. Furthermore, because filtration technology and circulating viral lineages have changed over time (Desrosiers and Cousin, 2023; Paploski et al., 2019), sub-analysis (3) further examined temporal trends in filtration ventilation type effects, by dividing the Objective 2 (filtration type analysis) dataset into three study periods (2009–2014, 2015–2019, and 2020–2024). The variables *farm-weeks-at-risk, outbreak* and *number of neighboring farms* were redefined separately for each period in sub-analysis (3); the variable *number of pigs in the county* was not included in sub analysis (3) due to minor structural differences in census data that limited comparability across time periods. Considering the limited number of partially filtered farms, the effects of filtration approach were not assessed within the split 5-year periods. Modelling, including model selection and diagnostic procedures, for all sub-analyses followed the same approach as the main analyses.

Results

Descriptive analysis

Table 1 summarizes a descriptive summary of herd characteristics and outbreaks by filter approach and air filtration type in the two datasets analyzed. Overall, this study included farms from 25 production systems in 12 states, representing 0.62 million and 0.81 million sows in filtered herds analyzed under the filtration approach and ventilation pressure type objectives, respectively. In total, 376 herds were analyzed for the filtration approach and 413 for the ventilation pressure type. The ventilation pressure type analysis had a larger sample size because it included more non-filtered herds within 150 km of the 175 filtered herds, whereas the filtration approach analysis included 150 filtered herds and therefore fewer neighboring non-filtered herds. The annual cumulative incidence of farms in different filtration approach and ventilation pressure was shown in Figure 2A and 2B, respectively. In the descriptive summaries (Table 1, Figure 2), non-filtered herds had a higher average number of PRRS outbreaks and longer farm-weeks-at-risk compared to filtered herds, regardless of filtration approach or ventilation pressure type. In the dataset used to analyze filtration type, farms with positive pressure filtration had, on average, more neighbor farms, larger herd size, and were located in counties with higher pig populations, compared to both non-filtered and negative pressure filtered farms (Table 1). Moran's I was 0.3 for the filtration ventilation dataset and 0.4 for the filtration approach dataset (both $p < 0.001$), indicating significant positive spatial autocorrelation, where PRRS outbreaks tended to cluster geographically. While the descriptive summaries offer useful context, the effects of filtration approach and ventilation type on PRRS occurrence are presented below through confounder-adjusted statistical analyses.

Effect of year-round and partial filtering approach on porcine reproductive and respiratory syndrome occurrence

Table 2 summarizes the GAM parametric terms evaluating the effects of filtration approach on PRRS incidence, along with incidence rates by filtration approach and herd size category. Observationally, the overall incidence rate was 30.60 PRRS outbreaks per 100 farm years, indicating that on average about 31 herds per 100 experienced a break annually during 2009–2024. When stratified by filtration approach, the crude incidence rates of PRRS were 35.30 for non-filtered herds, 22.75 for year-round filtered herds and 20.17 for partially filtered herds per 100 farm years. These observational estimates reflect unadjusted comparisons standardized by farm-years at risk. The final GAM accounted for potential confounding included the filtration approach, number of neighboring farms, herd size and number of pigs in the county, the spatial smooth term for farm coordinates, and an offset for farm-weeks-at-risk. PRRS incidence rate was 0.495 times that of non-filtered farms in year-round filtered farms (incidence rate ratio [**IRR**]=0.495, 95% confidence interval [**CI]**: 0.39-0.63, $p < 0.001$) and 0.502 times in partial pressure filtered farms (IRR=0.502, 95% CI: 0.31-0.82, $p = 0.006$), both of which were statistically significant. Regional pig density, indicated by the number of neighboring farms and number of pigs in the county, was significantly associated with an increased PRRS incidence rate. Although herd size was not statistically significant, it was retained in the final model as it is a key potential confounder of PRRS outbreak risk (Arruda et al., 2017). The spatial smooth term was significant ($p < 0.001$), indicating the significant relationship between the PRRS incidence rate and the location of the herds. The model explained 64.5% of the deviance, with an adjusted R^2 of 0.75. The basis dimension check indicated that the chosen basic dimension (k=100) was sufficient. Overall, no substantial multicollinearity was observed.

