EPIDEMIOLOGICAL AND ECONOMIC IMPLICATIONS OF AIR FILTRATION SYSTEMS TO PREVENT PRRSV IN LARGE SOW HERDS

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

BY

Carmen Alonso García-Mochales

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE

Peter Davies, Advisor

July, 2012
Acknowledgments

First of all, I would like to thank my advisor Dr. Peter Davies for his support, patience, and for all of the great discussion and brainstorming moments that we had during this MS project. Peter, thanks for sharing all of your great ideas, your Australian humor and the hospitality of your family during this 2 year experience here at the University of Minnesota.

To Dr. Scott Dee, for thinking on me when he had this project and for sharing his knowledge about pig production and biosecurity in pig farms.

I would like to thank my professor, William Lazarus, for having me as his student and for being very patient and helpful with all of my doubts and questions during all of our meetings. You have been a great support during this project.

Also I would like to give special thanks to Dr. Montserrat Torremorell for her friendship, support and for her unconditional advice. Also I would like to give my appreciation to Dr. Dale Polson for his contributions and ideas, many thanks for accepting my MS thesis invitation; and my appreciations to Dr. Bob Morrison and Dr. Han Soon Joo for their help and teachings during these 2 years.

And finally, I would like to thank my graduate school colleagues at the University of Minnesota, a great team to be involved with: Maria, Nubia, Leticia, Andres, Cesar, Daniel, Matt and Steve. Thanks for these two years of friendship and partnership.
Dedicated to:

My admired and loving parents, Maria del Carmen and Martin; to the best sister and brother, Raquel and Martin; and very especially, to my partner in life’s adventures, Tim.
# Table of contents

**Acknowledgments** .................................................................................................................................................. i  

**Dedication** ........................................................................................................................................................... ii  

**List of Tables** ....................................................................................................................................................... v  

**List of Figures** ....................................................................................................................................................... vii  

**CHAPTER 1: Literature review** .............................................................................................................................. 1  

1.1 Aerosol transmission of swine diseases among herds ......................................................................................... 2  

1.1.1 Characteristics and definitions of bioaerosols ............................................................................................... 2  

1.1.2 Review of selected swine diseases transmitted by aerosol .......................................................................... 5  

1.2 Review of cost – benefit analysis of biosecurity intervention to prevent transmission of infectious disease among herds ........................................................................................................................................ 24  

1.2.1 Cost-benefit analysis: enterprise budgets, whole-farm budgets, partial budgets, and capital budgeting ............................................................................................................................................... 26  

1.2.2 Review of cost – benefit biosecurity intervention studies to prevent transmission of infectious diseases among herds ........................................................................................................................................ 29  

**CHAPTER 2: Epidemiological study of air filtration systems for preventing PRRSV infections in large sow herds** ........................................................................................................................................... 34  

2.1 Chapter summary ...................................................................................................................................................... 35  

2.2 Introduction ........................................................................................................................................................... 36  

2.3 Materials and methods .......................................................................................................................................... 37
CHAPTER 3: Economic study of air filtration systems for preventing PRRSV infections in large sow herds .................................................................................................................. 58

3.1 Chapter summary ........................................................................................................ 59

3.2 Introduction .................................................................................................................. 60

3.3 Materials and methods ............................................................................................... 62

3.4 Results .......................................................................................................................... 67

3.5 Discussion ...................................................................................................................... 70

CHAPTER 4: An evaluation of interventions for reducing the risk of PRRSV introduction to filtered farms via retrograde air movement (back-drafting) through idle fans ....... 83

4.1 Chapter summary ........................................................................................................... 84

4.2 Introduction .................................................................................................................. 85

4.3 Materials and methods ............................................................................................... 87

4.4 Results .......................................................................................................................... 94

4.5 Discussion ...................................................................................................................... 95

General discussion ........................................................................................................... 114

General conclusions ....................................................................................................... 115

References ....................................................................................................................... 116
List of Tables

Table 2.1 Summary study inclusion criteria .................................................................50

Table 2.2 Farm-years at risk and incidence rates for farms in each period ..................51

Table 2.3 Relative risk between phases of non-filtered farms........................................52

Table 2.4 Relative risk between phases and against filtered farms..............................53

Table 3.1 Summary study inclusion criteria .................................................................76

Table 3.2 Sources of data for financial model of cost of a weaned pig .........................77

Table 3.3 Base line comparison of production variables between control and pre-filtered farms periods...........................................................................................................78

Table 3.4 Comparison of coefficients for univariate models for dependent variables....79

Table 3.5 Intercept and coefficients of multivariate models for dependent variables.....80

Table 4.1 Summary of results and controls of retrograde air movement through the plastic shutter..............................................................................................................99

Table 4.2 Summary of results and controls for determination of the minimum retrograde air movement required for PRRSV entry..............................................100

Table 4.3 Summary of results of retrograde air movement velocities and static pressure measured during the assessment of different interventions.................................101

Table 4.4 Summary of PRRSV PCR results during the evaluation of the tested interventions.........................................................................................................................102
List of Figures

Figure 2.1 Case definition. Example of a phylogenetic tree as an example of the 4 cut-offs of the study ..........................................................54

Figure 2.2 Time-line of the study. Types of farms and study phases ........................................55

Figure 2.3 Time-line and PRRS event distribution by 5% cut-off ........................................56

Figure 2.4 Smoothed curve of PRRSV event distribution by 5% cut-off ..................................57

Figure 3.1 Diagram of filtration scenarios used in the study ..............................................81

Figure 3.2 Filtration investment payback period in years for sensitivity analysis for both scenarios ........................................................................................................82

Figure 4.1 Diagram of the retrograde air movement testing model ..................................103

Figure 4.2 Diagram of the combined plastic shutter an canvas intervention ..................104

Figure 4.3 Diagram of nylon air chute intervention .........................................................105

Figure 4.4 Diagram of a combined aluminum shutter and air chute intervention ........106

Figure 4.5 Diagram of a double shutter intervention ..................................................107
CHAPTER 1:

LITERATURE REVIEW
1.1 Aerosol transmission of swine diseases among herds

Aerosol transmission is an important mechanism of disease spread in several animal species including swine. This review will initially discuss the nature of bioaerosols as well as salient features of 5 important infectious diseases of swine that can spread as bioaerosols.

1.1.1 Characteristics and definitions of bioaerosols

The spread of infectious disease is a global concern for health and economic reasons for the swine industry. Any process that results in the fragmentation of biological material will generate aerosols (Cox, 1995). An aerosol consists of material finely divided and suspended in air or other gaseous environments (Hirst, 1995). A bioaerosol is an aerosol containing particles of biological origin or activity that may affect living entities through infectivity, allergenicity, toxicity, pharmacological or other processes. Particle size may range from 0.5 to 100µm (Hirst, 1995). Bioaerosols in animal houses are often rich in both variety and number, especially in intensive livestock production. The main constituents of bioaerosols in animal houses are whole cells and fragments of the air spora (virus, bacteria, fungal spores, etc.) and non-specific organic and inorganic dust, including feed dust (Wathes, 1995).

Infectious aerosols are the subset of bioaerosols that carry viable pathogenic micro-organisms and therefore represent a potential mechanism for transmission of disease between individuals (Stark, 1999). Although clinical signs of sneezing and
coughing can generate large amounts of aerosolized particles from diseased individuals, the quantity of particles generated is lower than that generated during the normal breathing. However, the distributions of size of the particles generated differs between these two processes and is also highly variable among individuals (Ross et al., 1955). Use of the term ‘aerosol’ as a means of disease transmission in this context will imply that the aerosol is infectious.

The pathway of airborne disease transmission includes three components (Winkler, 1973): aerosol generation (or ‘take off’); aerosol transport to susceptible animals (or ‘aerial transport’); and inhalation of aerosols to susceptible animals (or ‘landing’ on the target). Disease transmission cannot occur unless all three components occur, but this process is influenced by many factors in farm animals.

Factors that influence airborne disease transmission are related to: 1) aerosol production; 2) aerosol survival, transport and concentration; and 3) aerosol inhalation and infection from the particles (Cox, 1995):

1) Factors related with the aerosol production are closely linked with the origin of the particles. Microbes and allergens in bioaerosols generated from dust or powders are partially rehydrated. However, particles originating from liquids as droplets will be reduced in size and weight and likely to remain airborne for longer time periods. The size of particles will determine the depth of penetration in the respiratory tract upon inhalation. The residues of
evaporated droplets are called ‘droplet nuclei’ and they can be inhaled into the pulmonary alveoli as the port of entry of infection. The process of concentration of infectious agents in the aerosol would be another important factor related with the concentration of infected animals in the farm; the higher the prevalence of infected animals in a farm, the higher the concentration of infectious agents in the aerosol in the building.

2) The ability of pathogens in aerosols to initiate disease in recipient hosts depends on how well they survive and maintain infectivity. Temperature, relative humidity (RH), topography and meteorological factors (like wind speed and solar effect) are important determinants of long distance transmission (Stark, 1999). The viable composition of infectious bioaerosols (viable bacterial or virus composition) will be influenced by the sensitivity of microbes to prevailing atmospheric factors, which is a function of their molecular structure and composition (e.g., anthrax spores versus enveloped and non-enveloped viruses) (Cox, 1995).

3) The particle size distribution of bioaerosols is dynamic and will vary between the sites of generation and deposition. Changes in the constitution of aerosols will be affected by the nature of the aerosol generated, the prevailing atmospheric conditions, and the distance/time between generation and deposition, which will in turn influence the pattern of
deposition of an aerosol in the respiratory tract of recipient hosts (Salem and Gardener, 1984). It is well established that droplet nuclei (2-3µm) will have a proportionally higher pulmonary deposition than in the upper respiratory tract. However, deposition of dust-borne bacteria and droplets is essentially limited to the nasopharyngeal area. To initiate infection, an infectious particle must be deposited at an anatomical site(s) that is permissive of the infectious process and must meet or exceed the minimal infectious dose (defined experimentally using controlled aerosols for some pathogens) (Hensel et al., 1993).

1.1.2 Review of selected swine diseases transmitted by aerosol

1.1.2.1 Foot and mouth disease virus (FMDV)

Etiology

FMDV, a member of genus Aphthovirus of the family Picornaviridae, is a virus that causes a very acute and severe vesicular disease. FMDV is on the World Organization for Animal Health (OIE) list of diseases due to its extensive spread within and between countries and its important economic consequences. With minor exceptions, FMDV affects cloven-hoofed animals and cattle, pigs, small ruminants (sheep and goats) and water buffalo are the species of greatest significance. Several other species may be infected with FMDV, but typically they do not play an important epidemiologic role. Horses and carnivores are highly resistant but can serve as
mechanical vectors for the agent if they become contaminated with the virus and then contact susceptible livestock (Thomson et al., 2003).

**Epidemiology**

Pigs usually become infected with FMDV by direct or indirect contact with infected animals, contaminated fomites or via consumption of FMDV-contaminated products (waste food). When animals are located in close proximity (e.g., in confinement facilities), the movement of the virus via aerosol is probably the predominant form of transmission (Beck and Strohmaier, 1987).

Intradermal or subdermal infection of the virus (damaged skin) is the most efficient route for infection, with a minimum infectious dose of $1 \times 10^2$ TCID$_{50}$. By comparison, a single infected animal may excrete $1 \times 10^{10}$ TCID$_{50}$ or more per day at the peak of excretion, most of it in vesicular fluid, saliva, nasal fluid and other excretions (Alexandersen et al., 2003).

Airborne transmission of FMDV is a dynamic, complex process affected by the species of animals, the number of animals, topography of the area and the meteorological conditions. Pigs aerosolize up to $1 \times 10^6$ TCID$_{50}$ per pig per day for most of the FMDV strains whereas ruminants aerosolize fewer viruses in their respiration but are highly susceptible to infection by inhalation. Swine are usually considered the most important species as a source of the virus (or amplifiers) and cattle and sheep as the recipient species (Alexandersen and Donaldson, 2002). Therefore, the pattern of airborne spread of FMDV is most often from infected pigs to cattle and sheep located
downwind (Alexandersen et al., 2012). It has been proposed that apart from infected animals, aerosols could also originate from incineration of infected carcass (Stark, 1999).

Long distance airborne spread requires atmospheric conditions that maintain the infectivity of the virus. FMDV infectivity is dependent on RH above 55%, stable atmospheric conditions and cloud cover. Donaldson et al. (1979) calculated that, given a RH of 60% and a wind speed of 10m/s, FMD virus could survive over 2.7 hours enabling translocation of more 100 km. Topography is important and large tracts of water act to preserve the virus plume and increase the probability of long distance airborne transmission. This information was successfully used to create models that predicted the airborne spread of the virus in the United Kingdom outbreaks in 1981 and 2001, and in Italy in 2003 (Alexandersen et al., 2003).

In pigs, the airborne viral excretion coincides with the appearance of vesicular lesions within the viremic phase. This pattern is similar in cattle but the amount of virus recovered from blood and breath is higher in pigs. The percentage of ruminants that become carriers of the disease is on average 50% with a maximum reported duration of 3.5 years in cattle and 9 months in sheep (Sutmoller and Olascoaga, 2002). Pigs do not act as long term carriers. FMDV can persist in the environment for long periods of time, for at least 20 weeks in hay and straw and in fecal slurry for 6 months in winter (Hyslop, 1970). Acid or alkaline disinfectants are highly effective.
**Pathogenesis and clinical signs**

After the initial replication of the virus in the pharynx or in the skin, FMD virus spreads to the regional lymph nodes and into the circulation. Viremia usually last between 4 to 5 days. The main sites for virus replication are cornified epithelia of the skin, tongue and mouth. Normal skin (hairy and hairless) also contains substantial amounts of the virus. Damaged mucosa is always associated with higher severity of the lesions (Alexandersen et al., 2012).

The incubation period is highly variable (1 to 14 days) and multifactorial based on dose, species and route of infection (Alexandersen et al., 2003). In experimental conditions, the mean incubation period was 1 to 3 days in pig-to-pig direct contact and 3.5 days in direct cattle-to-cattle contact. FMD is characterized by an acute febrile reaction and the formation of the vesicles in and around the mouth and on the feet. Lameness and lesions may not be consistent findings in all animals.

**Prevention and control**

Airborne disease transmission of FMDV is problematic and its consequences can be dramatic. FMDV has a wide host range, a low infective dose, a rapid rate of replication, a high level of viral excretion, and multiple modes of transmission. In previously unaffected regions, the implementation of a response as soon as possible is essential to control the disease. Extreme measures are required to eradicate the disease. Stamping out has been shown to be effective to control and eradicate the disease in many countries (Alexandersen et al., 2003). Vaccination strategies have to be
tailored to the strains circulating in the area due to the lack of cross protection between heterologous strains (Alexandersen et al., 2012).

### 1.1.2.2 Pseudorabies virus (PRV) or Aujeszky’s disease virus (ADV)

#### Etiology

PRV, a member of genus Varicellovirus of the family *Herpesviridae*, was first isolated from a diseased ox, cat and a dog by a Hungarian physician Aladar Aujeszky, who differentiated the disease from rabies. Pigs are the natural host for PRV but the virus can naturally infect cattle, sheep, cats, dogs and rats, causing fatal disease. Only swine are able to survive a productive PRV infection. The disease became widely known as Aujeszky’s disease, or commonly “mad itch” in non-porcine animals, and in 1931 it was discovered in domestic pigs in the United States.

#### Epidemiology

In the 1980s, PRV increased in importance in many countries due to the emergence of more virulent strains and the changes in the swine industry. Following significant control and eradication programs, PRV has since been eradicated from several countries and is only present in southeastern Europe, Latin America, Africa and Asia. In PRV-free countries, vaccination is usually prohibited.

Despite the success of PRV elimination from domestic pigs, the disease is present in some populations of nondomestic swine, which represent a threat for PRV reintroduction to commercial populations (Muller et al., 2011). PRV is not very
contagious disease except for piglets ($1 \times 10^2$ TCID$_{50}$). Higher exposures are necessary for oral when compared with intranasal infection. The virus is spread primarily by direct contact between swine or by contact with PRV-contaminated fomites (bedding or water) or other infected animals. Nasal mucosa and oral cavities are the main portals of entry (Donaldson et al., 1983).

Virus shedding starts 1-2 days after infection, prior to the onset of viremia and clinical signs reach a peak at 2-5 days and lasting up to 17 days. At the peak of virus excretion, one pig may excrete $1 \times 10^{5.3}$ TCID$_{50}$ into the air for a 24h period (Wittmann, 1991). The survival of airborne ADV was best at 55% RH and at 4°C (Schoenbaum et al., 1990). After recovery, pigs remain latent carriers of virus which can be reactivated, for example, by transport or other stresses.

Airborne transmission of PRV could happen between buildings and for short distance depending on climate conditions. It was shown that the status of neighboring herds as well as pig density and herd size in a region can influence the risk of a herd becoming infected with PRV (Christensen et al., 1990; Grant et al., 1994; Leontides et al., 1994). Although an enveloped virus, PRV is somewhat resistant to environmental conditions, depending on pH, humidity, and temperature. In slurry, PRV remains infectious for 1-2 months, depending on the season. Most common disinfectants are suitable to inactivate the virus but effectiveness is reduced by the presence of organic material. In practices, 20 kg Ca(OH)$_2$/m$^3$ is recommended for disinfecting infected slurry.
**Pathogenesis and clinical signs**

After oronasal infection of the natural host and primary replication in epithelial cells of the upper respiratory tract, the virus goes to the neurons and by fast axonal retrograde transport creates either lytic or latent infection. Viremia disseminates infection to several organs and the replication of the virus in CNS causes nonsuppurative meningo encephalitis characterized by severe central nervous disorder (Mattenleiter et al., 2012).