Effect of negative and positive air filtration ventilation pressure on porcine reproductive and respiratory syndrome occurrence

The final GAM assessing the effects of air filtration ventilation type on the PRRS incidence rate along with incidence rates by filtration ventilation type and herd size are presented in Table 3. Observationally, by filtration ventilation type, the incidence rates of PRRS were 32.81 per 100 farm years for non-filtered herds, 22.75 for negative pressure filtered herds and 26.89 for positive pressure filtered herds. The results of GAM showed that compared to non-filtered farms, those with negative-pressure filtration had 0.492 times the PRRS incidence rate (IRR = 0.492, 95% CI: 0.39-0.62, $p < 0.001$) whereas those with positive-pressure systems showed 0.416 times the incidence rate (IRR = 0.416, 95% CI: 0.32-0.54, $p < 0.001$), both differences were statistically significant. As in the filtration approach model, higher regional pig density was associated with an increased PRRS incidence rate, whereas herd size remained a non-significant factor. The spatial smooth term revealed a significant association between the PRRS incidence rate and the herd's geographical coordinates ($p < 0.001$). The model explained 64.6% of the deviance with an adjusted R^2 of 0.75. Model diagnostics indicated a sufficient basis dimension and no major multicollinearity.

Sub analyses

The results of the three sub-analyses on (1) comparison of year-round versus partial filtration approaches; (2) comparison of positive versus negative pressure filtration systems and (3) effects of filtration ventilation type across three time periods (2009–2014, 2015–2019, and 2020–2024) were summarized in Table 4 and Supplementary Figure S3. When focusing on the filtered farms sub-analyses (1) and (2), the difference in PRRS incidence rate between year-round and partial filtration approaches, as well as between positive and negative pressure ventilation systems, were inconclusive, reflecting a lack of statistical significance rather than indicating equivalence (Bello and Renter, 2018). When estimating the effects of filtration ventilation type across different study periods, negative pressure filtration consistently showed significantly lower rates of PRRS outbreaks, with decreasing IRRs as 0.640, 0.520, and 0.491 in 2009-2014, 2015-2019, and 2020-2024, respectively. In sub-analysis (3) for 2009–2014, positive pressure filtration was excluded due to its early stage of adoption at the time, with only a single farm implementing the positive pressure filtration system during the study period. Positive pressure filtration, included in the latter two periods 2015-2019 and 2020-2024, also showed consistently significant protective effects. Regional pig density, reflected by the number of neighboring farms and/or pigs in the county, was typically significantly associated with a higher likelihood of PRRS outbreaks, although the IRR of number of neighboring farms in the 2009–2014 analysis was 1.012 (Table 4, 95% CI: 0.98-1.05, not shown).

Discussion

The study presented here using a large dataset over a 16-year period provides evidence that PRRS incidence rate in air-filtered herds was found to be more than half times lower compared to non-filtered herds, regardless of filtration approach or ventilation pressure type. These findings demonstrate a significant and sustained protective effect of air filtration as an important component of biosecurity measures on PRRS occurrence.

The protective effect of air filtration on PRRS occurrence observed in this study was smaller but comparable to findings from other field-based studies, which used varying approaches to estimate filtration effectiveness, including comparisons of herds before and after filtration or comparisons between filtered and non-filtered herds or both. When comparing PRRS outbreaks before and after filtering, Reicks (2014) reported a drop in PRRS incidence from 52.5% to 11.3% across 97 swine sites over 8 years. When comparing filtered and non-filtered herds, Moeller et al. (2022) showed that the odds of a PRRS outbreak were nearly 90% lower in filtered herds than in non-filtered herds during 7-year study period. Havas et al. (2023) analyzed 2-year data from 67 Midwest U.S. farms and showed non-filtered sites had 20-fold higher odds of PRRS outbreak than filtered ones. A similar 2-year study conducted by Dee et al., (2024) reported PRRS incidence of 8.9% in herds with full next-generation biosecurity (including filtration) versus 40.0% without filtration. When comparing the odds of breaking with PRRS both before and after filtration and between filtered and non-filtered herds, most of previous studies consistently demonstrate strong protective effects of air filtration. Dee et al. (2012) reported an 8-fold higher odds of infection in non-filtered or pre-filtration herds over 3.5 years. Alonso et al. (2013) observed an 80% risk reduction after filtration using 7 years of data. In a swine-dense area, Thomas (2018) found positive-pressure filtration reduced PRRS introductions 4.3-fold within farms and 5-fold compared with neighboring non-filtered herds using 18-month data. In contrast, Vilalta et al. (2018b) observed an inconclusive trend toward lower incidence rates in filtered versus non-filtered farms within 3 miles, acknowledging the limited sample size of 37 farms, while their data showed a statistically significant 85% higher risk before filtration in 111 herds.The difference in the protective effects estimated in our study compared to these others may be attributed to several factors. First, our study encompassed a broader population across 12 states and 25 production systems with a longer study period, capturing greater variability in management practices and system performance. A longer follow-up also means that most farms will eventually experience a break, whereas shorter studies (1–2 years) may only capture immediate differences. Second, during our study period, more virulent PRRSV-2 variants emerged, such as 1-7-4 L1A (2013-2014) and 1-4-4 L1C (L1C.5, 2020-2021), whose increased infectivity and ex-vivo viability could have led to outbreaks in both filtered and non-filtered herds through alternative transmission routes (Melini et al., 2025; Rawal et al., 2023; Kikuti et al., 2021; Paploski et al., 2019; Linhares et al., 2017). It was observed in experimental situation that different PRRS variants exhibit varying abilities to become airborne and differing viral loads (Torremorell and Mena, 2025), which may results in varying risks of aerosol transmission. Although air filtration was substantially associated with a reduction of the risk of PRRS introduction, it does not provide complete protection against PRRSV introduction under field conditions. The Minimum Efficiency Reporting Values (**MERV**) 14, 15,16 filters, commonly used in swine farms, are designed to capture 75%, 85%, 95% of particles in the 0.30-1.0 μm range (US EPA, 2019). However, their effectiveness can be influenced by exposure pressure, airflow dynamics, system performance, filter maintenance and management practices. A previous study showed that in air-filtered farms with a high biosecurity level, new PRRS introductions can still occur (Dee et al., 2024) Additionally, while non-filtered herds did not adopt air filtration, improvements in baseline biosecurity over time, driven by the emergence of other pathogens such as porcine epidemic diarrhea epidemic and growing industrial awareness of the importance of biosecurity, may have diminished the relative advantage of filtration (Alarcón et al., 2021).