Infection of pigs with PRV produces high fever, followed by anorexia, dyspnea, excessive salivation, vomiting, trembling, and eventually marked incoordination (Mattenleiter et al., 2012). The presence and severity of the clinical signs, as well as morbidity and mortality, depend on the age and immunological status of the pig (Nauwynck, 1997). Mortality could reach 100% in 2 to 3 week-old piglets with severe signs of central nervous system involvement. Clinical signs in sows and gilts depend on the phase of gestation and include embryonic death, mummified fetuses abortions or still deaths (Mattenleiter et al., 2012).

**Prevention and control**

Depending on the country, the control of the disease was achieved by blanket vaccination with inactivated vaccines (breeding animals) and modified live virus vaccine (finishers), or with test and removal programs. Vaccine is efficacious in reducing the disease, however new outbreaks did occur due to the introduction of virus by trade or
air. The combination of highly efficacious differentiating infected from vaccinated animals (DIVA) vaccines and accurate differential ELISAs made eradication of PRV from large areas of the world practical and feasible (Mattenleiter et al., 2012).

1.1.2.3 Mycoplasma hyopneumoniae or enzootic pneumonia (MH)

Etiology

MH, a member of genus Mycoplasma of the family Mycoplasmataceae, class Mollicutes, are the smallest known cells that are able to propagate in a cell free medium, and have the smallest genomes with a limited number of genes resulting in a lack of biosynthetic pathways (Thacker and Minion, 2012). Culture and isolation of MH is slow and complex and sometimes contaminated with other bacteria or other mycoplasmas (M. hyorhinis). There are 119 species in the Mycoplasma genus identified, of which MH is most important for the swine industry because of its high prevalence around the world. MH-initiated pneumonia, also known as an enzootic pneumonia, plays a primary role in the porcine respiratory disease complex (PRDC), leading to important economic losses to the swine industry (Thacker and Minion, 2012).

Epidemiology

MH is most commonly transmitted by nose to nose contact from infected swine carrier pigs to penmates, and susceptibility is age independent (Etheridge et al., 1979).
MH has been detected in nasal secretions of infected pigs by both culture and PCR (Calsamiglia et al., 1999). Epidemiological studies of risk factors have suggested that airborne infection may be an important mechanism of disease spread between herds and it seems to be climate dependent (Goodwin, 1985; Stark et al., 1992).

Fano et al. (2005) demonstrated possible indirect transmission from 2 month old MH-inoculated pigs to indirect contact exposure pigs (Fano et al., 2005). A successful laboratory model was created to demonstrate experimental aerosol movement and airborne transmission at the Swine Disease Eradication Center (SDEC) of the University of Minnesota. All samples collected at 1.75m and 150m, were positive for MH DNA by nPCR (Cardona et al., 2005). More recently, the same group demonstrated airborne transport of infectious MH using an air cyclonic collector up to 9.2km downwind from a source population of MH infected pigs (Otake et al., 2010a). In that study, none of the meteorological variables evaluated were statistically significant. Some avian mycoplasmas studies back in the early 70’s showed a possible survival at 25°C and RH of 40 to 50% (Beard and Anderson, 1967).

MH infection is maintained in most pig breeding herds by transmission via nose-to-nose contact from sow to piglets (Calsamiglia and Pijoan, 2000). The agent transmits within herds via nose-to-nose from pig to pig, which is not very efficient and the spread is slow. Numerous factors influence the dynamics and severity of MH disease at a herd level, including type of housing, ventilation systems, management practices, climatic conditions, and one vs two vs three-site production systems (Sibila et al., 2004).
The first signs of enzootic pneumonia are typically observed in pigs around 6 weeks of age, but all ages of pigs are susceptible. Concurrent infections with PRRSV may shorten the incubation period and, in some cases, may result in outbreaks of MH at younger ages (Thacker et al., 1999).

**Pathogenesis and clinical signs**

The pathogenesis of MH is complex and begins with the binding of the microorganism to the cilia of epithelial cells in the airway of the pig. This colonization by MH results in ciliostasis, clumping, loss of cilia and a decline in the efficiency of clearance of invading pathogens by the mucociliary apparatus (Thacker and Minion, 2012). Consequently, secondary pathogens can cause bronchopneumonia with MH as a primary pathogen, and this disease complex is traditionally termed enzootic pneumonia. Not all the MH infections result in clinical pneumonia. The development of clinical pneumonia depends on the number of organisms that colonize the respiratory tract, virulence of strains (high/low virulence) (Meyns et al., 2007), and time.

Enzootic pneumonia describes the typically endemic pattern of disease occurring in traditional farrow to finish farms. However, outbreaks (epidemics) can also occur when the organism is introduced into a naïve herd. In the endemic form affected animals exhibit dry non-productive cough that may persist during the finisher period, and sometimes fever, decreased appetite and labored breathing (Thacker and Minion, 2012).
Prevention and control

The control of the MH associated disease can be accomplished in a number of ways. Firstly, management practices and housing conditions in the herd are important (i.e. all-in/all-out production, limiting factors that may destabilize herd immunity, optimal stocking densities, prevention of other respiratory diseases, and optimal housing and climatic conditions). Strategic medication with antimicrobials active against MH and, preferably, also against major secondary bacteria may be useful during periods when the pigs are at risk for respiratory disease. Vaccination is also employed to reduce clinical signs, lung lesions and medication use, and improve production performance (Maes et al., 2008). Elimination of the agent from populations, based on temporally stopping the introduction of animals and/or medication strategies, is the goal for many practitioners, but re-infections of negative herds is a frequent event (Hege et al., 2002). Air filtration (based on MERV 14 and MERV 16 filters) has been demonstrated to prevent the airborne transmission of MH to at risk populations. A research production regional model based on multiple replicates, confirmed the risk of aerosol transmission in the spread of PRRSV together with MH from a infected source population (Dee et al., 2010a).
1.1.2.4 Swine influenza virus (SIV)

**Etiology**

Influenza viruses are members of the family *Orthomyxoviridae*. They are negative-sense single-stranded RNA viruses with a segmented genome. Three different types of influenza virus exist: A, B and C, defined by the nucleocapsid protein (NP) and the matrix proteins (M1 and M2). Only influenza A virus are known to be of clinical significance as swine pathogens. Influenza A virus subtypes are defined by the hemagglutinin (HA or H) and neuraminidase (NA or N) antigens. The combination of the 16 different HA and 9 NA types defines a virus within one of 144 subtypes (e.g., H1N1 or H3N2) (Van Reeth et al., 2012).

Only influenza A type viruses can infect a variety of animal species, including humans, swine, equines, canines, felines, marine mammals and avians. The segmented nature of the influenza genome allows two viruses that co-infect a single host, to exchange RNA segments during viral replication. This process of reassortment involves the complete gene segments encoding the HA and/or NA genes and has been termed antigenic shift and is a common and important mechanism of influenza virus evolution (Taubenberger and Kash, 2010). Mutations that change only amino acids in the antigenic portions of the surface glycoproteins HA and NA have been termed antigenic drift. This process is very important for influenza viruses adapted to humans (Taubenberger and Kash, 2010).

Influenza viruses have enormous public health significance. Since the disease was first described as a clinical disease of swine in the United States in 1918, coinciding
with the human pandemic (Spanish flu). The first evidence of transmission of swine influenza to farm personnel was in 1976 (Easterday, 1980). Since then, many more reports confirm possibility of interspecies transmission of influenza viruses from humans to pigs (Nelson et al., 2011), pigs to humans (Shu et al., 2012), pigs to birds, and from birds to pig (Vincent et al., 2008). Swine have been considered a potential “mixing vessel”, because pigs have receptors for both avian and human influenza viruses (Ito, 2000). Therefore, they can serve as hosts for viruses from either birds or humans.

Epidemiology

Pigs can be infected with swine, human and avian influenza viruses and therefore, transmission of influenza is not only limited to within species events, but also to interspecies events (Kundin, 1970). Different subtypes of influenza have been isolated in different parts of the world reflecting events of avian-to-swine transmission in swine populations. Human isolates have also occasionally been isolated from pigs, in particular H3N2 viruses in Asia and occasionally in pigs in Europe and North America.

Influenza virus outbreaks occur typically in during late fall and early winter in cold climates associated with colder temperatures and cold autumn rains. However, several studies have demonstrated that in modern swine facilities influenza transmission can occur throughout the year (Taubenberger and Kash, 2010).

The primary route of transmission within farms is pig-to-pig contact, with virus titers in nasal secretion at the peak of shedding of the order of $1 \times 10^7$ infectious
particles/mL. Airborne transmission of SIV was demonstrated by Xie et al. (2007) using a guinea pig model. They calculated that the horizontal distance travel by particles with initial diameters of 30-50µm is less than a meter during normal breathing and more than 6m during sneezing (Xie et al., 2007). Different animal models have been used to explain the airborne transmission of the disease (ferrets and guinea pigs) comparing contact with airborne transmission. Some of the important observations from those studies were that different influenza strains differ considerably in their capacity for airborne transmission and that this transmission is dependent on RH, temperature and virus characteristics (Lowen et al., 2007; Lakdawala et al., 2011; Koster et al., 2012). Airborne detection of SIV, at the farm level and 2.1 km downwind, has been recently reported by Corzo et al (2012, Personal Communication).

Pathogenesis and clinical signs

In pigs, influenza A viruses produce a highly contagious acute respiratory disease. SIV is endemic in most of the swine populations around the world, and is one of the respiratory pathogens involved in the porcine respiratory disease complex (Thacker et al., 2001). The virus tends to spread easily in susceptible populations and many pigs become infected with one or more virus subtype, sometimes without showing clinical signs (Van Reeth et al., 1996).

SIV is an acute infection and virus clearance is very rapid. The lungs are the major target organ and infection in pigs is limited to the respiratory tract with virus replication
demonstrated in epithelial cells of the nasal mucosa, tonsil, trachea, lungs and tracheobronchial lymph nodes (Van Reeth et al., 2012). Nasal secretions are the primary route of virus excretion. With an incubation period of 1 to 3 days, characteristic clinical signs of acute infections are pyrexia, anorexia, inactivity and reluctance to rise. The virus can be detected as early as 1 day post infection from nasal secretion and up to 5-7 days post infection (Van Reeth et al., 1996). Morbidity is high (near 100%) but mortality is typically low (usually less than 1%) unless there are concurrent infections with secondary bacteria or viruses.

**Prevention and control**

Vaccination of animals is a common strategy for control of influenza on swine farms. Currently, the licensed commercial vaccines available are based on inactivated whole virus preparations with H1N1 and H3N2 viral strains. Because the increase of genetic diversity of influenza A viruses circulating among pig farms and the limited ability of inactivated vaccines to offer cross-protection, the use of autogenous vaccines is increasing (Vincent et al., 2008).

Biosecurity is, as for all diseases, a key point to protect populations against new strains of SIV. Most of the standard biosecurity protocols in place in pig farms to prevent the introduction of pig pathogens are also useful for influenza (Otake et al., 2002b; Dee et al., 2004). Indirect transmission via fomites has been recently documented by Allerson and others (2012). However, due to its zoonotic nature, both mechanical
aspects and the biological aspects of transmission related to human infection with SIV need to be accounted for (Romagosa and Davies, 2009).

1.1.2.5 Porcine reproductive and respiratory syndrome virus (PRRSV)

Etiology

PRRSV is a small enveloped, single stranded RNA virus that belongs to the Arteriviridae family in the order Nidovirales. There are two major genetic lineages represented by type 1 (European viruses) and type 2 PRRSVs genotypes (North American viruses) that vary by 44% in nucleotide sequence. The PRRSV genome consists of 2 large open reading frames ORF 1a and ORF 1b that comprise 75% of the viral genome and are translated and processed into 14 non-structural proteins (nsp). The seven structural proteins are encoded by ORFs 2-7 (Snijder and Meulenberg, 1998). The three main structural proteins (N, M and GP5) are required for particle formation and viral infectivity, while minor proteins (GP2a, GP3 and GP4) are only essential for viral infectivity. Phylogenetic analyses based on ORF5, which encodes the major envelope glycoprotein (GP5), have shown that both types of PRRSV 1 and 2 are very diverse (Zimmerman et al., 2012).

Epidemiology

PRRSV is present in most swine production countries in the world with some exceptions being Norway, Finland, New Zealand, Australia, Brazil and Cuba (Zimmerman
et al., 2012). Only domestic and feral pigs are known to be susceptible to PRRSV and the susceptibility of other members of the superfamily Suidae is unknown.

The direct and indirect routes of PRRSV transmission include saliva and nasal secretions from infected pigs (Wills et al., 1997), contaminated semen (Christopher-Hennings et al., 1995; Prieto and Castro, 2005), vehicles (Dee et al., 2004), insects (Otake et al., 2002; Otake et al., 2003), and fomites (Otake et al., 2002b; Otake et al., 2002c). Indirect transmission by aerosols is dependent on the viral variant and environmental factors. After several studies conducted under laboratory conditions, Dee et al. demonstrated, in several replicates at a production research facility, the airborne transmission of PRRSV from a source to an at-risk population in a production regional model. They defined possible risk factors for aerosol transmission to be directional winds of low velocity, sporadic wind gusts, low temperatures, high relative humidity and low sunlight levels (Dee et al., 2010b). Airborne transmission of the virus has been demonstrated out to distances of 9.1km (Otake et al., 2010a).

Vertical transmission of PRRSV occurs transplacentally from viremic dams to fetuses resulting in reabsorption or abortion of fetuses, or birth of stillborn and congenitally infected pigs (Christianson et al., 1992). If this cycle of transmission is not interrupted, PRRSV tends to circulate in herds indefinitely (endemically) due to the persistence of the infection in naïve animals (Dee and Joo, 1994). Transmission between herds was first defined as ‘neighborhood infection’ by Robertson (1992). In his PRRSV studies of cases in England and Belgium, he concluded that airborne transmission of PRRSV was the cause of many outbreaks (Robertson, 1992). The term of ‘area spread’
was introduced by Lager et al. in 2002 in a study with seven herds within 40 km² area. The high degree of homology between isolates of the different farms suggested a common source of all these viruses (Lager et al., 2002).

PRRSV is fragile and quickly inactivated by heat and drying. Many studies have defined the stability of its infectious properties under specific conditions of temperature, moisture and pH. The virus is stable for months at -7 and -20 °C (Zimmerman et al., 2012) and in a recent study, Linhares et al. (2012) demonstrated the ability of the virus to remain infective in manure at low temperatures (Linhares et al., 2012b).

**Pathogenesis and clinical signs**

The pathogenicity of PRRSV was fully reviewed by Zimmerman et al. (1997). The primary site for replication is alveolar macrophages of the lung and other cells of the macrophage lineage located in lymph nodes, spleen, placenta and umbilical cord (Lawson et al., 1997). The virus can persist in pigs for long periods of time evading the immune system. Using polymerase chain reaction (PCR), PRRSV RNA has been detected in breeding gilts out to 120 days post-infection. Infection persisted in serum up to 210 days of age in pigs infected *in utero* as fetuses at 85-90 days of gestation (Benfield et al., 1997; Batista et al., 2002a).

Outbreaks of PRRSV involve episodes of reproductive failure (third-trimester abortion, premature parturition, and elevated levels of fetal losses) as well as a reduced growth performance and elevated mortality, secondary to respiratory disease (Loula,
However, the intensity of the disease appears to vary among isolates with the North American type 2 strains being the most pathogenic. Very severe outbreaks were reported from China during the summer of 2006 and a highly virulent type 2 virus variant was reported to be the cause (Li et al., 2007).

**Prevention and control**

PRRS has proven to be a difficult and frustrating disease to control. The methods for control and elimination of PRRSV leading to recent initiatives of voluntary regional control and elimination programs of PRRSV in swine dense regions in North America were reviewed by Corzo et al (2010). Methods to control the spread of the disease include semen control (Christopher-Hennings et al., 1995a), gilt acclimation (Dee et al., 2002), management practices, partial depopulation (Dee and Joo, 1994), live virus exposure (Batista et al., 2002b), and vaccination programs with MLV vaccines (Cano et al., 2007).

Elimination of PRRSV has been the focus for many practitioners and researchers for the last 10 years. The different methods that have been described to eliminate the virus from the sow herd include test and removal (Dee and Molitor, 1998), whole herd depopulation/repopulation and herd closure (Torremorell et al., 2003). However, successful elimination on many farms has often been negated by reintroduction of new PRRSV despite stringent biosecurity measures, leading to recognition of the important role of aerosol transmission of the virus.
The assessment of biosecurity risks related with the introduction of PRRSV must be an ongoing strategy for producers. The American Association of Swine Veterinarian (AASV) developed a Production Animal Disease Risk Assessment Program (PADRAP) mainly focused on the risk assessment of PRRSV (American Association of Swine Veterinarians, 2011). This is a web-based program that offers a set of risk assessment surveys that are used by practitioner veterinarians (members of the association). It is a unique tool for veterinarians to help producers systematically assessing risk factors that may be associated with clinical outcomes. The assessments performed, once the survey is completed, are added to the dataset maintained at Iowa State University College of Veterinary Medicine for further analysis.

1.2 Review of cost – benefit analysis of biosecurity interventions to prevent transmission of infectious disease among herds

Biosecurity is defined by the OIE as “the implementation of measures that reduce the risk of the introduction and spread of disease agents; it requires the adoption of a set of attitudes and behaviors by people to reduce risk in all activities involving domestic, captive/exotic and wild animals and their products”(FAO/OIE/World Bank, 2008). It is closely related to disease transmission, which refers to any mechanism by which an infectious agent is transferred from an infected host, animated or inanimate, to a susceptible host (Neumann, 2012). Transmission is a survival strategy for most infectious agents and it is classified as horizontal or vertical, and may occur by direct or indirect routes (Halloran, 2001).
Biosecurity is difficult to evaluate based on experimental or historic data. However, it is one of the most important production strategies that we need to address in order to prevent disease introduction (Deen, 2005). Many practitioners or researchers without extensive knowledge of animal health economics often cite reference on ‘the cost of X disease is..’ to justify their recommendations or projects. Focusing on the cost of uncontrolled disease ignores the fact that disease control strategies also have a cost, and generally do not eliminate the disease entirely, so that some residual disease remains even after implementation of a control strategy. Producers adopting effective health-management practices receive short term increases in profits. However increased profits lead to increased industry supply and price adjustments which in the longer term return profit levels to a new equilibrium level due to the industry macroeconomics (Buhr et al., 1993). Marsh (1999) postulated that crude estimates of aggregate disease costs are typically overstated. Alternatively, economic analysis techniques are designed to estimate the benefit of disease control and strategies at different levels (farm, regional, national or international). Strategies at wider geographic levels may be simpler to construct than at other levels, and can provide decision-makers with guidance with respect to the cost-effectiveness of reducing disease prevalence (Marsh, 1999).