This study evaluated the effects of positive and negative ventilation pressure air filtration systems on PRRS occurrence. While both systems significantly reduced PRRS incidence rate compared to non-filtered farms, positive pressure showed a slightly higher protective effect (IRR: 0.492 for negative vs 0.416 for positive, Table

3); however, no conclusive difference was observed when comparing positive and negative filtered farms (Table 4, Figure S3, Sub-analysis 2). This inconclusive result may be due to the limited number of positive-pressure farms (n=47) included in this study. Positive pressure filtration is a relatively recent practice in U.S. sow farms and often is adopted when building farms as it requires retrofitting facilities. Although positive-filtered farms had shorter median farm-weeks-at-risk than negative-filtered farms (367 vs. 453 weeks, Table 1), this difference was addressed by including farm-weeks-at-risk as an offset in the model. Additionally, sub-analysis for 2020–2024 had similar farm-weeks-at-risk for positive and negative filtered farms (both median 261 weeks, not shown in the results). Although negative pressure farms had lower IRR (0.491 vs. 0.621) compared to positive pressure farm in Sub-analysis (3) 2020-2024, further comparison between these two types of ventilation pressure farms, excluding non-filtered herds, revealed inconclusive differences during the 2020–2024 study period (not shown in the results). When evaluating filtration strategies, including ventilation pressure or filtration approach, an advantages and disadvantages of each option is warranted. Positive-pressure systems push filtered air outward, preventing unfiltered air from entering the barn through openings or cracks present in farm exterior walls, door or window frames (Smith et al., 2019; Ramirez et al., 2016). However, positive pressure systems require special building materials to prevent moist air from the barn from infiltrating the structural components and causing them to rot. These systems also require more fans to be activated to maintain the static pressure set point in the attic and require solid wind blocks to prevent air backdraft due to directional wind against the exhaust shutters (Hueser, 2022; Thomas, 2018; Reicks, 2009). Negative-pressure systems are easier to retrofit into existing buildings, yet any opening, crack, or seam will leak unfiltered air into the barn, requiring intensive maintenance and generating costs (Hueser, 2022).