For most farm businesses the aim of the manager is to generate profit. This may be achieved by increasing quality of products, reducing production cost, or by increasing the efficiency of production of livestock products (e.g., pork meat) by controlling the effects of the disease on the animal population (Marsh, 1999). The techniques
employed in animal health economics for decision making can be grouped into quantitative modeling techniques, decision analysis (i.e. decision trees), simulations, optimizing mathematical models, cost-benefit analysis and budgeting analysis (Mlangwa and Samui, 1996). Most veterinary decisions are based on budget analysis and these methods will be reviewed as part of the introduction to this thesis.

1.2.1 Cost-benefit analysis: enterprise budgets, whole-farm budgets, partial budgets, and capital budgeting

Planning is one of the most important functions of a business manager. Planning is the determination of the intended strategy and course of action for a business such as a swine operation. Budgets are important tools in the planning process and they report the quantified estimates of expected results due to carrying out a specific plan or set of actions (Olson, 2010c). Enterprise budgets, whole-farm budgets and partial budgets are three of the main types of budgets used in farm management.

Economists define an “enterprise” as any coherent portion of the general input-output structure of the farm business that can be separated and analyzed as a distinct entity (AAEA Task Force, 2012). A business such as a swine operation may be viewed as a single enterprise or several enterprises.

An enterprise budget is a complete projected income statement for an enterprise, used for planning the future. It is not an historical accounting. Their goal is to predict what will happen in the future under various strategies and different
considerations, such as to filter or alternatively, not to filter. Budgets help managers to recognize and quantify possible implications that might happen in the future based on their decisions. An enterprise budget shows the projected receipts, cost and net returns to be expected if specific methods and inputs are used to produce a specified amount of a product (i.e. kilograms of pork meat) (Olson, 2010a). An enterprise budget is often expressed on a per-unit basis (per acre or per hundredweight of pork) and serves as a building block for a partial budget or a whole-farm budget.

The generation of a full enterprise budget requires either a sophisticated financial accounting system, or detailed manual calculations. Allocating the cost of the facilities and labor to different cost centers and determining how particular costs will change under alternative strategies are some of the most challenging aspects of budgeting but, for many decisions, facility and labor costs will not change and can be ignored. An enterprise budget can be used effectively as part of ongoing monitoring to provide information on the profitability of the livestock production system (Marsh, 1999).

A whole-farm budget is a budget of the expected costs and returns for a specific combination of enterprises. To avoid complications such as the allocation of facility capital and labor costs mentioned above, an alternative to a whole-farm budget is a partial budget, which is a listing of only those costs and returns expected to change due to a proposed change in the business (Olson, 2010c). A partial budget compares a scenario or situation “without the project”, with the situation “with the project”.

27
Partial budgets are the most common budget type utilized for veterinarians and researchers to compare different scenarios or interventions (Dee et al., 1997; Lane et al., 1997; Allore and Erb, 1998). The name “partial”, tells us that the whole budget and the whole farm is not addressed. It is suited for addressing relatively small changes in the enterprise in a less complex format than the complete enterprise budgeting analysis (Olson, 2010d).

The changes that the partial budget refers to are classified in 2 groups:

- Positives: Additional revenue or reduced expenses
- Negatives: Reduced revenue or additional expenses

Partial budgets are extremely flexible but do have limitations: the analysis can only evaluate one alternative at a time (i.e. one project or intervention); only one set of values can be evaluated unless a sensitivity analysis is done; and it is essentially limited to an annual time step (Olson, 2010d).

“Capital Budgeting Analysis” is a process to evaluate how we invest in capital assets (e.g., biosecurity interventions) that could provide cash flow benefits for more than one year (Olson, 2010a). Regarding biosecurity in a farm, we are trying to answer the following question: Will the future benefits of this biosecurity project be large enough to justify the investment given the risk of the disease involved?
1.2.2 Review of cost–benefit biosecurity intervention studies to prevent transmission of infectious diseases among herds

The use of economics has been advocated as an important tool in the management of animal diseases and in the implementation of intervention options at the herd level. Evaluating the economic advantage or disadvantage of each disease control intervention should always be a key strategy. Unfortunately, this step does not always precede biosecurity procedures in production farms. Most biosecurity procedures are untested as to their economic importance and even fewer have been tested for farm-level determinants (Deen, 2005).

In the literature, most of the economic studies regarding biosecurity interventions take into account the entry of transboundary or exotic diseases. Among livestock species, poultry and swine industries are the ones with the highest number of scientific publications in this field (Sen et al., 1998; Boklund et al., 2009; Fasina et al., 2011; Fasina et al., 2012).

After reviewing the literature in this field there are some advantages and disadvantages of these types of studies that should be considered:

**Strengths of biosecurity economic studies**

- Their goal is to guide farmers in a decision-maker strategy. Their purpose is not to ‘predict the future’ or ‘to be right’. Rather, their aim is to make the best decision regarding biosecurity given the available information and to evaluate
the direct economic benefit to farmers from the prevention of disease (Marsh, 1999).

- Most of them are based on large sample sizes. Because of the difficulties related to the sometimes complex accounting and production data, the great majority of the studies are based in large sample sizes in order to achieve representative information.

- Simulations and stochastic procedures are used frequently in order to isolate a more obvious outcome over time. In stochastic modeling, risk is taken into consideration by the use of probabilistic distributions or by using random numbers drawn from probability distributions (Mlangwa and Samui, 1996). A good example is the study done by Boklund and others (2009) in which they simulated the epidemiological and economic consequences of classical swine fever strategies and the cost of biosecurity in the face of outbreaks in different parts of the country and different types of farms (production vs nucleus herd) (Boklund et al., 2009).

- Sensitivity analysis is a common approach that complements these cost-benefit studies by evaluating the results in different scenarios. The most common scenarios evaluated are different feed and market prices (i.e. meat and eggs) (Fasina et al., 2012), decrease in total margin (net return) (Fasina et al., 2011), probability of exposure and severity of disease (morbidity and mortality) (Sen et al., 1998), and efficiency of the biosecurity intervention (protection efficacy or effectiveness of intervention) (Harding, 1999).
Most of the time these studies are supported by great graphic designs that explained some difficult economic concepts in simple graphs. Harding (1999) explained, in 3 clear graphs, the cost of biosecurity strategies versus their relative effectiveness preventing the entry of Mycoplasma, PRRSV and transmissible gastritis enteritis virus (TGEV) (Harding, 1999). Sen and others (1998) demonstrated the expected net profit (or loss) in $US for a 2,000 bird batch for 4 different strategies: no protection for the disease, vaccination only, biosecurity only, and vaccination and biosecurity (Sen et al., 1998).

**Weaknesses of biosecurity economic studies**

- Quality of the data. One of the most difficult aspects of any economic analysis is the acquisition of good data (Marsh, 1999). Working closely with farmers and financial departments will help in these types of studies but this is not always possible. Studies based on financial survey data or with a high number of assumptions demonstrate a lack of connectivity between the researcher and the subjects of the analytic process.
- Difficulty in evaluating biosecurity compliance. Some of the studies calculate the capital cost of the biosecurity interventions but they do not measure the cost of poor compliance by farm workers due to the complexity of implementing these measures (Deen, 2005). If the degree of compliance could be measured, these data would be very helpful information for the completion
of a sensitivity analysis. It could be also important to illustrate possible failures in
the design or training of the interventions.

- Most of the factors measured in biosecurity are not linear (Deen, 2005).
Completing all the steps partially is much better in biosecurity than doing half of
the steps extremely well. This means that there is no zero risk with biosecurity.
In biosecurity, there is only a mechanism for risk reduction and this is a concept
that is difficult to evaluate economically.

- Value of money. Most of the studies of the cost-effectiveness of
biosecurity include a time horizon that is limited to one year or less. The longer
the period, the greater the number of factors that should be included in the
analysis. Many studies do not have any time horizon; however, the term of
analysis and time value of money are important aspects to consider.

After the completion of this literature review, the author has observed that
although many swine industry researchers have undertaken biosecurity studies for
different diseases, only a very small number of interventions or strategies have been
evaluated in terms of the economics. Real production and financial data has been used
to evaluate the benefits of isolation units (Bonneau, 1998), nursery depopulation
strategies (Dee et al., 1996) and herd closure for PRRSV (Schaefer and Morrison, 2007).
Although the last two options are control strategies for the infected herds, they can be
preventive interventions when the decreased transmission of viruses among herds is
considered.
The adoption of individual biosecurity interventions or generally enhanced biosecurity level requires farmers to accept additional costs that do not bring them direct benefits. The decision to implement biosecurity intervention strategies needs to involve both epidemiological and economic analysis. Veterinary practitioners need to combine both strategies to help farmers to implement the correct decisions.

The research undertaken in this thesis focuses on the biosecurity intervention of air filtration for large confinement sow farms to prevent introduction of PRRSV via aerosols. The work involves 1) an assessment of the effectiveness of air filtration in reducing the risk of new PRRSV introduction into farms; 2) an analysis of the simple payback period for investment in air filtration based on analysis of production data from commercial farms; and 3) an experimental study of tools to prevent back drafting of air into negative pressure filtered facilities.
CHAPTER 2:

EPIDEMIOLOGICAL STUDY OF AIR FILTRATION SYSTEMS FOR PREVENTING PRRSV

INFECTION IN LARGE SOW HERDS
2.1 Chapter summary

Porcine reproductive and respiratory syndrome virus (PRRSV) is the most economically significant pathogen in the US swine industry. Aerosol transmission among herds is a major concern in pig dense regions and filtration of incoming air, in combination with standard biosecurity procedures, has been demonstrated to prevent transmission of PRRSV into susceptible herds. To quantify the impact of air filtration on reducing risk of PRRSV outbreaks, we compared the incidence rate of new PRRSV introductions in 20 filtered and 17 non-filtered control sow herds in a swine dense region of North America during a 7 year study period. Events of novel virus introduction were ascertained by objective phylogenetic analysis of PRRSV ORF5 gene sequences. Putative new viruses were defined as exogenous (introduced) based on ORF5 nucleotide sequence differences compared to previous farm isolates. The influence of sequence difference cut-off values ranging from 2 to 10% on case definition and relative risk were evaluated. Non-filtered farms incurred about 0.5 outbreaks per year, with a seasonal increase in risk in cooler periods. Baseline risk, prior to filtration, in treatment farms was about 0.75 per year, approximately 50% higher than in control farms. Air filtration significantly reduced risk of PRRSV introduction events to 0.22 to 0.06 outbreaks per year, depending on the percent difference cut-off value used to classify a virus isolate as new to the herd. Overall, air filtration led to an approximately 80% reduction in risk of introduction of novel PRRSV, indicating that on large sow farms with good biosecurity in swine-dense regions, approximately four-fifths of PRRSV outbreaks may be attributable to aerosol transmission.
2.2 Introduction

Despite diverse strategies to control Porcine Reproductive and Respiratory Syndrome virus (PRRSV), including gilt pool management or acclimation (Dee et al., 1995); vaccination programs (Cano et al., 2007); and “herd-closure” (Torremorell et al., 2003), the disease continues to cause tremendous losses in North America swine production (Neumann et al., 2005; Holtkamp et al., 2011).

Multiple routes of PRRSV transmission are well documented, including semen (Christopher-Hennings et al., 1995a), nasal secretions (Rossow et al., 1994), motor vehicles (Dee et al., 2004), insects (Otake et al., 2002; Otake et al., 2003), fomites such as needles and coveralls (Otake et al., 2002b; Otake et al., 2002c) and aerosols (Otake et al., 2002a; Pitkin et al., 2009b). In 2009 a series of field studies demonstrated a major role for bioaerosol transmission in the spread of PRRSV among farms and the potential for air filtration systems to protect herds at risk (Dee et al., 2010a).

Numerous North American sow farms subsequently implemented air filtration systems that showed a substantial reduction in the risk of PRRSV introduction (Dee et al., 2010; Spronk et al., 2010). Dee et al. (2012) recently reported that the odds for a new PRRSV infection in unfiltered breeding herds was eight times higher than the odds after filtration in a cohort of filtered farms (Dee et al., 2012). However, there is a need for better define a new introduction of a PRRSV strain during the surveillance process of these breeding herds; a need for a better analysis to quantify the effectiveness of air filtration systems due to their significant capital cost and the residual risk of failures leading to PRRS outbreaks on filtered farms. Virus introductions may occur due to
biosecurity breaches unrelated to air filtration, from aerosol introduction via non-filtered routes such as temporally inactive fans in negatively ventilated facilities (Alonso et al., 2012) or possible due to failure of filters themselves. We recently demonstrated experimentally that a minimum retrograde air velocity of 0.76 m/s was required to transfer PRRSV through an idle fan, and that some interventions now used on fans on commercial farms were not fully protective in preventing virus entry (Alonso et al., 2012).

The overall goal of air filtration technology is to prevent the transmission of PRRSV bioaerosols between swine farms. The objective of this study was to assess the impact of air filtration systems on the incidence of PRRSV events under commercial production conditions. A companion investment analysis addresses the economic outcomes of investment in air filtration on a subset of these sow farms.

2.3 Materials and methods

Study population

Thirty-seven volunteer single-site, farrow-to-wean herds located in the pig dense region of southern Minnesota and northern Iowa, USA were enrolled. Twenty farms were filtered ‘treatment’ farms and 17 non-filtered control farms and clients of three collaborating veterinary practices. The participating farms had a breeding inventory herd of at least 2,400 sows; a history of at least 3 PRRSV introductions within the 4 years prior to the study; 3 or more pig sites within a radius of 4.7 km; a standard biosecurity program validated by the herd veterinarians; computerized record-keeping;
and, for filtered farms, the implementation of an air filtration system operating throughout the year (Dee et al., 2010; Spronk et al., 2010; Dee et al., 2012).

All farms used negative pressure ventilation. Of filtered farms, 70% had the filters installed in the attic; 10% had the filters installed as panels or sidewalls for tunnel ventilation; and 20% had a combination of both systems. Ten of the filtered farms used mechanical filters constructed of ‘microfine’ glass fiber media (Camfill-Farr, Stockholm, Sweden) and the remainder used electrostatic filters constructed of a 100% synthetic media (Clarcor, Jeffersonville, In, USA). The electrostatic filters were all rated EU9 (MERV 16) while 40% of the mechanical filters were EU9 (MERV 16) and 60% were EU8 (MERV 14) (Dee et al., 2009). One farm had a combination of attic and sidewall filtration as well as a combination of both MERV 16 and MERV 14 mechanical filters, both of them previously determined to be 95% and 75% efficient, respectively, at capturing particles with diameters between 0.1 to 0.3 μm (Dee et al., 2009).

Study design

All farms were enrolled by February 2010, and farm was considered the unit of analysis for the study. Farms were classified as non-filtered control farms and filtered treatment farms. The study was observational, and the decision to implement air filtration was made by producers independently of the conduct of the study. Farm data were collected both retrospectively and prospectively until June 30, 2011. For non-filtered control farms, retrospective data were collected commencing on October 1,
2004. For filtered farms, retrospective data were collected commencing 4 years prior to the date of filtration for 16 farms, while the remaining 4 farms provided data for 2.7 to 3.7 years (mean = 3.2 years) of prefiltration data (Table 2.1).

Each farm received regular veterinary oversight from one of three specialist swine practices in Minnesota. During the first phase of the study until August 2008, PRRSV status of herds was monitored by the veterinary practice for each herd without standardization. From September 2008, monitoring was standardized and PCR testing of pools of serum from 30 piglets at weaning was performed monthly in addition to evaluation of clinical disease and production records, on all farms (Egli et al., 2001).

**Case definition**

A case, i.e. introduction of a new PRRSV isolate, was defined as the detection of a PRRSV isolate that was genetically distinct from isolates previously detected on the farm based on objective cut-offs of nucleotide sequence changes in viral RNA. The ORF5 genes of all PRRSV isolates were sequenced from PCR products at the Veterinary Diagnostic Laboratories of University of Minnesota or Iowa State University (Kapur et al., 1996). The DNAlasergene 9.0 software package was used to assemble contigs into consensus ORF5 sequences, perform the sequencing analysis, and generate dendrograms (phylogenetic trees, PT).

All farm dendrograms portrayed the results in the form of a tree with a scale of the total nucleotide substitutions (x100) (Fig. 2.1). More closely related isolates cluster
on peripheral branches (right hand side) of the trees. An event (i.e. introduction of new virus) was defined as the detection of a PRRSV isolate that differed in at least a specific percentage (2, 3, 5 or 10%) of nucleotides from sequences of all previous PRRSV isolates from the herd, as illustrated in Figure 2.1.

**Statistical analysis**

Data for all of the farm variables and PT event information was entered into Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and exported to SAS 9.1 (SAS Institute, Cary, North Carolina, USA) for descriptive statistics and statistical analysis. Means, standard deviations, minimum and maximum values for quantitative variables, and frequency counts and percentages for qualitative variables were calculated. The total number of introduction events, and number of pig locations within a 4.7 km radius, were compared between filtered and non-filtered farms using a t-test with an alpha value of $p \leq 0.05$.