As for filtration approaches, some farms choose not to filter during the warmer season which can approximately last 4 months to save the costs of cool cell operation. Previous studies did not find conclusive evidence of a protective effect of partial-year filtration. Sanhueza et al. (2020) did not find a conclusive impact of partial-year filtration on PRRS outbreak during different seasons in the U.S. breeding herd between 2009 and 2018. Reicks (2009, 2014) reported that partial-year filtered farms broke with PRRS during summer when the filtration systems were off. In our study, similar significant protective effects were found in partial-year and year-round filtered herds when compared to the non-filtered herd, although no conclusive difference was observed when comparing only year-round and partial-year filtered herds (Table 4, Figure S3, Sub-analysis 1). However, the limited number of partial-year filtered farms (n = 22), reflecting relatively limited field adoption, may have affected the statistical significance of the protective effects and should be interpreted with caution. As small sample size may result in unstable coefficients and insufficient statistical power, and inconclusive results between year-round and partial-year filtration may simply be due to the insufficient sample size (Andrade, 2020; Faber and Fonseca, 2014). Therefore, further investigation is recommended to assess whether seasonal filtration can provide comparable protection to continuous filtration, as aerosol transmission does not only occur exclusively during the colder seasons (Lim et al., 2023; Sanchez et al., 2023; Desrosiers, 2004), and summer PRRS outbreaks have been reported to occur at 3 cases per 100 farm-summers (Sanhueza et al., 2019). Ultimately, beyond filtration approach and ventilation pressure, successful filtering of particles with pathogens requires filtration system audits, maintaining appropriate filter and pre-filter replacement frequency, and ensuring consistent operational management (Smith et al., 2019; Thomas, 2018).

Our research demonstrated the effectiveness of air filtration in reducing the incidence rate of PRRS in sow herds. Previous studies have emphasized that these benefits are contingent on broader biosecurity measures (Dee et al., 2024; Moeller et al., 2022; Pitkin et al., 2009). Future studies are therefore recommended to evaluate the combined impact of different biosecurity protocols, such as components of transportation, fomites, feed and water, personnel, and especially the compliance of these measures. However, collecting both large-scale data and detailed information on daily biosecurity practices at the farm level remains a key challenge.

When analyzing the occurrence of infectious diseases, spatial autocorrelation is a crucial source of bias if not properly accounted for (Lin and Wen, 2022; Mergenthaler et al., 2022; Tobler, 1970). Neglecting spatial autocorrelation can lead to underestimation of standard errors, inflated estimated model performance, biased variable selection, and consequently produce misleading regression model results (Gaspard et al., 2019; F. Dormann et al., 2007; Segurado et al., 2006), addressing this is particularly relevant for PRRS. Numerous studies have demonstrated that the PRRS status of neighboring farms significantly impacts the risk of virus introduction (Jara et al., 2021; Arruda et al., 2017; Wang et al., 2016; Velasova et al., 2012; Mortensen et al., 2002). Moreover, the perceived increased risk in higher density areas may also impact the decision to implement an air filtration system and what type of system is used. When assessing the effectiveness of air filtration on PRRS introduction using field data, spatial autocorrelation is often addressed by including the number of neighboring farms within a fixed radius (e.g., 4.7 km) or the number of pigs in the region as control variables (Alonso et al., 2013a; Dee et al., 2012; Spronk et al., 2010). However, this static approach may not capture the variations in local spatial risk, such as actual proximity and distribution of neighboring farms, highlighting the need for further spatial adjustment when evaluating the protective effect of air filtration. In this study, spatial autocorrelation was addressed by incorporating a spatial smooth term into the GAM, and results from all models confirmed a significant association between PRRS incidence and herd location, providing an effective way to account for pig density in herd health analyses.

Technological improvements in air filtration applied in pig farms, particularly the development and adoption of filters with higher MERV ratings, occurred during the study period. MERV ratings, which range from 1 to 16, indicate a filter's ability to capture particles of varying sizes, with higher ratings offering greater efficiency in bioaerosol removal (Ouyang et al., 2023; US EPA, 2019). When air filtration practice emerged in the U.S. swine industry before 2010, MERV 14-16 filters were tested under experimental conditions and adopted in the production region model, or in the boar stud, gilt development unit, and sow farms located in pig-dense areas (Dee et al., 2006, 2010; Spronk et al., 2010). As time went by, more farms choose to use MERV 15 or 16 when launching an air filtration system (Thomas, 2018; Wenke et al., 2018; Alonso et al., 2013b). High-efficiency particulate air (**HEPA**) filtration systems are capable of removing smaller particles than MERV 14-16 filters, with an efficiency of $\geqslant$ 99.97% for particles larger or smaller than 0.3 μm (US EPA, 2019). Experimentally, HEPA completely prevented aerosol transmission of PRRSV, whereas breakthrough transmission was observed with MERV 14–15 filters (Dee et al., 2006). The HEPA systems have been reported to be used in conjunction with positive pressure ventilation systems in France and Canada and mainly in boar studs; however, the high costs of USD 1 500-2 000 per sow or boar have limited its widespread adoption in commercial sow farms (Desrosiers, 2023; Batista et al., 2009). Although the surveillance dataset in this study did not include MERV-specific information, an attempt was made to account for technological upgrades by conducting a temporal sub-analysis (Sub-analysis 3), which divided the study period into three five-year intervals. A declining trend in IRRs for the negative pressure filtered farm across these periods compared to non-filtered farms suggests a possible reflection of progressive improvements in filtration technology. Another attempt to account for filtration generation was by including the filtration start year as a categorical variable. For each farm, this variable was defined as the year air filtration was first reported. If filtration began before MSHMP enrolment, the year of enrolment was used as the default. However, the variable did not significantly improve model fit or explain additional variation. Notably, filters with different MERV ratings can offer comparable protective effects and present similar challenges. Dee et al. (2009b) demonstrated that both MERV 14 and MERV 16 filters provided similarly strong protection against PRRSV. Torremorell (2018) highlighted that virus introduction due to leakage was more pronounced in winter than in summer, regardless of whether MERV 14 or 16 filters were used. On the other hand, filters with the same MERV rating can still vary in performance. Factors such as construction material, manufacturing quality, resistance to airflow, longevity, environmental conditions (e.g., temperature, humidity, dust), and maintenance practices can significantly influence their real-world effectiveness (Wenke et al., 2017).