Incidence rates (events per herd-month at risk) and confidence intervals were calculated using SAS software. Several comparisons of incidence between the filtered and unfiltered farms were made, with the analysis stratified into two phases of time being before (phase 1) and after (phase 2) August 15, 2008 - the date at which the first farm implemented filtration (Fig. 2.2). Thus incidence in non-filtered control farms was calculated in both the early and late phases (periods A and B) to assess if risk of events differed between phases (without filtration). Similarly, incidence in prefiltered farms
was compared in phase 1 (period C) and phase 2 (periods D – herd-months at risk before filtration) to further evaluate any temporal variation between phases. Incidence in filtered farms could only be estimated in phase 2 (period E – herd-months at risk after filtration). Comparison among periods was made using relative risks (incidence density ratios).

2.4 Results

The 37 study farms overall housed approximately 123,000 sows. The mean farm size was similar for both groups, at 3,220 (range 2,419 to 5,324) and 3,454 (range 2,402 to 5,578) sows for filtered and non-filtered farms, respectively (p=0.42). Filtered farms had a mean of 8.85 (range 4 – 17) surrounding pig finishing sites within 4.7 km compared to 7.41 (range 3 – 15) sites for non-filtered farms (p = 0.27). Filtered farms were not allocated randomly and the number of months at risk after filtration ranged from 5 months to 35 months. Among filtered farms, date of filter installation was not correlated with previous virus introduction risk (Spearman’s rank correlation, r = -0.08, p = 0.73).

During the 7 year study period, a total of 671 sequences were analyzed in the PTs. Non-filtered control farms had a total of 213 sequences (range 4 to 27 per farm) and filtered farms had 458 (range 2 to 55 per farm). The percent similarity of these sequences was compared with all previous viruses isolated on respective farms preceding and during the study period. A total of 100, 116, 126 or 139 new virus introductions were identified from the farm PTs using the four selected cut-offs (10%,
5%, 3% or 2% respectively) (Table 2.2). Figure 2.3 presents a time line of the PRRSV introduction events for each individual farm based on the 5% cut-off. A smoothed (5 month moving average) graph of incidence for all farms throughout the study showed a distinct pattern of seasonality (increase in cooler months) in the initial phase of the study, that was no longer clearly evident during the latter phase as treatment farms implemented filtration systems (Fig. 2.4).

Regardless of cut-off value, incidence of introduction events in non-filtered control farms did not differ significantly (95% CI of relative risk included the null value of 1.0) before or after August 15, 2008 (i.e. phase 1 vs phase 2), indicating equivalent risk over the course of the study (Table 2.3). Similarly, in filtered farms no difference was observed in incidence of new infections in phase 1 prior August 15, 2008 (Fig. 2.2, period C), and in the months at risk between August 15 and the date of filtration on the respective farms (Fig. 2.2, period D). Merging of the data from both groups of unfiltered farms (periods A and C vs periods B and D), to increase power, also indicated no significant difference in risk between phase 1 and phase 2 at any cut-off (relative risks ranged from 0.98 to 1.37). In contrast, all relative risks for non-filtered control farms vs. prefiltered treatment farms indicated a reduced risk of introduction events (approximately 30 to 50% lower) during both phase 1 (A vs. C) and phase 2 (B vs. D) of the study (Table 2.3). Merging the data from both phases yielded statistically significant (P < 0.05) and consistent estimates demonstrating lower incidence for control farms across all cut-offs (mean relative risk = 0.63; range 0.62 to 0.68). Collectively these data indicate relatively stable risk of PRRSV introduction events in unfiltered facilities over
the duration of the study (phase 1 vs. phase 2), but that risk prior to filtration of treatment farms was significantly and substantially higher than for the non-filtered control farms.

The incidence rate of new PRRSV introduction events in filtered farms in period E (0.6 to 2.2 events per 10 herd-years at risk depending on cut-off value, Table 2.2) was substantially lower than all incidence rates observed in control farms or prefiltered treatment farms in the other 4 periods analyzed (3.3 to 9.2 events per 10 herd-years at risk). For all possible comparisons with unfiltered farms (i.e. across study periods and cut-offs), 95% confidence intervals for relative risk estimates did not include 1, indicating significantly lower risk for farms that were filtered (Table 2.4).

Across all possible temporal and farm type comparisons, the point estimates for relative risk increased linearly and substantially with cut-off value (Table 2.4), ranging from 2.3 to 10. Based on our observation of similar exposure risk over time (Table 2.3), yet significantly different risk between control and prefiltered farms, we considered the most appropriate comparison for estimating the impact of filtration to be between the filtration period (period E) and the prefiltration periods of the same farms (periods C plus D). In this model, each farm serves as its own control. Paired comparison, at a 5% cut-off, of incidence rates of treatment farms before and after filtration indicated an absolute risk reduction of 0.6 introductions per year (p < 0.001, Wilcoxon sign rank test). If the control farms were used as the comparison group, relative risk estimates were lower than for historic controls, but we know these farms had significantly lower
baseline risk (mean RR of 0.63) and the resultant estimates would be expected to be biased towards the null (i.e. underestimating the effect of filtration).

2.5 Discussion

Installation of air filtration systems on large sow farms is an expensive intervention, involving initial capital costs of the order of $150 – 200 per sow (or approximately $450,000 to $600,000 for 3,000 sow-herds similar to those in the study (Reicks and Polson, 2011). The fact that installation of such systems is now common enough to enable this study reflects the major economic impact of PRRSV on swine production in the Midwestern USA. The overall findings from the study confirm that air filtration systems significantly reduce the frequency of introduction of novel PRRSV isolates into breeding farms. However, the study has some inherent methodological constraints that contribute uncertainty regarding the magnitude (absolute and relative reduction of risks) of the observed effects. These primarily relate to the selection of unfiltered comparison groups (i.e. contemporary non-filtered control farms vs. historical prefiltration data from the filtered farms), and the methodology used for case definition of new virus introductions.

While control and treatment farms were effectively matched for herd size and were in areas of dense hog production, farms that elected to implement air filtration were found to have a higher historic risk of PRRSV introduction than the non-filtered control farms. This is not unexpected, as motivation to invest in prevention is likely to be correlated with historic problems with disease. Although the number of surrounding
finishing sites was numerically (though not statistically) higher for treatment compared to control farms, this is only a crude proxy of likely geographic risk to PRRSV aerosol exposure, which would also be influenced by the size, proximity, pig-flow and sourcing of pigs in nearby herds, and likely terrain and vegetation. Difference in rigor or compliance of biosecurity protocols between the control and filtered farms could also contribute to the observed difference in baseline risk, but is considered less likely due to the relatively uniform veterinary oversight across the study farms. Because producers chose by convenience to implement filtration at different times, the contributions of herd-months at risk in the prefiltration (period CD) and particularly postfiltration periods (period E) varied considerably among treatment farms (e.g. 5 to 34 months-at-risk under filtration). However, because filtration date was not correlated with prefiltration incidence, this is not likely to be a substantial source of bias.

The case definition of new virus introductions is critical, but unresolved. Currently, ORF5 sequence analysis is the standard method used to differentiate a new viral introduction (exogenous) from a genetic variant of a previously identified farm isolate (endogenous). However, PRRS is an RNA virus that is among the most genetically labile virus (Murtaugh et al., 2010). ORF5 contains 603 nucleotides, thus 1% of sequence difference reflects mutation of 6 nucleotides. Clinically, discriminating between new introduction and ongoing evolution involves judgment regarding the extent of difference observed between isolates, the intensity of previous herd monitoring, the time interval between isolates detected in a herd, and increasingly information about PRRSV isolates found in neighboring farms. Nevertheless, a 2% or 3% ORF5 nucleotide
sequence difference is commonly used to classify PRRSV field isolates as different from a farm virus. Based on observed rates of sequence variation in experimental and field studies of 0.5-1% per year, it is probable that isolates of more than 2 or 3% difference represent a new introduction into herds that are routinely monitored for sequence variation (Yoon et al., 2001; Yuan et al., 2001; Chang et al., 2002; Murtaugh et al., 2003).

Recently in an initial study of a subset of farms used in this study, Dee et al. (2012) used an experimentally based rate of nucleotide change (> 0.5% per 367 days) to define new PRRSV introductions and estimated an approximately eight-fold reduction in odds of PRRSV introduction to filtered farms. The authors did not evaluate the sensitivity of the outcome to this assumption of the rate of viral changes in the population, which was derived from observations on viral passage in groups of three pigs (Chang et al., 2002). As population size is an important determinant of rate of viral change in populations (Duffy et al., 2008) the estimate obtained is arguably inappropriate for direct extrapolation to populations of thousands of animals. To address this concern, we examined the sensitivity of our analysis to evaluate the effect of using various sequence difference cut-offs on risk assessment. It is evident that misclassification of viral origin (i.e. endogenous vs. exogenous) can occur depending on the population of PRRSV in a local region, and the incomplete nature of sampling. For example, detection of isolates differing by just two nucleotides separated by a one week interval would typically be interpreted as endogenous origin. However, the possibility that both isolates derived from separate events of aerosol transmission from a neighboring herd cannot be definitively excluded. Similarly, a virus with 8% ORF
sequenced difference is much more likely to be exogenous, but might be observed if historic information was imperfect (i.e. not all PRRSV variants in the herd had been documented) or due to recombination events between existing viruses.

We observed an approximately 3-fold difference in relative risk of new virus introductions between the lowest and highest cut-offs of 2% and 10%. It was previously suggested that ORF 5 sequence changes greater than 1% be interpreted as “not closely related” PRRSV isolates (Yoon et al., 2001; Yuan et al., 2001). However, a less strict guideline that accounts for variation in time intervals between recovery of isolates being compared, variation in apparent rates of ORF5 change, and the importance of differentiating internal versus external biosecurity weaknesses may be more useful (Murtaugh and Faaberg, 2001). Assuming similar mutation rates and evolutionary pressures in filtered and unfiltered farms (particularly reasonable when using historic controls), misclassification of endogenous viral change to be exogenous introductions of novel viruses in both control and treatment groups would lead to underestimation of the filtration benefit and a broader confidence interval (Höfler, 2005). Thus, the largest confidence interval (2.3 to 38.8) was observed at the 10% cut off where the number of cases is lowest. Other than by random error, it is difficult to identify a scenario for differential misclassification rates (false negative or false positive) between the filtered and unfiltered farms. It is conceivable that more frequent virus introductions (detected or undetected) into a herd would increase the viral diversity in a population and hence the detection of more diverse endogenous isolates over time through recombination events. Thus observed evolution rate in a farm would not be independent of
introduction rates, and could lead to differential misclassification rates among filtered and unfiltered farms.

The seasonality observed, during phase 1 of the study, in the incidence of PRRSV introductions (with increased risk in late fall and winter) is consistent with clinical experience in the Midwest USA region. The apparent attenuation of the seasonal pattern in phase 2 of the study further suggests that much of the seasonal fluctuation in risk is related to aerosol transmission among herds, which is likely to be greatly influenced by climatic factors. However, it has been demonstrated that other potential routes of transmission for PRRSV are also facilitated at cooler temperatures (Dee et al., 2002).

The use of dendrograms in swine practices has become an important tool for veterinarians and producers to evaluate their biosecurity programs and strategies. The sensitivity of the conclusions reached to the cut-off selected for case definition reflects the uncertainties inherent in using sequencing data to differentiate events of virus introduction and evolution within herds (Murtaugh and Faaberg, 2001).

In summary, regardless of cut-off used to discriminate endogenous and exogenous outbreaks, our results support a previous evaluation of the efficacy of air filtration that used a different approach for case definition and reported greater risk reduction (Dee et al., 2012). We propose that the relative risks using cut-offs in the range of 3% to 5% provide the most reliable (though possibly conservative) estimates of the impact of air filtration on the risk of PRRSV introduction in the farms studied. Based on attributable fraction using this estimate, we infer that approximately 80% of new PRRSV
introductions into herds with good biosecurity in swine dense regions may be attributable to airborne risk. Thus, air filtration is a promising intervention that needs to be further evaluated in order to support the significant investment costs.
Table 2.1

Inclusion criteria, filtration date and time-line for all herds in the study.

<table>
<thead>
<tr>
<th>Farms</th>
<th>Treatment</th>
<th>Herd size</th>
<th>Sites &lt; 4.7km</th>
<th>Start Date</th>
<th>Filtration Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Control</td>
<td>2,874</td>
<td>4</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C2</td>
<td>Control</td>
<td>3,144</td>
<td>15</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C3</td>
<td>Control</td>
<td>3,310</td>
<td>5</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C4</td>
<td>Control</td>
<td>3,214</td>
<td>4</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C5</td>
<td>Control</td>
<td>3,090</td>
<td>4</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C6</td>
<td>Control</td>
<td>2,936</td>
<td>4</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C7</td>
<td>Control</td>
<td>4,916</td>
<td>5</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C8</td>
<td>Control</td>
<td>3,792</td>
<td>13</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C9</td>
<td>Control</td>
<td>3,570</td>
<td>13</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C10</td>
<td>Control</td>
<td>2,577</td>
<td>6</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C11</td>
<td>Control</td>
<td>2,993</td>
<td>9</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C12</td>
<td>Control</td>
<td>2,419</td>
<td>8</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C13</td>
<td>Control</td>
<td>5,324</td>
<td>4</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C14</td>
<td>Control</td>
<td>2,624</td>
<td>3</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C15</td>
<td>Control</td>
<td>2,505</td>
<td>3</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C16</td>
<td>Control</td>
<td>5,002</td>
<td>12</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C17</td>
<td>Control</td>
<td>4,602</td>
<td>14</td>
<td>1-Oct-04</td>
<td>NA</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T1</td>
<td>Filtered</td>
<td>2,556</td>
<td>9</td>
<td>1-Oct-04</td>
<td>15-Aug-08</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T2</td>
<td>Filtered</td>
<td>3,128</td>
<td>17</td>
<td>1-Oct-04</td>
<td>15-Sep-08</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T3</td>
<td>Filtered</td>
<td>3,827</td>
<td>9</td>
<td>1-Oct-04</td>
<td>15-Sep-08</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T5</td>
<td>Filtered</td>
<td>3,240</td>
<td>9</td>
<td>1-Oct-04</td>
<td>30-Sep-08</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T6</td>
<td>Filtered</td>
<td>2,402</td>
<td>4</td>
<td>1-Oct-04</td>
<td>15-Nov-08</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T7</td>
<td>Filtered</td>
<td>3,553</td>
<td>11</td>
<td>16-Apr-05</td>
<td>15-Apr-09</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T8</td>
<td>Filtered</td>
<td>2,406</td>
<td>7</td>
<td>1-Oct-06</td>
<td>30-Aug-09</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T9</td>
<td>Filtered</td>
<td>2,540</td>
<td>8</td>
<td>10-Jan-04</td>
<td>30-Sep-09</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T4</td>
<td>Filtered</td>
<td>3,296</td>
<td>5</td>
<td>1-Oct-05</td>
<td>30-Sep-09</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T10</td>
<td>Filtered</td>
<td>3,210</td>
<td>10</td>
<td>30-Oct-05</td>
<td>29-Oct-09</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T11</td>
<td>Filtered</td>
<td>2,422</td>
<td>5</td>
<td>27-Jan-06</td>
<td>26-Jan-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T12</td>
<td>Filtered</td>
<td>2,613</td>
<td>14</td>
<td>1-Jan-06</td>
<td>15-Feb-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T13</td>
<td>Filtered</td>
<td>5,216</td>
<td>4</td>
<td>1-Jul-06</td>
<td>1-Jun-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T14</td>
<td>Filtered</td>
<td>3,669</td>
<td>8</td>
<td>1-Oct-06</td>
<td>1-Oct-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T15</td>
<td>Filtered</td>
<td>2,506</td>
<td>13</td>
<td>1-Oct-06</td>
<td>1-Oct-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T16</td>
<td>Filtered</td>
<td>2,610</td>
<td>6</td>
<td>1-Oct-06</td>
<td>1-Oct-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T17</td>
<td>Filtered</td>
<td>5,578</td>
<td>10</td>
<td>2-Nov-06</td>
<td>1-Nov-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T18</td>
<td>Filtered</td>
<td>2,795</td>
<td>11</td>
<td>2-Nov-06</td>
<td>1-Nov-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T19</td>
<td>Filtered</td>
<td>3,680</td>
<td>5</td>
<td>15-Dec-06</td>
<td>15-Dec-10</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T20</td>
<td>Filtered</td>
<td>3,155</td>
<td>12</td>
<td>1-Jan-07</td>
<td>1-Jan-11</td>
<td>30-Jun-11</td>
</tr>
</tbody>
</table>

NA- not applicable
Table 2.2

Farm-years at risk, annual incidence rates (IR) and 95% CI for each of the periods (A, B, C, D, E) defined by study phase (1 - before filtration initiated; 2 – after first farm filtered) and farm type (non-filtered control farms; filtered farms pre- and post-filtration).

<table>
<thead>
<tr>
<th>Period</th>
<th>Study phase</th>
<th>Non-filtered</th>
<th>Pre-filtered</th>
<th>Filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd-years at risk</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cut-off*</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>PRRSV events</td>
<td>72.3</td>
<td>48.9</td>
<td>57.3</td>
<td>26.0</td>
</tr>
<tr>
<td>IR</td>
<td>0.54</td>
<td>0.51</td>
<td>0.75</td>
<td>0.92</td>
</tr>
<tr>
<td>95%CI</td>
<td>(0.39, 0.73)</td>
<td>(0.35, 0.76)</td>
<td>(0.56, 1.01)</td>
<td>(0.62, 1.38)</td>
</tr>
<tr>
<td>PRRSV events</td>
<td>39</td>
<td>25</td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td>IR</td>
<td>0.49</td>
<td>0.43</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>95%CI</td>
<td>(0.35, 0.67)</td>
<td>(0.31, 0.71)</td>
<td>(0.57, 1.03)</td>
<td>(0.56, 1.28)</td>
</tr>
<tr>
<td>PRRSV events</td>
<td>34</td>
<td>18</td>
<td>41</td>
<td>19</td>
</tr>
<tr>
<td>IR</td>
<td>0.47</td>
<td>0.37</td>
<td>0.71</td>
<td>0.73</td>
</tr>
<tr>
<td>95%CI</td>
<td>(0.34, 0.66)</td>
<td>(0.23, 0.58)</td>
<td>(0.53, 0.97)</td>
<td>(0.47, 1.14)</td>
</tr>
<tr>
<td>PRRSV events</td>
<td>32</td>
<td>16</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>IR</td>
<td>0.44</td>
<td>0.33</td>
<td>0.65</td>
<td>0.50</td>
</tr>
<tr>
<td>95%CI</td>
<td>(0.31, 0.63)</td>
<td>(0.2, 0.53)</td>
<td>(0.47, 0.89)</td>
<td>(0.29, 0.86)</td>
</tr>
</tbody>
</table>

* Cut-off = % heterology used to classify a virus isolate as novel to a herd
Table 2.3

Relative risks (95% CI) of new PRRS virus introductions in unfiltered farms between phases of the study and control (non-filtered) and treatment (prefiltered) farms.

<table>
<thead>
<tr>
<th></th>
<th>A vs B</th>
<th>C vs D</th>
<th>A vs C</th>
<th>B vs D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>1.06 (0.64, 1.74)</td>
<td>0.81 (0.51, 1.37)</td>
<td>0.72 (0.46, 1.08)</td>
<td>0.55 (0.32, 0.97)*</td>
</tr>
<tr>
<td>3%</td>
<td>1.14 (0.63, 1.79)</td>
<td>0.88 (0.53, 1.48)</td>
<td>0.65 (0.42, 1.03)</td>
<td>0.51 (0.31, 1.01)</td>
</tr>
<tr>
<td>5%</td>
<td>1.27 (0.72, 2.26)</td>
<td>0.97 (0.57, 1.69)</td>
<td>0.66 (0.42, 1.04)</td>
<td>0.51 (0.26, 0.96)*</td>
</tr>
<tr>
<td>10%</td>
<td>1.33 (0.74, 2.46)</td>
<td>1.29 (0.69, 2.43)</td>
<td>0.68 (0.43, 1.1)</td>
<td>0.66 (0.31, 1.36)</td>
</tr>
</tbody>
</table>

* Confidence interval does not include 1
Table 2.4.

Relative risks (95% CI) of new PRRS virus introductions in non-filtered control (A, B) and prefiltered treatment (C, D) farms compared with filtered farms (period E – reference group).

<table>
<thead>
<tr>
<th></th>
<th>B vs E</th>
<th>D vs E</th>
<th>CD vs E</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>2.32 (0.99, 5.32)</td>
<td>4.18 (1.79, 9.6)*</td>
<td>3.71 (1.69, 8.0)*</td>
</tr>
<tr>
<td>3%</td>
<td>2.69 (1.13, 7.79)*</td>
<td>5.31 (2.02, 14.08)*</td>
<td>4.87 (1.98, 12.21)*</td>
</tr>
<tr>
<td>5%</td>
<td>2.85 (1.02, 8.56)*</td>
<td>5.61 (1.96, 16.92)*</td>
<td>5.54 (2.06, 15.6)*</td>
</tr>
<tr>
<td>10%</td>
<td>5.50 (1.18, 22.41)*</td>
<td>8.33 (1.78, 34.9)*</td>
<td>10.00 (2.3, 38.85)*</td>
</tr>
</tbody>
</table>

* Confidence interval does not include 1
Figure 2.1

Example of case definition using a phylogenetic tree analyzed at 4 different cut-offs. This sample shows that often sequences will be part of one or other cluster depending on the cut-off utilized. In this example, the analysis would identify 7 new PRRSV virus introductions at the 2% and 3% cut-offs, 5 at 5% cut-off and 3 new introductions at the 10% cut-off.
Figure 2.2

Three month periods at risk for incidence comparison (vertical columns). Each horizontal line represents a farm in the study, continuous and dashed lines un-filtered and filtered periods, respectively. A and B areas represent time at risk for non-filtered control farms before (phase 1) and after (phase 2) the first farm was filtered. Period C indicates the time at risk for treatment farms before (phase 1) the first farm was filtered. Periods D and E indicate the times at risk in phase 2 before (D) and after (E) filtration events for each filtered farm.
Figure 2.3

PRRSV event distribution timeline by farm for filtered and non-filtered periods. Total number of events analyzed by the 5% cut-off of heterology between clusters. Each horizontal line represents the time-line of a farm in the study. Black and red colors represent un-filtered and filtered periods, respectively, and each dot is one, two, or three independent outbreaks (events) during the three month period, depending on the color as indicated.

![Timeline](image-url)
Figure 2.4

Smoothed PRRSV event incidence (5 month moving average) during the study period analyzed by the 5% cut-off of difference between strains of different clusters for all farms (arrow indicates date of first farm filtration).
CHAPTER 3:

ECONOMIC STUDY OF AIR FILTRATION SYSTEMS FOR PREVENTING PRRVS INFECTIONS

IN LARGE SOW HERDS
3.1 Chapter summary

Air filtration systems implemented in large sow herds have been demonstrated to decrease the probability of having a porcine reproductive and respiratory syndrome virus (PRRSV) outbreak. However, implementation of air filtration represents a considerable capital investment, and does not eliminate the risk of new virus introductions. The specific objectives of the study were: 1) to determine productivity differences between a cohort of filtered and non-filtered sow farms; and 2) to employ those productivity differences to model the profitability of filtration system investments in a hypothetical 3,000 sow farm. Variables included in the study were quarterly production data from respective herds; air filtration status; number of pig within 4.7 km of the farm; occurrence of a PRRSV outbreak in a quarter, and season. For the investment analyses, three scenarios were compared in a deterministic spreadsheet model of weaned pig cost: 1) control, 2) filtered conventional attic, and 3) filtered tunnel ventilation. Model outputs indicated that a filtered farm produced 5,927 more pigs per year than unfiltered farms. The payback period for the investment, excluding consideration of differential value of PRRSV negative weaned pigs, was estimated to be 5.35 years for scenario 2 and 7.13 years for scenario 3. A differential of $5 in the weaned pig sales price depending on PRRSV status and the % of time that these farms will be producing PRRSV negative pigs, reduced the estimated payback period to 2.1 years for scenario 2 and 2.8 years for scenario 3.
3.2 Introduction

Porcine reproductive and respiratory syndrome virus (PRRSV) infection was first recognized as a novel disease causing reproductive and respiratory disease in U.S swine in the late 1980’s (Keffaber, 1998). Soon thereafter outbreaks of a similar syndrome also occurred in Europe (Wensvoort et al., 1991), and two distinct genotypes of the PRRSV were subsequently identified from these early North American and European cases (Murtaugh et al., 2010). Subsequently PRRSV emerged to be a major pandemic swine disease, now universally regarded as the most significant health problem in the US swine industry (Neumann et al., 2005; Holtkamp et al., 2011). A member of the Arteriviridae, PRRSV is an RNA virus with remarkable capacity for genetic change via recombination and mutation, which has contributed greatly to the difficulty experienced in controlling the disease (Murtaugh et al., 1995; Kapur et al., 1996). PRRSV has diverse clinical manifestations in both breeding and growing pigs and can cause dramatic production losses due to reproductive failure (particularly abortions in late gestation), increases in the number of weak live-borne pigs and preweaning mortality, severe pneumonia in neonatal and nursery piglets, reductions in growth performance and increased rates of mortality and culled pigs (Zimmerman et al., 2012).

The economic impact of an acute outbreak of PRRSV was estimated to be at $255/sow in breeding herds and between $6.25 and $15.25/pig in the growing phase (Holck and Polson, 2003). However, the economic impact of PRRSV is not confined to the acute phase of the initial outbreak. Prolonged losses can occur due to both diminished reproductive and growing pig performance. Neumann, et al. (2005)
estimated the annual economic impact of PRRS for U.S. pork production to be $560 million in 2005, with 45% of losses due to a decline in the average daily gain and feed efficiency in growing pigs; 43% due to mortality in growing pigs, and 12% attributed to reproductive losses (Neumann et al., 2005). A more recent study incorporating updated estimates of disease prevalence and apparently more virulent new PRRSV strains estimated the annual cost to be $664 million (approximately 20% higher than the 2005 estimate), and attributed 55% of losses to effects on growing pigs (Holtkamp et al., 2011). Producers have made substantial investments across diverse strategies to control PRRS, including gilt pool management or acclimation (Dee et al., 1995); vaccination programs (Cano et al., 2007); biosecurity interventions including transport and insect control (Otake et al., 2002; Dee et al., 2004), and “herd closure” (Torremorell et al., 2003). As management and biosecurity procedures evolved to address the multiple routes of PRRSV transmission, it has become apparent that much of the residual risk of infection in hog dense regions is associated with airborne transmission (Alonso et al., 2012 submitted).

Both field and experimental studies support the likely importance of aerosol transmission of PRRS and the potential for air filtration systems to reduce the risk of new virus introductions (Dee et al., 2010; Spronk et al., 2010; Dee et al., 2012; Alonso et al., 2012 submitted). In the US Midwest, numerous sow farms have implemented air filtration systems in swine dense areas (Dee et al., 2010; Spronk et al., 2010). The aim of the present study was to assess actual production data in filtered and non-filtered farms to determine potential productivity differences, and use observed differences to model
the economic impact of two options for filtration interventions using a partial budget analysis.

3.3 Materials and methods

Description of the study population

Production and descriptive data were collected retrospectively from 21 volunteer single-site farrow-to-wean herds already enrolled in an epidemiologic study for evaluating the efficacy of filtration systems in large sow herds (Alonso et al., 2012 submitted). The group of farms consisted of a voluntary sub-group from the previous study of 13 filtered ‘treatment’ farms and 8 non-filtered ‘control’ farms that were clients of three collaborating veterinary practices. All farms were located in the pig dense region of southern Minnesota and northern Iowa, USA; had a complete sow inventory that was in full production (i.e. weaning had started); and met specific inclusion criteria described elsewhere (Alonso et al., 2012 submitted).

Study design

All farms were selected for the study by February 2010. The specific production variables for the economic analysis were collected retrospectively at the end of the study period (i.e. June 30, 2011). As previously published, there were different data starting points depending on farm type. Quarterly data for all non-filtered control farms where obtained from October 1, 2004 (period 1) with the exception of 2 farms which started July 2005 (period 4) due to some instability in the sow herd inventory.
filtered farms, the goal was to obtain production data from 4 years prior to the date of filtration up until June 30, 2010. This was achieved for 10 filtered farms, with the remaining 3 farms providing a mean of 3.5 years (range from 3.17 to 3.87) of pre-filtration data (Table 3.1).

For the production analysis, the following information was required from each farm: 1) quarterly production data; 2) the quarterly total of new PRRSV isolates per site as represented in farm level phylogenetic trees (PT) under a cut-off equal to or greater than 5% (Alonso et al., 2012 submitted); and 3) the number of pig production sites within 4.8 km (3 miles) of the farm. These data were obtained from 27 quarterly periods (81 months, Table 3.1). Based on this information, the production of a modeled filtered and non-filtered farm was defined after adjusting each dependent variable on different independent explanatory variables. The selected independent variables were considered to significantly influence overall production results.

These results from the production analysis were used as inputs for a spreadsheet model to calculate weaned pig cost for three investment scenarios (Lazarus, 2009). The analyses were based on a representative 3,000 sow herd with a feed cost of $278/sow/year (Center for Farm Financial Management, University of Minnesota., 2012). The scenarios included: 1) control non-filtered farm, 2) conventional filtration based on attic ventilation (Figure 3.1a), and 3) a combination of attic and horizontal filtered panels in tunnel ventilation (Figure 3.1b). The model information for scenarios 2 and 3 included the pre-filters and filter cost. They were identical with the exception of initial filter installation and equipment costs which were $150/sow (attic only) and
$200/sow (tunnel ventilation) respectively (Reicks and Polson, 2011). Filtration was assumed to impact veterinary expenses, and cost estimates included the annualized cost of replacing both pre-filters (every six months) and filters (every 3 years).

**Production data and weather variables**

All participating herds were willing to share production data and used similar computerized record software (PigCHAMP 1996 or PigCHAMP Care 2010). Producers were requested to send quarterly production data reports, in EXCEL format, for the entire study period (Table 3.1). The production data extracted from each farm’s records included farrowing rate, piglets weaned per litter, piglets weaned per sow per year (PSY), female replacement rate and female death rate. These production data variables, averaged over the entire study period for both groups of farms, were similar for the production variables analyzed (range p = 0.22 to p = 0.99).

Risk of introduction of PRRSV appears to vary seasonally in the US Midwest (higher in cooler weather) and many production variables are also influenced by season (Xue et al., 1994). A dichotomous variable was used to adjust for the potential influence of cooler weather during winter quarters (October – December; January – March) compared to the warmer quarters (April through September).

**Statistical analysis**

Data for all farms and quarters were consolidated in an Excel spreadsheet (Microsoft EXCEL; Microsoft Corporation, Redmond, Washington, USA) and included
production data variables [farrowing rate (%), pigs weaned per litter, pigs weaned per sow per year, sow mortality (%) and sow culling rate (%)], the occurrence of a new PRRSV sequence introduction in a quarter, and the number of pig sites surrounding each sow farm. The data were exported to SAS 9.1 (SAS Institute, Cary, North Carolina, USA) and descriptive statistics were derived using the MEANS procedure. The MIXED model procedure, based on repeated measures by farm, was performed to compare production variables at baseline (before or without filtration) between control farms and pre-filtered farm periods. For variables with no significant differences, control and pre-filtered periods were merged together for comparison with filtered period data.

Linear regression on previous repeated measure analysis (MIXED procedure) for each production variable was conducted. Effects of ‘filtration’ (non-filtered versus filtered farm periods), number of pig sites within 4.7 km (‘sites’), the presence of a new PRRSV sequence in the period (‘outbreak’), and quarterly season information (‘winter quarters’) were analyzed with univariate models for each production variable (farrowing rate, pigs weaned per litter, pigs weaned per sow per year, sow mortality and sow culling rate).

Multivariate models for respective production variables were then developed using backward elimination of variables and interactions that were not statistically significant (p > 0.05), starting from the full model (all explanatory variables included).
**Investment analysis**

For the investment analysis, outcomes from the multivariate models for production variables were used as inputs for the PigNet swine enterprise budget (version 2) partial budget model (Lazarus, 2009) to determine the cost of production of a weaned pig based on a 3,000 filtered and non-filtered model sow farm. Table 3.2 specifies the data sources and values used for the investment analysis. Payback periods were estimated for both filtration systems based on two scenarios. The first scenario evaluates only the observed impact on the breeding herd assuming no difference in weaned pig selling price between groups of weaned pigs that are positive or negative for PRRSV. However, given that most of the financial benefit of PRRS control may be attributed to improved growing pig performance, we also evaluated the sensitivity of calculated payback periods to differential weaned pig selling price of PRRSV negative weaned pigs. Based on the differential frequency of PRRSV introduction in the herds (16.8 months vs. 94.8 months; Alonso et al., 2012 submitted), and an expected period of 7 months producing PRRSV positive weaned pigs after an outbreak as determined by the recent review by Linhares and others (2012). In this study, Linhares completed the surveillance of 30 farrow-to-wean breeding herds that had experienced a PRRSV outbreak and had closed the herd to new replacements for a minimum of 180 days. The surveillance determined the ‘time to negative’ or the mean time to produce negative weaned pigs was 6.7 months (Linhares et al., 2012a). Based on this data, it was calculated that over the long term, filtered farms could expect to produce negative PRRSV weaned pigs 92.6% of the time \([(16.8-7)/16.8]\), and unfiltered farms 58.3% of the
time [(94.8-7)/94.8]. This ratio was used to determine payback periods based on a price premium that ranged from $1 to $10 for the production of PRRSV negative pigs after completing a survey of large swine producers in Minnesota regarding the reasonable range in weaned pig selling price for producing negative versus positive weaned pigs in the state of Minnesota.

### 3.4 Results

The study involved analysis of quarterly production data across 21 farms over a period of almost seven years. Control farms were followed for a mean of 6.56 years (range from 6 to 6.75) and filtered farms for a mean of 5.63 (range from 4.75 to 6.75). Filtered farms had a mean of 3.93 years of pre-filtered data and 1.71 years of post-filtered data. The 21 farms in the study housed a total of 66,000 sows. Both groups of farms were of similar size (p = 0.48), with control sow farms housing a mean of 3,259 sows (range from 2,410 to 5,324) and filtered farms housing 3,254 (range from 2,402 to 5,216). The number of pig sites within 4.7 km of the farms did not differ between the groups [control 6.9 (range 3 to 13); filtered 8.9 (range 4 to 17) p = 0.48]. Comparison of baseline data from the pre-filtered and control farms showed no significant differences for all the parameters analyzed other than a small difference in pigs weaned per sow per year (p = 0.04) (Table 3.3).
Regression analysis

Results from Table 3.4 shows the coefficients for the respective variables for the univariate models comparing non-filtered farms (control and pre-filtered merged data ‘filtration’ = 0) and filtered farms (‘filtration = 1’). The number of sites surrounding the farm (i.e. ‘sites’) was not a statistically significant risk factor for any of the production variables studied. In contrast, the ‘occurrence of a PRRSV introduction’ and ‘filtration effect’ were significantly associated with the changes in all dependent variables or production variables studied. ‘Filtration’ had the largest effect on farrowing rate, with 4% higher farrowing rate in filtered when compared with non-filtered farms.