As with any other study, ours has some limitations to consider. First, although the MSHMP database covers approximately 65% of U.S. sow herds, it represents a subset of the national population and may not fully represent the geographic or production diversity of the entire industry. To partially address this, we incorporated county-level swine inventory from the United States Department of Agriculture (**USDA**) Census as a proxy for regional pig density, which improved model performance when comparing models with and without this variable. Second, in the main analysis and sub-analyses (1) and (2), the number of neighboring farms and the number of pigs in the county were used as static measures, although these factors fluctuate over time. However, given the aggregated, long-term nature of this study, these static measures were considered reasonable proxies to capture the general density and regional risk environment across the study period. Third, while accounting for random effects of site would ideally address the repeated structure of the data, model fit assessments consistently indicated better fit for models without random terms. Despite these constraints, air filtration was significantly associated with lower PRRS incidence rate across all models, supporting the robustness and consistency of its protective effect. Although, air filtration adoption decision and its effectiveness in the field can vary based on a range of factors, including both external factors (e.g., number of positive farms in the neighborhood, proximity to the positive farms in the neighborhood, distance to the main roads, wind direction and speed, altitude) and internal factors (e.g., the farm owner's perceived risk based on outbreak history, air filtration system costs, filter efficiency, filter maintenance and auditing, frequency of filter change, potential leakage, enhanced biosecurity and its compliance). Different strains and variants were shown to have different capacity of becoming airborne (Torremorell and Mena, 2025; Cho et al., 2007); however, variants information of each outbreak was not available in the studied dataset. In addition to the previously discussed lack of data on MERV rating and farm-level biosecurity measures, information on the brand and type of filter and pre-filter, as well as the frequency of their replacement, was not available for the enrolled herds, all of which may influence the effectiveness of air filtration. Future studies with more practical data on filtration specifications, maintenance practices, and system performance are recommended to further validate and refine these findings for industry's reference and improvement.

Ethics approval

Not applicable

Data and model availability statement

The dataset used is privately owned by the production systems. Data are, however, available from the authors upon reasonable request to the corresponding author and with permission from the production systems involved although restrictions might apply.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT solely in order to check and improve the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of interest

This project was funded by American Air Filter Company, Inc. which were not involved in study design, data acquisition, curation or analysis. The study design, data collection, analysis, findings, conclusions, and interpretations are solely those of the authors and do not necessarily reflect the views or positions of AAF.

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Figure captions

Fig. 1. Schematic diagram of pig farm layout examples of negative ventilation pressure air filtration system (A) and positive ventilation pressure air filtration system (B). Images for pigs and fan: Flaticon.com

Fig. 2. Cumulative incidence of porcine reproductive and respiratory syndrome (PRRS) outbreaks in breeding farms by PRRS year (defined as July 1 to June 30 of the following year), comparing (A) farms with different filtration approach (year-round vs. partial vs. non-filtered) and (B) farms with different ventilation pressure types (positive vs. negative vs. non-filtered)

Table 1

Descriptive summary of two datasets used to analyze porcine reproductive and respiratory syndrome (PRRS) occurrence in relation to air filtration, by filtration approach and filtration pressure type in U.S. sow farms from 2009 to 2024.