Results from the multivariate model are shown in Table 3.5. ‘Sites’ was excluded from the models (not significant). ‘Outbreak’ was also excluded from the model due as it was arguably confounded with filtration or an intermediate variable (that is, the putative mechanism for the filtration effect is through reduction of the risk of outbreaks). The final models therefore included ‘filtration’ (variable of interest), and ‘winter_quarters’ (to adjust for seasonal fluctuations) and their interactions. The models indicated that filtered farms, when considering outbreak periods and time periods between outbreaks, had an absolute improvement in farrowing rate of 3.99%, 1.9 piglets more weaned per sow per year and an absolute decrease of 2.35% in the sow mortality rate. No interactions were statistically significant and ‘winter_quarters’ was not a significant factor influencing culling rate or mortality rate.
Profitability analysis

The hypothetical, filtered 3,000-sow farm producing at the levels listed in Table 3.3 produces 76,890 pigs weaned per year; a total of 5,927 pigs more per year than the hypothetical non-filtered farm. At a weaned-pig price of $39.32, the additional pigs would increase this farm’s net return to the facility investment, management and risk by $113,625/year after covering operating costs.

A conventional attic filtration system would cost $150/sow or $450,000 total to install (scenario 2), so the simple payback period (non-discounted) for this investment was calculated to be 5.35 years (Olson, 2010b). For a filtered farm model with a combination of attic and sidewall filtration systems costing $200 per sow or $600,000 total to install (scenario 3), the simple payback period increased to 7.13 years.

Producing PRRSV positive pigs and moving them to the next production phases, could be an important disadvantage that needed to be accounted for. Assuming a difference in weaned pig selling price of $5 dollars per pig for farms producing PRRSV negative or positive weaned pigs, and the proportion of time that filtered and unfiltered farms were predicted to produce negative PRRSV weaned pigs (given inter-outbreak intervals of 16.8 months in non-filtered facilities vs. 94.8 months in filtered farms), the mean difference in pig value between these farms over a year period was estimated to be $1.7. These estimations decreased the calculated payback period of these investments to 2.1 years for attic only filtered farms and 2.8 years for the combination of an attic and tunnel filtered ventilated facility. Figure 3.2 represents the sensitivity analysis of the payback period for both filtration systems, from $1 to $10 premium for
producing PRRSV negative pigs in non-filtered farms, after the adjustment of these assumptions across this of price differences.

3.5 Discussion

The concept that air filtration could prevent airborne pathogen transmission to animals raised commercially in confinement was demonstrated 40 years ago with Marek's disease in poultry (Burmester and Witter, 1972; Grunder et al., 1975). The probable importance of aerosol transmission of PRRSV was immediately recognized during the initial European PRRSV epidemic 20 years ago (Desrosiers, 2004), yet steps to directly address this mode of transmission in North America have only been initiated relatively recently (Reicks, 2008). Although initial observations on reducing the risk of PRRSV introduction on swine farms have been encouraging (Dee et al., 2012; Alonso et al., 2012 submitted), the substantial capital costs involved in retrofitting farms with air filtration systems are daunting to many producers.

Unlike the poultry industry, studies of the financial impacts of biosecurity interventions in swine production are uncommon in the literature (Gifford et al., 1987; Fasina et al., 2012; Siekkinen et al., 2012). Partial budget analysis allows us to estimate the financial consequences of a biosecurity intervention considering only the income and costs that are likely to be influenced by this intervention. Partial budgeting is a relatively simple process that is easily applied for field situations. Although costs of interventions can often be determined with reasonable certainty, quantifying expected financial benefits accruing from the investment can be challenging. Previous analyses of
investment in air filtration for controlling PRRSV have been based on predictions of economic impact derived from reduced risk of outbreaks (Reicks and Polson, 2011). The current study represents the first attempt to assess return on investment in filtration technologies derived from actual production data recorded on filtered and unfiltered farms.

The inherent trade-offs between investment cost and feasibility of filtration on one hand, and risk reduction and expected economic benefits on the other, are not yet well characterized. For all applications of air filtration, optimizing the balance between costs and effectiveness of filtration alternatives (e.g. high cost high-efficiency particulate air (HEPA) filters versus less expensive filters) is an important considerations (Kowalski et al., 2002). It should be noted, that even in animal laboratory facilities where substantial investment is justifiable, absolute risk abatement (“zero risk”) cannot be guaranteed and complementary disinfection technologies may be incorporated (Kowalski et al., 2002). Early studies using an experimental model reported that HEPA filtration completely prevented PRRSV transmission, and that lesser reduction in transmission was achieved with a cheaper filtration option comprising a mosquito netting prefilter, a fiberglass furnace filter, and an electrostatic furnace filter (Dee et al., 2005; Dee et al., 2006).

HEPA filtration is the ‘gold standard’ intervention, pragmatic concerns of cost and feasibility in commercial production prompted evaluation of less expensive filtration options in experimental chambers using experimentally generated PRRSV aerosols (Dee et al., 2009). HEPA filtration was the only intervention that completely prevented
transmission, but reductions in transmission were also achieved with lower cost filters with minimum efficiency reporting values (MERV) of 14 and 15. Extension of these studies, in controlled field models incorporating MERV 4 fiberglass pre-filters and MERV 16 (Pitkin et al., 2009b), or MERV 14 (Dee et al., 2010b) filters, suggested reasonable efficacy of these lower cost filters in negatively ventilated facilities, supporting the ongoing adoption of these approaches in the swine industry (Reicks, 2009).

Overall, air filtration in this population of commercial farms was associated with measurably improved productivity for several variables which translated to estimated payback periods of the order of 5 to 7 years based on sow herd productivity alone. Improvement in the production performance of a filtered farm was also reported by Joyce (2011), including estimated improvements of 1.8 pigs weaned per sow per year, 7.7% in farrowing rate and a reduction of 5.8% in the sow mortality rate (Joyce, 2011). These observations support our more extensive data across 21 farms over 6.7 years, and in both studies farrowing rate was the variable most impacted. Polson et al. (1992) described an outbreak that was 4 months in duration in a 250-sow herd in Minnesota. This experienced a reduction of 3.8 piglets weaned per sow per year during the year of the outbreak. In our study, there was an observed reduction of 1.9 piglets weaned per sow per year in non-filtered control farms when compared to filtered farms using quarterly data from periods with and without outbreaks. Using the losses experienced in the single herd study as a baseline helps to put the comparative losses in our study into perspective (Polson et al., 1992). However, given that much of the economic impact of PRRSV is attributed to sub-optimal performance in growing pigs (Neumann et al., 2005;
Holtkamp et al., 2011) any evaluation limited to breeding herd performance will be highly conservative.

Much shorter payback periods of the order of 2 to 3 years were calculated when downstream benefits of weaning PRRS negative pigs were incorporated. However, unlike the breeding herds, adequate performance data were not available to directly estimate the anticipated “downstream” financial benefits (meaning benefits resulting from improved performance of growing pigs) accruing from filtered breeding populations. All sow farms in the study were “farrow to wean” herds, meaning that pigs were transferred to other sites after weaning. In some cases, ownership of pigs was retained (meaning that the sow farm owner would capture the benefits of better performance of growing pigs). On other farms weaned pigs were sold to other parties and the sow farm owner would not be financially rewarded for better performance of healthier growing pigs, unless receiving a premium price based on superior health status of the weaned pigs.

Our approach to incorporating growing pig benefits was based on the assumption that in a rational market a premium would be available for producing pigs of higher health status due to expectations of superior performance. Firstly, we contacted some large swine producers in Minnesota and were given the opinion that a premium of the order of $5 to $10 per pig would be a reasonable differential price for production of PRRS negative pigs in this state. For this reason we used a premium of $10 as the upper limit of the sensitivity analysis. Secondly, because PRRSV introductions still occurred in filtered farms, albeit at reduced frequency, the downstream financial benefits derived
from filtration are a function of the relative proportions of groups of PRRSV negative pigs weaned from filtered and unfiltered farms. Assuming that herds implemented herd closure methods to eliminate PRRSV following an outbreak (Schaefer and Morrison, 2007), a lag period of 7 months after an outbreak before PRRSV negative pigs would be weaned was assumed for all herds (Meier et al., 2000). Based on the difference in frequency of PRRSV outbreaks observed on these farms (Alonso et al., 2012 submitted) we estimated that over the long term 93% of weaned pig groups from filtered farms would be PRRSV negative, compared with 59% of groups from unfiltered farms. It was observed that payment of even modest premiums for PRRSV negative weaned pigs had substantial impact on reducing the estimated payback periods (Figure 3.2).

Some caveats should be noted with respect to our estimates of payback period, and the inferences that may be drawn from them. The study is observational rather than experimental, and the potential for confounding by other factors influencing production performance needs to be recognized. Our choice to aggregate the data into quarters was arbitrary, and the influence that this may have had is unknown. Over the course of approximately 7 years of data, many other factors are likely to have influenced production in these herds, and the only factors we examined were time of year, the occurrence of a PRRSV outbreak (both significantly associated with performance variables), and surrounding pig farm density (no significance impact, though all were in high density areas). Quarterly information may fail to detect variability due to PRRSV or other factors that are short term or spread across quarters (i.e. different diseases, inventory changes or management changes). The changes in productivity are therefore
relatively crude, and represent the changes observed in the study herds under their particular circumstances regarding the severity of the PRRSV outbreaks occurring, and any other unmeasured factors. Arguably the biggest caveat to extrapolation of these findings relates to the level of baseline PRRS risk. Study herds were selected based on location in hog dense areas and a history of multiple PRRSV outbreaks (i.e. high risk scenario for area transmission of PRRSV) and with an established biosecurity program to prevent other routes of disease introduction (i.e. low risk for non-airborne transmission). The estimates of payback period are not relevant to operations with much lower baseline risk of PRRSV introduction. Also, our period of observation of filtered farms was relatively short, and PRRSV risk (and therefore failure rate for filtered farms) may vary considerably between years.

In conclusion, our analysis of recorded production performance of large sow farms at high risk of PRRSV introduction yielded estimates of payback period that support the intervention of air filtration as a pragmatic biosecurity intervention for large sow farms in hog dense areas on the US Midwest. While the payback periods (5 to 7 years) estimated purely on breeding herd performance may be unattractive to many farmers, modest premiums from production of PRRSV negative pigs markedly reduced the estimated payback period.
Table 3.1

Inclusion criteria summary of farms in the study. Farm size, number of periods with at least one PRRSV isolate in the phylogenetic trees, filtration dates and total of quarterly periods analyzed for all herds in the study.

<table>
<thead>
<tr>
<th>Farms</th>
<th>Treatment</th>
<th>Herd size</th>
<th>Sites &lt; 4.7 km</th>
<th>PRRSV periods</th>
<th>Starting Date</th>
<th>Staring Period</th>
<th>Filtration Date</th>
<th>Total Periods</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Control</td>
<td>3,652</td>
<td>5</td>
<td>4</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C2</td>
<td>Control</td>
<td>5,324</td>
<td>4</td>
<td>1</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C3</td>
<td>Control</td>
<td>2,505</td>
<td>3</td>
<td>2</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C4</td>
<td>Control</td>
<td>2,410</td>
<td>8</td>
<td>2</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C5</td>
<td>Control</td>
<td>2,419</td>
<td>6</td>
<td>2</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C6</td>
<td>Control</td>
<td>2,397</td>
<td>3</td>
<td>2</td>
<td>1-Oct-04</td>
<td>1</td>
<td>NA</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C7</td>
<td>Control</td>
<td>3,570</td>
<td>13</td>
<td>4</td>
<td>1-Jul-05</td>
<td>4</td>
<td>NA</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>C8</td>
<td>Control</td>
<td>3,792</td>
<td>13</td>
<td>3</td>
<td>1-Jul-05</td>
<td>4</td>
<td>NA</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T1</td>
<td>Filtered</td>
<td>2,556</td>
<td>9</td>
<td>3</td>
<td>1-Oct-04</td>
<td>1</td>
<td>15-Aug-08</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T2</td>
<td>Filtered</td>
<td>3,128</td>
<td>17</td>
<td>6</td>
<td>1-Oct-04</td>
<td>1</td>
<td>15-Sep-08</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T3</td>
<td>Filtered</td>
<td>2,402</td>
<td>4</td>
<td>2</td>
<td>1-Oct-04</td>
<td>1</td>
<td>15-Nov-08</td>
<td>27</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T4</td>
<td>Filtered</td>
<td>3,553</td>
<td>11</td>
<td>5</td>
<td>1-Oct-05</td>
<td>5</td>
<td>15-Apr-09</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T5</td>
<td>Filtered</td>
<td>2,406</td>
<td>7</td>
<td>3</td>
<td>1-Jul-06</td>
<td>8</td>
<td>30-Aug-09</td>
<td>20</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T6</td>
<td>Filtered</td>
<td>3,296</td>
<td>5</td>
<td>4</td>
<td>1-Oct-05</td>
<td>5</td>
<td>30-Sep-09</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T7</td>
<td>Filtered</td>
<td>2,540</td>
<td>8</td>
<td>2</td>
<td>1-Oct-05</td>
<td>5</td>
<td>30-Sep-09</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T8</td>
<td>Filtered</td>
<td>3,210</td>
<td>10</td>
<td>3</td>
<td>1-Oct-05</td>
<td>5</td>
<td>29-Oct-09</td>
<td>23</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T9</td>
<td>Filtered</td>
<td>2,613</td>
<td>14</td>
<td>2</td>
<td>1-Jan-06</td>
<td>6</td>
<td>15-Feb-10</td>
<td>22</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T10</td>
<td>Filtered</td>
<td>5,216</td>
<td>4</td>
<td>3</td>
<td>1-Jul-06</td>
<td>8</td>
<td>01-Jun-10</td>
<td>20</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T11</td>
<td>Filtered</td>
<td>2,610</td>
<td>6</td>
<td>2</td>
<td>1-Jul-06</td>
<td>8</td>
<td>01-Oct-10</td>
<td>20</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T12</td>
<td>Filtered</td>
<td>3,669</td>
<td>8</td>
<td>3</td>
<td>1-Oct-06</td>
<td>9</td>
<td>01-Oct-10</td>
<td>19</td>
<td>30-Jun-11</td>
</tr>
<tr>
<td>T13</td>
<td>Filtered</td>
<td>2,506</td>
<td>13</td>
<td>3</td>
<td>1-Oct-06</td>
<td>9</td>
<td>01-Oct-10</td>
<td>19</td>
<td>30-Jun-11</td>
</tr>
</tbody>
</table>
Table 3.2
Sources of data for financial model of cost of a weaned pig.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cull Sow weight</td>
<td>Lbs/head</td>
<td>450</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Feed cost/piglet weaned</td>
<td>$/pig weaned</td>
<td>12</td>
<td>(Center for Farm Financial Management, University of Minnesota, 2012)</td>
</tr>
<tr>
<td>Weaned pig price sold</td>
<td>$/pig weaned</td>
<td>39.32</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Cull gilt price</td>
<td>$/cwt</td>
<td>45</td>
<td>(Stein, 2010)</td>
</tr>
<tr>
<td>Cull sow price</td>
<td>$/cwt</td>
<td>30</td>
<td>(Stein, 2010)</td>
</tr>
<tr>
<td>Replacement gilt purchase</td>
<td>$/head</td>
<td>185</td>
<td>(Stein, 2010)</td>
</tr>
<tr>
<td>Semen Cost</td>
<td>$/dose</td>
<td>7</td>
<td>(Stein, 2010)</td>
</tr>
<tr>
<td>Utilities, fuel, repairs, supplies</td>
<td>$/pig weaned</td>
<td>2.54</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Vet. Medicine</td>
<td>$/pig weaned</td>
<td>2.4</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Trucking &amp; marketing costs</td>
<td>$/pig weaned</td>
<td>0.63</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Prof. fees &amp; contractor misc.</td>
<td>$/pig weaned</td>
<td>2</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
<tr>
<td>Hired labor</td>
<td>$Hr*pig weaned/wk</td>
<td>8.59/52</td>
<td>(Department of Economics, University of Iowa, 2012)</td>
</tr>
</tbody>
</table>
Table 3.3

Comparison of production variables for control and pre-filtered farms periods (mean and SD for quarterly values).

<table>
<thead>
<tr>
<th>Production variable</th>
<th>Control</th>
<th>Pre-filtered</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Farrowing rate %</td>
<td>83.97 ± 4.32</td>
<td>83.57 ± 5.6</td>
<td>0.61</td>
</tr>
<tr>
<td>Weaned piglets/litter</td>
<td>9.9 ± 0.77</td>
<td>9.7 ± 0.72</td>
<td>0.49</td>
</tr>
<tr>
<td>Piglets weaned/sow/year</td>
<td>23.75 ± 2.77</td>
<td>22.97 ± 2.75</td>
<td>0.04*</td>
</tr>
<tr>
<td></td>
<td>44.81 ± 14.83</td>
<td>43.67 ± 13.17</td>
<td>0.59</td>
</tr>
<tr>
<td>Sow mortality %</td>
<td>9.35 ± 2.46</td>
<td>10.11 ± 3.64</td>
<td>0.10</td>
</tr>
</tbody>
</table>

* P value < 0.05
Table 3.4  
Comparison of coefficients for univariate models for dependent variables

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Filtration\textsuperscript{a}</th>
<th>Sites\textsuperscript{b}</th>
<th>Outbreaks\textsuperscript{c}</th>
<th>Winter_quarters\textsuperscript{d}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrowing rate %</td>
<td>4.19*</td>
<td>0.03</td>
<td>-2.8*</td>
<td>-1.86*</td>
</tr>
<tr>
<td>Weaned piglets/litter</td>
<td>0.78*</td>
<td>0.02</td>
<td>-0.49*</td>
<td>-1.46*</td>
</tr>
<tr>
<td>Pigs weaned/sow/year</td>
<td>2.04*</td>
<td>0.03</td>
<td>-2.66*</td>
<td>-0.03*</td>
</tr>
<tr>
<td>Sow culling %</td>
<td>-1.8*</td>
<td>0.01</td>
<td>-1.7*</td>
<td>-0.26</td>
</tr>
<tr>
<td>Sow mortality %</td>
<td>-2.35*</td>
<td>0.05</td>
<td>2.15*</td>
<td>-1.15</td>
</tr>
</tbody>
</table>

* P value < 0.05

\textsuperscript{a} Filtration status in the analysis: control + pre-filtered farm periods vs filtered farm periods. Dichotomous variable

\textsuperscript{b} Sites: Number of pig sites surrounding the sow farm. Continuous variable

\textsuperscript{c} Outbreaks: Presence of a new PRRSV introduction in the PT of the farm under a 5% cut-off

\textsuperscript{d} Winter_quarters: October to March vs April to September. Dichotomous variable
Table 3.5

Intercept and coefficients of multivariate models for production variables.

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Intercept</th>
<th>Filtration&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Winter_quarter&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrowing %</td>
<td>86.97</td>
<td>3.99*</td>
<td>-1.59*</td>
</tr>
<tr>
<td>Weaned piglets/litter</td>
<td>10.45</td>
<td>0.76*</td>
<td>-0.21*</td>
</tr>
<tr>
<td>Piglets weaned/sow/year</td>
<td>24.74</td>
<td>1.91*</td>
<td>-1.03*</td>
</tr>
<tr>
<td>Sow culling %</td>
<td>42.23</td>
<td>-1.81</td>
<td>-</td>
</tr>
<tr>
<td>Sow mortality %</td>
<td>7.44</td>
<td>-2.35*</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> Filtration status: control + pre-filtered (0) vs filtered (1)

<sup>b</sup> Winter_quarters: October to March (1) vs April to September (0)
Figure 3.1 3.1a Diagram of a defined conventional attic filtered farm (negative pressure ventilation). Air entrance via under roof inlets, attic and filters locations and side panel exhausted fans are represented. Red arrows symbolized the movement of the non-filtered air going from the outside to the inside of the facility. Green arrows symbolized the air movement after filtration event in the attic of the facility. 3.1b Diagram of an attic filtered farm combined with a side panel as part of a tunnel ventilation exchange of air system.
Figure 3.2

Filtration investment payback period in years for sensitivity analysis in scenarios 2 (conventional attic air filtration system) and 3 (combination of attic and tunnel ventilation air filtration system). Considering no premium or an equal pig selling price independently of PRRSV status, the payback period was estimated to be 5 years for scenario 2 and 7 years for scenario 3. A $5 differential between both farms in the selling price of pigs with different PRRSV status, the annual cost between filtered and non-filtered control farms was estimated to differ by $1.7, decreasing the payback period to 2.1 and 2.8 for scenario 2 and 3 consecutively.
CHAPTER 4:

AN EVALUATION OF INTERVENTIONS FOR REDUCING THE RISK OF PRRVS

INTRODUCTION TO FILTERED FARMS VIA RETROGRADE AIR MOVEMENT (BACK-DRAFTING) THROUGH IDLE FANS

Published in:

4.1 Chapter summary

Porcine reproductive and respiratory syndrome virus (PRRSV) is an economically significant pathogen of pigs that can be transported via the airborne route out to 9.1 km. To reduce this risk, large swine facilities have started to implement systems to filter contaminated incoming air. A proposed means of air filtration failure is the retrograde movement of air (back-drafting) from the external environment into the animal air space through non-filtered points such as idle wall fans; however, this risk has not been validated. Therefore, the purpose of this study was threefold: 1. to prove that PRRSV introduction via retrograde air movement through idle fans is a true risk; 2. to determine the minimum retrograde air velocity necessary to introduce PRRSV to an animal airspace from an external source; and 3. to evaluate the efficacy of different interventions designed to reduce this risk. A retrograde air movement model was used to test a range of velocities and interventions, including a standard plastic shutter, a plastic shutter plus a canvas cover, a nylon air chute, an aluminum shutter plus an air chute and a double shutter system. Results indicated that retrograde air movement is a real risk for PRRSV introduction to a filtered air space; however, it required a velocity of 0.76 m/s. In addition, while all the interventions designed to reduce this risk were superior when compared to a standard plastic shutter, significant differences were detected between treatments.
4.2 Introduction

The economic impact of porcine reproductive and respiratory syndrome virus (PRRSV) has been recognized worldwide (Neumann et al., 2005). Due to the inability to consistently control the disease and minimize the economic loss through traditional strategies such as vaccination and animal flow, attempts to eliminate the virus have been initiated (Cano et al., 2007). Unfortunately, while elimination of the existing (resident) variant is possible (Torremorell et al., 2003), re-infection of farms through the introduction of new viral variants has been an ongoing challenge and can occur by a number of well-documented routes (Lager et al., 2002). Routes of PRRSV transmission include infected pigs (Wills et al., 1997), contaminated semen (Christopher-Hennings et al., 1995a), vehicles (Dee et al., 2004), insects (Otake et al., 2003), and fomites (Otake et al., 2002b). In addition, airborne transmission has been proven to be an important route of PRRSV spread between farms with recent data demonstrating airborne transport out to distances of 4.7 and 9.1km (Dee et al., 2009; Otake et al., 2010b).

Due to the significance of this latter route in swine-dense regions, air filtration technology has been introduced as an effective method of minimizing the risk of airborne transmission of PRRSV to AI centers and breeding herds (Spronk et al., 2010). This technology was initially validated using a production region model (Pitkin et al., 2009a; Dee et al., 2010b). This research provided a clear understanding of the role of aerosol transmission in the spread of PRRSV, the meteorological conditions associated with this event, as well as evaluated the ability of several commercial filtration systems to protect at-risk populations.
Based on these data, a large number of North American production systems have implemented air filtration systems to reduce the risk of airborne spread of PRRSV (Spronk et al., 2010; Dee et al., 2012). While preliminary results have been promising, concerns have been raised regarding potential causes of failure. One proposed means of failure of filtration in negative pressure ventilated facilities is the introduction of PRRSV-contaminated bioaerosols via retrograde air movement (back-drafting) through non-filtered points, such as idle wall fans (Feder, 2008). Across the majority of North American swine production facilities, mechanical fans are important components of the ventilation system that force the exchange of air to remove heat and gasses in order to create a healthy environment. To accomplish this goal, facilities are operated under negative pressure and have up to 4 to 5 stages of exhaust fans that function according to the temperature in the animal space. When in operation, these fans create a pressure differential between the inside and the outside of the facility (i.e. static pressure). Under conditions of negative pressure ventilation, air will move from areas of high to low pressure; therefore, incoming air will enter through air inlets and/or openings in the building. Since air will follow the path of least resistance, it has been hypothesized that any non-filtered structural openings (i.e. temporally inactive exhaust fans) could serve as points of entry for PRRSV via retrograde air movement. However, the concept has not been proven and the dynamics of this risk factor have not been evaluated.

In addition, several interventions have been developed to reduce this risk by focusing on reducing retrograde air movement through temporally inactive exhaust fans. These interventions include double shutters, air chutes and canvas covers;
however, their efficacy has not been validated to date. Therefore, the objectives of this study were to demonstrate that the risk of PRRSV introduction to filtered farms through retrograde air movement is a true risk; to determine the minimum velocity of air required to successfully transport PRRSV from the external environment into a filtered air space through an idle fan, and to validate commercially available interventions designed to prevent this risk.

4.3 Materials and methods

Description of the retrograde air movement testing model

The study was conducted at the Swine Disease Eradication Center at the University of Minnesota. It utilized a 25m² facility equipped with a filtration system consisting of 6 polypropylene filters having a minimum efficiency reporting value (MERV) of 14 (EU 8) designed to filter all incoming air from the external environment (Pitkin et al., 2009b). The facility was ventilated using a negative pressure system which consisted of a total of two exhaust fans and 6 inlets designed to pull filtered air into the animal air space. The air inlets (30.5cm x 20.3cm) were distributed equally along the north and south walls of the facility. Both fans (4E35-240V, Multifan, Volstermans Ventilation Inc, IL) adapted in a fiberglass frame (54cm x 54cm), had a 30 cm blade diameter and a 1620 rpm motor capacity. Both fans were equipped with a standard plastic shutter and an external hood that are commonly encountered on commercial swine farms. Each of the plastic shutters consisted of 6 movable horizontal slats (42cm x 6.1cm) for emitting air. In order to initiate retrograde air movement through an idle fan,
all of the inlets in the facility were closed and one of the 30cm-fans was intentionally stopped while the other remained in operation resulting in the movement of air from the external environment into the filtered air space via the non-functional fan. Throughout the study, the operational fan (located at the north end of the animal space) ran at a velocity of 104 m/s which generated a negative static pressure of 573 Pa in the room (Fig. 4.1).

**Source of PRRSV aerosol challenge**

To develop a PRRSV-positive aerosol challenge, a previously published means of generating artificial aerosols was used (Dee et al., 2009). For the purpose of this study, 4 different concentrations of the virus were selected, including $1 \times 10^1$ TCID$_{50}$/ml, $1 \times 10^3$ TCID$_{50}$/ml, $1 \times 10^5$ TCID$_{50}$/ml and $1 \times 10^7$ TCID$_{50}$/ml. The artificial PRRSV-positive aerosols were created using a modified live PRRS virus vaccine (Ingel Vac MLV, Boehringer Ingelheim Vetmedica, St. Joseph, MO) in combination with a cold fog mister (Hurricane ULV/mister, Curtis Dyna-Fog Ltd. Westfield, IN) as previously described (Dee et al., 2009). Beginning with $1 \times 10^1$ TCID$_{50}$/ml, the mister was set at a flow rate of 100 mL/min and was placed outside of the facility 45 cm from the external surface of the idle fan (Fig. 4.1).
Protocols of sample collection

For the collection of aerosols in the filtered air space, a liquid cyclonic collector was used (Midwest MicroTek, Brookings, SD) (Cage et al., 1996). This instrument was capable of collecting 450 L of air per minute of operation and was capable of detecting concentrations of PRRSV RNA in aerosols down to a level of $1 \times 10^1$ TCID$_{50}$/mL (Dee et al., 2009). For the purpose of this study, the instrument was housed inside the filtered facility and placed 1.5 m off the floor and 45 cm from the interior of the idle fan (Fig. 4.1). Air samples were collected at 1 min intervals and, during every replicate, the functioning exhaust fan, the cold fog mister and the collector were running simultaneously. In order to recover the aerosolized particles, 5 ml of sterile saline was added to the collection vessel. Upon completion of 1 minute sampling period, all machines were turned off and a 2 mL aliquot of saline was removed from the cyclonic collector vessel, stored in sterile plastic tubes (Falcon tubes, Becton Dickinson, Franklin Park, NJ) and refrigerated prior to testing. All air samples were tested for the presence of PRRSV RNA by the TaqMan polymerase chain reaction (PCR) (Perkin-Elmer Applied Biosystems, Foster City, California, USA) (Egli et al., 2001) at the Minnesota Veterinary Diagnostic Laboratory.

During the complete sample collection period, two investigators (A and B) were involved. Investigator A was located inside the facility and was responsible for the air sampling collection, the retrograde air speed measurements at the intervention level and the operation of the exhaust fan. Investigator B was located outside of the facility and was responsible for operating the cold fog mister. To minimize the risk of
contamination between replicates, the door of the facility remained sealed at all times and a system of signals was used to indicate the start and finish of each consecutive sampling period. After each replicate, the collection vessel was removed by Investigator A, rinsed with sterile saline and dried with an absorbent paper towel. After each concentration, Investigator B rinsed and dried the cold fog mister as previously described.

**Assessment of risk for retrograde movement of PRRSV and determination of minimum air velocity**

In order to prove the risk of retrograde air movement as well as measure the minimum velocity of air required to transport PRRSV from the external environment into the filtered air space, the idle fan was outfitted with a standard plastic shutter consisting of a 40.5cm x 40.5cm framed opening fitted in the wall with 6 movable horizontal louvers (42cm x 6.1cm) for exhausting air. The louvers, rotated to an open position when the fan is operational and air was exhausted out of the building. They collapsed to a closed position when the fan stopped due to negative pressure created by the other fan in the room as well as gravity. Velocity (m/s) of retrograde air movement through the idle fan was measured using an anemometer (DCFM8906, Tech Instrumentation, Inc., Elizabeth, NC, USA) positioned at a distance of 5 cm. The readings were collected at four points (2, 5, 8 and 11 o’clock respectively) around the outer circumference of the fan and one central point. After collecting velocity data at each of these points, the anemometer automatically calculated an average value of the velocity.
readings. Air volume (m³/min) measurements were subsequently calculated. Velocity readings were initiated at the lowest detectable level at a controller reading of 68%, 80%, 85% and 100% of fan capacity across all 4 concentrations of the virus.

**Interventions evaluated**

For the purpose of the third objective of the study, the interventions tested consisted of a plastic shutter plus canvas cover, a nylon air chute, an aluminum shutter plus a nylon air chute, and a double shutter system involving aluminum and a plastic shutter. A description of each intervention is provided below.

- **Plastic shutter plus canvas cover**

  In addition to the standard plastic shutter, this intervention included a canvas (Tyvek, DuPont, Wilmington, DE) that covered the external fan opening within the fan housing. Equipped with wooden counterweight along its distal border, the cover was attached along the top of the fan housing and opened when the fan was running to allow the exhausted air to leave the room (Fig. 4.2a). In contrast, when the fan was idle, the negative static pressure and the counterweight caused the canvas cover to collapse against the external surface of the fan housing in an effort to seal the opening and reduce retrograde air entry through the shutter (Fig. 4.2b).
• **Nylon air chute**

This intervention consisted of an air chute (35cm diameter x 71cm length) manufactured for the purpose of the study (Ag Property Solutions, Emmetsburg, IA, USA). Made of light weight strong ripstop nylon, it was attached to the external fan opening which inflated when exhausted fan air passed through it (windsock effect) (Fig. 4.3a). Upon cessation of air movement, the chute collapsed against the exterior fan housing (Fig. 4.3b).

• **Aluminum shutter plus air chute**

This intervention incorporated an internal aluminum shutter (56.5cm x 56.5cm) (Biosecure Air Inc, Fairmont, MN, USA) in combination with an external nylon air chute (Fig. 4.4b). The internal shutter system consisted of 5 horizontal slats housed within an aluminum frame that was fitted into a wooden frame on the inside wall of the facility (Fig. 4.4a).

• **Double shutter system**

This intervention consisted of a combination of the standard plastic external shutter (Fig. 4.5b) and an internal aluminum shutter (Biosecure Air Inc, Fairmont, MN, USA) (Fig. 4.5a). Both shutters operated in concert with one another.
Controls

A set of positive and negative controls were conducted to enhance the rigor of the experimental design. The objective of the positive controls was to prove that a PRRSV-positive aerosol could be transported from the external environment into the facility air space through the idle fan, in the absence of any intervention. A set of 2 positive controls, across all 4 virus concentrations and static pressure levels were conducted during each phase of the study. The purpose of the negative controls was to ensure the lack of viral contamination via aerosol, fomites or personnel inside the facility, during the entire process and prior each phase of the study. The process of aerosol generation and collection was repeated using virus-negative aerosols (i.e. sterile saline) that were transferred through the idle fan into the air space of the facility in the absence of any intervention.

Data analysis

For the purpose of the statistical analysis, each 1 minute collection period was considered to be a replicate. Ten replicates of each concentration of the virus were conducted across the 3 objectives. This sample size allowed for detection of a 30% infection rate and 80% of power in the study with an alpha level of 0.05. For the purpose of the efficacy evaluation all interventions results were compared with the common plastic shutter. In addition, the difference in the proportion of PCR-positive air samples between the different interventions applied in the idle fan compared with the plastic shutter alone were analyzed by a two-tailed Fisher’s exact test.
4.4 Results

**Validation of Retrograde air movement through the common plastic shutter**

The results of the retrograde air movement validation are summarized in Table 4.1. In summary, across all 4 concentrations tested, PRRSV RNA positive air samples were detected within the filtered air space, indicating the movement of virus via retrograde air entering through the idle fan. During this assessment, the average velocity recorded across the 5 measurement points of the idle fan was 0.76 m/s at 573 Pa. In contrast, PRRSV RNA was not detected in any of the negative control samples, indicating a high level of sanitation and sampling quality across all replicates.

**Determination of minimum air velocity required for retrograde movement of PRRSV**

The results of this phase of the study are presented in Table 4.2. As seen in objective 1, a minimum velocity average of 0.76m/s was needed to transport PRRSV from the external source into the animal airspace through the plastic shutter. In contrast, all samples collected across the other velocities (0.61 m/s, 0.51 m/s and 0.41 m/s) tested were PCR negative (Table 4.2).

**Evaluation of interventions**

Results from this section are summarized in Tables 4.3 and 4.4. Again, as seen in objectives 1 and 2 retrograde air movement was only detected when the standard plastic shutter was employed (Table 4.3). In addition, across all concentrations, all interventions tested significantly reduced the number of positive samples compared to
the plastic shutter alone (Table 4.4). The plastic shutter/canvas cover intervention significantly reduced the number of positive air samples when compared to plastic shutter alone at concentrations of $10^1$, $10^3$, and $10^5$ ($p = 0.01$, $p < 0.005$, $p < 0.005$ respectively). However, at the highest concentration of $10^7$, the difference was not significant. In contrast, all air samples collected in the animal airspace were PRRSV RNA negative when either the Nylon air chute, aluminum shutter plus nylon air chute or the double shutter system were employed (Table 4.4). These differences were significant ($p < 0.05$) when compared to the standard plastic shutter.