Variables	Filtration approach analysis dataset				Filtration type analysis dataset			
	Non-filtered (N=226)	Year-round (N=128)	Partial (N=22)	Overall (N=376)	Non-filtered (N=238)	Negative (N=128)	Positive (N=47)	Overall (N=413)
Total number of sows	718 634	553 675	65 300	1 337 609	754 934	553 675	260 922	1 569 531
Outbreak								
Mean (SD)	3.5 (2.9)	2.1 (2.4)	1.0 (0.8)	2.9 (2.8)	3.3 (2.9)	2.1 (2.4)	1.8 (1.7)	2.8 (2.7)
Median [Q1, Q3]	3 [1, 5]	1 [0, 4]	1 [0, 1]	2 [1, 5]	3 [1, 5]	1 [0, 4]	1 [0, 3]	2 [0, 4]
Farm-weeks-at-risk								
Mean (SD)	509.7 (230.1)	483.8 (222.6)	246.0 (142.1)	493.0 (228.6)	525.4 (239.4)	483.8 (222.6)	353.8 (102.4)	493.0 (228.6)

Median [Q1, Q3]	465 [339, 792]	453 [334, 686]	191 [161, 262]	442 [339, 714]	521 [339, 809]	453 [334, 686]	367 [314, 424]	442 [339, 714]
Number of neighboring farms[1]								
Mean (SD)	7.9 (5.7)	7.5 (5.6)	7.2 (3.9)	7.7 (5.6)	7.7 (5.6)	7.5 (5.6)	11.4 (6.1)	8.1 (5.8)
Median [Q1, Q3]	7 [3, 12]	6 [3, 10]	7 [4, 10]	7 [4, 11]	7 [4, 11]	6 [3, 10]	12 [8, 16]	7 [4, 11]
Sow herd inventory								
Mean (SD)	3 180 (1 727)	4 326 (2 081)	2 968 (969)	3 558 (1 901)	3 172 (1 713)	4 326 (2 081)	5 552 (2 647)	3 800 (2 114)
Median	3 000	4 000	2 500	3 198	3 000	4 000	4 200	3 500
[Q1, Q3]	[1 600, 4 200]	[2 500, 5 544]	[2 500, 2 775]	[2 500, 5 000]	[1 600, 4 188]	[2 500, 5 544]	[4 000, 7 200]	[2 500, 5 200]
Herd size by category								
Small (<2 500)	75	14	3	92	78	14	0	92
Medium (2 500-5 000)	107	57	16	180	115	57	26	198

Large (>5 000)	44	57	3	104	45	57	21	123
Number of pigs in the county[2] (per 50 000 pigs)								
Mean (SD)	4.4 (5.3)	5.0 (4.6)	5.6 (4.4)	4.7 (5.0)	4.2 (5.2)	5.0 (4.6)	7.4 (4.9)	4.8 (5.1)
Median [Q1, Q3]	2.2 [0.9, 5.8]	4.1 [1.5, 6.8]	5.0 [2.7, 6.8]	2.8 [1.1, 6.5]	2.0 [0.6, 5.7]	4.1 [1.5, 6.8]	8.6 [3.3, 10.6]	2.9 [1.1, 6.8]
Moran'I (p-value)	0.4 (p < 0.001)				0.3 (p < 0.001)			

[1] Number of neighboring farms = number of the Morrison Swine Health Monitoring Project-monitored pig farms within a 35 km radius of the farm.

[2] Number of pigs in the county (per 50 000 pigs) = county-level hog inventory data based on the 2022 Census of Agriculture conducted by the United States Department of Agriculture (USDA).

Table 2

Number of outbreaks and incidence rate by filtration schedule and herd size and the generalized additive model (GAM) estimates of the effects of air filtration approach (year-round vs. partial filtered vs. non-filtered) on porcine reproductive and respiratory syndrome (PRRS) incidence rate in U.S. sow farms from 2009 to 2024.

GAM parametric terms	Total number of PRRS outbreaks	Total farm years at risk	Incidence rate per 100 farm years	GAM results			
				IRR[1]	Confidence interval (IRRs)		p-value[2]
					Lower limit	Upper limit	
Overall	1 074	3 510	30.60	–	–	–	–
Filtration schedule							
Non-filtered	782	2 215	35.30	Ref.			
Year-round	271	1 191	22.75	0.495	0.39	0.63	<0.001***
Partial	21	104	20.17	0.502	0.31	0.82	0.006**
Number of neighboring farms[3]				1.038	1.01	1.06	0.002**
Herd size							

Small (<2 500)	249	896	27.78	Ref.			
Medium (2 500-5 000)	609	1 740	34.99	1.170	0.96	1.43	0.1
Large (>5 000)	216	874	24.72	1.068	0.84	1.37	0.6
Number of pigs in the county[4] (per 50 000 pigs)				1.048	1.02	1.07	<0.001***

[1] IRR (incidence rate ratio) indicates how each variable affects the incidence rate, accounting for farm-weeks at risk. IRR > 1 means a higher rate than the reference rate; IRR < 1 means a lower rate than the reference rate.