4.5 Discussion

The risk of airborne introduction of PRRSV has catalyzed rapid adaptation of air filtration across the North American swine industry. Due to the cost of such systems, it is important that we clearly understand how to maximize their success and the return on investment. Therefore, we took the position that determining whether retrograde air movement through idle fans is a true risk, the minimum air velocity required to facilitate this risk and whether commercially available interventions designed to minimize this risk are efficacious is important. Under the conditions of this study, our data indicated that retrograde air movement is a real risk for the introduction of PRRSV to a swine facility; however, it requires a minimum velocity of air for it to occur. This information is important for it justifies that a plan to manage retrograde air movement through inactive wall fans is critical for the long-term success of air filtration programs. The finding surrounding the minimum air velocity required for retrograde air movement to
occur in our opinion was not surprising, for it is logical that a standard plastic shutter can provide some level of protection. This assumption is validated by the results of the positive controls where retrograde air movement of PRRSV occurred across all concentrations in the absence of an intervention. However, it clearly can be overwhelmed as these interventions are by no means designed to be “air tight”. Another advantage of this information is that due to the fact that a minimum velocity has been calculated, swine veterinarians can now accurately measure retrograde air movement through idle fans on filtered farms using an anemometer and assess the level of risk. For the first time, the measurements of the anemometer used for the study are communicated and a practical approach is presented for practitioners to study and evaluate this event. The authors have practiced this approach on several commercial filtered sow farms and found that in situations where proper interventions are in place, retrograde air movement of 0.76m/s can be completely prevented. In contrast, if interventions are lacking or damaged, air leaks demonstrating velocities greater than or equal to 0.76m/s are frequently detected.

In addition, our data demonstrated significant differences in the ability of several commercially available interventions to reduce retrograde air risk. Specifically, the double shutters (plastic and aluminum), the air chute alone, and the aluminum shutter plus an air chute were superior to the combination of plastic shutter and canvas cover. One potential reason for the inability of the shutter and canvas intervention to perform equally may be the effect of “cross winds”, which, when observed during our study, caused the covers to move away from the exterior housing exposing the standard
shutter to aerosolized virus challenge. This information is valuable for swine veterinarians and producers now have data to use when making decisions regarding which intervention to select. In addition, it will help the industry manage their expectations if only one intervention is possible due to fan design, i.e. the presence of exterior hoods which without modification would eliminate the air chute option. Now that this is understood, facilities with this type of fan design can apply double shutters or even remove the hoods to allow for air chute application.

However, as all studies, our experiment possessed acknowledged limitations, including the inability to test the interventions on an actual farm, the use of artificial PRRSV aerosols at potentially non-representative concentrations and conditions involving a limited range of static pressures and air velocities (Pohl, S., 2009). However, our decision was validated by the fact that the transport of PRRSV via retrograde air movement only occurred at a specific level of pressure and velocity (Table 4.2). Clearly, further studies should be conducted to address these limitations and better understand whether the interventions can function properly under commercial conditions.

In summary, this is the first study to scientifically evaluate the risk of retrograde air movement and the ability of commercially available products to reduce this risk. As a result, the information derived from this study helps to advance our understanding of how producers and veterinarians can enhance the success of air filtration systems in order to prevent sustainable freedom from PRRSV infection. Air filtration is a valuable tool and a significant investment that needs to be managed, ensured, and protected
with the support of adequate research. Focusing on biosecurity risks associated with the movement of retrograde air is an important step in protecting this investment.
Table 4.1

Summary of results from the assessment of retrograde air movement through the plastic shutter (proof of concept) and its respective controls across the range of viral concentrations used for challenge. Results are shown as number of PCR positive air samples detected / total number of samples tested.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>$10^1$TCID$_{50}$/ml</th>
<th>$10^3$TCID$_{50}$/ml</th>
<th>$10^5$TCID$_{50}$/ml</th>
<th>$10^7$TCID$_{50}$/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic shutter</td>
<td>10/10</td>
<td>10/10</td>
<td>9/10</td>
<td>10/10</td>
</tr>
<tr>
<td>Controls +</td>
<td>2/2</td>
<td>2/2</td>
<td>2/2</td>
<td>2/2</td>
</tr>
<tr>
<td>Controls -</td>
<td>0/2</td>
<td>0/2</td>
<td>0/2</td>
<td>0/2</td>
</tr>
</tbody>
</table>
Table 4.2

Summary of results for the determination of the minimum retrograde air velocity required for PRRSV entry across the range of viral concentrations and the respective controls. Results are shown as number of PCR positive air samples detected / total number of samples tested.

<table>
<thead>
<tr>
<th>Fan capacity (%)</th>
<th>Retrograde air velocity (m/sec)</th>
<th>Static pressure (Pa)</th>
<th>(10^1) TCID\text{_{50}}/ml</th>
<th>(10^3) TCID\text{_{50}}/ml</th>
<th>(10^5) TCID\text{_{50}}/ml</th>
<th>(10^7) TCID\text{_{50}}/ml</th>
<th>+ controls</th>
<th>- controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.76</td>
<td>573</td>
<td>10/10</td>
<td>10/10</td>
<td>10/10</td>
<td>10/10</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>85</td>
<td>0.61</td>
<td>448</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>80</td>
<td>0.51</td>
<td>348</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>68</td>
<td>0.41</td>
<td>12.4</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>2/2</td>
<td>0/2</td>
</tr>
</tbody>
</table>
Table 4.3

Summary of the range of retrograde air velocities and static pressures measured during the assessment of different interventions.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Velocity (m/s)</th>
<th>Volume (m3/min)</th>
<th>Static Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic shutter alone</td>
<td>0.76</td>
<td>3.4</td>
<td>573</td>
</tr>
<tr>
<td>Plastic shutter + Canvas flap</td>
<td>&lt; 0.41*</td>
<td>NA</td>
<td>573</td>
</tr>
<tr>
<td>Air chute</td>
<td>&lt; 0.41</td>
<td>NA</td>
<td>573</td>
</tr>
<tr>
<td>Aluminum shutter + Air chute</td>
<td>&lt; 0.41</td>
<td>NA</td>
<td>573</td>
</tr>
<tr>
<td>Double shutter (Plastic + Al.)</td>
<td>&lt; 0.41</td>
<td>NA</td>
<td>573</td>
</tr>
</tbody>
</table>

*The canvas cover intervention did not maintain its sealed position during the challenge due to the effects of external crosswinds. Although retrograde air movement was occurring, it was not sustained and could not be detected by the anemometer during reading time.
Table 4.4

Summary of the evaluation of the tested interventions designed to reduce the risk of retrograde air movement and PRRSV introduction. The results are shown as number of PCR positive air samples detected / total number of samples tested.

<table>
<thead>
<tr>
<th>PRRSV concentrations</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^1$ TCID$_{50}$/mL</td>
<td>10/10</td>
<td>4/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>$10^3$ TCID$_{50}$/mL</td>
<td>10/10</td>
<td>3/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>$10^5$ TCID$_{50}$/mL</td>
<td>9/10</td>
<td>3/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>2/2</td>
<td>0/2</td>
</tr>
<tr>
<td>$10^7$ TCID$_{50}$/mL</td>
<td>10/10</td>
<td>6/10</td>
<td>0/10*</td>
<td>0/10*</td>
<td>0/10*</td>
<td>2/2</td>
<td>0/2</td>
</tr>
</tbody>
</table>

A: Plastic shutter
B: Plastic shutter plus canvas cover
C: Nylon air chute
D: Aluminum shutter plus nylon air chute
E: Double shutter system plastic-aluminum
+
-: Positive controls
-: Negative controls
*: significantly different when compared to plastic shutter alone (A) (p<0.05)
Figure 4.1

A diagram of the retrograde air movement testing model utilized in the study, depicting the release of PRRSV-positive artificial aerosol from the outside of the facility, the location of the exhaust fan, the location of the treatments/idle fan, and the placement of the cyclonic collector during the collection of air samples.
**Figure 4.2**

The combined plastic shutter and canvas intervention.

**Fig. 4.2a.** External view of the intervention, with the canvas open during the exhausting of air.

**Fig. 4.2b.** External view of the intervention, with the canvas collapsed over the housing of the idle fan secondary to the elevated static pressure of the filtered facility.
Figure 4.3

Nylon air chute intervention.

**Fig. 4.3a** External view of the intervention, with exhausted air passing through the nylon material producing the windsock effect.

**Fig. 4.3b** External view of the intervention, with the air chute collapsed against the opening of the fan due to the elevated static pressure of the filtered facility.
Figure 4.4

The combined aluminum shutter and air chute intervention.

**Fig. 4.4a.** Internal view of the intervention, demonstrating the aluminum shutter in a closed position.

**Fig. 4.4b.** External view of the intervention, demonstrating the air chute collapsed against the fan housing.
**Figure 4.5**

The double shutter intervention.

**Fig. 4.5a.** Internal view of the intervention, demonstrating closure of the aluminum shutter.

**Fig. 4.5b.** External view of the intervention, demonstrating the plastic shutter with closed louvers due to elevated static pressure in the filtered facility.
General discussion

Aerosol transmission is an important mechanism of disease spread for several significant diseases in the swine industry. Specifically for PRRSV, it has seriously delayed the eradication efforts across North America for a number of years. While elimination of PRRSV is possible on an individual farm basis, the economic impact of re-infection has driven the industry to implement additional biosecurity measures such as incoming air filtration systems in large breeding herds. While preliminary results seemed very promising during the laboratory and experimental research phases of this method, concerns have been raised regarding potential causes of failure after its implementation in these breeding herds. Therefore, the general objective of this thesis was to evaluate the impact of air filtration systems in reducing the risk of PRRSV outbreaks in large sow herds located in a dense swine region of North America.

The thesis consisted in 4 chapters. The first half part of chapter 1 provided a comprehensive literature review of the nature of aerosols as well as 5 of the most important infectious diseases that can be transmitted as bioaerosols. Aerobiology is a branch of biology that focuses on the sources, dispersal, and deposition of airborne biological particles. Aerosol generation, aerosol transport and aerosol ‘landing’ (i.e. the process involving inhalation and deposition of airborne particles in susceptible animals) are the three steps that have been generally reviewed for disease airborne transmission to occur. Following this general introduction, the etiology, epidemiology, pathogenesis, clinical signs, prevention and control strategies have been summarized for 5 of the most
important swine diseases using the most recently published work within each field. Special effort has been made to highlight the information regarding airborne transmission for each of the diseases. Veterinary researchers are not fully specialized in this field and further studies are needed to fill the gaps in the literature for some of these swine diseases in regards to occurrence, distance, and quantities of airborne infectious particles.

Since a main objective of this thesis was the evaluation of the economic impact of air filtration systems in large sow farms as a biosecurity measure, the goal of the second part of chapter 1 was to review the majority of studies regarding the cost-benefit of biosecurity interventions related to the prevention of infectious diseases into swine herds as well as other animal production industries. The author’s review of this field revealed that only a very small number of these biosecurity interventions have been economically evaluated. In general, completing an objective biosecurity evaluation is not a simple task. However, it is one of the most important strategies that we need to address to prevent disease introduction. As discussed in this chapter, biosecurity interventions are very difficult to evaluate due to farm level determinants and the lack of research regarding the exponential aspect of the disease risk (not linear) and the compliance of all the people involved in the activity. It is important to note that there is no such thing as “zero risk” if the mechanism is present. Therefore, in biosecurity there is never a complete failure or a complete success. We need to always talk in terms of risk reduction. In the summary of this chapter, several strengths and weaknesses of these studies have been generally analyzed.
Following the identification of some of these gaps in knowledge, the evaluation of filtration systems was designed. Chapters 2 and 3 provided an epidemiological and economic analysis of the intervention based on the performance of large breeding herds under filtration when compared with non-filtered farms. The overall findings of chapter 2 confirm that air filtration systems significantly reduce the frequency of the introduction of novel PRRSV isolates into breeding herds. A group of 37 farrow-to-weaned selected sow farms, approximately 123,000 sows in total, were enrolled for the epidemiological study. The geographic distribution of these farms, the 3 swine veterinary clinics that serviced these farms and, for filtered farms, the different types of filters and filtration systems that they had in place, were a representative sample of what is present in the field.

The case definition of new virus introduction was a key aspect of the study. For that reason, we utilized a standardized evaluation strategy for all farms. The percentage ORF5 sequence dissimilarity in dendrograms and matrix were strictly evaluated and applied by the author and different cut-offs values (2%, 3%, 5% and 10%) were used to define the detection of new PRRSV introduction in the farm. The calculation of incidence rate (IR) and relative risk (RR) for these farms by this standardized approach differentiated this study with previous studies (Dee et al., 2012). The concept of virus evolution and rate of viral change was examined using the sensitivity analysis of various sequence difference cut-offs from the risk assessment. Misclassification of viral origin (endogenous vs. exogenous) while evaluating air filtration strategies is a concern that is very present among practitioners and that we have tried to address in our study. As
mentioned in our work, further studies are needed in large populations of animals to better understand important RNA virus changes and evolutionary pressure.

Chapter 3 was designed to accompany the previous epidemiological study and to further analyze the impact of air filtration systems. For this study, a subgroup of the previous farms made their production data available. This data was used to determine the potential productivity differences and to model the economic impact of the two filtration intervention options through the use of a partial budget analysis. Results from this study demonstrated that, farms under air filtration, had significantly improved productivity when compared with control farms and the payback period reflected this economic impact.

As an introduction of this chapter, the potential economic losses resulting from a PRRSV outbreak were reviewed as outlined in previous studies (Neumann et al., 2005; Holtkamp et al., 2011). The review revealed that up to 55% of the total outbreak losses in 2011 were due to the effect of PRRSV in the growing herd. In our study, based only on real production data of breeding herds, we wanted to understand this important piece of the puzzle. We studied the sensitivity of difference in weaned pig selling price of these farms in order to evaluate the payback period for the investment. We linked this part of the study with the results of our previous epidemiological work on new PRRSV isolate introductions. It was calculated that filtered farms could expect to produce PRRSV negative pigs 93% of the times and unfiltered farms 58% of the times. Consequently, it was calculated that the 5 and 7 year investment payback period for
scenarios 2 (i.e. attic filtration) and 3 (i.e. combination attic and tunnel filtration) could be decreased to 2 and 3 years respectively.

Production data improvements in filtered farms, when compared with non-filtered farms, could not be directly compared with the production impact of the disease determined in previous studies (Polson et al., 1992; Neumann et al., 2005; Holtkamp et al., 2011). In contrast, the objective of our study was to estimate the productivity benefits of a biosecurity intervention. To accomplish this objective, we obtained the modeled improvement of this difference in productivity between two time periods (i.e. one with and one without the intervention) and added the control data to the pre-filtered periods. Farms from both of these periods experienced outbreaks so the comparison could not be equivalent to the presence or complete absence of the disease in either specific scenario.

Overall, chapter 2 and chapter 3 utilized both analysis approaches, epidemiological and economic, in order to assist farmers make a sound decision regarding the potential implementation of this biosecurity intervention strategy.

Chapter 4 identified and analyzed one of the most important concerns that has been raised regarding the potential failure of filtration as a biosecurity intervention. As mentioned before, there is never “zero risk” of new PRRSV introduction into filtered facilities. In fact, filtered farms have experienced PRRSV outbreaks after filters were installed. The introduction of the PRRSV via retrograde movement of non-filtered air through different entry points in these farms needed to be proven and studied.
Improperly covered idle fans were one of these important risk points for virus entry. Results from this study demonstrated the following new knowledge:

1. There is a risk of PRRSV introduction into filtered farms via retrograde air movement through idle fans.

2. Under the different static pressure scenarios we determined that there is a minimum retrograde air movement required to successfully transport the PRRSV from the external environment into a filtered facility through an idle fan covered by a standard plastic shutter.

3. Some of the interventions that are applied in the field to prevent this risk do not provide full protection.

The fact that filtered farms are ventilated under negative pressure raised the important need to better understand the relationship between the static pressure effect (sometimes higher than expected) in these facilities and the potential risk of PRRSV introduction via retrograde air movement through non-filtered entry points as a path with the least resistance (e.g. structural breaks in walls, poorly sealed doors and windows, idle fans, etc.). To simulate potential retrograde air movements through idle fans, we created a filtration scenario in a 25 m² facility. Static pressure and air retrograde air velocity were measured. The important limiting factors of the study included: 1) the use of an aerosol generator to produce PRRSV aerosols that were potentially non-representative of typical particle size and concentration, 2) the use of measurement tools for static pressure and air velocity that were limited in their
sensitivity. Clearly, further studies should be conducted to address these limitations in order to better understand this risk and the interventions under commercial conditions.

In conclusion, this thesis provides a strong analysis of the impact of incoming air filtration systems when installed and applied in large breeding herds that should help both producers and practicing veterinarians when deciding on how to best control PRRSV in breeding swine herds. Based on our study, 80% of new PRRSV introductions into non-filtered herds in swine dense regions with good biosecurity could be prevented with the use of air filtration and the overall improved biosecurity associated behaviors. The information derived from this study helps to advance our understanding of how we can enhance the success of preventing airborne transmission of this infectious disease and the subsequent re-infection with this devastating virus.
General conclusions

1. Air filtration systems significantly reduce the frequency of novel PRRSV introductions into large breeding herds in swine dense regions

2. Filtered farms had a significant improvement in productivity when compared with non-filtered farms

3. The increase of the percentage of time producing negative pigs increases the profitability analysis of this investment

4. Retrograde air movement of air that is potentially contaminated with PRRSV through idle fans is a real risk for virus introduction into filtered facilities
References


Dee, S., Joo, H.S., Pijoan, C., 1995. Controlling the risk of PRRSV in the breeding herd through management of the gilt pool. J. Swine Health Prod. 3 (2), 64-69.


Dee, S., Deen, J., Cano, J., Batista, L., Pijoan, C., 2006. Further evaluation of alternative air-filtration systems for reducing the transmission of porcine reproductive and respiratory syndrome virus by aerosol. Canadian journal of veterinary research 70, 168-175.


Dee, S., Otake, S., Deen, J., 2010. Use of a production region model to assess the efficacy of various air filtration systems for preventing airborne transmission of porcine reproductive and respiratory syndrome virus and *Mycoplasma hyopneumoniae*: Results from a 2-year study. Virus Res. 154, 177-184.