[2] ** $p \leq 0.01$; *** $p \leq 0.001$.

[3] Number of neighboring farms = number of the Morrison Swine Health Monitoring Project-monitored pig farms within a 35 km radius of the farm.

[4] Number of pigs in the county (per 50 000 pigs) = county-level hog inventory data based on the 2022 Census of Agriculture conducted by the United States Department of Agriculture (USDA).

Table 3. Number of porcine reproductive and respiratory syndrome (PRRS) outbreaks, incidence rate by filtration ventilation type and herd size and the generalized additive model (GAM) parametric estimates of air filtration ventilation type (positive vs. negative vs. non-filtered) on PRRS incidence rate in U.S. sow farms from 2009 to 2024.

GAM parametric terms	Total number of PRRS outbreaks	Total farm years at risk	Incidence rate per 100 farm years	GAM results			
				IRR[1]	Confidence interval (IRRs)		p-value[2]
					Lower limit	Upper limit	
Overall	1 146	3 915	29.27	–	–	–	–
Filtration ventilation type							
Non-filtered	789	2 405	32.81	Ref.			
Negative	271	1 191	22.75	0.492	0.39	0.62	<0.001***
Positive	86	320	26.89	0.416	0.32	0.54	<0.001***
Number of neighboring farms[3]				1.026	1.00	1.05	0.03*
Herd size							

Small (<2 500)	245	903	27.13	Ref.			
Medium (2 500-5 000)	661	2 001	33.04	1.219	1.00	1.49	0.05
Large (>5 000)	240	1 012	23.72	1.120	0.88	1.43	0.4
Number of pigs in the county[4] (per 50 000 pigs)				1.058	1.03	1.08	<0.001***

[1] IRR (incidence rate ratio) indicates how each variable affects the incidence rate, accounting for farm-weeks at risk. IRR > 1 means a higher rate; IRR < 1 means a lower rate.

[2] * $p \leq 0.05$; *** $p \leq 0.001$.

[3] Number of neighboring farms = number of the Morrison Swine Health Monitoring Project-monitored pig farms within a 35 km radius of the farm.

[4] Number of pigs in the county (per 50 000 pigs) = county-level hog inventory data based on the 2022 Census of Agriculture conducted by the United States Department of Agriculture (USDA).

Table 4. Generalized additive model (GAM) estimates of three sub-analyses: Sub-analysis (1) comparison of year-round versus partial filtration approaches; Sub-analysis (2) comparison of positive versus negative pressure filtration systems; and Sub-analysis (3) effects of filtration ventilation type across three time periods (2009–2014, 2015–2019, and 2020–2024) on porcine reproductive and respiratory syndrome (PRRS) incidence rate in U.S. sow farms.

Term	Sub-analysis (1)		Sub-analysis (2)		Sub-analysis (3)					
					2009-2014		2015-2019		2020-2024	
	IRR[1]	p-value	IRR[1]	p-value	IRR[1]	p-value	IRR[1]	p-value	IRR[1]	p-value
Filtration approach										
Year-round	Ref.		NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]
Partial	0.960	0.9	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]
Filtration ventilation type										
Non-filtered	NA[2]	NA[2]	NA[2]	NA[2]	Ref.					
Negative	NA[2]	NA[2]	Ref.		0.640	0.03	0.520	0.001	0.491	<0.001
Positive	NA[2]	NA[2]	1.249	0.4	NA[2]	NA[2]	0.639	0.04	0.621	0.03
Number of neighboring farms[3]	1.052	0.02	NA[2]	NA[2]	1.012	0.5	1.066	<0.001	1.040	0.007
Sow herd inventory	1.000	0.4	1.000	0.3	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]

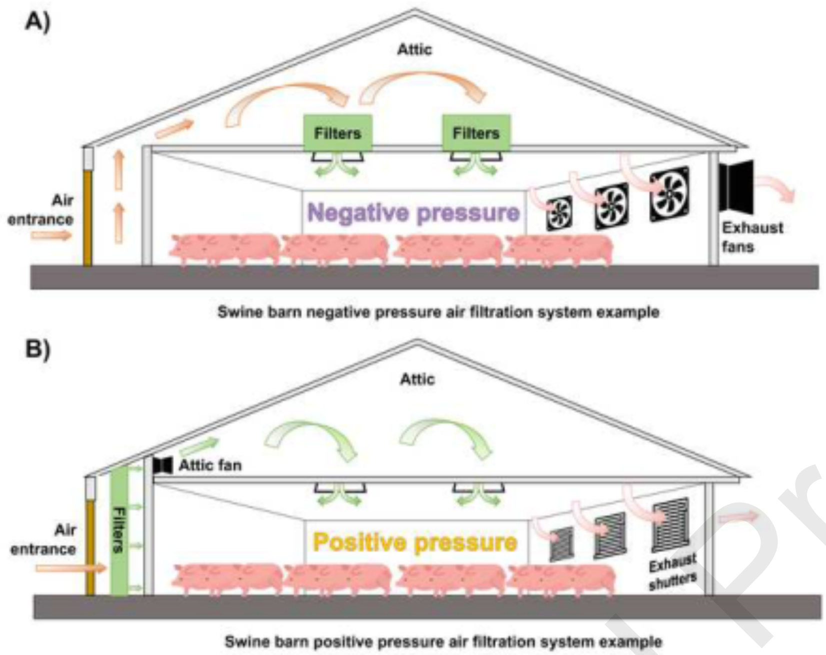
Number of pigs in the county (per 50 000 pigs)[4]	1.057	0.005	1.085	<0.001	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]	NA[2]
Herd size										
Small (<2 500)	NA[2]	NA[2]	NA[2]	NA[2]	Ref.					
Medium (2 500-5 000)	NA[2]	NA[2]	NA[2]	NA[2]	1.042	0.8	1.170	0.4	1.255	0.1
Large (>5 000)	NA[2]	NA[2]	NA[2]	NA[2]	1.028	0.9	1.092	0.7	1.232	0.2

[1] IRR (incidence rate ratio) indicates how each variable affects the incidence rate, accounting for farm-weeks at risk. IRR > 1 means a higher rate; IRR < 1 means a lower rate

[2] NA indicates that the corresponding term was not included in the specific analysis.

[3] Number of neighboring farms = number of the Morrison Swine Health Monitoring Project-monitored pig farms within a 35 km radius of the farm.

[4] Number of pigs in the county (per 50 000 pigs) = county-level hog inventory data based on the 2022 Census of Agriculture conducted by the United States Department of Agriculture (USDA).



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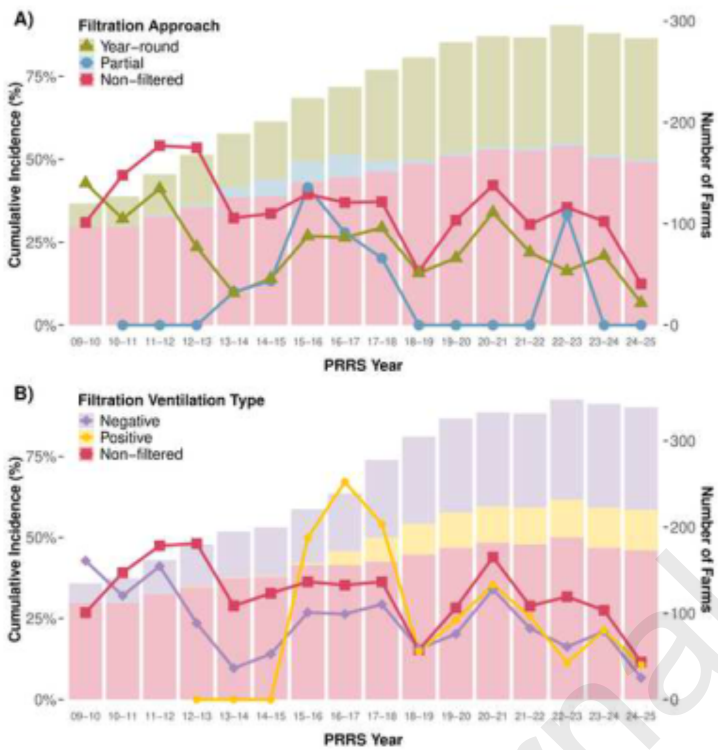
A)
Filtration Approach
Year–round
Partial
Non–filtered
Cumulative Incidence (%)
Number of Farms
PRRS Year
B)
Filtration Ventilation Type
Negative
Positive
Non–filtered
Cumulative Incidence (%)
Number of Farms
PRRS Year